



THE INTEGRATED
RANGELAND FIRE
MANAGEMENT
STRATEGY ACTIONABLE
SCIENCE PLAN



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The Integrated Rangeland Fire Management Strategy Actionable Science Plan

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The Integrated Rangeland Fire Management Strategy Actionable Science Plan

Executive Summary

The Integrated Rangeland Fire Management Strategy (hereafter Strategy, DOI 2015) outlined the need for coordinated, science-based adaptive management to achieve long-term protection, conservation, and restoration of the sagebrush (*Artemisia* spp.) ecosystem. A key component of this management approach is the identification of knowledge gaps that limit implementation of effective strategies to meet current management challenges. The tasks and actions identified in the Strategy address several broad topics related to management of the sagebrush ecosystem. This science plan is organized around these topics and specifically focuses on fire, invasive plant species and their effects on altering fire regimes, restoration, sagebrush and greater sage-grouse (*Centrocercus urophasianus*), and climate and weather.

The Strategy calls for the development of an actionable science plan (Plan hereafter) with prioritized research needs. For the purposes of this plan, “actionable” is defined three ways. First, the science community is able to take immediate actions to fill the identified science gaps. Second, science outcomes provide information that could directly inform actions taken by managers to protect, conserve, or restore the sagebrush ecosystem. Third, the Plan outlines the actions to facilitate the process of funding and implementing research efforts and effectively communicating research results to the management community. This definition of “actionable” is responsive to the tasks identified in the Strategy related to Science and Research (DOI 2015, Section 7(b)viii).



Toward these goals, the priority science needs identified in this Plan represent a shared vision of the near-term science needed to inform another generation of management strategies and tools. The list of needs was developed by considering the science planning and prioritization efforts conducted in the past 5 years by Federal and State agencies (Appendix Table 1). A compiled list of needs was prioritized in open sessions during which a group of managers and researchers provided input. A team of experts then developed narratives describing the selected highest-priority needs. These narratives are the main component of this Plan. Each narrative contains background information about the science need, explores recent science and syntheses associated with that need, discusses management-relevant science gaps that remain and are pertinent to the prioritization of the need, and outlines a series of short-term (1 to 3 years) and long-term (greater than 3 years) actions for development of new knowledge, syntheses, or decision-support tools.

Agency leadership and program managers should be familiar with the “next-steps” section of each narrative and take action to assure (i) synthesis of existing knowledge is easily accessible and applicable in a management context; (ii) tools are available to put new or existing knowledge in hands of on-the-ground managers and resource specialists; (iii) new research is initiated where information is lacking or questions still remain; and (iv) similar proposals are reviewed for overlap or redundancy.

Completing the science to address the priority needs outlined in the Plan will require an inter-agency, integrated approach and teamwork. Science and management partnerships will be necessary to ensure that questions are addressed in a management-relevant manner and appropriate data are available for analysis. Funding and other resources will need to be devoted to the high-priority science, which may hinge on an understanding that priorities in this Plan represent a shared vision of science priorities in coming years. Even with commitment of new or directed resources, funding all of the priority needs will be challenging. Proper sequencing of research and funding to maximize the knowledge gained will be important, as will be systematic tracking and sharing of information about science activities and resources involved. Steps to ensure the availability of funds may include integrated departmental and bureau-level planning for Plan implementation through a commitment to long-term budget activities. This could include development of an annual budget request involving multiple bureaus and focused on Plan implementation. In multiple ways, teamwork and partnerships are essential to achieve success. Science-based management that addresses rangeland fire, invasive plant species, and other threats to the sagebrush ecosystem is an essential and ultimate goal. The actionable science outlined in this Plan provides a blueprint for success in achieving that goal and ultimately protecting, conserving, and restoring the sagebrush ecosystem upon which so many ecological and socioeconomic outcomes depend.

Introduction

Long-term success of management efforts in the sagebrush (*Artemisia* spp.) ecosystem (Figure 1) relies largely on minimizing human-caused threats and the risk of altered rangeland fire regimes resulting from the establishment of nonnative annual grasses in the understory, while creating and restoring landscapes that are resistant to invasive plant species and resilient to disturbance. The development of strategies to achieve this success depends on application of the best available science, identification of gaps in scientific knowledge relevant to management, and implementation of a science-based adaptive management approach. In the past five years, Federal and State agencies have made considerable strides identifying and prioritizing science needs for suppressing uncharacteristic rangeland fire, controlling invasive plants, and restoring sagebrush-steppe ecosystems. Considerable research is underway to address rangeland health, habitat, and fire effects, including invasive plant management. Despite these efforts, a large number of knowledge gaps exist, and this information is needed to address management objectives associated with fire dynamics and the rehabilitation and restoration of the sagebrush ecosystem, especially in the face of climate change. In response to this need, the Integrated Rangeland Fire Management Strategy (Strategy hereafter; DOI 2015) calls for the development of an actionable science plan (Plan hereafter) of prioritized research needs.

The intent of this Plan is to describe “actionable” science (Beier et al. 2015). The Plan is actionable in three ways. First, the Plan provides a set of prioritized research needs that can be acted upon by the scientific community. Second, the science needs in the plan, once met, will provide information that can directly inform actions taken by both fire management and natural resource managers which focus on protection, conservation, or restoration of the sagebrush ecosystem. Third, the Plan outlines a set of actions to facilitate the process of funding the identified science needs, implement research efforts, and effectively communicate research results to managers and stakeholders. Implementation of the Plan will (i) enhance the delivery of current scientific information to managers; (ii) provide support to managers in interpretation of the science; (iii) allow for feedback between managers and researchers to identify new research needs based on both emerging issues and field results; and (iv) assure development and delivery of tools and services needed by managers to use the science.

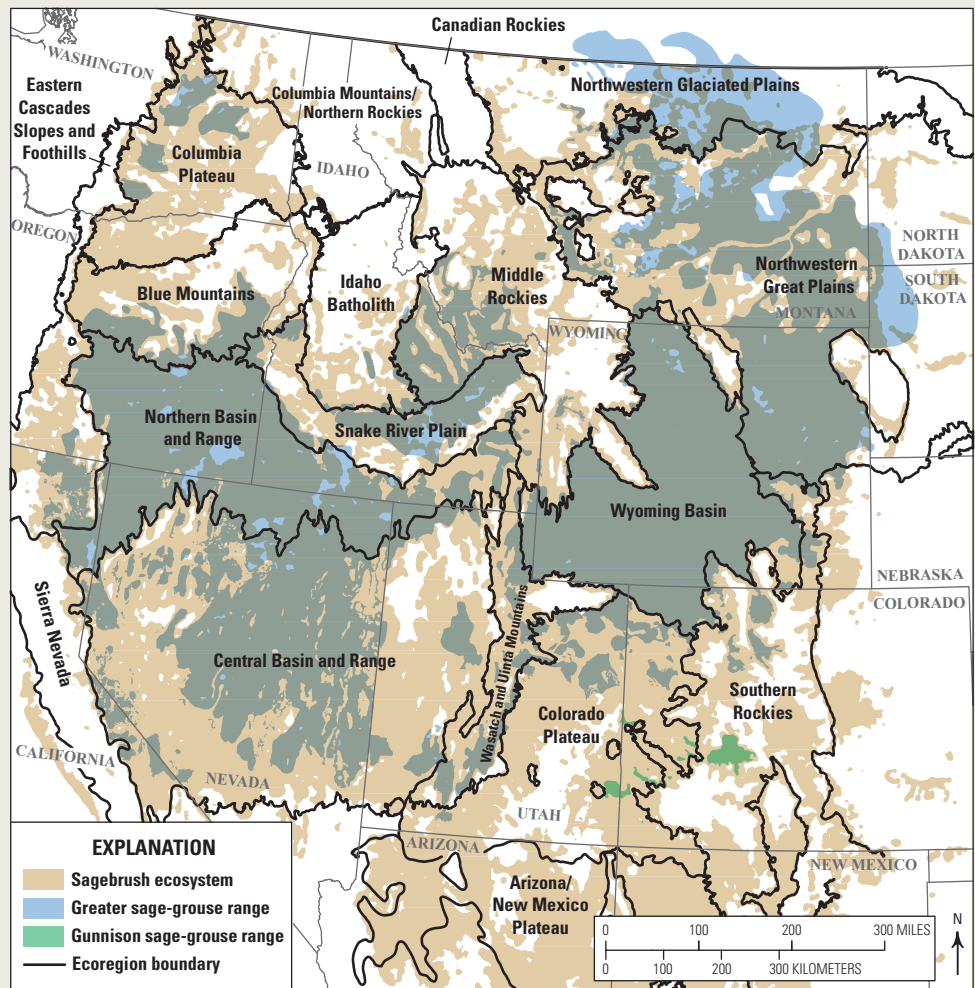


Figure 1. Location of the sagebrush ecosystem and distribution of greater and Gunnison sage-grouse in the western United States. U.S. Environmental Protection Agency Level III ecoregions are labeled on the map.

This Plan was developed by leveraging work already done by Federal and State agencies to identify science needs. Existing planning documents and recently completed science plans were reviewed, and a comprehensive, up-to-date list of science needs was gleaned from them. With engagement of research and management communities, a set of high-priority needs was selected from that list, and the steps to address those priorities were described. This process focused on science needs within the Great Basin, where invasive plant species and fire are primary ecosystems threats, but recognized the needs are broadly applicable to the entire sagebrush ecosystem.

The organizational structure of this Plan is straightforward. It consists of a description of the steps taken to derive the science priorities. For each priority, a narrative describes background information about each science need, a short review of recent science and syntheses for each science need, a discussion of management-relevant science gaps that led to the prioritization of each need, and a series of short-term and long-term steps for development of new knowledge, syntheses, or decision-support tools. Short-term is considered to be a period of 1 to 3 years, and long-term is considered to be greater than 3 years. The priority science needs are categorized into five topics outlined in the Strategy: fire, invasive plant species, restoration, sagebrush and greater sage-grouse (*Centrocercus urophasianus*; hereafter sage-grouse), and climate and weather. Steps for implementation follow the narratives.

Process

Review of existing work was an important consideration in developing the Plan. In response to Section 7(b)viii, Action Item #2 of the Strategy, the U.S. Geological Survey (USGS) initiated a review of existing publications and Federal and State strategies and reports to identify previously stated science gaps and research needs related to fire, invasive plant species, sagebrush, sage-grouse, restoration practices, and climate impacts. Thirty-two sources (Appendix Table 1) were searched for references to science and research needs by a multi-agency team (Document Review Team). This search yielded a list containing 512 expressed needs. The list was then refined by organizing needs into topical areas, standardizing language, and removing duplicate needs. A refined list of 314 science needs was then delivered to the Section 7(b)viii, Action Item #3 team (Science Plan Team), and that team further reduced the list by combining similar needs and removing those that were either “not actionable” (that is, had little management applicability) or “not science” (that is, any need specific to development of plans or strategies). The new list of needs was then reviewed by the representatives tasked with implementation of the 83 Action Items outlined in the Strategy. Their specific charge was to identify any additional science needs beyond those identified. The result was a list of 149 science needs (Appendix Table 2).

The next step was to engage stakeholders. A series of town-hall-style prioritization sessions were convened to select a set of highest-priority needs from the full list of 149 science needs. Extensive outreach occurred to engage a broad spectrum of stakeholders in this process. An estimated 1,000 individuals were notified and invited to participate by invitations distributed through the Great Basin Fire Science Exchange and other websites, Federal agency networks, and by notifications in community email lists, including those of the Great Basin and Great Northern Landscape Conservation Cooperatives (LCCs), Western Association of Fish and Wildlife Agencies (WAFWA), and other community partners. Approximately 100 individuals participated in the sessions.

Two discussion sessions were held for each of three broad topics of science needs (Invasives and Fire; Restoration; and Sagebrush, Sage-Grouse, and Climate). The sessions were 2 hours in length, interactive, and web-based. Each session covered the full list of questions for the topic, so participants only needed to attend one session per topic. Science needs were presented in blocks of three to nine needs at a time, and participants were asked to read all of the needs in a subset and then select what they considered to be the highest-priority need. Participants also were asked to submit comments supporting their selections based on their knowledge of management needs, scientific expertise, or both. They also were asked to submit information about the state of the science and to report any knowledge of ongoing research addressing the science needs. After prioritization of the needs within each block, a final prioritization round was conducted for those needs that received the most selections during the first round. This allowed participants to evaluate across the set of prioritized needs within each topic and for the session organizers to gather additional information about participants’ highest interests among the needs presented.

The input from these sessions was compiled by a Science Plan Team for selection of the highest-priority needs for inclusion in this Plan (Appendix Table 2). Two criteria guided what the Science Plan Team selected. A science need had to have received at least 20 percent of the combined vote of the two topic sessions, and the science need had to have been selected as a priority during the final prioritization round. The final list of 42 needs that met these criteria was then provided to a multi-disciplinary team of contributors from the research and management community (Content Contributors). Their charge was to develop a narrative outlining the background, recent science and synthesis, existing science gaps, and next steps for each need. During development of these narratives, it was determined that five of the needs would not be addressed as narratives because they overlapped significantly with others or were addressed in the overall science plan. In the end, 37 narratives were selected and addressed in the Plan (Table 1). The full Plan was sent out for colleague and technical review (Appendix Table 3) and revised accordingly.

Table 1. List of 37 priority science needs in the areas of fire, invasive plant species, restoration, sagebrush and sage-grouse, and climate and weather.

Topic	Need
Fire	<p>Determine the relationship between fire and the sagebrush ecosystem including fire-return intervals, post-fire recovery, fire behaviors, fuel accumulation, ignition sources, frequency of ignition events, and patterns of variation in all of these factors among regions to help inform habitat management and conservation.</p> <p>Assess changes in greater sage-grouse demographic rates, including (i) survival, reproductive success, and movement patterns in response to burned areas and (ii) the interactive effects of fire or treatment size and timing on the response of sage-grouse individuals and populations.</p> <p>Develop spatial risk analysis relative to conservation of greater sage-grouse habitat through mapped projections of fire probability to develop strategic approaches and aid in targeting of pre-suppression and suppression efforts.</p> <p>Determine the community and species-specific responses to fuels management treatments (e.g., conifer removal) in both a short- and long-term context.</p> <p>Assess the effects of fuel treatments, installation of fire breaks, and similar manipulation of fuels and (or) landscape patterns intended to reduce wildfire spread and burn intensities on greater sage-grouse habitat use, movement patterns, and population trends to help minimize the potential detrimental effects of fire-risk reduction measures to the species.</p> <p>Assess the long-term effects of sagebrush reduction treatments on hydrology, geochemical cycling, vegetation, wildlife (e.g., greater sage-grouse), fuels, fire behavior, and economics.</p> <p>Assess the role of fire in maintaining healthy sagebrush communities by identifying the balance between loss of intact sagebrush and recovery of young sagebrush required for habitat maintenance for different regions, communities, and ecological types.</p> <p>Determine which fuel breaks have met the objective of preventing fire spread or fire severity, and determine the characteristics of those that are successful, including synthesis of the literature, critical evaluation of techniques and plant materials used in fire breaks (species, structure, placement, and native versus nonnative species), and economic tradeoffs.</p>
Invasive species	<p>Improve understanding of the natural and anthropogenic factors that influence invasive plant species distributions, including invasion history, surface disturbance, habitat condition, and fire history, and determine whether those factors can help identify tradeoffs among alternative management approaches.</p> <p>Improve measures for prevention, eradication, and control of invasive plant species, and use risk assessments to weigh potential benefits and deleterious effects of different measures on native plant species.</p> <p>Conduct invasive plant inventory, including spatial data on infestations and current range maps, to improve the ability for managers to prioritize actions to prevent and control nonnative plant populations before they become established and spread.</p> <p>Assess effectiveness of targeted grazing with livestock to reduce nonnative annual grasses and understand the impact on native plants in the sagebrush ecosystem.</p> <p>Conduct detailed optimization studies on production and delivery systems of biocontrol agents, followed by evaluation in scaled-up field inoculation trials.</p> <p>Investigate cheatgrass die-off and potential biocontrols for cheatgrass to provide effective tools for site preparation.</p>
Restoration	<p>Develop methods for “jumpstarting” growth and recovery of sagebrush and native grasses and forbs to encourage rapid re-establishment of sagebrush and enable re-colonization by sage-grouse as soon as possible to help offset effects of wildfire and help mitigate potential effects of future fires.</p> <p>Develop and improve seeding methods, seed mixes, and equipment used for post-fire rehabilitation or habitat restoration to improve native plant (especially sagebrush) reestablishment.</p> <p>Determine the criteria and thresholds that indicate restoration and rehabilitation success or failure across the range of environmental conditions that characterize sage-grouse habitat. Develop decision support tools that define success or failure and the need for follow-up actions.</p> <p>Complete a generalized seed-zone map and determine (1) if it is more effective to develop seed-transfer zones by species or subspecies, (2) which climate parameters are most useful in developing transfer zones, (3) thresholds in climate adaptations, and (4) effects of using seed collected throughout a specified transfer zone versus seed collected from the local area to restore sagebrush habitats. Also demonstrate that actual planting success is improved for a given seed-transfer specification.</p>

Table 1. List of 37 priority science needs in the areas of fire, invasive plant species, restoration, sagebrush and sage-grouse, and climate and weather.—Continued

Topic	Need
Restoration— Continued	<p>Conduct retrospective studies of selected native plant restoration projects to evaluate short- and long-term responses of plant communities to these treatments and to biotic and abiotic conditions.</p> <p>Develop site preparation and seeding and transplanting strategies that improve plant establishment and community diversity.</p> <p>Assess the long-term effects of conifer removal treatments on hydrology, geochemical cycling, vegetation, wildlife, fuels, fire behavior, and economics.</p> <p>Evaluate the effectiveness of various rehabilitation or restoration activities in sage-grouse habitat to help determine if offsite mitigation is a viable option, because if restoration of sites to conditions useful for sage-grouse is not possible (for near-term benefits), then mitigation procedures might warrant reevaluation.</p> <p>Develop decision-support tools to assist in planning and implementing conifer removal treatments that will maximize maintenance of sagebrush systems, greater sage-grouse, and other sensitive species.</p> <p>Assess soil degradation and develop treatments, soil amendments, and other site-preparation techniques that enhance germination, establishment, and development of healthy sagebrush communities capable of resisting invasion by nonnative plant species.</p>
Sagebrush and sage- grouse	<p>Investigate sage-grouse movement patterns, the habitat characteristics that are conducive, restrictive, or preventive to those movements, and the genetic structure of populations to help inform management practices to improve or maintain connections.</p> <p>Conduct a series of large-scale, replicated grazing studies that address how different livestock species, grazing systems, disturbance histories, and other environmental conditions affect sage-grouse habitat.</p> <p>Identify thresholds beyond which effects on sage-grouse behavior, population response(s), or habitat use are minimized relative to different types of disturbances and related activities, for example, effects of wildfire, energy development, and other surface-disturbing activities.</p> <p>Develop next-generation mapping techniques to provide regular interval updates and continue to enhance grassland and shrubland vegetation mapping (e.g., every 2–5 years).</p> <p>Develop spatially explicit sage-grouse population models that incorporate biological processes and habitat dynamics and investigate scenarios that reflect local management possibilities (options, opportunities, and obstacles).</p> <p>Identify seasonal habitats for sage-grouse across their entire range.</p> <p>Develop sagebrush ecosystem-wide models identifying conditions necessary to support sagebrush-associated species, other than sage-grouse, using an individual species approach or species groups when necessary.</p> <p>Develop thresholds for the extent and magnitude of a threat (e.g., cover of pinyon and juniper, density of oil and gas wells, road density, etc.) above which the habitat can no longer support sagebrush-obligate species.</p> <p>Conduct long-term monitoring to assess development of community structure, community function, dynamics in native seedings, as well as suitability of resulting communities in meeting specific management goals, such as sage-grouse habitat restoration.</p>
Climate and weather	<p>Improve understanding of the complex set of variables that controls seeding success and improve accuracy of predictive meteorological data and models to identify years when the potential for seeding success is high or low.</p> <p>Study the propagation and production of native plant materials to identify species or genotypes that may be resilient to climate change.</p> <p>Identify areas for seed collection across elevational and latitudinal ranges of target species to protect and maintain high-quality sources for native seeds.</p> <p>Develop predictive models of climate change effects, targeting restoration species, including regionally suitable culturally significant species, and genetic diversity using 20-year or mid-century climate models.</p>

Priority Science Needs

This section contains a narrative for each of the 37 priority science needs (Table 1) within the five primary topics: fire, invasive species, restoration, sagebrush and sage-grouse, and climate and weather. Each narrative contains the same sections: background information, a summary of recent science and syntheses, and information about science gaps and next steps. The background information explains the context of the science need and the primary science and management issues related to the need. The summary of recent science and synthesis is a general review of the relevant, completed science related to the need. The last two sections of each narrative explain what research gaps still exist and the new research, syntheses, and tools that are needed to fill the science gaps. The last of these two sections, “Next Steps,” presents first the steps that could be accomplished in the short-term (1 to 3 years), followed by those that are considered long-term (accomplished in more than 3 years).

Fire

Fire as altered by nonnative annual grasses is a significant threat to maintaining a large contiguous sagebrush ecosystem. This section contains the priority science needs related to fire and to fire management (Table 2). These priorities include the need to understand the effectiveness of fuel treatments, the effect of these treatments on sage-grouse populations, the role of fire in maintaining healthy sagebrush communities, an assessment of fire regimes in the sagebrush ecosystem, and improved spatially-explicit understanding of fire risk.



Table 2. Science needs and next steps in the Fire topic. Next steps include new research, syntheses, and tools that are needed to fill the identified science gaps. The list separates those steps that could be accomplished in the short term (1 to 3 years), followed by those that are considered long term (accomplished in more than 3 years).

#	Need	Timing	Type	Next step
1	Determine the relationship between fire and the sagebrush ecosystem including fire-return intervals, post-fire recovery, fire behaviors, fuel accumulation, ignition sources, frequency of ignition events, and patterns of variation in all of these factors among regions to help inform habitat management and conservation.	Short-term	New research	Initiate fire history studies to understand historical and contemporary fire regimes (i.e., fire frequency, intensity, severity, seasonality, size distribution, and patchiness) across the sagebrush ecosystem.
		Long-term	New research	Initiate empirical and mechanistic studies of rates of sagebrush recovery from fire, taking advantage of datasets documenting historical fires. Such studies should examine trends over time in vegetation, fuels, and potential fire behavior across the entire range of ecological communities in the sagebrush ecosystem.
			Synthesis	Collect data at research sites through time using a combination of field investigation and remotely sensed information to develop long-term datasets useful in understanding post-fire recovery rates or other fire regime attributes. (Also see Sagebrush and Sage-grouse Science Need #4 and 9). Compile information about historical and contemporary fire regimes and sagebrush recovery from fire, and then assess how fire regimes and recovery patterns differ by region, vegetation type, and other factors.
2	Assess changes in greater sage-grouse demographic rates, including: (i) survival, reproductive success, and movement patterns in response to burned areas and (ii) the interactive effects of fire or treatment size and timing on the response of sage-grouse individuals and populations.	Short-term	New research	As wildfires occur across the range of ecological communities in the sagebrush ecosystem, determine the short-term effects on greater sage-grouse populations and their demography. Prioritize study sites where pre-fire data are available for sage-grouse populations.
			Synthesis	Integrate the effects of fire (both prescribed and natural) on sage-grouse habitat and demography to predict short-term effects on local and regional populations. Build on modeling outlined in Sagebrush and Sage-grouse Science Need #5.
			Tool	Review and synthesize information about sage-grouse habitat selection, behavior (e.g., site fidelity), and demographic response to fire on greater sage-grouse populations across the species' range. Identify under-represented regions or systems, types of fires, and populations for future study.
		Long-term	New research	Improve decision-support tools to inform prioritization of suppression and fuels management activities to maximize protection of sage-grouse habitat.
			New research	Continue ongoing studies and begin new studies that monitor the response of greater sage-grouse populations to wildfire at local and landscape scales to improve understanding of the factors that influence long-term (greater than 10 years) population recovery. Analyze wildfire monitoring data to determine the effects of rangeland fire (e.g., severity and patchiness), vegetation, or other factors on sage-grouse population dynamics.
New research	Use case-specific data and integrative models to assess the magnitude of demographic and behavioral responses to fire by local and regional sage-grouse populations. Assess the degree to which populations are likely to be similarly or differentially affected by fire based on habitat, landscape, and population characteristics.			

Table 2. Science needs and next steps in the Fire topic. Next steps include new research, syntheses, and tools that are needed to fill the identified science gaps. The list separates those steps that could be accomplished in the short term (1 to 3 years), followed by those that are considered long term (accomplished in more than 3 years).—Continued

#	Need	Timing	Type	Next step
3	Develop spatial risk analysis relative to conservation of greater sage-grouse habitat through mapped projections of fire probability to develop strategic approaches and aid in targeting of pre-suppression and suppression efforts	Short-term	New research	Assess and adjust the methods used to collect fuels data across the sagebrush ecosystem to ensure they meet the input requirements at appropriate spatial scales for fire behavior models and can support efforts to improve model validations and predictions. Using fuel and fire behavior data from prescribed fires and wildfires, run next generation physics-based fire behavior models to generate predictions of fire behavior for multiple vegetation types across the range of ecological communities in the sagebrush ecosystem. Use the resultant data to inform adjustments of operational fire behavior model inputs and outputs to improve predictive power.
			Synthesis	Compare different tools and methods for assessing wildfire risk across the range of ecological communities in the sagebrush ecosystem and summarize advantages and disadvantages of different approaches.
			Tool	Enhance operational fire behavior models so that they can incorporate spatially explicit fuel moisture data. Validate these improved models with fuel and fire behavior data from prescribed fires and wildfires. As needed, develop new fuel models to better reflect fuel complexes across the range of ecological communities in the sagebrush ecosystem and improve the predictive power of models of fire behavior. Incorporate these enhanced models into existing management tools (e.g., state-and-transition models, fire behavior models).
		Long-term	New research	Using fuel and fire behavior data from prescribed fires and wildfires, validate the performance of next generation physics-based fire behavior models for predicting operationally meaningful fire characteristics for multiple vegetation types across the range of ecological communities in the sagebrush ecosystem.
			Tool	Incorporate new science on fire effects on sage-grouse habitat and populations into new wildfire risk assessments. Using tested tools and methods, develop the next generation methodology for assessing wildfire risk for the sagebrush ecosystem and expand the area over which wildfire risk assessments have been completed in the sagebrush ecosystem. As next generation physics-based models become validated for operational use, incorporate their use into methods for assessing wildfire risk.

Table 2. Science needs and next steps in the Fire topic. Next steps include new research, syntheses, and tools that are needed to fill the identified science gaps. The list separates those steps that could be accomplished in the short term (1 to 3 years), followed by those that are considered long term (accomplished in more than 3 years).—Continued

#	Need	Timing	Type	Next step
4	Determine the community and species-specific responses to fuels management treatments (e.g., conifer removal) in both a short- and long-term context.	Short-term	New research	Analyze collected data on effects of different conifer removal treatments (e.g., mastication, fire, lop and scatter) on various plant and animal species and ecological communities at different spatial scales.
			Revisit treatments to evaluate long-term (greater than 10 years) effects of conifer removal on various species and ecological communities at different spatial scales.	
		Long-term	New research	Revisit treatments to evaluate long-term (greater than 15 years) effects of different conifer removal treatments on various species and ecological communities at different spatial scales. Conduct mechanistic studies that reveal relationships between treatments and system responses to conifer removal and the underlying ecological basis for changes observed.
			Synthesis	Synthesize findings on long-term species and community responses to conifer removal at different spatial scales.
5	Assess the effects of fuel treatments, installation of fire breaks, and similar manipulation of fuels and (or) landscape patterns intended to reduce wildfire spread and burn intensities on greater sage-grouse habitat use, movement patterns, and population trends to help minimize the potential detrimental effects of fire-risk reduction measures to the species.	Short-term	New research	A critical evaluation, against clear standards, of the existing fuel breaks, their characteristics, and effectiveness in changing fire behavior, reducing fire spread, and decreasing response time. Field sampling to measure vegetation and soil characteristics of fuel breaks. The sampling design would evaluate (1) the age of fuel breaks, (2) types and frequency of treatments applied, (3) vegetation species used in treatments, and (4) types of soil and vegetation. Evaluation of current Sagebrush Focal Areas and Greater Sage-Grouse Priority Habitat areas and existing fragmentation patterns relative to proposed new fire and fuel breaks. Field research on sage-grouse movements and habitat use relative to fuel breaks. The research design could include outfitting sage-grouse with global positioning system (GPS) transmitters to obtain fine-scale spatial and temporal data on movements. Sage-grouse could be marked in an existing system of fuel breaks but also used in a study that includes a pre- and post-treatment design.
			Synthesis	A synthesis to determine the applicability of past research on fragmentation and treatment effects to inform proposed Strategy actions.
		Long-term	New research	Long-term assessment of effects of fuel breaks on sage-grouse movement patterns, habitat use, and population trends. Optimization model for fuel breaks that includes (1) cost-benefit analysis of fuel breaks relative to habitat lost, (2) delineation of high-probability ignition zones, and (3) incremental changes in existing response times with additional fuel breaks. Long-term assessment of effects of fuel breaks on adjacent sagebrush communities, especially through spread of nonnative plants used in the fuel breaks (e.g., kochia [<i>Bassia scoparia</i>]).
			Tool	Based on the results of evaluating fuel-break effectiveness against clear standards, develop a decision support tool to identify strategic placement and identification of an effective number of fuel breaks.

Table 2. Science needs and next steps in the Fire topic. Next steps include new research, syntheses, and tools that are needed to fill the identified science gaps. The list separates those steps that could be accomplished in the short term (1 to 3 years), followed by those that are considered long term (accomplished in more than 3 years).—Continued

#	Need	Timing	Type	Next step
6	Assess the long-term effects of sagebrush reduction treatments on hydrology, geochemical cycling, vegetation, wildlife (e.g., greater sage-grouse), fuels, fire behavior, and economics.	Short-term	New research	Analyze data already collected to gain new understanding of effects of sagebrush removal on fuels, wildlife species, and hydrology. Collect new data on SageSTEP or similar long-term sites to evaluate effects that have occurred more than 10 years since sagebrush removal. Evaluate the effects of treatments on vegetation, fuels, wildlife, hydrology, and geochemical cycling across ecological communities in the sagebrush ecosystem.
		Long-term	New research	Revisit experimental study sites to evaluate long-term (greater than 15 years) effects of sagebrush removal on vegetation, fuels, wildlife, hydrology, and geochemical cycling across the range of ecological communities in the sagebrush ecosystem.
			Synthesis	Synthesize findings of long-term effects of sagebrush removal treatments on a variety of ecological attributes.
7	Assess the role of fire in maintaining healthy sagebrush communities by identifying the balance between loss of intact sagebrush and recovery of young sagebrush required for habitat maintenance for different regions, communities, and ecological types.	Short-term	New research	Determine additional empirical data needs that can help demonstrate if prescribed fire mimics the ecological role of historical fire regimes for a given landscape and ecological community type. Determine the interactive effects of livestock grazing, in the short-term and before and after wildfire and prescribed fire, on recovery of native species and functional diversity of ecological communities. (Also see Table 3, Science Need #1, Long-term next step 3; and Science Need #4.) Evaluate existing treatment effectiveness monitoring data (e.g., from BLM, Natural Resources Conservation Service) to quantify native herbaceous cover and functional diversity thresholds needed to resist invasion of nonnative annual grasses. (Also see Table 5, Sagebrush and Sage-Grouse Science Need #5.)
		Long-term	New research	Determine long-term (greater than 10 years) rates of recovery of various components of the sagebrush ecosystem after a fire. Priority components include sagebrush, native forbs, and deep-rooted native perennial grasses. Determine how pre-fire conditions and post-fire management, including livestock grazing, influence long-term recovery. (Also see Table 5, Sagebrush and Sage-Grouse Science Need #9.)
			Synthesis	Summarize science about potential risks (e.g., partial to complete loss of sagebrush and other native plant species, extensive post-fire recovery period, and incursion of nonnative plant species) and benefits (e.g., improved habitat structural conditions for sage-grouse and enhanced grass-forb cover) of fire and how these benefits differ across the sagebrush ecosystem.

Table 2. Science needs and next steps in the Fire topic. Next steps include new research, syntheses, and tools that are needed to fill the identified science gaps. The list separates those steps that could be accomplished in the short term (1 to 3 years), followed by those that are considered long term (accomplished in more than 3 years).—Continued

#	Need	Timing	Type	Next step
8	Determine which fuel breaks have met the objective of preventing fire spread or fire severity, and determine the characteristics of those that are successful, including synthesis of the literature, critical evaluation of techniques and plant materials used in fire breaks (species, structure, placement, and native versus nonnative species), and economic tradeoffs.	Short-term	New research	Review Fuels Treatment Effectiveness Monitoring (FTEM) records and compile fire-fuel break incursion reports if verifiable data are available. The FTEM is an interagency qualitative system in which local fire managers document the effectiveness of fuels treatments in locations that actually experience wildland fire.
		Long-term	New research	Analysis of the economic tradeoffs between fuel-break types, as affected by different fuel types, and in comparison to other non-fuel break alternatives. Multi-year critical, against clear standards, evaluation of fuel-break effects on fire spread, intensity, and severity. Consider multiple fuel-break types, techniques, fuel types, and overall fuel environments. Assess fuel-break longevity and maintenance. Conduct a quantitative assessment of the long-term viability of fuel breaks including the type, timing of construction, and frequency of maintenance.
			Tool	Develop a database and standardized protocol for entry of information that allows for assessment of treatment effectiveness across fuel types.



Fire Science Need #1: Determine the relationship between fire and the sagebrush ecosystem including fire-return intervals, post-fire recovery, fire behaviors, fuel accumulation, ignition sources, frequency of ignition events, and patterns of variation in all of these factors among regions to help inform habitat management and conservation.

Topic: Fire; Subtopic: Fire ecology and effects; Associated SO 3336 Task: 7(b)iii and v

Background

Knowledge of the historical range of variability in fire regimes (e.g., fire frequency, intensity, severity, and patchiness) and current departures from historical fire regimes can inform fire management strategies. Studying historical fire regimes in the sagebrush ecosystem is challenging because few trees are present. This limits the amount of information recorded about past fires in tree-ring patterns. Scientists have inferred historical fire regimes in the sagebrush ecosystem by examining fire scars on trees in the woodland and sagebrush ecotone, the recovery time of sagebrush following disturbance, charcoal and phytoliths in soil sediments, and historical records. Syntheses of such work show that historical fire regimes differed among sagebrush types. Although there is disagreement about the frequency and extent of historical fires, most studies agree that historical fire frequency or rotation across all sagebrush types was on the order of several decades to centuries. Studies also agree that in many places fires have become either more frequent due to spread of nonnative annual grasses or less frequent due to grazing and fire suppression.

Summary of recent science and syntheses

Two recent syntheses summarize the data about historical fire regimes in sagebrush systems and highlight the differences in interpretation of historical fire regimes (Baker, 2011; Miller et al., 2011). These differences mostly stem from using different methods (e.g., directly calculating fire rotation for sagebrush versus estimates using fire-return intervals derived from trees). These and additional studies (e.g., Balch et al., 2013; Brooks et al., 2015) summarize information about the current fire regime and document the increasing frequency of fire in many areas. Ongoing studies of sagebrush recovery after fire in the northern Columbia Basin also suggest relatively long recovery rates in the Columbia Basin and continue to shed light on the role of fire in the sagebrush ecosystem (Shinneman and McIlroy, *in press*).

Existing science gaps

Much uncertainty still remains regarding historical fire regime attributes, and additional study would likely reduce some of this uncertainty. However, discrepancies in measured fire regime attributes among different studies may not be easily resolved given difficulties of assessing fire history in the sagebrush ecosystem. It may be best to focus fire history studies in systems with higher than average resistance and resilience (e.g., high-elevation sagebrush communities), where use of fire to achieve objectives is a more viable management option, to help inform the appropriate use of fire as a management tool. It also may be valuable to study fire history in less resistant and resilient sagebrush communities where fire-prone, nonnative plant species are relatively uncommon and fire may have been historically infrequent. Across sagebrush community types, studies of the rate of sagebrush recovery from immature to mature plant stages are relatively rare (D. Shinneman, personal communication). Developing a network of studies of sagebrush recovery rates in relation to key factors (e.g., elevation, invasive annual grass cover) across the Great Basin would provide useful information about historical fire regimes, as well as regionally-specific estimates of expected recovery time after fire. Such studies also could provide important information about attributes of fire regimes today, and how those regimes affect the sagebrush ecosystem.

Next steps

Short-term (1 to 3 years)

- New research: Initiate fire history studies to understand historical and contemporary fire regimes (i.e., fire frequency, intensity, severity, seasonality, size distribution, and patchiness) across the sagebrush ecosystem.
- New research: Initiate empirical and mechanistic studies of rates of sagebrush recovery from fire, taking advantage of datasets documenting historical fires. Such studies should examine trends over time in vegetation, fuels, and potential fire behavior across the entire range of ecological communities in the sagebrush ecosystem.

Long-term (greater than 3 years)

- New research: Collect data at research sites through time using a combination of field investigation and remotely sensed information to develop long-term datasets useful in understanding post-fire recovery rates or other fire regime attributes. (Also see Sagebrush and Sage-Grouse Science Needs #4 and #9, Table 5).
- Synthesis: Compile information about historical and contemporary fire regimes and sagebrush recovery from fire, and then assess how fire regimes and recovery patterns differ by region, vegetation type, and other factors.

Fire Science Need #2: Assess changes in sage-grouse demographic rates, including (i) survival, reproductive success, and movement patterns in response to burned areas and (ii) the interactive effects of fire or treatment size and timing on the response of sage-grouse individuals and populations.

Topic: Fire; Subtopic: Fire ecology and effects; Associated SO 3336 Task: 7(b)iii and v

Background

Without management intervention, rangeland fire is expected to increase in size over the next three decades in many parts of the sage-grouse range (e.g., Great Basin; Coates et al., *in press*) and negatively affect sage-grouse habitat conditions and sage-grouse population trajectories. Yet the magnitude of wildfire effects on sage-grouse behavior, demography, and abundance are poorly understood. Although studies have examined changes to sage-grouse habitat and documented altered habitat selection in individual study areas, little is known about how local patterns of change relate to seasonal habitat selection responses in other locations. Further, the current understanding of the short- and long-term demographic consequences to sage-grouse in burned landscapes is poor, and when and why they return to habitats recovering from fire remains unknown. Sage-grouse demographic and behavioral responses likely differ with the size, intensity, severity, timing, and pattern of fires, along with time since prior disturbances, rates of vegetation recovery, and other site conditions. A comprehensive understanding of how these factors combine to affect sage-grouse demographic and behavioral outcomes in fire-affected areas across the range of the species would be useful to guide both sage-grouse and fire management practices.

Summary of recent science and syntheses

The effects of wildfire and its cumulative impacts have been associated with reduced sage-grouse lek counts across the Great Basin (Coates et al., *in press*), yet the mechanisms by which populations are adversely affected are not well understood. Habitat selection studies have indicated that sage-grouse avoid burned habitat during all seasons (Connelly et al., 2000; Byrne, 2002; Erickson, 2011) or return to previously burned nest sites only to experience low demographic success (Lockyer et al., 2015). A wide variety of site characteristics also are likely to influence habitat selection and demographic success in burned habitats. Possible characteristics influenced include sagebrush height and horizontal cover (Lockyer et al., 2015), presence of invasive plant species (Lockyer et al., 2015), and patch and landscape

contextual variables (e.g., size of fire, proximity to lekking habitat, proximity to development or forested areas, prevalence of predators, and anthropogenic disturbance; Fedy et al., 2014; Coates et al., *in press*).

Early studies of effects of fire on sage-grouse responses mostly focused on prescribed fire or small-scale wildfire and primarily occurred in low elevations in south-central Idaho (Connelly et al., 2003; Fischer et al., 1997). Recent and ongoing case studies are broadening this context. Research in Oregon, California, and Nevada (e.g., Lockyer et al., 2015, and ongoing projects by P. Coates, C. Hagen, and colleagues) is addressing large fires and a variety of landscapes. Inferences from local studies to other areas are limited, because previous case studies were short-term and lacked pre-fire data. Although investigators involved in new studies (e.g., a study by P. Coates assessing the impacts of the 2012 Rush Fire in northeastern California and northwestern Nevada on sage-grouse population trends) are starting to consider demographic responses of sage-grouse to fires using before-and-after data comparisons. Additional study areas and long-term data are required to understand how sage-grouse responses vary with ecological sites and conditions and as vegetation is established after a fire.

Existing science gaps

A better understanding of how fire, habitat, and population characteristics combine to influence sage-grouse demography and recovery is needed. Effective fire and fuels management and planning for habitat restoration depends on site-specific conditions and population-specific actions. Therefore, it is important to understand the mechanisms by which sage-grouse demography and behavior are affected by fire. This involves developing a new knowledge of the (1) conditions under which sage-grouse avoid burned habitat or continue to use it, (2) demographic outcomes (i.e., nest success, survival) associated with bird use of those habitats, (3) minimum and optimal habitat requirements for the recolonization of burned and previously used areas, and (4) responses to post-fire seeding, planting, and other management to restore vegetation, including the use of native versus nonnative species.

Next steps

Short-term (1 to 3 years)

- New research: As wildfires occur across the range of ecological communities in the sagebrush ecosystem, determine the short-term effects on sage-grouse populations and their demography. Prioritize study sites where pre-fire data are available for sage-grouse populations.
- New research: Integrate the effects of fire (both prescribed and natural) on sage-grouse habitat and demography to predict short-term effects on local and regional populations. Build on modeling outlined in Sagebrush and Sage-Grouse Science Need #5 (Table 5).
- Synthesis: Review and synthesize information about sage-grouse habitat selection, behavior (e.g., site fidelity), and demographic response to fire on sage-grouse populations across the species' range. Identify under-represented regions or systems, types of fires, and populations for future study.
- Tool: Improve decision-support tools to inform prioritization of suppression and fuels management activities to maximize protection of sage-grouse habitat.

Long-term (greater than 3 years)

- New research: Continue ongoing studies and begin new studies that monitor the response of sage-grouse populations to wildfire at local and landscape scales to improve understanding of the factors that influence long-term (greater than 10 years) population recovery.
- New research: Analyze wildfire monitoring data to determine the effects of rangeland fire (e.g., severity and patchiness), vegetation, or other factors on sage-grouse population dynamics.
- New research: Use case-specific data and integrative models to assess the magnitude of demographic and behavioral responses to fire by local and regional sage-grouse populations. Assess the degree to which populations are likely to be similarly or differentially affected by fire based on habitat, landscape, and population characteristics.

Fire Science Need #3: Develop spatial risk analysis relative to conservation of greater sage-grouse habitat through mapped projections of fire probability to develop strategic approaches and aid in targeting of pre-suppression and suppression efforts.

Subtopic: Fire ecology and effects; Associated SO 3336 Task: 7(b)ii, iii, and v

Background

Wildfire risk assessments, which evaluate the probability of wildfire affecting highly valued resources, are increasingly used in planning fuel treatments and wildfire management strategies across large landscapes. In such assessments, fire behavior models are used to determine the probability that wildfire of a given intensity will start and spread across a given area. This resulting burn probability, which incorporates potential fire intensity and probability of ignition, can be assessed against mapped highly valued resources, such as sage-grouse habitat, to inform fuel and wildfire management strategies that may protect those resources from potential damage from wildfire (Miller and Ager, 2013).

Conducting wildfire risk assessments requires data on fuels (e.g., loading, continuity, moisture content) that are spatially and temporally accurate to get reasonable predictions on potential fire behavior from fire behavior models. Current operational fire behavior models are based on the Rothermel spread equation (Rothermel, 1972). Fuel models, which include all inputs for fuel characteristics needed to run fire behavior models, have been developed for several vegetation types and greatly simplify the modeling process (Scott and Burgan, 2005). Spatial data from fuel models that can be used in fire behavior modeling are widely available (i.e., Landfire, <http://www.landfire.gov/>, last accessed August 30, 2016). These data, however, are not always accurate, especially in systems in which fuel complexes can change rapidly due to climate, disturbance, or spread of invasive species.

Summary of recent science and syntheses

Although few have attempted to conduct wildfire risk assessments in sagebrush ecosystems, some scientists have recently developed novel methods to assess wildfire risk in the Great Basin. For example, a software program called Circuitscape (McRae and Shah, 2008) was used to simulate the effect of fuel breaks on potential fire spread patterns in a study area across southern Idaho, northern Nevada, and eastern Oregon (Welch et al., 2015). The developers of this tool now are working with the Bureau of Land Management in this tri-state area to design the placement of fuel breaks. A similar approach was taken in northern Arizona, where investigators used predicted fire behavior characteristics from FlamMap to parameterize Circuitscape (Gray and Dickson 2016). They found that adjusting available spatial data on fuel models to incorporate the presence of cheatgrass (*Bromus tectorum*) allowed fire behavior simulations to perform reasonably well against actual wildfire spread patterns. An advantage of this approach to assessing wildfire risk over methods that have been used in other regions (Ager et al., 2010) is that it requires much less computational power (B. Unnasch, personal communication); however, whether this approach has broad applicability is uncertain.

Existing science gaps

Additional wildfire risk assessments are needed throughout the sagebrush ecosystem to inform strategies for protecting highly valued resources, such as sage-grouse habitat. In addition, a quantitative assessment is needed of the advantages and disadvantages of different methods used to determine wildfire risk. Accurate risk assessments, however, remain elusive in sagebrush ecosystems because of a lack of accurate fuels data needed to run fire behavior models. For example, annual grasses, which are significant carriers of fire in many sagebrush systems, are often not accurately reflected in available spatial fuel model data (Gray and Dickson 2016). As a result, fuel characteristics that need to be included are not well represented in standard fuel models (e.g., fine-fuel continuity) despite their importance for fire spread. Fuel characteristics that are more detailed than those represented in standard fuel models have been incorporated recently into management tools such as state-and-transition models and the Rangeland Vegetation Simulator; however, the fuel characteristics reflected

in such tools have not been used to validate fire behavior models (M. Reeves, personal communication). Moreover, current fire spread models cannot incorporate spatial variability in fuel moisture across a landscape, which is likely an important factor in determining fire spread patterns (R. Parsons, personal communication).

Fire behavior prediction in the sagebrush ecosystem also may be improved through enhanced understanding of the underlying physics associated with fire behavior models. Recent advances have been made in physics-based fire behavior models and, although they are not yet operational, they could be used to determine appropriate adjustment factors to inputs or outputs of currently operational fire behavior models to improve prediction. In the long-term, development of physics-based fire behavior models whose performance can be validated in an operational context may lead to better fire behavior predictions for use in fire management and ultimately more accurate assessments of wildfire risk.

Wildfire risk assessments also require knowledge of the potential impacts of wildfire (positive or negative) on a highly valued resource of interest, in this case sage-grouse habitat. To accurately assess the risk of wildfire in relation to sage-grouse habitat, a greater understanding of the effects of fire on sage-grouse is needed. Science needs associated with fire effects on sage-grouse habitat and populations are addressed in other science needs in this document.

Next steps

Short-term (1 to 3 years)

- New research: Assess and adjust the methods used to collect fuels data across the sagebrush ecosystem to ensure they meet the input requirements at appropriate spatial scales for fire behavior models and can support efforts to improve model validations and predictions.
- New research: Using fuel and fire behavior data from prescribed fires and wildfires, run next generation physics-based fire behavior models to generate predictions of fire behavior for multiple vegetation types across the range of ecological communities in the sagebrush ecosystem. Use the resultant data to inform adjustments of operational fire behavior model inputs and outputs to improve predictive power.
- Synthesis: Compare different tools and methods for assessing wildfire risk across the range of ecological communities in the sagebrush ecosystem and summarize advantages and disadvantages of different approaches.
- Tool: Enhance operational fire behavior models so that they can incorporate spatially explicit fuel moisture data. Validate these improved models with fuel and fire behavior data from prescribed fires and wildfires.
- Tool: As needed, develop new fuel models to better reflect fuel complexes across the range of ecological communities in the sagebrush ecosystem and improve the predictive power of models of fire behavior. Incorporate these enhanced models into existing management tools (e.g., state-and-transition models, fire behavior models).

Long-term (greater than 3 years)

- New research: Using fuel and fire behavior data from prescribed fires and wildfires, validate the performance of next generation physics-based fire behavior models for predicting operationally meaningful fire characteristics for multiple vegetation types across the range of ecological communities in the sagebrush ecosystem.
- Tool: Incorporate new science on fire effects on sage-grouse habitat and populations into new wildfire risk assessments.
- Tool: Using tested tools and methods, develop the next generation methodology for assessing wildfire risk for the sagebrush ecosystem and expand the area over which wildfire risk assessments have been completed in the sagebrush ecosystem.
- Tool: As next generation physics-based models become validated for operational use, incorporate their use into methods for assessing wildfire risk.

Fire Science Need #4: Determine the community and species-specific responses to fuels management treatments (e.g., conifer removal) in both a short- and long-term context.

Topic: Fire; Subtopic: Fire prevention and fuels reduction; Associated SO 3336 Task: 7(b)iii

Background

In some sagebrush landscapes, woodland species have established or increased in density in recent times, interrupting the continuity of intact sagebrush landscapes. This plant community change may have potential detrimental implications for sage-grouse and other sagebrush-obligate species through effects on habitat availability (Baruch-Mordo et al., 2013). To ameliorate these potential effects, removal of conifer species with mechanical treatments (e.g., thinning, mastication, and mowing) and prescribed fire are common practices. The short-term (i.e., less than 10 years) response of individual plant and animal species and communities to conifer removal treatments has been evaluated in a network of sites across the Great Basin via the SageSTEP project (McIver and Brunson, 2014). However, given the slow rate of change in these systems, data collected over a period of 15 to 20 years after treatment are needed to understand community and species response to conifer removal treatments.

Summary of recent science and syntheses

Results of studies assessing the outcome of conifer removal on a variety of plant and animal communities were published as a compilation of papers in a special issue of *Rangeland Ecology and Management* (McIver and Brunson, 2014). The data used in the analyses were collected over a period of time less than 10 years after treatments were applied. Knick et al. (2014) found little change in the bird community following mechanical and prescribed fire treatments, possibly because of high residual shrub cover or long distances from treated sites to intact sagebrush communities. McIver and Macke (2014) found little change in butterfly community structure following prescribed fire and mechanical treatments. Both mechanical treatments and prescribed fire resulted in an initial decrease in native perennial grasses and forbs, but these species recovered 2 to 3 years after treatment (Miller et al., 2014a). Starting in 2016, SageSTEP treatment plots will be monitored again to assess effects 10 years after treatment. The goal is to monitor treatments for up to 25 years after treatment (J. McIver, personal communication).



Photo credit: Matthew J. Germino, USGS

Existing science gaps

Although short-term effects of conifer removal on a variety of species and communities have been evaluated less than 10 years from time of treatment, assessment of long-term effects may yield different results. Given that many sagebrush species and communities recover on the order of years to decades (McIver and Brunson 2014), the species and community response to conifer removal treatments need to be evaluated for a minimum of 10 years and probably longer. This is particularly true for plant species with relatively long recovery times (e.g., shrubs) and wildlife species that utilize those plants for feeding, nesting, etc. Also, some data on effects of treatments on plant and animal species have been collected but not analyzed. The SageSTEP experiment is an example of an ongoing project that presents an opportunity to examine the short- and long-term effects of conifer removal treatments across the Great Basin. Many previous research projects, however, were not representative of the broad-scale (100,000s of hectares) projects currently planned for improving sage-grouse habitat in Idaho, Nevada, and Utah, as well as elsewhere in the sagebrush biome. A need clearly exists for additional monitoring of responses of sagebrush-obligate species to conifer reduction efforts, particularly in areas planned for landscape-scale conifer removal.

Next steps

Short-term (1 to 3 years)

- New research: Analyze collected data on effects of different conifer removal treatments (e.g., mastication, fire, lop and scatter) on various plant and animal species and ecological communities at different spatial scales.
- New research: Revisit treatments to evaluate long-term (greater than 10 years) effects of conifer removal on various species and ecological communities at different spatial scales.

Long-term (greater than 3 years)

- New research: Revisit treatments to evaluate long-term (greater than 15 years) effects of different conifer removal treatments on various species and ecological communities at different spatial scales.
- New research: Conduct mechanistic studies that reveal relationships between treatments and system responses to conifer removal and the underlying ecological basis for changes observed.
- Synthesis: Synthesize findings on long-term species and community responses to conifer removal at different spatial scales.

Fire Science Need #5: Assess the effects of fuel treatments, installation of fire breaks, and similar manipulation of fuels and (or) landscape patterns intended to reduce wildfire spread and burn intensities on greater sage-grouse habitat use, movement patterns, and population trends to help minimize the potential detrimental effects of fire-risk reduction measures to the species.

Subtopic: Fire Prevention/Fuels Reduction; Associated SO 3336 Task: 7(b)ii.

Background

Fuel breaks typically consist of long strips or corridors of various width in which vegetation is intensively managed to limit fire intensity and spread. Managers change fire behavior within fuel breaks using treatments designed to disrupt fuel continuity, reduce fuel accumulations and volatility, or increase the proportion of plants with high moisture content (Maestas et al., 2016). Managers usually create or maintain fuel breaks by disking to create strips of bare soil, mowing to reduce height of vegetation (sometimes along roads to enhance their effect as a fuel break), or planting strips of less flammable vegetation than what is present. In concept, a system of fuel breaks strategically placed across a region also can help to control fire size by increasing access and reducing response time for fire suppression.

Fire management and prevention actions recommended through the Strategy include creation of new fuel breaks and maintenance of existing breaks. Those breaks would be in and around extensive areas identified using the Fire and Invasives Assessment Tool (FIAT). In addition to maximizing fire-suppression effectiveness, it is likely that temporary fire breaks will be created during large wildfire events. These fire and fuel breaks will be located to provide protection of Sagebrush Focal Areas and Greater Sage-Grouse Priority Habitats. However, the effects of fuel and fire breaks on sage-grouse population trends, habitat use, and movement corridors are poorly understood.

Summary of recent science and syntheses

Fuel breaks can influence local vegetation and change patterns and processes in landscapes. Actions to create or maintain fuel breaks require intensive, repeated, and sustained soil disturbance and vegetation management. Many nonnative invasive plants, such as cheatgrass, medusahead rye (*Taeniatherum caput-medusae*), halogeton (*Halogeton glomeratus*), Russian thistle (*Salsola kali*), and tansy mustards (*Descurainia* spp.), readily invade disturbed soils. Once established, invasive plants can spread into surrounding areas and cause other changes that reduce suitability of an area for sage-grouse (Ielmini et al., 2015).

Sagebrush landscapes increasingly are fragmented by human and natural disturbance. Less than 5 percent of the remaining sagebrush landscape is more than 2.5 kilometers (km) from an existing road (Knick et al., 2011). Expanding access along current and new fuel breaks, particularly for off-highway vehicles, would further increase disturbance and spread of invasive plants (Gelbard and Belnap, 2003). Increased access also exacerbates the potential for human-caused ignitions. One-fourth of the fires on Bureau of the Land Management (BLM)-managed lands in 2006 were caused by humans (Miller et al., 2011).

Habitat requirements and population dynamics are relatively well-known for sage-grouse (Connelly et al., 2011; Garton et al., 2011; Johnson et al., 2011). Sage-grouse are sensitive to disturbances that remove sagebrush from the landscape. Across the sage-grouse range, regions most likely to sustain long-term populations contained greater than 65 percent intact sagebrush in a landscape (Knick et al., 2013; Chambers et al., 2014b). These same regions are targeted for fuel breaks, which will increase sagebrush fragmentation within existing strongholds for sage-grouse. In Utah, sage-grouse were unlikely to use portions of treated areas that were greater than 30 meters (m) from an existing sagebrush edge (Dahlgren et al., 2006). This is the basis for the generalization that fuel breaks greater than 30 m wide reduce the habitat available for sage-grouse.

Existing science gaps

No studies within the sagebrush ecosystem have addressed the effectiveness of fuel breaks as control actions that reduce the size of large fires. Most information is anecdotal and, as a result, quantitative information is lacking for at least three characteristics of fuel breaks necessary to permit an assessment: (1) whether fuel breaks are effective in facilitating control of fire spread, (2) whether additional fuel breaks would decrease the response time, and (3) what the ecological “costs” are of fuel breaks from potential nonnative plant invasions, disruption of processes in the surrounding plant community, and loss of habitat for sage-grouse and other sagebrush-obligate species. Most fires currently are contained shortly after ignition and burn only a small area. Access for fire management activities to most of the fire-prone regions is not a limiting factor (Maestas et al., 2016); however, detection and response time can be. Also unknown is whether more fuel breaks will aid in the control of the fires that escape initial attack and become large landscape events. Finally, we do not know whether more fuel breaks will prevent the few fires that escape containment and become large landscape events.

Additional information also is needed to understand how sage-grouse respond to fuel breaks, particularly breaks that create wide strips of unsuitable habitat. It is likely sage-grouse perceive fuel breaks relative to the surrounding landscape configuration. For example, fuel breaks established in large contiguous blocks of sagebrush may have greater effect on sage-grouse than those in already fragmented habitats. What constitutes a reasonable threshold between an effective number of fuel breaks in an area and the risks to sage-grouse habitat is not understood.

Next steps

Short-term (1 to 3 years)

- New research: A critical evaluation, against clear standards, of the existing fuel breaks, their characteristics, and effectiveness in changing fire behavior, reducing fire spread, and decreasing response time.
- New research: Field sampling to measure vegetation and soil characteristics of fuel breaks. The sampling design would evaluate (1) the age of fuel breaks, (2) types and frequency of treatments applied, (3) vegetation species used in treatments, and (4) types of soil and vegetation.
- New research: Evaluation of current Sagebrush Focal Areas and Greater Sage-Grouse Priority Habitat areas and existing fragmentation patterns relative to proposed new fire and fuel breaks.
- New research: Field research on sage-grouse movements and habitat use relative to fuel breaks. The research design could include outfitting sage-grouse with global positioning system (GPS) transmitters to obtain fine-scale spatial and temporal data on movements. Sage-grouse could be marked in an existing system of fuel breaks but also used in a study that includes a pre- and post-treatment design.
- Synthesis: A synthesis to determine the applicability of past research on fragmentation and treatment effects to inform proposed Strategy actions.

Long-term (greater than 3 years)

- New research: Long-term assessment of effects of fuel breaks on sage-grouse movement patterns, habitat use, and population trends.
- New research: Optimization model for fuel breaks that includes (1) cost-benefit analysis of fuel breaks relative to habitat lost, (2) delineation of high-probability ignition zones, and (3) incremental changes in existing response times with additional fuel breaks.
- New research: Long-term assessment of effects of fuel breaks on adjacent sagebrush communities, especially through spread of nonnative plants used in the fuel breaks (e.g., forage kochia [*Bassia prostrata*]).
- Tool: Based on the results of evaluating fuel-break effectiveness against clear standards, develop a decision support tool to identify strategic placement and identification of an effective number of fuel breaks.

Fire Science Need #6: Assess the long-term effects of sagebrush reduction treatments on hydrology, geochemical cycling, vegetation, wildlife (e.g., greater sage-grouse), fuels, fire behavior, and economics.

Subtopic: Fire prevention/fuels reduction; Associated SO 3336 Task: 7(b)iii, iv, and vi

Background

In the sagebrush ecosystem, removal of sagebrush is an option to reduce the potential for high-intensity fire and increase diversity and abundance of native perennial grasses and forbs. A major consideration is how to remove sagebrush using fire, mechanical, or chemical treatments without creating opportunities for nonnative annual grass expansion or causing other undesirable effects. Research that evaluates the effects of treatment on vegetation, hydrology, geochemical cycling, fuels and fire behavior, and economics can determine not only effectiveness of treatments in improving ecosystem condition, but also sensitivities to treatments. Many ecological attributes in the sagebrush ecosystem, such as biological soil crusts or sagebrush shrubs, have relatively slow recovery rates. As a result, treatments need to be evaluated for at least 10 years to fully understand their effects on various attributes (McIver and Brunson, 2014). Although a great deal of information is available about effects of sagebrush removal, most are site-specific, short-term, and focused on a narrow range of variables (McIver and Brunson, 2014).



Summary of recent science and syntheses

In studies lasting less than 10 years, response effects of different sagebrush removal treatments on hydrology, geochemical cycling, vegetation, some wildlife species, fuels, and economics have been evaluated in a network of sites across the Great Basin as part of the SageSTEP project. Initial findings are published in a special issue of *Rangeland Ecology and Management* (McIver and Brunson, 2014). Chambers et al. (2014) found that resistance to nonnative annual grass invasion following sagebrush removal treatments was higher in cool and moist sagebrush sites and where pre-treatment native forb and grass cover was greater than 20 percent. Prescribed fire showed potential to increase niches for nonnative annual grass establishment, given that it resulted in larger gaps between perennial grasses, increased exposed mineral soil, and decreased biological soil crusts (Pyke et al., 2014). Treatments, especially prescribed fire, also resulted in increases in availability of soil nutrients (Rau et al., 2014) and an increase in the diversity of butterfly species present (McIver and Macke, 2014). The economics of various treatments were summarized (Taylor et al., 2013). Starting in 2016, SageSTEP treatment plots will be monitored again to assess effects 10 years after sagebrush removal, with a long-term plan to monitor treatments for up to 25 years after removal (J. McIver, personal communication).

Existing science gaps

Given that many sagebrush ecosystem attributes recover on the order of years to decades (McIver and Brunson, 2014), evaluation of sagebrush removal treatments for a minimum of 10 years will help to more fully understand treatment effects. The SageSTEP experiment is an example of a study that is examining the short- and long-term effects of sagebrush removal in sites across the Great Basin. Although many short-term effects have been summarized, additional analyses of collected data are needed to understand short-term effects on many ecological attributes (McIver et al., 2014). For example, data have been collected on fuels, hydrology, and bird communities following sagebrush removal, but they have not been analyzed and summarized.

Next steps

Short-term (1 to 3 years)

- New research: Analyze data already collected to gain new understanding of effects of sagebrush removal on fuels, wildlife species, and hydrology.
- New research: Collect new data on SageSTEP or similar long-term sites or new sites to evaluate effects that have occurred more than 10 years since sagebrush removal. Evaluate the effects of treatments on vegetation, fuels, wildlife, hydrology, and geochemical cycling across ecological communities in the sagebrush ecosystem.

Long-term (greater than 3 years)

- New research: Revisit experimental study sites to evaluate long-term (greater than 15 years) effects of sagebrush removal on vegetation, fuels, wildlife, hydrology, and geochemical cycling across the range of ecological communities in the sagebrush ecosystem.
- Synthesis: Synthesize findings of long-term effects of sagebrush removal treatments on a variety of ecological attributes.

Fire Science Need #7: Assess the role of fire in maintaining healthy sagebrush communities by identifying the balance between loss of intact sagebrush and recovery of young sagebrush required for habitat maintenance for different regions, communities, and ecological types.

Subtopic: Fire ecology and effects; Associated SO 3336 Task: 7(b)v

Background

The role of fire in the sagebrush ecosystem has changed dramatically in the last century. In many areas it has transitioned from a regime dominated by infrequent fires that allowed for natural sagebrush recovery to a regime dominated by frequent fire and increased dominance of nonnative annual grasses following the fire event. In many portions of the sagebrush ecosystem, especially in the Great Basin, a regime of frequent fires has detrimental consequences for species, such as sage-grouse (Coates et al., *in press*). In other regions, the lack of fire may be detrimental to sagebrush ecosystems by encouraging spread of coniferous species and suppressing understory forb diversity, ultimately leading to degraded sage-grouse habitat (Knick et al., 2005). Research on fire effects is needed to decide where and when it is appropriate to use prescribed fire or allow wildfires to burn in the sagebrush ecosystem to meet management objectives.

Summary of recent science and syntheses

Many studies have examined the effects of prescribed fire on vegetation in portions of the sagebrush ecosystem. Information from studies in the Great Basin was summarized in a synthesis of fire effects on vegetation and soils (Miller et al., 2013) and in an accompanying field guide for managers (Miller et al., 2014a). These documents synthesized all of the literature available at time of publication regarding fire effects on vegetation and provide criteria for selecting appropriate sites for use of prescribed fire and other treatment types.

Existing science gaps

The tools and syntheses that exist would be improved with research that quantifies levels of native herbaceous cover and functional diversity, both prior to and following fire, that enable systems to be resistant to nonnative annual grass invasion (J. Chambers, personal communication). This could be partially addressed with existing treatment effectiveness monitoring data. Information is needed on the interactive effects of livestock grazing, both historical and post-fire, and prescribed fire on recovery of native herbaceous species (J. Chambers, personal communication). Knowledge of the rate of sagebrush recovery following fire is also needed (see Fire Science Need #1). It is also important to invest in science outreach and training to both decision makers and their natural resource staffs to assure they are aware of and use the information already available (J. Chambers, personal communication).

Next steps

Short-term (1 to 3 years)

- New research: Determine additional empirical data needs that can help demonstrate how prescribed fire mimics the ecological role of historical fire regimes for a given landscape and ecological community type.
- New research: Determine the interactive effects of livestock grazing, in the short-term and before and after wildfire and prescribed fire, on recovery of native species and functional diversity of ecological communities. (Also see Table 3, Invasives Science Need #1, Long-term next step 3; and Invasives Science Need #4).
- New research: Evaluate existing treatment effectiveness monitoring data (e.g., from BLM, Natural Resources Conservation Service [NRCS]) to quantify native herbaceous cover and functional diversity thresholds needed to resist invasion of nonnative annual grasses (Also see Table 5, Sagebrush and Sage-Grouse Science Need #5).

Long-term (greater than 3 years)

- New research: Determine long-term (greater than 10 years) rates of recovery of various components of the sagebrush ecosystem after a fire. Priority components include sagebrush, native forbs, and deep-rooted native perennial grasses. Determine how pre-fire conditions and post-fire management, including livestock grazing, influence long-term recovery. (Also see Table 5, Sagebrush and Sage-Grouse Science Need #9).
- Synthesis: Summarize science about potential risks (e.g., partial to complete loss of sagebrush and other native plant species, extensive post-fire recovery period, and incursion of nonnative plant species) and benefits (e.g., improved habitat structural conditions for sage-grouse and enhanced grass-forb cover) of fire and how these benefits differ across the sagebrush ecosystem.



Fire Science Need #8: Determine which fuel breaks have met the objective of preventing fire spread or fire severity, and determine the characteristics of those that are successful, including synthesis of the literature, critical evaluation of techniques and plant materials used in fire breaks (species, structure, placement, and native versus nonnative species), and economic tradeoffs.

Subtopic: Fire Prevention/Fuels Reduction; Associated SO 3336 Task: 7(b)ii.

Background

The Great Basin, in particular, is experiencing a period of significant transformation due to large-scale wildfires and increased fire frequencies caused, in part, by nonnative annual grass invasions (Brooks et al., 2015). One component of the management response to this situation is installation of fuel breaks in strategic locations before fires occur. Fuel breaks are designed to disrupt fuel continuity, reduce fuel accumulations and volatility, or increase the proportion of plants with high moisture content (Maestas et al., 2016). Fuel breaks generally are grouped into three categories: roadside disking, mowed fuel breaks, and vegetative fuel breaks. Although use of fuel breaks is commonplace in the Great Basin and is a prescribed pre-suppression strategy for Federal, State, and private land managers, no specific research within the sagebrush ecosystem has been conducted to evaluate their effectiveness. In addition, the effectiveness of fuel breaks created before fire occurs is often unknown because the areas where they are placed are not affected by wildfire or are only burned 10 or more years after they are created, when their effectiveness may be diminished due to reversion to a vegetation type capable of carrying fire.

Summary of recent science and syntheses

Even though they have been created extensively since the late 1990s, no research has explored the effectiveness of fuel breaks in limiting the spread of fire in the sagebrush ecosystem. In addition, reduction in fire severity often is not the primary objective of fuel breaks, given that where the fire occurs within a sagebrush community, the effects are often severe. Evidence exists that fuel breaks are important tools for controlling large fires in forested ecosystems; however, fuel composition and structure in forests are much different than in sagebrush communities. Qualitative assessments by the BLM (i.e., based on interviews with fire management specialists) indicate that fire behavior is frequently influenced by a fuel break (Moriarti et al., 2015). Placement of fuel breaks, however, is subjective and often based on local fire management considerations. The NRCS 2016 Technical Note #66 (Maestas et al., 2016) provides a comprehensive explanation of fuel breaks in the Great Basin and indicates that additional research is needed on fire behavior and intensity related to fuel-break fire incursions. In 2015, the BLM initiated an informal search on the rationale, justification, and effectiveness of implementing fuel breaks and fuel treatments in sagebrush habitats (D. Havlina, personal communication). An informal analysis of the literature indicated a scarcity of information on treatment type, scale, or recommended design criteria that would improve the placement and configuration of fuel breaks.

Existing science gaps

Additional research is needed to quantify the direct effects of fuel breaks on fire behavior, including attributes such as fire intensity, spread rates, and spotting mechanisms. Research should consider fuel-break size, type (brown strip, green strip, mowed, intensively grazed, and herbicide), and the fuel-break location in the fuel environment. Plant species composition in green strips is also an important consideration. As noted by Havlina, numerous publications and technical management guides are available that may serve as partial foundation for a synthesis, but additional new research is needed. An analysis of economic tradeoffs between fuel-break types also should be conducted, along with comparing opportunity costs between fuel breaks and other potential alternative treatment types, strategies, and priorities.

Next steps

Short-term (1 to 3 years)

- New research: Review Fuels Treatment Effectiveness Monitoring (FTEM) records and compile fire-fuel break incursion reports if verifiable data are available. The FTEM is an interagency qualitative system in which local fire managers document the effectiveness of fuels treatments in locations that actually experience wildland fire.
- New research: Analysis of the economic tradeoffs between fuel-break types, as affected by different fuel types.

Long-term (greater than 3 years)

- New research: Multi-year critical, against clear standards, evaluation of fuel-break effects on fire spread, intensity, and severity. Consider multiple fuel-break types, techniques, fuel types, and overall fuel environments.
- New research: Assess fuel-break longevity and maintenance. Conduct a quantitative assessment of the long-term viability of fuel breaks including the type, timing of construction, and frequency of maintenance.
- Tool: Develop a database and standardized protocol for entry of information that allows for assessment of treatment effectiveness across fuel types.

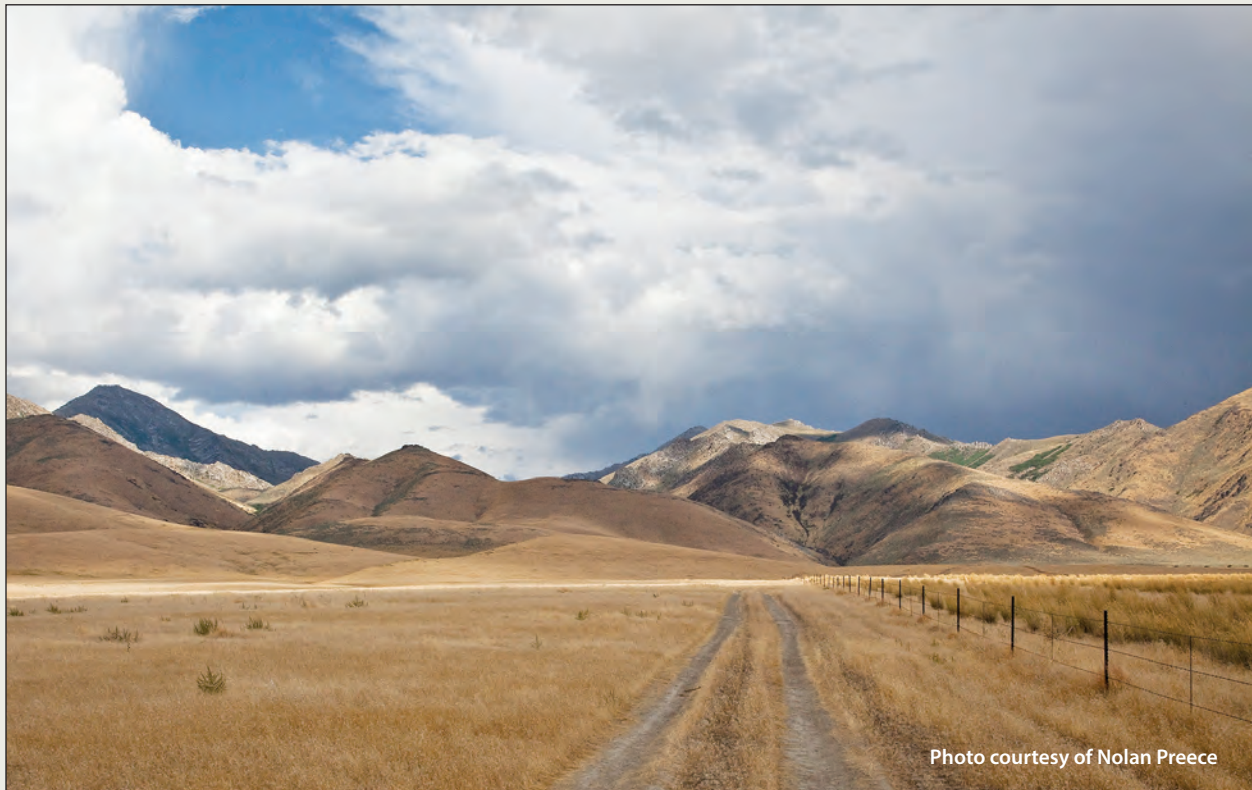


Photo courtesy of Nolan Preece

Invasives

This section contains priority science needs related to the control of invasive plant species with a special emphasis on cheatgrass, the primary invasive threat to the sagebrush ecosystem (Table 3). These needs include investigating potential biocontrols for cheatgrass, improving production and delivery systems of successful biocontrol agents, assessing the effectiveness of targeted grazing with livestock to reduce nonnative annual grasses, determining the natural and anthropogenic factors that influence invasive plant species distributions, assessing prevention, eradication, and control measures for invasive plant species, and developing maps showing locations of invasive plant species to inform early detection and other control measures.



Table 3. Science needs and next steps in the Invasives topic. Next steps include new research, syntheses, and tools that are needed to fill the identified science gaps. The list separates those steps that could be accomplished in the short term (1 to 3 years), followed by those that are considered long term (accomplished in more than 3 years).

#	Need	Timing	Type	Next step
1	Improve understanding of the natural and anthropogenic factors that influence invasive plant species distributions, including invasion history, surface disturbance, habitat condition, and fire history, and determine whether those factors can help identify tradeoffs among alternative management approaches	Short-term	New research	<p>Develop high-resolution maps of the current distribution of cheatgrass, and create mechanisms or geospatial tools to update the maps regularly.</p> <p>Create high-resolution maps of the current distributions of other invasive nonnative annual grasses such as medusahead rye (<i>Taeniatherum caput-medusae</i>) and ventenata (<i>Ventenata dubia</i>).</p> <p>Conduct a meta-analysis of literature addressing the distribution, spread, and environmental associations of cheatgrass. Focus on relationship between disturbance events and activities that affect cheatgrass abundance, including wildfire, prescribed fire, grazing, roads, industrial activities and infrastructure, habitat treatments, and environmental conditions associated with cheatgrass abundance and dominance.</p> <p>Map and model additional invasive plants. Prioritization of this work should consider potential of an invasive plant to negatively affect ecosystems, habitats, or both.</p> <p>Develop locally specific spatially-explicit soil maps, including soil temperature and moisture estimates, to inform spatial models and decision support tools at management-relevant scales.</p>
			Synthesis	Review the literature about the role of weather and climate in facilitating the spread of nonnative annual grasses.
		Long-term	New research	<p>Initiate treatment and restoration experiments using cooperative efforts between management and research. Distribute study areas across the region using environmental gradients to capture and explain variability in response, seeking single or combined treatments that “mimic” positive effects of disturbance on habitat quality, and that minimize stimulation of nonnative annual grasses, annual forbs, and perennial invaders.</p> <p>Conduct studies aimed at understanding the distribution, spread, and environmental associations of other rapidly spreading nonnative annual grasses (e.g., medusahead rye and ventenata), including the effects of weather and climate.</p> <p>Conduct integrated landscape (remote-sensing) and local (field-based) assessment of post-disturbance recovery rates to assess differences in rates and composition due to climate, soils herbivory, land use, and other environmental patterns. Assess implications of recovered areas for wildlife use, fuel dynamics and fire potential, and ecosystem services.</p> <p>Also refer to Invasives Science Need #4, long-term next steps.</p>

Table 3. Science needs and next steps in the Invasives topic. Next steps include new research, syntheses, and tools that are needed to fill the identified science gaps. The list separates those steps that could be accomplished in the short term (1 to 3 years), followed by those that are considered long term (accomplished in more than 3 years).—Continued

#	Need	Timing	Type	Next step
2	Improve measures for prevention, eradication, and control of invasive plant species, and use risk assessments to weigh potential benefits and deleterious effects of different measures on native plant species	Short-term	New research	Investigate the complex interrelationships among various components within ecosystems that create multiple, indirect responses by invasive plant species to specific vegetation-management actions.
			Synthesis	Develop guidelines to evaluate causes of invasion, succession, and retrogression (e.g., cheatgrass die-off).
		Long-term	New research	Investigate strategies for prevention of new plant invasions that are based on the ecology of seed dispersal. Investigate the potential for integrating invasive plant management within a systems approach to facilitate problem solving and the attainment of well-defined goals, rather than practice-based outcomes.
			Synthesis	Develop a conceptual framework and associated tools that assist in identifying which vectors are major contributors to invasive plant species dispersal. Then develop dispersal-management strategies to minimize or interrupt these major vectors.
3	Conduct invasive plant inventory, including spatial data on infestations and current range maps, to improve the ability for managers to prioritize actions to prevent and control nonnative plant populations before they become established and spread	Short-term	New research	Initiate standardized early-season field collection to inform early detection efforts and map development. Develop nonnative annual grass spatial datasets to inform annual predictive fire models and identify of potential treatment areas.
			Tool	Develop a centralized clearinghouse of occurrence data for invasive plants that aggregates data from existing data entry systems and databases.
		Long-term	New research	Develop datasets to map current cheatgrass and sagebrush extent and productivity, in relation to annual weather conditions, that will readily integrate into fire models to identify spatially explicit fire probabilities, and enable prediction of future cheatgrass distributions using projected climate scenarios.



Photo credit: Jaepil Cho

Table 3. Science needs and next steps in the Invasives topic. Next steps include new research, syntheses, and tools that are needed to fill the identified science gaps. The list separates those steps that could be accomplished in the short term (1 to 3 years), followed by those that are considered long term (accomplished in more than 3 years).—Continued

#	Need	Timing	Type	Next step	
4	Assess effectiveness of targeted grazing with livestock to reduce nonnative annual grasses and understand the impact on native plants in the sagebrush ecosystem	Short-term	New research	Implement and intensively monitor landscape-level, targeted-grazing demonstration projects to strategically reduce fine fuels.	
				Implement and assess several projects to establish grazed “fire breaks” in combination with other fuel treatment methods, determining relative importance of targeted grazing versus other treatments.	
				Determine thresholds of residual herbaceous fuels required to alter fire behavior and facilitate suppression under various weather conditions.	
				Evaluate the economic efficiencies of using targeted grazing as a short-term wildland fuel treatment.	
				Evaluate the potential role of livestock grazing to reduce fuel loads in mixed shrub and grass vegetation types in the short-term.	
				Evaluate the rate, frequency, and timing of grazing events necessary to maintain targeted fuel levels.	
				Evaluate the interactions between the modifications of fine fuels by grazing and sage-grouse nesting and brood-rearing success, including measurement of the impacts of grass height on nesting cover and insect availability.	
		Long-term	New research	Evaluate the role of livestock in spreading invasive weeds, and explore methods to ameliorate the problem of the spread of invasive weeds.	
				Synthesis	Develop science-based guidance for implementing and assessing effectiveness and resource and economic impacts of targeted grazing projects to manage wildland fuels.
				Develop management strategies to accomplish cost-effective high herbaceous biomass utilization.	
				Continue short-term monitoring and research studies in grazing demonstration areas to ensure that management practices are effective and sustainable.	
				Evaluate the effects of grazing over large areas on fire intensity and patchiness, and extent of burned area.	
				Determine the ecological impact of “heavy utilization” to accomplish fuel reduction on the wildlife, plant, and soil microbial communities, especially those related to or dependent on native plants.	
				Investigate the effects of feral horses and burros, in combination with livestock, and as a single change agent.	
Synthesis	New research	Develop strategies to replace nonnative annual grasses with grazing-tolerant and fire-resilient plant materials, particularly those that support sage-grouse nesting and brood-rearing, in targeted grazing demonstration areas.			
		Evaluate the potential role of livestock grazing to reduce fuel loads in mixed shrub and grass vegetation types over long time frames; include type of livestock (cattle vs. sheep), pre-grazing condition, seasonal precipitation (amount and timing), and interactions with other treatment methods, including fire, chemical, and mechanical treatments conducted individually or in combinations.			

Table 3. Science needs and next steps in the Invasives topic. Next steps include new research, syntheses, and tools that are needed to fill the identified science gaps. The list separates those steps that could be accomplished in the short term (1 to 3 years), followed by those that are considered long term (accomplished in more than 3 years).—Continued

#	Need	Timing	Type	Next step
5	Conduct detailed optimization studies on production and delivery systems of biocontrol agents, followed by evaluation in scaled-up field inoculation trials	Short-term	New research	Develop a study design and protocols that can be used in a U.S. Department of the Interior (DOI) pilot study to ensure consistency in site selection, product application, data collection, and data management to evaluate efficacy and impacts to non-target species across a broad geographical area. Develop and conduct improved trials of the effectiveness and effects of ACK55 to address requirements for EPA registration. Evaluate the effectiveness of weed-suppressive bacteria treatments through time to reduce cheatgrass dominance over large areas.
			Synthesis	Complete a review of all open-source and non-open-source literature highlighting successful and unsuccessful applications of weed-suppressive bacteria as a nonnative annual grass biopesticide.
			Tool	Develop a user-friendly centralized data management system to promote the exchange of information and facilitate investigation of efficacy and non-target effects of weed-suppressive bacteria.
		Long-term	New research	Investigate effects of biocontrol agents on soil microbial communities. Research and develop new delivery mechanisms (e.g., pellets, granules) that will foster successful bacteria application over large areas.
			Tool	Develop best management practices and associated guidance for proper use of biocontrols.
6	Investigate cheatgrass die-off and potential biocontrols for cheatgrass to provide effective tools for site preparation	Short-term	New research	Expand analysis of die-offs to include large expanses of cheatgrass-dominated desert valleys across the Great Basin, and use geospatial statistical tools to improve die-off predictive models. Develop technology to measure pathogen loads in soil using molecular-genetic techniques. Carry out studies on small plots where pathogen load and environmental conditions are manipulated to determine how and where failure of cheatgrass can be induced by management as a site-preparation technique prior to restoration seeding. Determine the effects of cheatgrass pathogens on non-target hosts, including species likely to be included in restoration seeding mixes. Continue and expand studies to assess effectiveness of restoration seedings in new die-offs (mapped in real-time), including reestablishment of deep-rooted perennial grasses and sagebrush.
			Long-term	New research

Invasives Science Need #1: Improve understanding of the natural and anthropogenic factors that influence invasive plant species distributions, including invasion history, surface disturbance, habitat condition, and fire history, and determine whether those factors can help identify tradeoffs among alternative management approaches.

Subtopic: Impacts and Interactions; Associated Strategy Tasks: 7(b)iv and vii

Background

The distribution of invasive plant species results from numerous interacting ecological processes. While these processes have been studied, knowledge regarding their effects and interactions sufficient to guide management is often lacking. For example, invasive plant species distributions have been modeled across the western United States (Bradley 2009), relations between invasive plants and human infrastructure have been described regionally (Nielsen et al., 2011), and the local response of cheatgrass and sagebrush ecosystems to fire and grazing have been documented. However, research that helps to put these pieces together for management application and use in regional and local contexts is needed. A thorough, applied understanding of these interactions can help identify management actions that could be used to disrupt the current cycle of invasive plant species spread, avoid actions and areas that aggravate the problem, and promote actions that increase ecosystem resilience.

Summary of recent science and syntheses

Although a substantial body of research has documented relations between invasive plants and invaded environments, consistent results are not easily attained. The problem of widespread distribution and rapid spread of invasive nonnative annual grasses is well documented (e.g., Young and Allen, 1997; Bradley, 2009), as are the common associations of invasive plants with natural and anthropogenic disturbances (see Germino et al., 2016a, for a synthesis and modern interpretation of this literature for *Bromus* species). Recent research on the resistance and resilience of sagebrush ecosystems to fire and nonnative annual grasses (Chambers et al., 2014b) provides a conceptual framework for predicting the susceptibility of priority sage-grouse habitats to nonnative annual grasses, especially cheatgrass, based on the environmental potential of the location (invasion potential). Regional soil maps provide broad information about the landscape distribution of environmental factors that affect the distribution and condition of sagebrush habitats. Recent research also has expanded perspectives about relationships between abundance of cheatgrass and fire (e.g., Taylor et al., 2014; Duniway et al., 2015; Morris and Leger, 2016), grazing (e.g., Davies et al., 2016), and climate (e.g., Creutzburg et al., 2015; Hardegee et al., 2016). These results may have direct applications to management, and they provide the foundation for understanding interactions among these important determinant factors.

Mealor et al. (2013) developed a handbook focused on management of cheatgrass. This publication recommended prioritization of treatment activities based on level of infestation, value of the landscape (e.g., presence of important wildlife habitat), management options, landscape context (presence of healthy sagebrush stands), and recovery potential of the ecosystem.

Existing science gaps

A local understanding and interpretation of resistance and resilience concepts using locally specific soil maps, temperature, and moisture estimates is needed. These locally specific soil maps and the moisture estimates need to be available as spatially explicit, gridded digital datasets that can be ingested into spatial models at relevant spatial scales. Examining the responses of invasive plant species and the native vegetation to treatments and other disturbances will document treatment effectiveness and habitat restoration. An assessment of the effects of multiple acute and chronic disturbances and anthropogenic features on native and invasive vegetation composition and productivity will support planning and mitigation. An evaluation of the effects of different grazing practices, in different environments and in

interaction with other disturbances such as fire, on native and nonnative plant abundance and productivity will shed light on trade-offs between different management strategies. Evaluating the suite of current and potential sagebrush ecosystem invaders can help managers prepare for long-term responses.

Next steps

Short-term (1 to 3 years)

- New research: Develop high-resolution maps of the current distribution of cheatgrass, and create mechanisms or geospatial tools to update the maps regularly.
- New research: Create high-resolution maps of the current distributions of other invasive nonnative annual grasses such as medusahead rye and ventenata (*Ventenata dubia*).
- New research: Conduct a meta-analysis of literature addressing the distribution, spread, and environmental associations of cheatgrass. Focus on relationship between disturbance events and activities that affect cheatgrass abundance, including wildfire, prescribed fire, grazing, roads, industrial activities and infrastructure, habitat treatments, and environmental conditions associated with cheatgrass abundance and dominance.
- New research: Map and model additional invasive plants. Prioritization of this work should consider potential of an invasive plant to negatively affect ecosystems, habitats, or both.
- New research: Develop locally specific spatially-explicit soil maps, including soil temperature and moisture estimates, to inform spatial models and decision support tools at management-relevant scales.
- Synthesis: Review the literature about the role of weather and climate in facilitating the spread of nonnative annual grasses.

Long-term (greater than 3 years)

- New research: Initiate treatment and restoration experiments using cooperative efforts between management and research. Distribute study areas across the region using environmental gradients to capture and explain variability in response, seeking single or combined treatments that “mimic” positive effects of disturbance on habitat quality, and that minimize stimulation of nonnative annual grasses, annual forbs, and perennial invaders.
- New Research: Conduct studies aimed at understanding the distribution, spread, and environmental associations of other rapidly spreading nonnative annual grasses (e.g., medusahead rye and ventenata), including the effects of weather and climate.
- New research: Conduct integrated landscape (remote-sensing) and local (field-based) assessment of post-disturbance recovery rates to assess differences in rates and composition due to climate, soils herbivory, land use, and other environmental patterns. Assess implications of recovered areas for wildlife use, fuel dynamics and fire potential, and ecosystem services.
- New research: Also refer to Invasives Science Need #4, long-term next steps.



Invasives Science Need #2: Improve measures for prevention, eradication, and control of invasive plant species, and use risk assessments to weigh potential benefits and deleterious effects of different measures on native plant species.

Subtopic: Risk reduction/prevention; Associated Strategy Task: 7(b)vii

Background

Invasive plant species have many negative effects on rangelands throughout the world. Invasive plants can displace desirable species, alter ecological processes, reduce wildlife habitat, degrade riparian systems, and decrease productivity (DiTomaso, 2000; Masters and Sheley, 2001). Invasive plants are estimated to spread across 100 million hectares (ha) in the United States (National Invasive Species Council, 2001). Experts recognize invasive species as second only to habitat destruction as a threat to biodiversity. Furthermore, Wilcove et al. (1998) estimated that invasive species have contributed to the placement of 35 to 46 percent of the plants and animals designated as threatened or endangered under the Federal Endangered Species Act. In 1994, the financial impact of invasive plant species in the United States was estimated to be \$13 billion per year (Westbrooks 1998). The amount of land infested by invasive plants is rapidly increasing (Westbrooks 1998), and subsequently, the negative impacts of invasive plants are escalating.

Summary of recent science and syntheses

The scientific literature documents only short-term vegetation responses to invasive plant management and rarely addresses secondary ecosystem responses to management. The ability of managers to protect lands not yet invaded is encumbered by the difficulties associated with employing early detection techniques and with effective eradication efforts once new infestations are identified. Some strategies for maintaining invasion-resistant plant communities are beginning to emerge. Herbicides provide short-term control of most invasive weeds, but without additional management, weeds return rapidly. Documentation of biological control's influence on plant development is robust, but positive effects on control and vegetation dynamics are exceedingly rare. Grazing management can be a useful method for directing vegetation dynamics, but the timing, intensity, and frequency of grazing, as well as the class of livestock, are only known for a few invasive weed species. Restoration of rangelands infested with invasive plants is difficult and often unsuccessful when nonnative plant material is seeded, and even less when native species are seeded (Knutson et al., 2014). However, recent research indicates that the low success rate of native species may be due to selecting incorrect subspecies or ecotypes for the site (Richardson et al., 2015). There are cases where invasive plant management strategies can be effective, and in those cases, the strategies appear to favorably affect wildlife and other important ecological attributes of the ecosystem. However, some strategies may be associated with high ecological risks and high risk of failure in the long-term. More research is necessary if the anticipated benefits of invasive plant management are to be achieved.

Existing science gaps

Complex interrelationships among various components within ecosystems create multiple indirect responses to vegetation management that are very difficult to predict. This creates a strong need to manage invasive plants within the context of the entire ecosystem. Integrating invasive plant management within a systems approach would facilitate problem solving and the attainment of well-defined goals, rather than achieve only practice-based outcomes. Assessing the complex interrelationship among ecosystem components and processes and designing management strategies that influence the underlying ecological cause of invasion and dominance by invaders with predictable outcomes would improve management outcomes. Imposing management that addresses the actual cause of invasion is clear in some cases. Weed ecologists and scientists could develop guidelines to evaluate causes of invasion, succession, and retrogression. Once guidelines were developed, ecological principles could be developed

that provide guidelines for managers to use tools and strategies to influence conditions, mechanisms, and processes in favor of desired vegetation. Because multiple interactive ecological processes are addressed, integrated plant management strategies can be developed and employed much more effectively. In this way, various plant management strategies can be designed based on how the treatments influence the ecological processes that direct ecosystem change. Improving the tools and strategies with additional ecological understanding could enhance efforts to employ effective integrated management. Enhancing abilities to prevent invasion is critical for successful implementation of integrated invasive plant management. Most managers recognize the importance of prevention, but lack the resources to effectively employ prevention methods. Science-based prevention strategies that are based on the ecology of seed dispersal are severely needed. Land managers need a conceptual framework and associated tools that assist them in identifying which vectors are major contributors to invasive species dispersal and propose dispersal management strategies to minimize or interrupt these major vectors.

Next Steps

Short-term (1 to 3 years)

- **New research:** Investigate the complex interrelationships among various components within ecosystems that create multiple, indirect responses by invasive plant species to specific vegetation-management actions.
- **Synthesis:** Develop guidelines to evaluate causes of invasion, succession, and retrogression (e.g., cheatgrass die-off).

Long-term (greater than 3 years)

- **New research:** Investigate strategies for prevention of new plant invasions that are based on the ecology of seed dispersal.
- **New research:** Investigate the potential for integrating invasive plant management within a systems approach to facilitate problem solving and the attainment of well-defined goals, rather than practice-based outcomes.
- **Synthesis:** Develop a conceptual framework and associated tools that assist in identifying which vectors are major contributors to invasive plant species dispersal. Then develop dispersal-management strategies to minimize or interrupt these major vectors.

Invasives Science Need #3: Conduct invasive plant inventory, including spatial data on infestations and current range maps, to improve the ability for managers to prioritize actions to prevent and control nonnative plant populations before they become established and spread.

Subtopic: Monitoring; Associated Strategy Tasks: 7(b)iii and vii, Crosscut #2 and 3

Background

Early detection of invasive plant infestations enables managers to undertake control measures before the species' populations become large and widespread. This is the core mission of early detection and rapid-response programs. While programs exist for reporting noxious weed infestations (EDDMapS, CalWeedMapper, etc.), the various systems are not linked to provide a centralized clearinghouse of invasive plant species occurrence data across the multiple agencies and entities with responsibilities for controlling these species. Early detection of invasive nonnative annual grasses is a key priority within the sagebrush ecosystem, and existing systems often do not collect this information due to classification of these species at the State or local level. Even with invasive plant species that currently dominate large expanses of moisture-limited sage-grouse habitat, such as cheatgrass, early-season detection of invasions can help land managers prevent the continued spread of these species.

Summary of recent science and syntheses

Methods have been developed to enable near-real-time mapping of cheatgrass percent cover at a 250-m resolution based on the work of Boyte et al. (2015; 2016). These methods have been used to produce current-year maps for July 2015 and July 2016 (Boyte and Wylie, *in press*). When coupled with a time series (years 2000–2013) (Boyte et al., 2016), these datasets have revealed changing cheatgrass dynamics, including a 7.5-percent overall increase in cheatgrass percent cover in 2016 compared to 2015. Additional advances in remote sensing include improved detection of incremental change in annual herbaceous vegetation in the sagebrush ecosystem using Landsat imagery (Homer et al., 2012; Xian et al., 2015). These products allow rapid development of map products, as far back as the year 1984 (Homer et al., 2015), and these techniques will enable rapid mapping as Landsat data become available annually (C. Homer, personal communication). Germino et al. (2016a) summarized and synthesized the current knowledge, management implications, and research needs for the *Bromus* species in the arid and semiarid western United States, which have replaced native shrub, forbs, grasses, and biotic soil crusts to the detriment of the sagebrush ecosystem and the people and wildlife that inhabit it.

Existing science gaps

An understanding of environmental characteristics that govern the ability of *Bromus* species to invade sagebrush ecosystems and sage-grouse habitat (Belnap et al., 2016; Bradley et al., 2016; Chambers et al., 2016) could be further developed to improve knowledge of current distributions and invasive risk potential relative to weather, topography, and soil characteristics. These analyses could be enhanced by developing a time series of nonnative annual grass spatial datasets and comparing these datasets to environmental variables to understand the characteristics of relatively recently invaded areas. Finer spatial-scale soils data available in a digital format (McBratney et al., 2003; Henderson et al., 2005) and more frequently acquired moderate spatial-scale satellite data would enhance spatial modeling efforts of nonnative annual grasses. These nonnative annual grass species experience short growing seasons (detection periods when using coarse-scale satellite data for landscape and regional analysis) in sage-grouse habitat areas, and current efforts to map them at moderate to fine spatial scales are generally expensive and labor intensive (Xian et al., 2015). Increasing the image frequency would improve the availability of quality data and reduce costs and efforts to map invasive plant species at a mid-level (30-m) resolution. The launch of Landsat 9, scheduled for 2020, will offer more frequent satellite images at such a mid-level resolution.

Operational collection of field data to detect cheatgrass establishment early in the year could assist with map construction and accuracy assessment as well and inform cheatgrass control efforts and future fire risk assessment. Downscaling of Moderate Resolution Imaging Spectroradiometer (MODIS) Normalized Difference Vegetation Index (NDVI; Gu and Wylie, 2015a, b) has been applied to weekly NDVI to support efforts to map continuous land cover by providing vegetation productivity and important phenological time periods to facilitate land-cover separation. This approach leverages the strengths of MODIS (daily coverage to remove clouds in weekly products, temporal NDVI smoothing to interpolate across cloudy weeks, and the needed spectral bands for atmospheric correction) with the spatial context of Landsat. This may be a viable approach for getting quantification early in the growing season of potential cheatgrass production. These downscaling approaches could also be applied to near-real-time cheatgrass maps (with a resolution of 250 m) in and adjacent to sage-grouse priority habitats, or to assess restoration success.

Next steps

Short-term (1 to 3 years)

- New research: Initiate standardized early-season field collection to inform early detection efforts and map development.
- New research: Develop nonnative annual grass spatial datasets to inform annual predictive fire models and identify of potential treatment areas.

- Tool: Develop a centralized clearinghouse of occurrence data for invasive plants that aggregates data from existing data entry systems and databases.

Long-term (greater than 3 years)

- New research: Develop datasets to map current cheatgrass and sagebrush extent and productivity, in relation to annual weather conditions, that will readily integrate into fire models to identify spatially explicit fire probabilities, and enable prediction of future cheatgrass distributions using projected climate scenarios.

Invasives Science Need #4: Assess effectiveness of targeted grazing with livestock to reduce nonnative annual grasses and understand the impact on native plants in the sagebrush ecosystem.

Subtopic: Risk Reduction/Prevention; Associated Strategy Tasks: 7(b)iii and vii

Background

Multiple studies have examined the use of targeted grazing to achieve rangeland vegetation objectives, including reduction of fine fuels (Mosley and Roselle, 2006; Strand et al., 2014). Targeted grazing requires intensive management, with the seasonal timing, duration, and intensity of livestock use carefully controlled to accomplish management goals. There are several ways that contemporary livestock grazing practices can affect the consequences of wildfires in grassland and shrubland ecosystems. Carefully managed grazing can reduce the amount of fine fuels created by nonnative annual grasses, forbs, and woody plants. Grazing can reduce the potential for fire ignition and spread by removing understory vegetation, reducing the amount of fuel, and accelerating the decay of litter through trampling. Grazing also can alter the continuity of fuels to slow rates of spread and intensity, which can result in a naturally patchy burn and unburned islands of vegetation, which then can provide a seed source for re-establishment of plants after a burn (Kerby et al., 2006). The effects of grazing could result in fires with lower fire-line burn intensity, increased patchiness, decreased rate of spread, and increased subsequent survival of plants after fire. Grazing also can be applied in specified ways across landscapes in combination with fuel breaks to compartmentalize fires and improve the effectiveness of fire-fighting activities. Although targeted grazing can be an important tool to manage fire behavior and effects, the effectiveness of targeted grazing depends on the weather conditions during a fire, including daily and seasonal variations in temperature, relative humidity and wind (Strand et al., 2014), and the structural composition of the plant community. Few comprehensive studies have examined the interaction of factors influencing the efficacy of targeted grazing for reducing nonnative annual grasses and its impacts on native plants in the sagebrush ecosystem (Boyd et al., 2014; Strand et al., 2014).

Summary of recent science and syntheses

Initial findings about the value of livestock grazing to manage fuels in the sagebrush ecosystem indicate that when cattle grazed at moderate levels in areas of relatively low sagebrush canopy cover (4–10 percent), flame height and rate of fire spread was significantly reduced compared to areas with no grazing (Schachtschneider, 2016). Research on dormant season grazing in relatively intact sagebrush communities in eastern Oregon demonstrates the utility of livestock grazing in reducing residual herbaceous plants and favorably modifying fire behavior (Davies et al., 2016). In Arizona, herbaceous fuels were reduced and modeled fire behavior moderated by using a combination of low-stress herding and strategic placement of low-moisture block supplements (Bruegger et al., 2016). Recently a literature review on the impacts of historical livestock grazing patterns on fuels and the short-term effects of livestock on fuels and fires in the sagebrush ecosystem was completed (Strand et al., 2014). The researchers concluded that many ecological questions remain regarding use of livestock to manage vegetation and fuels.

Existing science gaps

Several research gaps remain regarding the use of livestock to manage fuel loads (Strand et al., 2014). They include understanding thresholds of residual herbaceous fuels required to alter fire behavior and facilitate suppression under various weather conditions, determining the effects of landscape-scale grazing on fire intensity and patchiness and extent of burned area, and evaluating the economic efficiencies of using targeted grazing as a wildland fuel treatment. Other gaps related to the use of targeted grazing include the need to understand the potential role of livestock grazing to reduce fuel loads in mixed shrub and grass vegetation types in the short- and long-term; the ecological impact of heavy utilization to accomplish fuel reduction on wildlife, plant, and soil microbial communities, especially those related to or dependent on native plants; the rate, frequency, and timing of grazing events necessary to maintain targeted fuel levels; and management strategies to accomplish high herbaceous biomass use without extensive fencing or new water developments (Launchbaugh et al., 2008). Another need is to understand the consequences of grazing landscapes sufficiently to modify fire behavior through reductions in fine-fuel loadings on sage-grouse and other sagebrush-obligate species. Understanding effects on sage-grouse habitat use and sage-grouse nesting and brood-rearing success is especially important.

Next steps

Coordination with Sagebrush and Sage-Grouse Science Need #2 (Table 5) may provide additional efficiency to address questions regarding ecological impacts.

Short-term (1 to 3 years)

- New research: Implement and intensively monitor landscape-level, targeted-grazing demonstration projects to strategically reduce fine fuels.
- New research: Implement and assess several projects to establish grazed “fire breaks” in combination with other fuel treatment methods, determining relative importance of targeted grazing versus other treatments.
- New research: Determine thresholds of residual herbaceous fuels required to alter fire behavior and facilitate suppression under various weather conditions.
- New research: Evaluate the economic efficiencies of using targeted grazing as a short-term wildland fuel treatment.
- New research: Evaluate the potential role of livestock grazing to reduce fuel loads in mixed shrub and grass vegetation types in the short-term.
- New research: Evaluate the rate, frequency, and timing of grazing events necessary to maintain targeted fuel levels.
- New research: Evaluate the interactions between the modifications of fine fuels by grazing and sage-grouse nesting and brood-rearing success, including measurement of the impacts of grass height on nesting cover and insect availability.
- New research: Evaluate the role of livestock in spreading invasive weeds, and explore methods to ameliorate the problem of the spread of invasive weeds.
- Synthesis: Develop science-based guidance for implementing and assessing effectiveness and resource and economic impacts of targeted grazing projects to manage wildland fuels.
- Synthesis: Develop management strategies to accomplish cost-effective high herbaceous biomass utilization.

Long-term (greater than 3 years)

- New research: Continue short-term monitoring and research studies in grazing demonstration areas to ensure that management practices are effective and sustainable.
- New research: Evaluate the effects of grazing over large areas on fire intensity and patchiness, and extent of burned area.
- New research: Determine the ecological impact of “heavy utilization” to accomplish fuel reduction on the wildlife, plant, and soil microbial communities, especially those related to or dependent on native plants.
- New research: Investigate the effects of feral horses and burros, in combination with livestock, and as a single change agent.
- Synthesis: Develop strategies to replace nonnative annual grasses with grazing-tolerant and fire-resilient plant materials, particularly those that support sage-grouse nesting and brood-rearing, in targeted grazing demonstration areas.
- Synthesis: Evaluate the potential role of livestock grazing to reduce fuel loads in mixed shrub and grass vegetation types over long time frames; include type of livestock (cattle vs. sheep), pre-grazing condition, seasonal precipitation (amount and timing), and interactions with other treatment methods, including fire, chemical, and mechanical treatments conducted individually or in combinations.

Invasives Science Need #5: Conduct detailed optimization studies on production and delivery systems of biocontrol agents, followed by evaluation in scaled-up field inoculation trials.

Subtopic: Biological Control; Associated Strategy Task: 7(b)vii

Background

The introduction of nonnative invasive annual grasses, primarily cheatgrass and medusahead rye, threaten the sagebrush ecosystem. The expansion of these two species is linked to accelerated loss of sagebrush habitat due to increased fire frequency, size, and intensity that precludes the reestablishment of sagebrush and reduces or eliminates native forbs and grasses (Link et al., 2006).

The limited success of mechanical and chemical treatment to control cheatgrass and medusahead rye over the past 50 years has led to exploration of other treatment methods (Mack 2011). *Pseudomonas fluorescens*, a weed-suppressive soil bacterium, is naturally occurring, ubiquitous, and non-pathogenic. Strains ACK55 and D7, as host-specific biopesticides, are among the new promising tools for nonnative annual grass control (Kennedy and Stubbs, 2007; Stubbs et al., 2014). Mack (2011) urges further evaluation and transfer of this research into widespread field application.

Summary of recent science and syntheses

Weed-suppressive bacteria (WSB) strains ACK55 and D7 have undergone extensive testing and have demonstrated selectivity for cheatgrass, medusahead rye, and jointed goat grass (*Aegilops cylindrica*) (Kennedy et al., 1991; Johnson et al., 1993; Tranel et al., 1993; Gurusiddaiah et al., 1994). Application of the WSB to the soil of sagebrush communities can reduce the canopy cover of nonnative annual grasses through suppression of root growth, tiller formation, and seed bank (Kennedy et al., 1991; Kennedy et al., 2001). Colonies of the WSB establish in the soil microbial community over winter and establish on roots of these annual grasses in early spring. They deliver natural compounds that inhibit root development and, subsequently, reduce competition with desirable native plants. A single application of WSB, coupled with competition by native plants, can reduce cheatgrass dominance within 3 to 5 years after application (Kennedy et al., in preparation).



Photo credit: David A. Pyke, USGS

Existing science gaps

Research on the use of *Pseudomonas fluorescens*, strain D7, as a biopesticide has focused on laboratory and small-scale field tests and has not addressed either its efficacy or its impacts on soil microbial communities and other non-target species across large areas (Aston and Gordon 2015). Additional implementation studies are needed before agencies can make recommendations and finalize protocols for the use of this bacterium as a biopesticide on Federal lands. Most research on WSB has been conducted in the vicinity of the Palouse Prairie in Washington where the bacterium was originally isolated. Trials with this WSB have expanded beyond Washington, but efficacy data are not available. Initially, studies will need to be conducted to evaluate efficacy of WSB across a broad geographical area where cheatgrass is an issue. This research needs to encompass the range of ecological conditions present within the sagebrush ecosystem in order to fully evaluate WSB as a new management tool for control of nonnative annual grasses (Aston and Gordon, 2015).

Next steps

Short-term (1 to 3 years)

- New research: Develop a study design and protocols that can be used in a U.S. Department of the Interior (DOI) pilot study to ensure consistency in site selection, product application, data collection, and data management to evaluate efficacy and impacts to non-target species across a broad geographical area.
- New Research: Develop and conduct improved trials of the effectiveness and effects of ACK55 to address requirements for EPA registration.
- New Research: Evaluate the effectiveness of WSB treatments through time to reduce cheatgrass dominance over large areas.
- Synthesis: Complete a review of all open-source and non-open-source literature highlighting successful and unsuccessful applications of WSB as a nonnative annual grass biopesticide.
- Tool: Develop a user-friendly centralized data management system to promote the exchange of information and facilitate investigation of efficacy and non-target effects of WSB.

Long-term (greater than 3 years)

- New research: Investigate effects of biocontrol agents on soil microbial communities.
- New research: Research and develop new delivery mechanisms (e.g., pellets, granules) that will foster successful bacteria application over large areas.
- Tool: Develop best management practices and associated guidance for proper use of biocontrols.

Invasives Science Need #6: Investigate cheatgrass die-off and potential biocontrols for cheatgrass to provide effective tools for site preparation.

Subtopic: Biological Control; Associated Strategy Task: 7(b)vii

Background

Cheatgrass and other nonnative annual grasses present a major obstacle to successful post-fire restoration of the sagebrush ecosystem. Seeding without some form of invasive plant control is often unsuccessful except occasionally immediately after wildfire removes the shrub canopy and reduces the nonnative annual grasses' seed bank (Hardegree et al., 2011). Once nonnative annual grasses have established dominance, as has happened over millions of acres of former sagebrush vegetation, these areas are often written off as hopelessly difficult to restore. However, in order to achieve the goal of no net loss of sagebrush habitat, it will be necessary to develop methods for restoring nonnative annual grass monocultures to structurally diverse native vegetation.

Summary of recent science and syntheses

Cheatgrass and other nonnative annual grass monocultures are susceptible to natural controls, including fungal plant pathogens. Use of an augmentative biocontrol approach using one or more of these pathogens has been explored. This is in contrast to the classical approach of introducing natural enemies from a plant species' native range to initiate long-term population decline. Instead, the concept is to increase the abundance of a naturally co-occurring pathogens or competitors above a threshold for adequate short-term control. This would provide a window of opportunity for the establishment of seeded species. Two fungal pathogens of cheatgrass have been studied in some detail for biocontrol potential: the head smut pathogen (*Ustilago bullata*) (Boguena et al., 2007; Meyer et al., 2008) and the seed-bank pathogen black fingers of death (*Pyrenophora semeniperda*) (Meyer et al., 2010; 2016a). Other species also are being investigated as possible biocontrol agents (see Meyer et al., 2016b, for review).

A notable phenomenon in cheatgrass monocultures is stand failure or “die-off,” sometimes over very large areas (Baughman and Meyer, 2013; Weisberg et al., 2016). In these areas, native seedlings can experience enhanced success due to increased availability of water and nutrients (Baughman et al., 2016). Remote-sensing methods using Landsat imagery (Weisberg et al., 2016) and MODIS time series (Boyte et al., 2015) have been developed to map die-offs over large areas and over long periods of time. Also, the principal pathogens responsible for the die-off phenomenon have been identified and demonstrated to be pathogenic on cheatgrass (Baughman and Meyer, 2013; Meyer et al., 2014; Franke et al., 2014). The mechanisms by which pathogens interact with each other to generate a die-off in the field are currently under investigation.

Existing science gaps

Augmentative bioherbicide biocontrol with fungal pathogens has been applied with some success in agronomic settings, but its use in wildland settings is untested. In order to arrive at a product that can be mass produced for large-scale application, many hurdles must be overcome. Studies to date suggest that no one pathogen can cause cheatgrass regeneration failure, particularly for multiple years. Instead, the die-off phenomenon appears to involve synergistic interactions among multiple pathogens in combination with specific predisposing environmental conditions. These interactions need to be studied to determine

the extent and efficacy of widely applicable biocontrol methods based on the die-off phenomenon. Once mechanistic relationships have been shown in experimental small-plot studies, the information gained needs to be integrated with modeling of real-time die-offs (e.g. Boyte and Wylie, *in press*) and die-off potential over large geographic areas in order to understand predisposing environmental conditions for die-off occurrence and also to locate areas where resource manipulation, inoculum addition, or both could trigger a die-off to use as a site-preparation method prior to restoration seeding. Technology development to scale up inoculum production of the key pathogens would be required before these treatment combinations could be tried on a sufficiently large scale to test model predictions of efficacy and to examine nontarget effects in the field. Once the potential of this approach for large-scale cheatgrass control has been confirmed, the process of refining the technology for commercial production, along with the testing necessary for product registration, could be completed.

Next Steps

Short-term (1 to 3 years)

- New Research: Expand analysis of die-offs to include large expanses of cheatgrass-dominated desert valleys across the Great Basin, and use geospatial statistical tools to improve die-off predictive models.
- New Research: Develop technology to measure pathogen loads in soil using molecular-genetic techniques.
- New Research: Carry out studies on small plots where pathogen load and environmental conditions are manipulated to determine how and where failure of cheatgrass can be induced by management as a site-preparation technique prior to restoration seeding.
- New Research: Determine the effects of cheatgrass pathogens on non-target hosts, including species likely to be included in restoration seeding mixes.
- New Research: Continue and expand studies to assess effectiveness of restoration seedings in new die-offs (mapped in real-time), including reestablishment of deep-rooted perennial grasses and sagebrush.

Long-term (greater than 3 years)

- New Research: Use die-off predictive models and information about seed-bed pathogen loads to determine where to install study trials over large areas to evaluate induced die-offs with and without inoculum additions.
- New Research: Carry out die-off induction trials over large geographic areas, and include post-die-off restoration seeding (using appropriate native plant materials) to determine how well this type of site preparation facilitates the establishment of seeded species across a range of site types in different environments.
- New Research: Develop technology to scale up inoculum production for promising strains of potential biocontrol organisms.

Restoration

Restoration of sagebrush habitats is important for maintaining the ecosystem in the face of the multiple threats posed by invasive plant species, wildfire, and numerous other disturbance factors. This section outlines the priority science needs related to sagebrush ecosystem restoration (Table 4). These priorities include several broad areas, including the need to improve application of restoration actions, determine the factors that lead to success of those actions, understand the effects of those actions, and develop strategic sourcing for acquiring, storing, and utilizing genetically appropriate seeds and other plant materials native to the sagebrush ecosystem for use in restoration projects.



Table 4. Science needs and next steps in the Restoration topic. Next steps include new research, syntheses, and tools that are needed to fill the identified science gaps. The list separates those steps that could be accomplished in the short term (1 to 3 years), followed by those that are considered long term (accomplished in more than 3 years).

#	Need	Timing	Type	Next step	
1	Develop methods for “jumpstarting” growth and recovery of sagebrush and native grasses and forbs to encourage rapid re-establishment of sagebrush and enable re-colonization by sage-grouse as soon as possible to help offset effects of wildfire and help mitigate potential effects of future fires.	Short-term	New research	Assess the minimum and ideal sagebrush cover, patch size, and landscape requirements for sage-grouse occupancy in fire-impacted habitats during breeding, nesting, brood-rearing, and wintering seasons.	
					Plant and measure the survival and growth of sagebrush seedlings greater than 1 year old versus seeded sagebrush in burned sage-grouse habitat, designing treatments to meet the multi-scale habitat-selection requirements of sage-grouse across a range of fire and site conditions.
					Monitor and analyze the use of re-vegetated treatments by sage-grouse and quantify their seasonal survival and reproductive success at those sites.
		Long-term	Tool	Develop spatially explicit habitat-population modeling tools to link habitat restoration efforts with modeled sage-grouse responses, and predict times to sagebrush and sage-grouse recovery based on burn severity and size, sage-grouse movement, and sage-grouse space-use.	
			New research	Evaluate the degree to which enhancing sagebrush recovery also fast-tracks the return of the associated community, including other types of vegetation and sagebrush-obligate species.	
			Synthesis	Assess the degree to which investments in sagebrush restoration are likely to compensate for lost sage-grouse population contributions, and evaluate the efficacy of sagebrush jumpstarting relative to the benefits that could be achieved using alternative means of recovering sage-grouse.	
		Synthesize the results of continued sagebrush and sage-grouse responses to develop post-fire sagebrush restoration guidelines for revegetating sage-grouse habitat.			
	Tool	Develop an integrative assessment tool that identifies priority sagebrush restoration areas based on their value for local and regional sage-grouse populations, likelihood of rapid restoration success (resistance and resilience concepts), and vulnerability to transitioning to nonnative conditions.			
2	Develop and improve seeding methods, seed mixes, and equipment used for post-fire rehabilitation or habitat restoration to improve native plant (especially sagebrush) reestablishment.	Short-term	Synthesis	Synthesize ecological and restoration-related data for commonly seeded or planted native species of the sagebrush ecosystem, including seed and seedling production data.	
			Tool	Centralize synthesized species data and links to tools and databases required for all aspects of restoration planning.	
				Identify priority equipment needs and support modification of existing equipment or development of new equipment by agricultural engineers.	
			Update Seed Lot Selection Tool (http://sst.forestry.oregonstate.edu/).		

Table 4. Science needs and next steps in the Restoration topic. Next steps include new research, syntheses, and tools that are needed to fill the identified science gaps. The list separates those steps that could be accomplished in the short term (1 to 3 years), followed by those that are considered long term (accomplished in more than 3 years).—Continued

#	Need	Timing	Type	Next step
2	Continued			<p>Develop a protocol for identifying subspecies composition of big sagebrush seed lots.</p> <p>Develop a basin and Wyoming big sagebrush seed-zone map and seed-transfer guidelines, and include information about projected changes in subspecies distributions with climate change.</p> <p>Complete the planning tool component of the Land Treatment Digital Library.</p>
		Long-term	New research	<p>Develop ecological data, where missing, for restoration-relevant species, including information related to potential performance onsite, including establishment requirements, growth rates, mature size, seed dispersal, pollinator requirements, and interactions with nonnative species.</p> <p>Develop the data necessary to identify additional native species for inclusion in restoration programs and to make recommendations for appropriate application in wildland seedings and plantings.</p>
			Synthesis	<p>Complete, synthesize, and test results of ongoing studies of sagebrush seed-lot handling, seed and seedling ecology, establishment requirements, and seeding methods.</p>
			Tool	<p>Update the Revegetation Equipment Catalog and add a synthesis of research-based recommendations for selection of equipment to meet specific needs.</p>
3	Determine the criteria and thresholds that indicate restoration and rehabilitation success or failure across the range of environmental conditions that characterize sage-grouse habitat. Develop decision support tools that define success or failure and the need for follow-up actions.	Short-term	New research	<p>Evaluate newly developed criteria and thresholds of treatment success across the range of sage-grouse to determine the efficacy.</p>
			Synthesis	<p>Synthesize information on land treatment effectiveness monitoring to establish criteria and thresholds of treatment success determination that account for time since treatment and environmental variation across the range of sage-grouse.</p>
		Long-term	New research	<p>Evaluate effect of extended rest from grazing after a restoration seeding (beyond the typical 2 years) on restoration success, including root growth development and at what point plant are established to the point of tolerating grazing by livestock or feral horses and burros.</p>
			Synthesis	<p>Continue to update information from the short-term synthesis (above) based on new and ongoing studies, especially considering long-term patterns of success or failure for treatments older than 5 years.</p>
			Tool	<p>Use short- and long-term data describing vegetation and sage-grouse responses to treatments to enhance the functionality of the USFWS Conservation Efforts Database, or to develop a decision-support tool that can be used by managers to record and report effectiveness monitoring data for treatments. The records and reporting should provide information about the probability of success over time, plus timely, relevant feedback for decisions for follow-up actions.</p>

Table 4. Science needs and next steps in the Restoration topic. Next steps include new research, syntheses, and tools that are needed to fill the identified science gaps. The list separates those steps that could be accomplished in the short term (1 to 3 years), followed by those that are considered long term (accomplished in more than 3 years).—Continued

#	Need	Timing	Type	Next step	
4	Complete a generalized seed-zone map and determine (1) if it is more effective to develop seed-transfer zones by species or subspecies, (2) which climate parameters are most useful in developing transfer zones, (3) thresholds in climate adaptations, and (4) effects of using seed collected throughout a specified transfer zone versus seed collected from the local area to restore sagebrush habitats. Also demonstrate that actual planting success is improved for a given seed-transfer specification.	Short-term	New research	Conduct meta-analyses of existing datasets, such as bunchgrasses, to determine generalities and thresholds for climatic variables in the sagebrush ecosystem.	
				Test the efficacy of existing seed-zone models in operational-scale restoration projects.	
			Synthesis	Review and synthesize all common garden studies related to the sagebrush ecosystem to find general, adaptive trends.	
		Long-term		Tool	Review seed-zone construction methods to determine best practices for seed-zone modeling.
					Develop statistical tools to incorporate variation and uncertainty into seed-zone models.
					Refine generalized seed-zone maps for the sagebrush ecosystem.
				New research	Develop a common garden network for high-throughput seed-transfer studies to speed up the process of developing data-rich seed-zone models (up to five per year for the sagebrush ecosystem). A minimum of 5 years is typically needed to establish and begin learning from a common garden, hence garden establishment is a short-term need.
					Perform molecular-marker studies on all taxa undergoing seed-zone development.
					Develop and improve empirical seed zones for those species commonly used in restoration and rehabilitation actions that are widespread, intraspecifically diverse, and locally dominant.
					Conduct a meta-analysis of new studies of seed transfer to test generalities.
Tool	Develop dynamic “on-the-fly” seed-transfer tools that use underlying data structures and models to include uncertainty and acceptable risk.				
	Further refine generalized seed-zone maps based on new knowledge.				
5	Conduct retrospective studies of selected native plant restoration projects to evaluate short- and long-term responses of plant communities to these treatments and to biotic and abiotic conditions.	Short-term	New research	Evaluate and synthesize outcomes of restoration projects that are underway or moving forward.	
				Re-sample those projects that have been quantitatively assessed before, to enable development of models that predict the temporal trajectory of vegetation on restoration projects.	
			Tool	Create a queryable database of existing treatments and outcomes to help managers prioritize and set expectations for treatments, and develop associated guide(s) to metrics for improving restoration success.	
		Long-term	Synthesis	Validate the accuracy of models produced in the short term, and continue to update these models for about 50–80 years following restoration treatment and for several hundred treatments spanning the region of interest.	

Table 4. Science needs and next steps in the Restoration topic. Next steps include new research, syntheses, and tools that are needed to fill the identified science gaps. The list separates those steps that could be accomplished in the short term (1 to 3 years), followed by those that are considered long term (accomplished in more than 3 years).—Continued

#	Need	Timing	Type	Next step	
6	Develop site preparation and seeding and transplanting strategies that improve plant establishment and community diversity.	Short-term	New research	Develop assessment of species biology, interactions with other species, and species response to specific site conditions for management-relevant species.	
			Synthesis	Synthesize available data on site preparation and seeding and transplanting strategies for sagebrush communities.	
		Long-term	New research	Continue research about seeding and planting strategies, incorporating species being added to the “pool” available for restoration. Test methods developed for major sagebrush plant communities and for a range of site conditions. Develop safe, effective, and reliable means of controlling nonnative annual grasses without risking damage to residual perennials or exposure of bare soil to wind erosion.	
			Synthesis	Expand existing databases such as the Land Treatment Digital Library to include seed sources, seed quality and seedling production specifications, planting details (e.g., annotated plans, equipment, weather, and site conditions), and long-term monitoring data.	
7	Assess the long-term effects of conifer removal treatments on hydrology, geochemical cycling, vegetation, wildlife, fuels, fire behavior, and economics.	Short-term	New research	Use retrospective studies of past management activities to evaluate timelines for post-treatment conifer succession and understory plant dynamics following different treatment types. Establish instrumented networks of watersheds with experimental conifer-removal treatments and controls to measure hydrologic (including snowpack and soil moisture), physical (temperature and energy balance), and biogeochemical outcomes. Determine the impacts of the biophysical setting for conifer removal, including slope, aspect, soil type, soil nutrient status, and conifer-encroachment status, on post removal vegetation and wildlife responses.	
			Long-term	New research	Initiate long-term research and retrospective analyses to quantify the effects of juniper treatment on hydrology, geochemical cycling, wildlife habitat, and fire and fuel dynamics. Use results from retrospective vegetation studies to determine economic viability of different treatment options based on treatment lifetime and cost of application.
				Synthesis	Synthesize findings from ongoing studies addressing the long-term effects of mechanical and fire-based conifer treatments on ecosystem properties.

Table 4. Science needs and next steps in the Restoration topic. Next steps include new research, syntheses, and tools that are needed to fill the identified science gaps. The list separates those steps that could be accomplished in the short term (1 to 3 years), followed by those that are considered long term (accomplished in more than 3 years).—Continued

#	Need	Timing	Type	Next step
8	Evaluate the effectiveness of various rehabilitation or restoration activities in sage-grouse habitat to help determine if offsite mitigation is a viable option, because if restoration of sites to conditions useful for sage-grouse is not possible (for near-term benefits), then mitigation procedures might warrant reevaluation.	Short-term	New research	Conduct research on the effectiveness of land treatment projects for providing habitat for sage-grouse, taking into account the subtleties of treatment type, treatment implementation, time since treatment, and landscape context. Multiple research projects will be needed that span the range of environmental conditions across the range of the sage-grouse.
			Synthesis	Conduct a review of existing state-and-transition models and other resources to determine relationships between current vegetation conditions and ecological site potential to inform mitigation measures relative to the ability of a site to achieve intended vegetation conditions.
		Long-term	Synthesis	Synthesize information from existing, ongoing, and new (above) research using rigorous, standard, and reproducible meta-analyses that capture the variety of treatments in type, space, and time.
			Tool	Using research and synthesis results to develop a decision support tool to inform mitigation efforts that incorporates information about existing vegetation conditions and threats (both local and landscape) relative to ecological site potential.
9	Develop decision-support tools to assist in planning and implementing conifer removal treatments that will maximize maintenance of sagebrush systems, greater sage-grouse, and other sensitive species.	Short-term	New research	Use retrospective studies of past management activities to evaluate timelines for post-treatment conifer succession and understory plant dynamics following mechanical (cutting and mastication) and prescribed fire treatment. Study the impacts of fire on conifer seed banks.
		Long-term	Synthesis	Synthesize findings from ongoing studies to collate and refine knowledge of initial and long-term understory plant response to treatment as a function of site characteristics and treatment method.
			Tool	Incorporate treatment economics and durability into decision-support models that consider large areas and include plant-cover attributes, location of priority wildlife habitat, and plant community resistance and resilience.
10	Assess soil degradation and develop treatments, soil amendments, and other site-preparation techniques that enhance germination, establishment, and development of healthy sagebrush communities capable of resisting invasion by nonnative plant species.	Short-term	New research	Assess soil degradation across sagebrush ecosystems in regards to fire, nonnative annual grass invasion, grazing, and other disturbances.
			Synthesis	Synthesize findings on effects of nonnative annual grass invasion and fire on soil biogeochemistry.
		Long-term	New research	Investigate the extent and ecological impacts of wind erosion. Further elucidate soil water and chemistry with plant establishment after fire.
			Tool	Continue developing water and wind-erosion models for post-fire environments in the sagebrush ecosystem. Develop restoration tools that incorporate soil properties in reestablishing plant communities.

Restoration Science Need #1: Develop methods for “jumpstarting” growth and recovery of sagebrush and native grasses and forbs to encourage rapid re-establishment of sagebrush and enable re-colonization by sage-grouse as soon as possible to help offset effects of wildfire and help mitigate potential effects of future fires.

Subtopic: Fire; Associated Strategy Tasks: 7(b)iv and v

Background

Wildfires in the sagebrush ecosystem usually result in sage-grouse habitat loss through combustion, plant mortality, and other environmental changes. Sagebrush is typically slow to recover following fire, taking 15 to 100 years to recover to pre-fire cover states (Baker, 2006; 2011), depending on the method of recovery (natural revegetation, seeding method, or seedling transplants), species, climatic conditions (i.e., precipitation; Nelson et al., 2014), and size and intensity of the burn. Large-area and severe fires, in particular, may leave few surviving plants as seed sources, and take decades to recover (Welch, 2005; Ziegenhagen and Miller, 2009). Fire can also result in the invasion of nonnative annual grasses (e.g., cheatgrass) and result in herbaceous-dominated sites, increasing the threat of rangeland fires in the sagebrush ecosystem (Coates et al., *in press*). Beyond the initial loss of sagebrush, the prolonged recovery to a mature sagebrush community could result in the interim avoidance or suboptimal use of recovering burned areas, to the detriment of sage-grouse populations and other sagebrush-obligate species (Baker, 2006; Coates et al., *in press*; Hanna and Fulgham, 2015).

Although efforts to re-vegetate burned or altered areas have occurred in the past, little is known about how sagebrush can be rapidly restored to support sage-grouse occupancy, demography, and persistence. Past wildfire restoration efforts (e.g., aerial seeding of grasses and sagebrush) have had limited success and often require more than 20 years before native shrub species reestablish (Arkle et al., 2014). Because the frequency of wildfire is expected to increase over the next three decades in many parts of the sage-grouse range (e.g., Great Basin; Coates et al., *in press*) and negatively impact sage-grouse habitat and long-term trajectories of sage-grouse populations, there is a need to evaluate new approaches to restore sagebrush after fire and evaluate their effectiveness in meeting the short and long-term needs of sagebrush-obligates.

Summary of recent science and syntheses

Sagebrush restoration studies have largely documented natural revegetation and the shorter-term success rates of post-disturbance seeding efforts. Natural recruitment from seeds can be inconsistent due to low seed viability, variable germination, and harsh site conditions (Perryman et al., 2001; Cione et al., 2002). Although methods such as aerial seeding of a mix of grasses and shrubs have been successful in establishing grass and herbaceous cover, the seeding of sagebrush can be limited by insufficient availability of source-identified seeds and associated low seedling survival in the year after seeding (Shaw et al., 2005; Herriman et al., 2016).

Interest in fast-tracking sagebrush restoration by planting nursery-grown seedlings or by transplanting has increased in recent years (e.g., McAdoo et al., 2013; Herriman et al., 2016). Use of seedlings is intended to circumvent high first-year mortality, and can double the survival rates compared to direct seeding (Herriman et al., 2016). Enhanced sagebrush recovery could reduce the time during which sage-grouse are most impacted by habitat loss and regrowth. During vegetation recovery, sage-grouse actively avoid burned habitat all year long (Connelly et al., 2000; Byrne, 2002; Erickson, 2011), or they return to previously burned nest sites and have low success (Lockyer et al., 2015). Studies of sage-grouse habitat selection indicate that sage-grouse require a minimum of 10 percent sagebrush canopy cover when foraging and for nesting and winter cover (reviewed in Connelly et al., 2000; 2011). Also, areas in the

Great Basin with greater than 40 percent total shrub canopy cover yield improved reproductive success (Lockyer et al., 2015). Other landscape characteristics are likely to influence the use of post-fire sagebrush landscapes. These include microsite characteristics, such as sagebrush height and horizontal cover and presence of cheatgrass (Lockyer et al., 2015), and patch and landscape contextual variables (e.g., size of fire, proximity to lekking habitat, and proximity to development or forested areas, Fedy et al., 2014; Coates et al., *in press*).

Existing science gaps

Little is known about the growth and survival rates of seeded or planted sagebrush in burn-affected landscapes or the efficacy of jumpstarting sagebrush regrowth to promote sage-grouse occupancy and demographic success. Although existing research indicates that planting sagebrush seedlings is likely to speed up recovery, a lack of empirical data indicating the magnitude of benefit for local sage-grouse populations in burn sites and regional population persistence limits overall understanding. Existing sage-grouse field data provide indications of possible responses (i.e., behavior, demography, and habitat selection) to fire-induced habitat loss and recovery. However, long-term field and model forecasting experiments are required to (1) assess the degree to which sagebrush can be rapidly grown and re-established at burn sites at a planting scale that is meaningful to sage-grouse, (2) assess the range of sage-grouse responses to fire-induced habitat loss and ongoing sagebrush restoration at a range of sites, and (3) evaluate the efficacy of alternative sagebrush restoration strategies in offsetting negative sage-grouse impacts.

Next steps

Short-term (1 to 3 years)

- New research: Assess the minimum and ideal sagebrush cover, patch size, and landscape requirements for sage-grouse occupancy in fire-impacted habitats during breeding, nesting, brood-rearing, and wintering seasons.
- New research: Plant and measure the survival and growth of sagebrush seedlings greater than 1 year old versus seeded sagebrush in burned sage-grouse habitat, designing treatments to meet the multi-scale habitat-selection requirements of sage-grouse across a range of fire and site conditions.
- New research: Monitor and analyze the use of re-vegetated treatments by sage-grouse and quantify their seasonal survival and reproductive success at those sites.
- Tool: Develop spatially explicit habitat-population modeling tools to link habitat restoration efforts with modeled sage-grouse responses, and predict times to sagebrush and sage-grouse recovery based on burn severity and size, sage-grouse movement, and sage-grouse space-use.

Long-term (greater than 3 years)

- New research: Evaluate the degree to which enhancing sagebrush recovery also fast-tracks the return of the associated community, including other types of vegetation and sagebrush-obligate species.
- Synthesis: Assess the degree to which investments in sagebrush restoration are likely to compensate for lost sage-grouse population contributions, and evaluate the efficacy of sagebrush jumpstarting relative to the benefits that could be achieved using alternative means of recovering sage-grouse.
- Synthesis: Synthesize the results of continued sagebrush and sage-grouse responses to develop post-fire sagebrush restoration guidelines for revegetating sage-grouse habitat.
- Tool: Develop an integrative assessment tool that identifies priority sagebrush restoration areas based on their value for local and regional sage-grouse populations, likelihood of rapid restoration success (resistance and resilience concepts), and vulnerability to transitioning to nonnative conditions.

Restoration Science Need #2: Develop and improve seeding methods, seed mixes, and equipment used for post-fire rehabilitation or habitat restoration to improve native plant (especially sagebrush) reestablishment.

Subtopic: Seed and other plant materials, Associated Strategy Tasks: 7(b)v and ix

Background

Site mapping and selection of an initial species list are necessary steps for planning post-fire rehabilitation or habitat restoration projects. Often these steps are informed by assessments of the disturbed and surrounding undisturbed areas and of the recovering or previously seeded areas and by use of available databases and geospatial tools (e.g., Web Soil Survey [<http://websoilsurvey.sc.egov.usda.gov/>], Landfire, Ecological Site Descriptions). Publications, manuals, plant guides, and recommendations of restoration ecologists aid in finalizing seeding and planting prescriptions. Seed-zone maps inform selection of adapted seed sources.

Applying a long-term planning strategy for restoration efforts can help to ensure availability of locally adapted seeds and native plant materials appropriate to the location, conditions, and management objectives for restoration activities. Use of site preparation and planting techniques designed for site specific conditions is necessary for successful re-establishment of sagebrush habitat. Use of seeding equipment capable of delivering a variety of seed types to suitable microsites at prescribed rates and able to segregate seeds of incompatible species is also a crucial consideration. Difficulty with re-establishment of sagebrush species partially originates from seed characteristics, including seed size, short-term viability, limited energy reserves, and specific microsite requirement. Incorrect labeling of seed lots (i.e., big sagebrush [*A. t. tridentata*] subspecies; Richardson et al., 2015), use of maladapted seed, and poor seed-lot management (e.g., improper seed handling, drying, and storage, particularly at low purity) can lead to reduced seed vigor and viability. Several additional factors can contribute to low seeding success, such as failure to prepare firm, weed-free seedbeds, failure to firm seeds into the soil surface in microsites where they will not receive excessive competition, and inadequate post-seeding management.

Summary of recent science and syntheses

Research to increase the number of native species used in restoration and to create guidelines for selecting adapted seed sources (Bower et al., 2014) is underway. This research includes investigations to improve methods for seed increase and seedling propagation. New equipment modifications to facilitate establishment of multi-seeding mixes are available but have not received widespread testing. New approaches include establishing patches or forb islands, catching snow, and use of technologies for seed enhancement for costly or difficult-to-establish species and innovative techniques for weed control. Recent research, primarily with basin (*A. t. tridentata*) and Wyoming big sagebrush (*A. t. wyomingensis*), is aiding in the identification of subspecies composition of seed lots, development of seed zones, the prediction of potential changes in subspecies distributions with climate change, development of improved guidelines for seeding and planting, and evaluation of past seeding efforts (Karrfalt and Shaw, 2013; Richardson et al., 2015; Germino et al., 2016b; Ott et al., 2016).

Existing science gaps

Research over the last two decades has expanded the list of native plant species used in restoration, provided tools for selection of adapted plant materials for current and projected future conditions, and improved technology and methods for establishing native species from seeds or plants. Further research is essential for all phases of this work. Syntheses, including documents, websites, webinars, and training, are essential to accelerate inclusion of new findings at the field level (Wiedemann, 2004) and to facilitate their testing and modification to meet specific restoration conditions.

Next steps

Also refer to Restoration Science Need #6 (Table 4).

Short-term (1 to 3 years)

- Synthesis: Synthesize ecological and restoration-related data for commonly seeded or planted native species of the sagebrush ecosystem, including seed and seedling production data.
- Tool: Centralize synthesized species data and links to tools and databases required for all aspects of restoration planning.
- Tool: Identify priority equipment needs and support modification of existing equipment or development of new equipment by agricultural engineers.
- Tool: Update Seed Lot Selection Tool (<http://sst.forestry.oregonstate.edu/>).
- Tool: Develop a protocol for identifying subspecies composition of big sagebrush seed lots.
- Tool: Develop a basin and Wyoming big sagebrush seed-zone map and seed-transfer guidelines, and include information about projected changes in subspecies distributions with climate change.
- Tool: Complete the planning tool component of the Land Treatment Digital Library.

Long-term (greater than 3 years)

- New Research: Develop ecological data, where missing, for restoration-relevant species, including information related to potential performance onsite, including establishment requirements, growth rates, mature size, seed dispersal, pollinator requirements, and interactions with nonnative species.
- New Research: Develop the data necessary to identify additional native species for inclusion in restoration programs and to make recommendations for appropriate application in wildland seedings and plantings.
- Synthesis: Complete, synthesize, and test results of ongoing studies of sagebrush seed-lot handling, seed and seedling ecology, establishment requirements, and seeding methods.
- Tools: Update the Revegetation Equipment Catalog and add a synthesis of research-based recommendations for selection of equipment to meet specific needs.



Restoration Science Need #3: Determine the criteria and thresholds that indicate restoration and rehabilitation success or failure across the range of environmental conditions that characterize sage-grouse habitat. Develop decision support tools that define success or failure and the need for follow-up actions.

Subtopic: Landscape Analysis and Decision Support; Associated Strategy Tasks: 7(b)iv and vi, and Crosscut 3

Background

Sage-grouse habitats have been carefully characterized across their range (Hagen et al., 2007; Connelly et al., 2011). This information has been used to establish guidelines for determining the habitat requirements of sage-grouse at multiple spatial scales (Connelly et al., 2000; Stiver et al., 2015). However, linking this habitat information to actual sage-grouse population ecology remains to be done (Aldridge and Boyce, 2007).

Federal, State, and private agencies and organizations have implemented thousands of land treatments to restore or rehabilitate sagebrush habitats altered by wildfire, conifer encroachment, and other causes. Many of these projects are too recent to fully re-establish sagebrush to suitable habitat levels but may meet the understory habitat requirements for sage-grouse (Arkle et al., 2014). As more of these seeding and planting efforts mature, there will be a need for systematic criteria and thresholds for determining when restoration or rehabilitation is successful across the range of environmental conditions that characterize sage-grouse habitats (Pyke, 2011). Decision-support tools may provide a critical resource for strategies for adaptive management, such as follow-up actions when treatments are partially successful at meeting sage-grouse habitat requirements.

Summary of recent science and syntheses

Several recent syntheses may help guide restoration of sagebrush ecosystems in the context of sage-grouse habitat (Pyke et al., 2015a,b; Stiver et al., 2015; Finch et al., 2016), and other syntheses are in development. Two studies that will provide useful information for this science need include the SageSuccess Project and the Soda Fire Emergency Stabilization and Rehabilitation Project. These projects are partnerships among the BLM, USGS, and United State Department of Agriculture Forest Service (USFS) to assess (1) why some post-fire seeding projects successfully establish big sagebrush and minimize nonnative annual grasses, and (2) the importance of seed sources and transfer for treatment success. Other syntheses have examined the importance of forbs, especially for brood-rearing (Curran et al., 2015; Dumroese et al., 2015). Furthermore, there are several tools that will provide important resources for this science need: BLM's Vegetation Treatment Solution (VTS) and the joint BLM and USGS Land Treatment Digital Library (Pilliod and Welty, 2013). Additionally, Joint Fire Science Program (JFSP) funding is directed at research evaluating the long-term effectiveness of restoration treatments to provide sage-grouse habitat. As the benchmarks necessary to achieve effectiveness are identified, this information can better inform how data would be evaluated in the U.S. Fish and Wildlife Service's (USFWS) Conservation Efforts Database (CED) which can catalog these efforts across all partners/agencies.

Existing science gaps

One of the challenges of evaluating success or failure of land-treatment projects is the criteria used, which vary temporally and spatially and depend on the objectives of the treatment. During post-fire Emergency Stabilization and Rehabilitation (ESR) treatments, for example, short-term objectives of stabilizing soil and minimizing establishment of invasive plants are often different than long-term objectives of restoring functioning ecosystems that support diverse flora and fauna. Furthermore, definitions of treatment success currently are not based on the proportion of a treatment area that meets *a priori* quantitative objectives. Finally, land-treatment objectives rarely have embraced the full range of environmental conditions that

characterize sage-grouse habitat. Hence, there is a need for establishing standard criteria and thresholds using available science to indicate restoration or rehabilitation success or failure considering temporal and spatial variation as well as natural environmental variation across the range of the species. Ultimately, managers would benefit from access to this information in a decision-support framework so that monitoring results could assist with adaptive management decisions in a manner sufficiently timely to allow adjustments to restoration, including follow-up actions.

Next steps

Short-term (1 to 3 years)

- **New Research:** Evaluate newly developed criteria and thresholds of treatment success across the range of sage-grouse to determine the efficacy.
- **Synthesis:** Synthesize information on land treatment effectiveness monitoring to establish criteria and thresholds of treatment success determination that account for time since treatment and environmental variation across the range of sage-grouse.

Long-term (greater than 3 years)

- **New Research:** Evaluate effect of extended rest from grazing after a restoration seeding (beyond the typical 2 years) on restoration success, including root growth development and at what point plant are established to the point of tolerating grazing by livestock or feral horses and burros.
- **Synthesis:** Continue to update information from the short-term synthesis (above) based on new and ongoing studies, especially considering long-term patterns of success or failure for treatments older than 5 years.
- **Tool:** Use short- and long-term data describing vegetation and sage-grouse responses to treatments to enhance the functionality of the CED, or to develop a decision-support tool that can be used by managers to record and report effectiveness monitoring data for treatments. The records and reporting should provide information about the probability of success over time, plus timely, relevant feedback for decisions for follow-up actions.

Restoration Science Need #4: Complete a generalized seed-zone map and determine (1) if it is more effective to develop seed-transfer zones by species or subspecies, (2) which climate parameters are most useful in developing transfer zones, (3) thresholds in climate adaptations, and (4) effects of using seed collected throughout a specified transfer zone versus seed collected from the local area to restore sagebrush habitats. Also demonstrate that actual planting success is improved for a given seed-transfer specification.

Subtopic: Seed and other plant materials; Associated Strategy Tasks: 7(b)iv, v, and ix

Background

Biologically diverse native plant communities are the foundation of productive sagebrush ecosystems and provide essential habitat for wildlife species of conservation concern, such as sage-grouse (Dumroese et al., 2015). The sagebrush ecosystem is under threat from a suite of disturbances that are mostly human-caused (Connelly et al., 2011), including interacting threats of nonnative plant invasions, changing fire regimes, and increased aridity and drought (Finch et al., 2015). In the face of continued habitat degradation, restoration of native plant communities may be necessary to maintain sagebrush ecosystems and support healthy wildlife populations (Chambers et al., 2014a; Dumroese et al., 2015). However, current restoration practices often fail to rehabilitate sage-grouse habitat (Arkle et al., 2014). This failure may, in part, be due to the fact that restoration success can hinge on the use

of plant materials that are adapted to, and “match,” the environments in which restoration projects are performed (Hufford and Mazer, 2003; McKay et al., 2005), yet few of the native plant materials in current use have been selected for traits that support establishment and survival in arid ecosystems (Leger and Baughman, 2015). A number of calls have been made to adopt the use of seed-transfer guidelines, originally developed in forestry (Ying and Yanchuk, 2006), to help develop genetically appropriate and environment-adapted native plant materials for use in restoration (Erickson, 2008; Johnson et al., 2010). Recent progress has been made by Federal agencies in shifting toward more use of genetically appropriate plant materials (Koch et al., 2015; see also Great Basin Native Plant Project, <http://www.greatbasinnpp.org/>), but significant challenges remain in both the development and use of seed-transfer guidelines for rangeland restoration (Basey et al., 2015, Kilkenny, 2015).

Summary of recent science and synthesis

Seed-transfer guidelines, of which spatially based seed zones are the most common form, are management tools that define acceptable distances that plant materials can be moved from their source and still preserve ecological and evolutionary relationships (Kilkenny, 2015). Seed zones can either be generalized, often based on large-scale bioclimatic models (e.g., Bower et al., 2014), or species-specific and based on a specific taxon’s trait and environment relationships (e.g., St. Clair et al., 2013). The provisional seed zones developed by Bower et al. (2014) are generalized seed zones designed to group similar climatic regions, which broadly correspond to plant climate-niche space. When combined with Level III Ecoregions (Omernik, 1987), the combined regions are currently assumed to be reasonably approximate areas of climatic adaptation for a number of taxa and are useful in defining seed-transfer guidelines for species without developed empirical seed zones (Bower et al., 2014; Kramer et al., 2015). However, additional testing and demonstration will be needed to validate these practices.

Because trait × environment relationships may differ significantly between species, empirical seed zones have been developed for a number of sagebrush ecosystem species including grasses (e.g., St. Clair et al., 2013), forbs (e.g., Johnson et al., 2013), and shrubs (e.g., Horning et al., 2010). Empirical seed zones have been developed primarily through common garden studies and are used to determine plant adaptation to a set of environments (Kilkenny, 2015). An increasing number of researchers also are using information from molecular-marker studies to inform seed-zone modeling (e.g., Shryock et al., 2015). Molecular-marker studies can define evolutionary relationships within and between taxa, and can help reduce the risk of inbreeding and outbreeding depression.

Existing science gaps

The sagebrush biome contains more than 5,000 plant taxa (Cronquist et al., 1972–2012), so it is unrealistic to develop empirical seed zones for all species. Generalized seed zones will need to be used for those without broad application for restoration or rehabilitation. The provisional seed zones currently in use delineate variation among a wide range of ecosystems across the entire lower 48 continental states (Bower et al., 2014). Specific local and regional environments may differ from the generalized model in relevant ways. Therefore, generalized seed zones will need to be constructed that are specific to the sagebrush ecosystem. Plant-environment interactions can be quite complex and differ across ecosystems (Peñuelas et al., 2013), so information from species-specific seed zones will need to be synthesized to determine which climate parameters are most useful to seed-zone construction and whether adaptive thresholds differ from the current provisional model in the sagebrush ecosystem. Information from both common garden studies that have been used to define seed transfer, and those that have been performed for other purposes, can be useful for this process.

Currently only a small number of restoration species have empirical seed zones. Therefore, new empirical seed zones will need to be produced in an efficient manner with a focus on those species commonly

used in restoration and rehabilitation actions that are widespread, intraspecifically diverse, and locally dominant. Future empirical seed zones should include information from molecular-marker studies, which can help determine whether subspecies or varieties should be treated separately because plant systematics are continuously updated and the entire North American flora is undergoing revision (Flora of North America Editorial Committee, 1993+). Information about molecular markers will also help inform actions necessary to understand and maintain genetic variation at a number of scales (Basey et al., 2015).

Not knowing the efficacy of seed zones at an operational restoration scale remains a significant gap in knowledge. Operational-scale studies will help determine how well plant materials developed from set sources throughout a specified transfer zone perform in comparison to materials sourced from the local restoration area, as well as demonstrate whether the use of seed-transfer guidelines increases restoration success.

Lastly, a number of methodological improvements are needed for both the development and usefulness of seed-transfer guidelines. Developing new statistical methods that incorporate variation and uncertainty can help managers determine relative risk in using specified plant materials. These novel statistical tools will also help in framing the possible effects of climate change on seed transfer (Kilkenny, 2015), and allow for the development of management tools that “go beyond the map” and fully use the richness of common garden datasets to dynamically define seed-transfer specifications that work for managers’ needs and goals.

Next steps

Short-term (1 to 3 years)

- New research: Conduct meta-analyses of existing datasets, such as bunchgrasses, to determine generalities and thresholds for climatic variables in the sagebrush ecosystem.
- New research: Test the efficacy of existing seed-zone models in operational-scale restoration projects.
- Synthesis: Review and synthesize all common garden studies related to the sagebrush ecosystem to find general, adaptive trends.
- Synthesis: Review seed-zone construction methods to determine best practices for seed-zone modeling.
- Tool: Develop statistical tools to incorporate variation and uncertainty into seed-zone models.
- Tool: Refine generalized seed-zone maps for the sagebrush ecosystem.

Long-term (greater than 3 years)

- New research: Develop a common garden network for high-throughput seed-transfer studies to speed up the process of developing data-rich seed-zone models (up to five per year for the sagebrush ecosystem). A minimum of 5 years is typically needed to establish and begin learning from a common garden, hence garden establishment is a short-term need.
- New research: Perform molecular-marker studies on all taxa undergoing seed-zone development.
- New research: Develop and improve empirical seed zones for those species commonly used in restoration and rehabilitation actions that are widespread, intraspecifically diverse, and locally dominant.
- New research: Conduct a meta-analysis of new studies of seed transfer to test generalities.
- Tool: Develop dynamic “on-the-fly” seed-transfer tools that use underlying data structures and models to include uncertainty and acceptable risk.
- Tool: Further refine generalized seed-zone maps based on new knowledge.

Restoration Science Need #5: Conduct retrospective studies of selected native plant restoration projects to evaluate short- and long-term responses of plant communities to these treatments and to biotic and abiotic conditions.

Subtopic: Seed and other plant materials; Associated Strategy Tasks: 7(b)iv, v, and ix

Background

One of the most direct but uncommonly used ways of improving the return on seeding or planting investment is to evaluate the successes of past efforts and the factors promoting or detracting from success. Many seeding and planting projects have been applied in the last few decades over a very large cumulative area of the Great Basin and surrounding ecoregions, and each project can be viewed as an experiment from which managers can learn. Collectively, these treatment projects encompass many years and acres of temporal and spatial variation. However, the assessment of success has generally not been adequate, and a significant opportunity exists to improve these assessments to enable adaptive management on specific projects or within management units, and to improve the base of science information for restoration. Additionally, sagebrush-steppe and related community types can take decades to reach a stable, mature, perennial composition. Most of the existing assessments have occurred within short timeframes of 1 to 3 years, which cannot capture the trajectory of the plant community relative to variable weather patterns. Long-term data and perspectives are needed.

Summary of recent science and syntheses

Several research efforts have begun to ask the basic questions from subsets of the available treatments, most notably Knutson et al. (2014) and Germino (2014), which assessed 125 seeding projects that were implemented from 1987 to 2010. These studies revealed how success of seedings can be influenced by strong competition from co-seeded species, climate of sites treated, selection of appropriately adapted seed, and post-fire weather. The resulting information indicates the importance of these variables in light of a number of other variables likely to affect seeding success (e.g., re-burn history, soils, other overlaying treatments, and post-treatment grazing), but does not provide a robust, quantitative, and predictive model that can guide future treatment applications. Such a model will require data from hundreds of past projects that are each an observation point (or “replicate”). These projects exist but have not been measured, although USGS-led teams that include the BLM and USFS are making some headway. The JFSP funded one project that starts in 2016 that will contribute to this process, including re-sampling to enable characterizing vegetation trajectories. That project also will produce a field guide to metrics for restoration success.

Existing science gaps

While considerable investments have been made in seeding and planting, relatively little effort has followed those investments, resulting in considerable uncertainty about how to best seed or plant in each new project. Key challenges to learning about factors affecting success of past restoration treatments include (1) obtaining the resources required to deploy field crews to many remote treatment areas to measure vegetation in short enough time periods to allow inter-comparison of sites, and (2) reducing uncertainty in the essential information about how restoration projects were implemented (e.g., boundaries and seed sources), which can require extensive communication and record searching. These data would help land managers know how to prioritize restoration investments across sites and years, how to set expectations for restoration investments, and how to explain restoration success or lack thereof in reporting. They also would give insights about restoration techniques to emphasize how specific seed selection needs to be and how co-treatments, such as seeding and herbicide, interact to affect restoration success.

Next steps

Short-term (1 to 3 years)

- New research: Evaluate and synthesize outcomes of restoration projects that are underway or moving forward.
- New research: Re-sample those projects that have been quantitatively assessed before, to enable development of models that predict the temporal trajectory of vegetation on restoration projects.
- Tool: Create a queryable database of existing treatments and outcomes to help managers prioritize and set expectations for treatments, and develop associated guide(s) to metrics for improving restoration success.

Long-term (greater than 3 years)

- Synthesis: Validate the accuracy of models produced in the short term, and continue to update these models for about 50–80 years following restoration treatment and for several hundred treatments spanning the region of interest.

Restoration Science Need #6: Develop site preparation and seeding and transplanting strategies that improve plant establishment and community diversity.

Subtopic: Site Development; Associated Strategy Tasks: 7(b)iv, vi, and ix

Background

Effective site preparation, including suppression of nonnative annual plants and, to an increasing extent, suppression of perennial invasive species, is essential to provide suitable microsites for seedling recruitment and plant establishment during the initial restoration phase. Similarly, innovative seeding and planting strategies are required to establish and maintain high species diversity on sites ranging from local to regional scales. Although restoration approaches to overcome limiting factors can be generalized to a certain extent, site conditions and restoration goals are highly varied, and measures must be adapted to the local situation and to problems that may occur during a restoration process. Past and ongoing research includes diverse approaches to the control of invasive nonnative annual grasses, primarily cheatgrass and medusahead rye, as well as rapidly spreading perennial exotics. Recent emphasis on ecological restoration to re-establish native communities requires greater knowledge of restoration species that will provide managers with additional options for establishing complex species combinations across varied and challenging landscapes.

Summary of recent science and syntheses

Ongoing studies of ways to control invasive plants are focused on mechanical site-preparation practices, pre- and post-emergent herbicides, native biocontrol agents, and the potential for planting successfully in cheatgrass die-off areas (Kennedy et al., 2015; Prevey and Seastedt, 2015; Baughman et al., 2016). Identification of biocontrol organisms and effective herbicides are some of the research possibilities for control of invasive plant species. Seed and planting mix studies examine seeding and propagation requirements, establishment, species interactions among native species, competitiveness of native species with exotics, and effective spatial arrangements for seedings and plantings (e.g., Ott et al., 2016). Nursery studies focus on determination of seedling propagation specifications for specific site conditions for planting. Monitoring of recent operational-scale seedings and plantings and retrospective studies of established rehabilitation seedings are providing insights into natural recovery and success of rehabilitation strategies (e.g., Knutson et al., 2014). Recent syntheses include NRCS Tech Notes, Fact Sheets, and Plant Guides (USDA NRCS, 2016), the Land Treatment Digital Library (<http://ltdl.wr.usgs.gov/>), and a number of weed control guides.

Existing science gaps

Safe, effective, and reliable means of controlling invasive plants without risking damage to residual perennials or exposure of bare soil to wind erosion are not yet available, and new products or strategies require testing over multiple locations. Selecting species for seeding or planting given existing site conditions and designing effective strategies for establishing them requires additional data about species biology, interactions with other species, and species response to specific site conditions. New or modified equipment may be required for treatment using some planting scenarios.

Next Steps

Short term (1 to 3 years)

- New research: Develop assessment of species biology, interactions with other species, and species response to specific site conditions for management-relevant species.
- Synthesis: Synthesize available data on site preparation and seeding and transplanting strategies for sagebrush communities.

Long term (greater than 3 years)

- New research: Continue research about seeding and planting strategies, incorporating species being added to the “pool” available for restoration. Test methods developed for major sagebrush plant communities and for a range of site conditions.
- New research: Develop safe, effective, and reliable means of controlling nonnative annual grasses without risking damage to residual perennials or exposure of bare soil to wind erosion.
- Synthesis: Expand existing databases such as the Land Treatment Digital Library to include seed sources, seed quality and seedling production specifications, planting details (e.g., annotated plans, equipment, weather, and site conditions), and long-term monitoring data.



Photo credit: BLM

Restoration Science Need #7: Assess the long-term effects of conifer removal treatments on hydrology, geochemical cycling, vegetation, wildlife, fuels, fire behavior, and economics.

Subtopic: Conifer removal; Associated Strategy Tasks: 7(b)iv and vi

Background

Fire-return intervals in the mid- to high-elevation areas of the sagebrush ecosystem have increased dramatically since European-Americans settled in the region. This initially occurred in association with fine-fuel removal via livestock grazing, and later was further changed with improved fire-suppression techniques (Pyne et al., 1996; Miller and Rose, 1999; Miller et al., 2000). In association with a reduced presence of fire, and perhaps altered climate, populations of fire-sensitive native conifers [primarily juniper (*Juniperus occidentalis*, *J. osteosperma*) and piñon pine (*Pinus monophylla*, *P. edulis*)] expanded to occupy approximately 19 million ha in the Intermountain Region (Johnson and Miller, 2006). Left undisturbed, conifer succession proceeds, understory herbaceous and shrub species can be reduced or eliminated (Miller et al., 2005), and habitat for sagebrush-obligate wildlife species is lost (USFWS, 2013). Reduction of conifers typically involves mechanical treatments or prescribed fire.

Summary of recent science and syntheses

Recent research efforts have produced considerable information about near-term (generally less than 15 years) effects of mechanical and fire-based conifer treatments. Hydrologically, conifer removal is associated with reduced soil erosion, increased groundwater availability, and prolonged release of water stored in snowpack (Pierson et al., 2007; Kormos et al., 2016; Ochoa et al., 2016). Conifers may increase soil nutrients in association with effects of nutrient islands (Neff et al., 2009). Post-fire carbon dynamics will depend on the time interval under consideration and the type of vegetative community that develops, plus conversion to nonnative annual grasses may lead to the site becoming a carbon source (Rau et al., 2010). As conifer abundance nears stand closure and understory species are reduced, the probability of a positive post-treatment understory plant response decreases (Miller et al., 2005). Additionally, as site aridity and soil temperature increase and as the abundance of pre-treatment perennial herbaceous species decreases, the chances of post-treatment conversion to annual dominance increases (Miller et al., 2014b; Roundy et al., 2014). Conifer removal has been shown to reduce total fuel loading (Rau et al., 2010); however, late-stage conifer woodlands may be less susceptible to fire than sagebrush/bunchgrass plant communities. When conifer woodlands do burn, post-fire restoration may be needed, particularly if perennial understory vegetation was limited before the fire occurred (Roundy et al., 2014).

Existing science gaps

While short-term effects of conifer removal on ecosystem properties have been well studied (e.g., McIver et al., 2014), long-term dynamics (over periods of 25 to 100 years) of these same properties are not well known. They likely depend strongly on post-treatment vegetation dynamics over time. Soil temperature and moisture regime play a large role in affecting post-treatment vegetation succession. Snowpack characteristics and the ratio of precipitation that falls as rain to that of snow are predicted to change in the sagebrush ecosystem, but the impacts of this on recovery following conifer removal are unknown. Less well understood is the role of treatment type (e.g., mechanical versus fire) in impacting the rate of post-treatment return of conifer. Fire may be a better tool than mechanical treatment for reducing conifer seed banks and eliminating seedlings, but fire carries risk of conversion to undesired nonnative annual grass species if those grasses are already present, and fire dramatically reduces sagebrush abundance.

Next steps

Short-term (1 to 3 years)

- New research: Use retrospective studies of past management activities to evaluate timelines for post-treatment conifer succession and understory plant dynamics following different treatment types.

- New research: Establish instrumented networks of watersheds with experimental conifer-removal treatments and controls to measure hydrologic (including snowpack and soil moisture), physical (temperature and energy balance), and biogeochemical outcomes.
- New research: Determine the impacts of the biophysical setting for conifer removal, including slope, aspect, soil type, soil nutrient status, and conifer-encroachment status, on post-removal vegetation and wildlife responses.

Long-term (greater than 3 years)

- New research: Initiate long-term research and retrospective analyses to quantify the effects of juniper treatment on hydrology, geochemical cycling, wildlife habitat, and fire and fuel dynamics.
- New research: Use results from retrospective vegetation studies to determine economic viability of different treatment options based on treatment lifetime and cost of application.
- Synthesis: Synthesize findings from ongoing studies addressing the long-term effects of mechanical and fire-based conifer treatments on ecosystem properties.

Restoration Science Need #8: Evaluate the effectiveness of various rehabilitation or restoration activities in sage-grouse habitat to help determine if offsite mitigation is a viable option, because if restoration of sites to conditions useful for sage-grouse is not possible (for near-term benefits), then mitigation procedures might warrant reevaluation.

Subtopic: Landscape Analysis and Decision Support; Associated Strategy Task: 7(b)iv

Background

The concerted and ongoing effort by Federal, State, and private land managers to implement rehabilitation and restoration actions for sage-grouse was one of the more important rationales used by the USFWS in its decision that the species was not warranted for listing under the Endangered Species Act during the 2015 status review. The compilation of many of these efforts into the CED was an important step toward documenting the array of on-the-ground efforts. However, records indicate that effectiveness monitoring of most sage-grouse habitat restoration efforts is inadequate. Even the interagency ESR Program's monitoring often lacks standardization and sometimes rigor (Wirth and Pyke, 2007), despite a 3-year mandate for implementation and effectiveness monitoring for each project.

Given what is known about sage-grouse habitat associations (e.g., Hagen et al., 2007; Connelly et al., 2011) and the guidelines that are available for determining whether habitats meet the necessary requirements for sage-grouse during different seasons of use (Connelly et al., 2000; Stiver et al., 2015), there has yet to be a comprehensive assessment of the effectiveness of various rehabilitation and restoration activities to determine if offsite mitigation is a viable option for sage-grouse (Pyke, 2011).

Summary of recent science and syntheses

Most syntheses have evaluated the effectiveness of post-fire seeding for stabilizing soils and minimizing invasive plant cover. Studies from the Great Basin indicate that post-fire ESR rehabilitation efforts are more effective at higher elevations, where precipitation is less limiting (Knutson et al., 2014), than at lower elevations. These chronosequence analyses also indicate that it can take up to several decades before big sagebrush fully recovers (i.e., in height and cover) even when understory vegetation (i.e., perennial bunch grass height and canopy cover) meets the habitat requirements for sage-grouse (Arkle et al., 2014). Several recent syntheses may help guide restoration of sagebrush ecosystems in the context of sage-grouse habitat (Pyke et al., 2015a, b; Stiver et al., 2015; Finch et al., 2016), while others are underway. Two recent, ongoing studies that will provide useful information for this science need include the SageSuccess Project and Soda Fire ESR Project. These and other ongoing projects will greatly advance our understanding of the factors influencing the effectiveness of various rehabilitation or restoration activities in sage-grouse habitat to help determine if offsite mitigation is a viable option.

Existing science gaps

Meta-analyses and syntheses are needed to fully evaluate the effectiveness of different types of treatments at rehabilitating or restoring sage-grouse habitat, yet there are many scientific studies that need to be conducted or completed first before these syntheses would be useful. One of the challenges is the many types of treatments that occur and the subtleties of each that limit generality. Another major challenge is the time required, often decades, before sagebrush and other overstory (shrub) species recover to pre-disturbance levels. Hence, more research needs to be conducted before general conclusions can be drawn from scientific evidence with adequate inference and estimates of certainty.

Next steps

Short-term (1 to 3 years)

- New research: Conduct research on the effectiveness of land treatment projects for providing habitat for sage-grouse, taking into account the subtleties of treatment type, treatment implementation, time since treatment, and landscape context. Multiple research projects will be needed that span the range of environmental conditions across the range of the sage-grouse.
- Synthesis: Conduct a review of existing state-and-transition models and other resources to determine relationships between current vegetation conditions and ecological site potential to inform mitigation measures relative to the ability of a site to achieve intended vegetation conditions.

Long-term (greater than 3 years)

- Synthesis: Synthesize information from existing, ongoing, and new (above) research using rigorous, standard, and reproducible meta-analyses that capture the variety of treatments in type, space, and time.
- Tool: Using research and synthesis results to develop a decision support tool to inform mitigation efforts that incorporates information about existing vegetation conditions and threats (both local and landscape) relative to ecological site potential.

Restoration Science Need #9: Develop decision-support tools to assist in planning and implementing conifer removal treatments that will maximize maintenance of sagebrush systems, greater sage-grouse, and other sensitive species.

Subtopic: Conifer removal; Associated Strategy Tasks: 7(b)iii, iv and vi

Background

Fire return intervals in mid- to high-elevation sagebrush ecosystems have lengthened dramatically post-European arrival, initially in association with fine-fuel removal via livestock grazing and later with improved fire suppression techniques (Pyne et al., 1996; Miller and Rose, 1999; Miller et al., 2000). In association with a reduced presence of fire, and perhaps altered climate, populations of fire-sensitive native conifers (primarily juniper and piñon pine) have expanded to occupy approximately 19 million ha in the Intermountain region (Johnson and Miller, 2006). Left undisturbed, conifer succession proceeds, understory herbaceous and shrub species can be reduced or eliminated (Miller et al., 2005), and habitat for sagebrush-obligate wildlife species is lost (USFWS, 2013). Use of mechanical treatments or prescribed fire are common techniques to reduce the threat posed by conifer expansion. Mechanical treatments are relatively expensive and do not reduce the long-lived conifer seed bank, and treatment lifetime can be short if seedlings are missed. Prescribed fire may reduce the seedbank, can kill trees of all sizes, and is more economical than mechanical treatments. However, fire also kills most species of sagebrush, thus impairing habitat, at least temporarily, for sagebrush-dependent wildlife (Bates et al., 2014; Miller et al., 2014a; Farzan et al., 2015).

Summary of recent science and syntheses

Recent research efforts have produced considerable information regarding short-term effects of mechanical and fire conifer treatments on dynamics of herbaceous and woody understory plant species. Pre-treatment woodland development is key to post-treatment understory response. As conifer abundance nears site closure and understory species are reduced, the probability of a positive post-treatment understory plant-response decreases (Miller et al., 2005). Additionally, as site aridity and soil temperature increase, and as the abundance of pre-treatment perennial herbaceous species decreases, the chances of post-treatment conversion to annual dominance increase (Miller et al., 2014b; Roundy et al., 2014). A growing list of published references provide information for spatially allocating conifer management in sage-grouse habitat based on location of leks, percentage of the landscape remaining in sagebrush cover, and spatial distribution of plant community resilience and resistance to nonnative annual grass invasion (Aldridge et al., 2008; Baruch-Mordo et al., 2013; Chambers et al., 2014b).

Existing science gaps

Knowledge gaps predominantly fall into two categories. The first is in regard to the potentially differential timeline for post-treatment conifer succession among different conifer treatments, particularly between fire and mechanical treatments (i.e., treatment “durability”). The second category involves development of decision-support systems for partitioning conifer treatments across large areas, taking into account treatment lifetime, treatment economics, initial landscape cover of conifer and sagebrush, the dispersion of priority habitats for sagebrush-dependent wildlife species across the landscape, and plant community resistance and resilience. Additionally, little is known about the impact of prescribed fire on conifer seed banks.

Next steps

Short-term (1 to 3 years)

- New research: Use retrospective studies of past management activities to evaluate timelines for post-treatment conifer succession and understory plant dynamics following mechanical (cutting and mastication) and prescribed fire treatment.
- New research: Study the impacts of fire on conifer seed banks.

Long-term (greater than 3 years)

- Synthesis: Synthesize findings from ongoing studies to collate and refine knowledge of initial and long-term understory plant response to treatment as a function of site characteristics and treatment method.
- Tool: Incorporate treatment economics and durability into decision-support models that consider large areas and include plant-cover attributes, location of priority wildlife habitat, and plant community resistance and resilience.

Restoration Science Need #10: Assess soil degradation and develop treatments, soil amendments, and other site-preparation techniques that enhance germination, establishment, and development of healthy sagebrush communities capable of resisting invasion by nonnative plant species.

Subtopic: Methods; Associated Strategy Task: 7(b)iv, v and iv

Background

Soils are foundational to seed germination, plant establishment, plant productivity, hydrology, nutrient cycling, and overall ecosystem function. Soil degradation, which may be caused by erosion, nutrient depletion, or both, is likely widespread in sagebrush ecosystems. However, there is a poor understanding of the extent and impact of soil degradation in this ecosystem. Wildfire and nonnative annual grass

invasion can cause changes in wind and water erosion, hydrophobicity, soil nutrients, and soil biota. Soil erosion after wildfire can exceed most other land disturbances (Neary, 2009). Soil loss due to water erosion has been estimated for non-Federal rangelands (Weltz et al., 2014); however, an assessment for water erosion on Federal rangelands, as well as wind-driven erosion, is needed. Indicators of soil health may provide early signs of ecosystem degradation (deSoyza et al., 1998; Brown and Herrick, 2016) and may prove useful in land management to prevent desertification. Soil treatments and amendments to rehabilitate nonnative annual grasslands and post-fire landscapes may include the use of chemical or biological amendments or mulch, installation of barriers against water and wind erosion, and application of polyacrylamide gels.

Summary of recent science and syntheses

Miller et al. (2013) reviewed the effects of fire on Great Basin vegetation and soils, with the vast majority of the review addressing vegetation rather than soils because of the bias that exists in the availability of information about soils. Considering the importance of soils for seed germination and plant establishment, the lack of knowledge of post-fire soil processes in relation to ecosystem recovery is surprising. Derner et al. (2016) also acknowledged the need for more information about soil health in regards to fire, as well as identifying transitions and thresholds in state-and-transition models. Most studies have focused on changes in soil biogeochemical cycling or water erosion after fire and annual grass invasion (Miller et al., 2013). A few studies have examined using soil amendments, such as carbon or salt, to reduce nonnative annual grass invasion (Morghan and Seastedt, 1999; Newingham and Belnap, 2006). The effects of seed drilling on soil physical and chemical properties are currently being examined (Shaw et al., 2011).

Existing science gaps

Soil properties are alluded to in management frameworks (resistance and resilience; see Miller et al., 2014a) and in the ESR Program, but rarely are soil properties measured (but see Toevs et al., 2011). Therefore, large information gaps exist for soil physical, chemical, and biological properties in relation to fire, nonnative annual grass invasion, and restoration. Examples of needed information include (1) estimations of soil degradation, including loss via wind and erosion, (2) effects of management (grazing, vegetation treatments, post-fire rehabilitation, invasive nonnative plant management) on soil properties, (3) effects of fire and nonnative annual grass invasion on soil biota (biological soil crust, pathogenic bacteria, and mycorrhizae) and their role in restoration, (4) further exploration of the use of chemical and physical amendments in restoration both ecologically and economically, and (5) linkages between soil water availability and germination and seedling establishment in post-fire environments. These questions may be asked across soil types, climate, and existing plant communities, as well as in relation to burn severity and fire frequency.

Next steps

Short-term (1 to 3 years)

- New research: Assess soil degradation across sagebrush ecosystems in regards to fire, nonnative annual grass invasion, grazing, and other disturbances.
- Synthesis: Synthesize findings on effects of nonnative annual grass invasion and fire on soil biogeochemistry.

Long-term (greater than 3 years)

- New research: Investigate the extent and ecological impacts of wind erosion.
- New research: Further elucidate soil water and chemistry with plant establishment after fire.
- Tool: Continue developing water- and wind-erosion models for post-fire environments in the sagebrush ecosystem.
- Tool: Develop restoration tools that incorporate soil properties in reestablishing plant communities.

Sagebrush and Sage-Grouse

This topic covers science needs related to improving sage-grouse conservation efforts and understanding components of the sagebrush ecosystem (Table 5). Priorities involving sage-grouse include identifying factors that affect sage-grouse movement patterns and population connectivity; understanding effects and thresholds of disturbance on sage-grouse behavior, habitat use, and populations; developing spatially explicit population models; and identifying seasonal habitats across the entire range of the species. Sagebrush ecosystem needs include development of next-generation vegetation mapping techniques, assessment of long-term dynamics of the sagebrush ecosystem, and development of an understanding of how grazing influences sagebrush vegetation and sage-grouse. Another priority is the need to understand the ecology of some of the other sagebrush-obligate and sagebrush-associated species, including the influence of habitat conditions and threats on the distribution of these species.



Photo credit: Tom Koerner, USFWS

Table 5. Science needs and next steps in the Sagebrush and Sage-grouse topic. Next steps include new research, syntheses, and tools that are needed fill to the identified science gaps. The list separates those steps that could be accomplished in the short term (1 to 3 years), followed by those that are considered long term (accomplished in more than 3 years).

#	Need	Timing	Type	Next step
1	Investigate sage-grouse movement patterns, the habitat characteristics that are conducive, restrictive, or preventive to those movements, and the genetic structure of populations to help inform management practices to improve or maintain connections.	Short-term	New research	<p>Compile and integrate disparate GPS tracking datasets to relate fine-scale movement patterns of sage-grouse relative to landscape characteristics, and identify variation in environmental resistance and barriers between seasonal habitats and between populations across the sage-grouse range.</p> <p>Initiate studies using high-frequency, fine-resolution GPS data to link sage-grouse movement processes to habitat conditions and anthropogenic features across the landscape.</p> <p>Expand studies done with genetic data collected from lek sites that provide broad-scale patterns of range-wide population connectivity, including use of single nucleotide polymorphisms (SNPs) and other advanced genetic and genomic techniques.</p> <p>Use fine-scale genetic data from individual sage-grouse to investigate how movement barriers impact population performance and genetic structure at local scales.</p> <p>Complete a range-wide genetic analysis to provide the first comprehensive assessment of sage-grouse genetic connectivity.</p>
		Long-term	Tool	<p>Develop new technology that allows for acquisition of movement data with increased frequency and resolution and reduced sage-grouse mortality.</p>
2	Conduct a series of large-scale, replicated grazing studies that address how different livestock species, grazing systems, disturbance histories, and other environmental conditions affect sage-grouse habitat.	Short-term	New research	<p>Investigate landscape factors that explain regional variation in movement patterns across different spatial scales using genetic and telemetry data.</p> <p>Complete studies of sage-grouse movements relative to habitat conditions and human features across the landscape using high-frequency, fine-resolution GPS data to understand how movement barriers affect population performance and genetic structure.</p>
				<p>Identify numerous study sites and initiate monitoring within pastures and plots at those sites that have different and explicit grazing treatments, documenting the past grazing regime at those study pastures and plots to experimentally link the timing and intensity of livestock grazing to sage-grouse demographics and population trends.</p> <p>Identify or refine detailed protocols for monitoring sage-grouse vital rates and estimating local grazing intensity that would be used at replicate study sites so that data from numerous sites and States can contribute to synthetic analyses.</p> <p>Conduct an assessment of feral horse and burro impacts on local vegetation and sage-grouse habitat selection, vital rates, and population trends. If done in conjunction with analysis of effects of livestock grazing, this would facilitate analyses of interactive effects.</p>

Table 5. Science needs and next steps in the Sagebrush and Sage-grouse topic. Next steps include new research, syntheses, and tools that are needed fill to the identified science gaps. The list separates those steps that could be accomplished in the short term (1 to 3 years), followed by those that are considered long term (accomplished in more than 3 years).—Continued

#	Need	Timing	Type	Next step
2	Continued		Synthesis	Develop a synthesis of grazing effects on sage-grouse habitat condition.
		Long-term	New research	<p>Coordinate the collection of consistent range-wide geospatial information documenting grazing timing and intensity at the allotment and pasture level to facilitate large-scale analyses of grazing information.</p> <p>Develop long-term replicated grazing studies across the sagebrush ecosystem and within different ecological sites across the range of sage-grouse to better understand the different effects of grazing on sage-grouse habitat selection, vital rates, and population trends.</p> <p>Implement consistent sampling at many sites in multiple states to ensure that results are rigorous and applicable throughout the sage-grouse range.</p> <p>Refer to Restoration Science Need #3, Long-term Next Step #1.</p>
3	Identify thresholds beyond which effects on sage-grouse behavior, population response(s), or habitat use are minimized relative to different types of disturbances and related activities, for example, effects of wildfire, energy development, and other surface-disturbing activities.	Short-term	New research	<p>Assess the relative influence of predators and infrastructure on sage-grouse behaviors and population dynamics, including distinction of altered sage-grouse behavior (avoidance) from direct impacts (mortality).</p> <p>Expand on the work of Blickley et al. (2012) by building into study designs assessments of effects of different types of noise (industrial, recreational, and road noises in sagebrush landscapes) and by including variations in volume and distance across large geographic areas and over multiple sage-grouse populations.</p> <p>Investigate the impacts of noise on sage-grouse nesting females, nest success, and brood and chick survival.</p> <p>Evaluate impacts of wind turbines and associated infrastructure on sage-grouse habitat use, seasonal survival, nesting, and brood-rearing success rates.</p> <p>Determine the effects of conifer removal relative to removal of anthropogenic tall structures, considering demonstrable effects on habitat use. Address in these studies how predators respond to treatments, including raptors, canids, corvids, and rodents.</p>
		Long-term	New research	<p>Determine the response of sage-grouse to removal of infrastructure, including sage-grouse demography, population size of sage-grouse, and habitat characteristics.</p> <p>Assess development scenarios to improve siting and density of future project development to decrease impacts of sage-grouse populations (e.g., concentrated and clustered development versus diffuse development).</p> <p>Assess the indirect effects of land use activities (density and distribution) and potential covariates on sagebrush habitats.</p>

Table 5. Science needs and next steps in the Sagebrush and Sage-grouse topic. Next steps include new research, syntheses, and tools that are needed fill to the identified science gaps. The list separates those steps that could be accomplished in the short term (1 to 3 years), followed by those that are considered long term (accomplished in more than 3 years).—Continued

#	Need	Timing	Type	Next step
4	Develop next-generation mapping techniques to provide regular interval updates and continue to enhance grassland and shrubland vegetation mapping (e.g., every 2–5 years).	Short-term	New research	<p>Complete a baseline sagebrush ecosystem-wide characterization of shrub and grass components for the entire sagebrush ecosystem.</p> <p>Conduct an ecosystem-wide analysis of sagebrush change back in time to 1983 from the baseline using the Landsat archive and ancillary data (e.g., fire data).</p> <p>Further explore how to integrate ground sampling and monitoring using remote sensing to synergistically advance monitoring applications (e.g., machine learning and approaches using big data).</p>
		Long-term	New research	<p>Using Landsat change trends, develop scenario maps of the future showing how sagebrush ecosystem could change based on expected climate, fire, and other change agents.</p> <p>Explore new mapping technologies that synergistically merge multiple new technologies and data to provide higher spatial, structural, and thematic resolution maps than now possible and that cover larger areas.</p> <p>Explore new technologies to map the location of sagebrush subspecies in more detail.</p>
5	Develop spatially explicit sage-grouse population models that incorporate biological processes and habitat dynamics and investigate scenarios that reflect local management possibilities (options, opportunities, and obstacles).	Short-term	New research	<p>Coordinate and establish sage-grouse telemetry study sites across the species’ range to collect consistent sage-grouse demographic rate information for use in development of a range-wide integrated population model and scenario modeling. This information will also help establish links between sage-grouse population change, protective measures, conservation efforts, restoration actions, and effectiveness of metrics for habitat monitoring.</p>
			Synthesis	<p>Synthesize existing data and literature about population ecology of sage-grouse, as well as habitat associations related to demographic rates. This synthesis should include information about specific sage-grouse life stages (e.g., nesting, brood-rearing, wintering, etc.) while assessing vital rates and specific habitat needs across different ecoregions that sage-grouse inhabit.</p> <p>Convene a multi-agency working group to develop the metrics and process for completing a range-wide framework for an integrated population model that can predict or explain sage-grouse population performance relative to management decisions.</p>
		Long-term	New research	<p>Develop a range-wide integrated population model that incorporates landscape-scale environmental, disturbance, and climate information to provide reliable estimates of sage-grouse population size, population performance, and models that can explain variation in population size and performance across multiple spatial scales.</p>

Table 5. Science needs and next steps in the Sagebrush and Sage-grouse topic. Next steps include new research, syntheses, and tools that are needed fill to the identified science gaps. The list separates those steps that could be accomplished in the short term (1 to 3 years), followed by those that are considered long term (accomplished in more than 3 years).—Continued

#	Need	Timing	Type	Next step
5	Continued			Use a spatially explicit simulation modeling environment to link data and models with vital rate and movement information. These models will allow for the evaluation of how multiple interacting management actions and changes in land use and resource condition affect local and regional populations. This biologically realistic and mechanistic approach to evaluating the population responses across life stages will aid in identifying effective alternative management actions impacting sage-grouse distribution, abundance, and persistence.
			Tool	Develop an online interface to facilitate access by State and Federal agencies to the range-wide integrated population model to inform sage-grouse management actions.
6	Identify seasonal habitats for sage-grouse across their entire range.	Short-term	New research	Compile and summarize habitat objectives from land use plans across the range of sage-grouse, and summarize literature to develop regional functional responses that link site-scale habitat objectives to fine- or mid-scale shrub map products, which will be used for seasonal habitat models range-wide.
				Collect existing telemetry data throughout the sage-grouse range and evaluate threshold-based seasonal habitat maps to evaluate sage-grouse resource selection models.
			New research	Develop empirically based seasonal habitat models for sage-grouse range-wide using existing telemetry data (above) and new data collected as part of a multi-partner population and habitat monitoring framework.
			Tool	Develop approaches to apply habitat objectives to shrub map products that allow the development of thresholded seasonal habitat models (several methods being pursued).
		Long-term	New research	Integrate seasonal habitat models into a large spatially explicit population-viability modeling approach that encompasses the range of sage-grouse.
				Develop spatially explicit simulations to evaluate the effects of land use change (energy development, climate-induced habitat changes, fires, restoration, etc.) on sage-grouse seasonal habitat, and thus population viability.
			Tool	Use results from work above to support multiple management applications across spatial and management hierarchies.
				Develop a modeling process to enable frequent updates of seasonal models to account for habitat lost due to fire and other disturbance, and gained through conservation and restoration actions.

Table 5. Science needs and next steps in the Sagebrush and Sage-grouse topic. Next steps include new research, syntheses, and tools that are needed fill to the identified science gaps. The list separates those steps that could be accomplished in the short term (1 to 3 years), followed by those that are considered long term (accomplished in more than 3 years).—Continued

#	Need	Timing	Type	Next step
7	Develop sagebrush ecosystem-wide models identifying conditions necessary to support sagebrush-associated species, other than sage-grouse, using an individual species approach or species groups when necessary.	Short-term	New research	Update existing expert opinion and habitat suitability models using current land-cover and human-disturbance mapping products. Develop empirically based models for those species where suitable and sufficient data exist. Initiate data collection to develop the information necessary to model those sagebrush-associated species that lack sufficient existing data to develop models.
			Synthesis	Conduct a comprehensive review and synthesis of available information for sagebrush-obligate and associated species to identify information that can inform modeling efforts. Develop standard monitoring strategies and protocols for priority species lacking current baseline habitat information. Identify and resolve information gaps for sagebrush-obligates and ecosystem management.
		Long-term	New research	Develop empirical models for sagebrush-associated species as data become available.
			Tool	Develop decision-support tools to inform management actions for individual or groups of sagebrush-associated species.
8	Develop thresholds for the extent and magnitude of a threat (e.g., cover of pinyon and juniper, density of oil and gas wells, road density, etc.) above which the habitat can no longer support sagebrush-obligate species.	Short-term	New research	Assess efficacy of current management strategies for conservation of sagebrush-obligates, and identify recommended changes using this information. Initiate additional research on the effects of habitat management and modification on pinyon-juniper-associated species, such as the juniper titmouse (<i>Baeolophus ridgwayi</i>) and the pinyon jay (<i>Gymnorhinus cyanocephalus</i>), to identify potential irreversible impacts to these species resulting from habitat management geared towards the restoration of sagebrush-steppe and sagebrush-obligates. Develop or refine monitoring protocols and initiate systematic monitoring for sagebrush-obligates and other sagebrush-associated species to develop data necessary for evaluation of thresholds established for sage-grouse conservation.
			Synthesis	Conduct a comprehensive review of data and literature for sagebrush-obligate species to identify types of responses to various disturbance factors and habitat change, the magnitude of those responses, and the underlying mechanisms.
		Long-term	New research	Evaluate the responses of sagebrush-obligate species relative to various disturbance factors and habitat change and the magnitude of those responses, and determine the underlying causal mechanisms for those responses. Continue research to identify habitat needs, connectivity, vital rates, etc. of sagebrush-obligate and sagebrush-associated species.

Table 5. Science needs and next steps in the Sagebrush and Sage-grouse topic. Next steps include new research, syntheses, and tools that are needed fill to the identified science gaps. The list separates those steps that could be accomplished in the short term (1 to 3 years), followed by those that are considered long term (accomplished in more than 3 years).—Continued

#	Need	Timing	Type	Next step
9	Conduct long-term monitoring to assess development of community structure, community function, dynamics in native seedings, as well as suitability of resulting communities in meeting specific management goals, such as sage-grouse habitat restoration.	Short-term	New research	<p>Identify and assess a standardized set of monitoring indicators and protocols, and evaluate their success for measuring efforts to meet habitat conservation and restoration goals.</p> <p>Develop high-quality geospatial information for environmental and human disturbance metrics including soil characteristics, temperature, precipitation, and infrastructure.</p> <p>Develop and assess new monitoring methods to improve monitoring efficiency (e.g., use of tablets and other devices, photo points, remote sensing, and LIDAR).</p> <p>Use radio-telemetry and spatially explicit simulation (population) modeling to evaluate the potential gains and losses of sage-grouse associated with alternative sagebrush restoration approaches.</p> <p>Use long-term temporally stamped sagebrush mapping products currently being developed (See Sagebrush and Sage-Grouse Science Need #4) to construct temporal data series of changes in sagebrush vegetation components (1984–2016) for evaluation of the time to recovery of sagebrush vegetation given the various treatments, disturbances, and restoration practices.</p>
		Long-term	Tool	<p>Develop decision-support tools to enable managers to evaluate potential outcomes of planned treatments using information about similar treatments conducted under equivalent environmental conditions, including pre-treatment vegetation, ecological site, weather, and disturbance.</p>
		Long-term	New research	<p>Complete evaluation of monitoring indicators and adopt those that provide clear information to detect community structure and function, evaluate success of management treatments, and detect habitat changes critical to sage-grouse and other sagebrush-obligate species.</p> <p>Use improved soil maps, maps and models of topography and climate, and information about post-disturbance vegetation response to refine and describe community responses to treatments across environmental gradients.</p> <p>Develop a set of long-term monitoring sites across the sagebrush ecosystem, stratified by ecological site conditions, resistance and resilience, and other environmental characteristics to facilitate evaluation of long-term community dynamics.</p> <p>Refer to Invasives Science Need #1 Short-Term Next Step #5 (Table 3).</p>
			Tool	<p>Work with the Natural Resources Conservation Service to complete and improve soil surveys and maps for public lands across the West.</p>

Sagebrush and Sage-Grouse Science Need #1: Investigate sage-grouse movement patterns, the habitat characteristics that are conducive, restrictive, or preventive to those movements, and the genetic structure of populations to help inform management practices to improve or maintain connections.

Subtopic: Connectivity and movement patterns; Associated Strategy Tasks: 7(b)iv and vi

Background

Sage-grouse depend on healthy sagebrush ecosystems, and availability of sagebrush habitat over large areas is necessary to fulfill life-history requirements and ensure population viability. Additionally, sage-grouse require a variety of sagebrush habitats for nesting, brood-rearing, winter forage and shelter, and other seasonal requisites. A better understanding of sage-grouse seasonal movement patterns can help to identify where connectivity between habitats may be restrictive, and what is occurring in those areas to cause the restriction. Additionally, connectivity between populations is essential to conserve population immigration and emigration, and to preclude the loss of genetic information, which is essential to prevent inbreeding depression and increased susceptibility to disease (Oyler-McCance et al., 2005; Bateson et al., 2014). Understanding seasonal habitat and population connectivity is key to making effective management decisions to ensure long-term viability of populations across the range of the species.

Evaluating sage-grouse space use is complicated because continuous monitoring of individuals is rarely possible. Direct observation and tracking of radio-marked individuals can be used to assess animal locations at specific points in time, but inferences made from these data are limited to those specific areas. Understanding movement patterns will provide key information for habitat management and conservation to ensure connectivity, as well as inform decisions addressing potential movement barriers. Habitat fragmentation that results in barriers to movement has occurred across the sage-grouse range and can have deleterious impacts on the ability of sage-grouse to access seasonal habitats. Fragmentation of sagebrush habitat also can create strong genetic separation and result in population subdivisions. Understanding sage-grouse movement patterns also can inform how sage-grouse perceive conifer encroachment, burned landscapes, and other potential barriers in sagebrush environments, such as transmission lines, energy developments, and other anthropogenic features.

Summary of recent science and syntheses

Sage-grouse genetic structure and sage-grouse movements are often studied independently. The most recent studies related to connectivity and movements across large spatial scales mostly rely on sophisticated analyses of nuclear and mitochondrial DNA (e.g., Row et al., 2015; Cross et al., 2016; Fedy et al., 2016; Oyler-McCance et al., 2016) and novel concepts from graph theory (Crist et al., 2015) to infer sage-grouse movement patterns and corridors in relation to landscape barriers and sage-grouse management units (e.g., priority areas for conservation, or PACs). Collectively, these studies found that distinct population clustering can occur at fine spatial scales, and the loss of just a few highly centralized population ‘hubs’ can have profound effects on connectivity across populations. In addition, advances in telemetry using GPS, coupled with high-resolution mapping of landscape features, have allowed for recent identification of behavioral choices sage-grouse make when encountering a potential barrier, such as conifers (Prochazka et al., *in press*), and resulting demographic (but not necessarily genetic) outcomes of those choices (Coates et al., 2016).

Existing science gaps

Few studies have directly linked movement parameters associated with habitat fragmentation (e.g., barriers) to population performance (but see Coates et al., 2016) or identified how specific barriers (e.g., conifer encroachment, fire scars, salt flats, rugged mountains) affect seasonal habitat connectivity or create genetic resistance on a landscape scale. Increased use of GPS tracking technology and advanced analytical techniques (e.g., step selection functions, behavioral change-point analyses, graph analysis, network and circuit theory) can allow identification of ecological and behavioral processes that influence



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sage-grouse habitat use. Such information can then be incorporated into existing analytical spatially explicit conservation planning frameworks and guide management actions aimed at sustaining sage-grouse seasonal and population connectivity. This information also can assist management of sage-grouse in response to changes in the spatial configuration of seasonal habitat across the sagebrush ecosystem.

Next steps

Short-term (1 to 3 years)

- New research: Compile and integrate disparate GPS tracking datasets to relate fine-scale movement patterns of sage-grouse relative to landscape characteristics, and identify variation in environmental resistance and barriers between seasonal habitats and between populations across the sage-grouse range.
- New research: Initiate studies using high-frequency, fine-resolution GPS data to link sage-grouse movement processes to habitat conditions and anthropogenic features across the landscape.
- New research: Expand studies done with genetic data collected from lek sites that provide broad-scale patterns of range-wide population connectivity, including use of single nucleotide polymorphisms (SNPs) and other advanced genetic and genomic techniques.
- New research: Use fine-scale genetic data from individual sage-grouse to investigate how movement barriers impact population performance and genetic structure at local scales.
- New research: Complete a range-wide genetic analysis to provide the first comprehensive assessment of sage-grouse genetic connectivity.
- Tool: Develop new technology that allows for acquisition of movement data with increased frequency and resolution and reduced sage-grouse mortality.

Long-term (greater than 3 years)

- New research: Investigate landscape factors that explain regional variation in movement patterns across different spatial scales using genetic and telemetry data.
- New research: Complete studies of sage-grouse movements relative to habitat conditions and human features across the landscape using high-frequency, fine-resolution GPS data to understand how movement barriers affect population performance and genetic structure.

Sagebrush and Sage-Grouse Science Need #2: Conduct a series of large-scale, replicated grazing studies that address how different livestock species, grazing systems, disturbance histories, and other environmental conditions affect sage-grouse habitat.

Subtopic: Composition, structure, and function; Associated Strategy Tasks: 7(b)iv and vi

Background

Grazing is one of the most common forms of land use across the western United States and within the range of sage-grouse. Livestock can alter the structure and composition of vegetation, and those changes can potentially affect the distribution and demographics of wildlife populations. Some plant species in sagebrush-dominated communities may be maladapted to repeated heavy grazing (Milchunas et al., 1998; Cagney et al., 2010), underscoring the importance of proper livestock management in these systems. Herbaceous cover at and around sage-grouse nest sites influences sage-grouse reproductive success (Hagen et al., 2007), but few rigorous studies document the effects of explicit grazing treatments and intensities on sage-grouse vital rates (Beck and Mitchell 2000; Crawford et al., 2004; Boyd et al., 2014). Land-management agencies are expected to make explicit recommendations regarding livestock management within sage-grouse breeding habitat without sufficient scientific information about the validity of those recommendations. Moreover, vegetation responses to the timing and intensity of grazing vary with local vegetation communities, moisture regimes, and disturbance histories, underscoring the need for rigorous, replicated studies designed to document the effects of livestock grazing treatments on sage-grouse across the sagebrush ecosystem.

Summary of recent science and syntheses

Several review papers about effects of livestock grazing on sage-grouse have highlighted the need for studies that directly quantify the effects of livestock grazing on sage-grouse (Beck and Mitchell, 2000; Crawford et al., 2004; Boyd et al., 2014). Livestock grazing is often assumed to have the greatest potential to negatively affect sage-grouse through effects on nesting and brood-rearing habitat (Boyd et al., 2014). Based on studies of grazing impacts on plant communities and habitat requirements of sage-grouse, recommendations typically call for management of livestock to avoid overutilization of forage and ensure sufficient vertical cover and forbs for nesting and brood-rearing (Beck and Mitchell, 2000; Boyd et al., 2014). Besides removal of forage, some livestock management activities can have negative impacts to sage-grouse populations, including fencing, development of water sources (piping of springs), and sagebrush treatments (Beck and Mitchell, 2000; Stevens et al., 2011; Boyd et al., 2014). Grazing also alters insect abundance and diversity (Goosey et al., 2016), which may affect chick productivity. A recent review of public grazing records indicated that sage-grouse population response varied with local vegetation productivity, and therefore, the compatibility of grazing with sage-grouse habitats likely depends on the timing and intensity of grazing (Monroe et al., 2016).

Existing science gaps

Studies are needed that experimentally link the timing and intensity of livestock grazing to sage-grouse demographics and population trends. These may include estimating effects of different livestock grazing treatments on sage-grouse distribution, reproductive success, and population trends. Importantly, replication over space and time is needed to account for interactions with variation in vegetation productivity (moisture regimes) both among sites and years. Comparisons to areas without livestock grazing are important so that grazing treatments can be compared to baseline conditions. Consideration of fire history on a site and site-specific grazing history by domestic livestock, native wildlife, and introduced grazers and browsers also is important. Also, the effects of increasing feral horse and burro populations in the sagebrush ecosystem, often above appropriate management level, are poorly understood and need to be considered when evaluating domestic livestock grazing, changes to vegetation, and consequences for sage-grouse.

Next steps

Short-term (1 to 3 years)

- New research: Identify numerous study sites and initiate monitoring within pastures and plots at those sites that have different and explicit grazing treatments, documenting the past grazing regime at those study pastures and plots to experimentally link the timing and intensity of livestock grazing to sage-grouse demographics and population trends.
- New research: Identify or refine detailed protocols for monitoring sage-grouse vital rates and estimating local grazing intensity that would be used at replicate study sites so that data from numerous sites and States can contribute to synthetic analyses.
- New research: Conduct an assessment of feral horse and burro impacts on local vegetation and sage-grouse habitat selection, vital rates, and population trends. If done in conjunction with analysis of effects of livestock grazing, this would facilitate analyses of interactive effects.
- Synthesis: Develop a synthesis of grazing effects on sage-grouse habitat condition.
- Synthesis: Coordinate the collection of consistent range-wide geospatial information documenting grazing timing and intensity at the allotment and pasture level to facilitate large-scale analyses of grazing information.

Long-term (greater than 3 years)

- New research: Develop long-term replicated grazing studies across the sagebrush ecosystem and within different ecological sites across the range of sage-grouse to better understand the different effects of grazing on sage-grouse habitat selection, vital rates, and population trends.
- New research: Implement consistent sampling at many sites in multiple States to ensure that results are rigorous and applicable throughout the sage-grouse range.
- New research: Refer to Restoration Science Need #3, Long-term Next Step #1



Photo credit: Teresa Stein, USFWS

Sagebrush and Sage-Grouse Science Need #3: Identify thresholds beyond which effects on sage-grouse behavior, population response(s), or habitat use are minimized relative to different types of disturbances and related activities, for example, effects of wildfire, energy development, and other surface-disturbing activities.

Subtopic: Connectivity and movement patterns; Associated Strategy Tasks: 7(b)iv, v, and vi

Background

The task of understanding the effects of multiple anthropogenic uses on sage-grouse and their habitats is complicated by the variety and combinations of environmental, ecological, and socioeconomic conditions across the species' range. Responses of individual birds and populations, coupled with variability in land use patterns and habitat conditions, add complexity and variability to research results (Doherty et al., *in press*). This variability presents a challenge for managers and planners seeking to use research results to guide management and develop conservation measures for sage-grouse. Improvements in the understanding of the causes and consequences of these differences can inform future habitat management actions. Current planning tools focus on managing the disturbance footprint (habitat loss, fragmentation) within identified priority habitat areas. However, this approach often cannot capture differences among infrastructure types, the quantity and configuration of activities associated with developed locations, sage-grouse behavioral responses and habitat choices, and implications for sage-grouse populations.

Thus, research is needed to build on the existing knowledge about relations between specific types of infrastructure on sage-grouse behaviors and habitat selection across multiple populations and with a design suitable for estimating effect distances. This research needs to consider and distinguish direct and indirect effects, such as habitat loss versus avoidance of areas due to perceived risk. Considerable research is also needed to separate the effects of roads, structures, and other infrastructure from the human activities associated with those features to build on existing studies connecting noise from roads and drilling rigs with behavioral response. Additional research is needed to better understand the effects of land management activities and associated habitat disturbance.

Summary of recent science and syntheses

In 2014, a USGS-led team conducted a literature review and developed a report describing known and estimated relations between sage-grouse and anthropogenic infrastructure and activities (Manier et al., 2014). The report addressed the potential effects of anthropogenic land use and disturbances on sage-grouse populations and provided ecologically based interpretations of evidence from the scientific literature. While this report provided important information to help guide land use planning, including revisions of resource management plans, some variability in methods and results, and limited information in other cases (e.g., the effects of noise and activities versus structures) limited interpretation and inference possibilities. The report described and interpreted published results and indicated minimum and maximum estimated effect distances for surface disturbance, linear features (e.g., roads and pipelines), energy development (oil, gas, wind, solar, and geothermal), tall structures (communication towers and facilities for transmission of electricity), low structures (fences and buildings), and activities without specific habitat loss (noise).

Existing science gaps

Information is limited in all of the categories described above. The majority of disturbance studies on sage-grouse have investigated the effects of energy development on lek attendance and nesting behaviors. However, existing information could be improved with a design that includes multiple sage-grouse populations and seasonal habitats, to describe similarities and differences in sage-grouse responses to infrastructure at local, regional, and range-wide scales. In general, studies that use consistent methods and study design across the sage-grouse range to investigate changes in sage-grouse behavior and population

demographics relative to disturbances will improve understanding of disturbance thresholds and inform improvements in protective measures and mitigation actions. Explicit consideration and descriptions of distance effects and possible thresholds and covarying factors are needed. Study designs that can separate the direct and indirect effects of anthropogenic features and studies that focus on the behavioral response of sage-grouse and other sagebrush-obligates to anthropogenic noise and activities will be important.

Next steps

Short-term (1 to 3 years)

- New research: Assess the relative influence of predators and infrastructure on sage-grouse behaviors and population dynamics, including distinction of altered sage-grouse behavior (avoidance) from direct impacts (mortality).
- New research: Expand on the work of Blickley et al. (2012) by building into study designs assessments of effects of different types of noise (industrial, recreational, and road noises in sagebrush landscapes) and by including variations in volume and distance across large geographic areas and over multiple sage-grouse populations.
- New research: Investigate the impacts of noise on sage-grouse nesting females, nest success, and brood and chick survival.
- New research: Evaluate impacts of wind turbines and associated infrastructure on sage-grouse habitat use, seasonal survival, nesting, and brood-rearing success rates.
- New research: Determine the effects of conifer removal relative to removal of anthropogenic tall structures, considering demonstrable effects on habitat use. Address in these studies how predators respond to treatments, including raptors, canids, corvids, and rodents.

Long-term (greater than 3 years)

- New research: Determine the response of sage-grouse to removal of infrastructure, including sage-grouse demography, population size of sage-grouse, and habitat characteristics.
- New research: Assess development scenarios to improve siting and density of future project development to decrease impacts of sage-grouse populations (e.g., concentrated and clustered development versus diffuse development).
- New research: Assess the indirect effects of land use activities (density and distribution) and potential covariates on sagebrush habitats.

Sagebrush and Sage-Grouse Science Need #4: Develop next-generation mapping techniques to provide regular interval updates and continue to enhance grassland and shrubland vegetation mapping (e.g., every 2–5 years).

Subtopic: Monitoring; Associated Strategy Tasks: Crosscut 2 and 3

Background

Accurate and timely information about the distribution, condition, and trend of shrub and grass vegetation is crucial for making effective management decisions and ensuring good stewardship of land resources in the sagebrush ecosystem. Ideally spatially contiguous maps will characterize landscapes to offer utility at multiple scales and, thus, allow for both consistent regional analysis and relevant local application. Such mapping information should support periodic updating in a way that allows for monitoring both abrupt and gradual ecosystem change. Historically, remote sensing and ground-based mapping and monitoring have not provided adequate accuracy or spatially contiguous multi-scale information to accomplish these goals. Sagebrush areas provide a challenging remote-sensing mapping environment because of sparse vegetation and high proportions of bare ground, leading to lower accuracies (except in broad ecosystem classifications). Products have focused on the tradeoffs between characterizing general land-cover classes

of sagebrush over large areas and providing detail in small study areas. New efforts have focused on improving remote-sensing mapping products at multiple scales, developing better structural classifications with Light Detection and Ranging (LIDAR) and exploiting high-resolution digital imagery for improved local classifications. These methods still need to be completed and integrated, and the resulting products explained before they are useful for land management decisions.

Summary of recent science and syntheses

Recent remote-sensing science in sagebrush has focused on three broad themes: developing new methods to characterize sagebrush and grass components, assessing the accuracy of these methods, and developing new approaches to track changes across time. The evolution of remote-sensing science is happening from local to regional scales using a variety of different satellite sensors, airborne sensors, and mapping techniques. For optical satellite (e.g., Landsat, WorldView), airborne digital imagery (e.g., National Agriculture Imagery Program [NAIP]), and unmanned aerial systems (UAS), sagebrush characterization has evolved from categorical classes (cover types) to analyzing continuous field components (percent estimates of components such as sagebrush, bare ground, grass, etc., called fractional vegetation; Homer et al., 2012; Sant et al., 2014). This approach provides a way to consistently characterize products across multiple scales and facilitates monitoring of abrupt and gradual change over time (Homer et al., 2013). Change metrics are readily understood by land managers and provide a direct link to ground monitoring and measurement activities. In general, higher spatial resolution of sensors provides improved discrimination of fractional vegetation at higher accuracy than historically possible. Yet, the product may be expensive to produce and inconsistent at regional scales. High-resolution data are ideal for local analysis and application, and can be used to map change across time or as a surrogate for measurements of ground plots (Homer et al., 2013). Advancements also are happening in use of LIDAR data to supplement sagebrush mapping (Aihua et al., 2015), and coupling LIDAR with optical data provides the best results in mapping cover and biomass (Glenn et al., 2016). Results can be impressive over local areas, but scarcity of regional data and high cost make use of LIDAR and other emerging technologies difficult for operational applications in the short term, although these conditions should evolve to offer significant possibilities in the long-term. For example, the USGS 3DEP program is increasing the availability of LIDAR. Importantly, new machine learning and classification methods are emerging that allow multi-scale analysis using disparate field data and remote-sensing data. For example, while LIDAR accurately provides shrub metrics, optical data is needed for grass components. Coupling these methods with multi-temporal remote-sensing data in a “big data” approach allows for discrimination of fractional cover, biomass, and other metrics in both shrub and grass components that are important for management decisions.

Existing science gaps

The current Landsat remote sensing of shrub and grass components across the West is a major step forward in improving the mapping of the sagebrush ecosystem. Additional understanding of the location, magnitude, and trend of historical change would be especially powerful, and could be completed by using the Landsat archive. Integration of ground-based monitoring data with remote-sensing data and with machine-learning techniques will provide a context for observed trends in the remotely sensed data. Continuing the research to more effectively scale up high-resolution mapping with LIDAR, photogrammetric detection and ranging (PHODAR), and UAS sensing to large regions and to implement sagebrush subspecies mapping will provide future mapping tools key to evolving products to the next generation.

Next steps

Short-term (1 to 3 years)

- New research: Complete a baseline sagebrush ecosystem-wide characterization of shrub and grass components for the entire sagebrush ecosystem.

- New research: Conduct an ecosystem-wide analysis of sagebrush change back in time to 1983 from the baseline using the Landsat archive and ancillary data (e.g., fire data).
- New research: Further explore how to integrate ground sampling and monitoring using remote sensing to synergistically advance monitoring applications (e.g., machine learning and approaches using big data).

Long-term (greater than 3 years)

- New research: Using Landsat change trends, develop scenario maps of the future showing how sagebrush ecosystem could change based on expected climate, fire, and other change agents.
- New research: Explore new mapping technologies that synergistically merge multiple new technologies and data to provide higher spatial, structural, and thematic resolution maps than now possible and that cover larger areas.
- New research: Explore new technologies to map the location of sagebrush subspecies in more detail.

Sagebrush and Sage-Grouse Science Need #5: Develop spatially explicit sage-grouse population models that incorporate biological processes and habitat dynamics and investigate scenarios that reflect local management possibilities (options, opportunities, and obstacles).

Subtopic: Population modeling; Associated Strategy Task: 7(b)iv

Background

Relationships between sage-grouse and their habitats vary by season, region, and environmental condition. Understanding how management decisions affect sage-grouse locally and regionally will require information about sage-grouse population characteristics, such as survival, recruitment, and dispersal rates. To guide effective multi-scale management decisions, information about how those population characteristics change over time and vary by habitat is essential. Advanced population analyses, such as integrated population models (IPMs; Abadi et al., 2010), can associate population changes with spatially explicit information about habitat conditions. These analyses can provide information regarding relationships between environmental conditions and specific demographic rates that affect population viability over short and long periods of time.

Federal and State agencies can use this information to determine habitat suitability, causes of population change, and effectiveness of land use plans for sage-grouse. The BLM committed to an adaptive management approach facilitated by monitoring both sage-grouse habitat and population performance. State fish and wildlife agencies conduct lek counts on over 4,000 leks per year, and in a memorandum of understanding, WAFWA committed to provide lek count data and analyses of lek count data to the BLM and USFS to inform adaptive management. This concurrent collection of intensive and extensive sage-grouse habitat and population performance data creates an unprecedented opportunity for integrating habitat and population performance in a modeling framework that will inform adaptive management.

Summary of recent science and syntheses

Several spatially explicit models have been developed to inform the distribution of sage-grouse populations across the range relative to habitat factors (Knick et al., 2013; Fedy et al., 2014; Walker et al., 2015). Recent modeling has expanded this work to include relative abundance to inform designation of priority areas and management strategies (Coates et al., 2016) and identify regional variation in population effects (Doherty et al., *in press*). The development of techniques for integrated population modeling (Abadi et al., 2010; Kéry and Shaub, 2012) has opened a new approach for understanding sage-grouse populations. Integrated population models are a powerful analytical tool that can combine demographic and survey data into a single comprehensive analysis in order to provide the most coherent

estimation in understanding population dynamics. The models allow explicit understanding of the relative importance of both landscape and local habitat conditions to sage-grouse demography. These models assess the biological effectiveness of land management decisions, while controlling for regional events (such as wildfire) as well as impacts of short-term variation in climate (such as rainfall), both of which can overwhelm local-scale management. These models have been developed for the Bi-State Distinct Population Segment of greater sage-grouse (Coates et al., 2014) and Gunnison sage-grouse (*C. minimus*; Davis et al., 2014) and have shown significant value for informing management in the region. Tools have been developed to facilitate an initial integrated population modeling approach for sage-grouse (Nowak and Lukacs, 2016).

Existing science gaps

IPMs, while powerful (Coates et al., 2014), also are very data intensive and sometimes challenging to implement. Through IPMs and other population modeling techniques, there is a need to identify which sage-grouse demographic rates are most important and which are most likely to respond to management actions. To accomplish this, it is necessary to assess vital rates relative to changes in both landscape and local habitat conditions. This is a critical need because it will highlight which management actions have the highest probability of positively affecting sage-grouse populations. Variation in lek sampling and counting protocols complicate aggregation of these data given the expansive range of sage-grouse, and resolving these differences will improve the usefulness of this information in these population modeling efforts. Also, data about sage-grouse demographic rates are currently limited to collections of independent, often short-term studies, scattered across the species' range. The lack of a coordinated and consistent approach to monitoring sage-grouse beyond the current level of lek counts is an impediment to understanding relationships between landscape-scale stressors and sage-grouse population performance (both specific vital rates and population trend). Given standardized approaches in data collection, IPMs set up a robust framework for assessing where and when management actions are needed based on the most reliable estimates of short- and long-term changes in population numbers.

Next steps

Short-term (1 to 3 years)

- New research: Coordinate and establish sage-grouse telemetry study sites across the species' range to collect consistent sage-grouse demographic rate information for use in development of a range-wide integrated population model and scenario modeling. This information will also help establish links between sage-grouse population change, protective measures, conservation efforts, restoration actions, and effectiveness of metrics for habitat monitoring.
- Synthesis: Synthesize existing data and literature about population ecology of sage-grouse, as well as habitat associations related to demographic rates. This synthesis should include information about specific sage-grouse life stages (e.g., nesting, brood-rearing, wintering, etc.) while assessing vital rates and specific habitat needs across different ecoregions that sage-grouse inhabit.
- Synthesis: Convene a multi-agency working group to develop the metrics and process for completing a range-wide framework for an integrated population model that can predict or explain sage-grouse population performance relative to management decisions.

Long-term (greater than 3 years)

- New research: Develop a range-wide integrated population model that incorporates landscape-scale environmental, disturbance, and climate information to provide reliable estimates of sage-grouse population size, population performance, and models that can explain variation in population size and performance across multiple spatial scales.
- New research: Use a spatially explicit simulation modeling environment to link data and models with vital rate and movement information. These models will allow for the evaluation of how multiple interacting management actions and changes in land use and resource condition affect

local and regional populations. This biologically realistic and mechanistic approach to evaluating the population responses across life stages will aid in identifying effective alternative management actions impacting sage-grouse distribution, abundance, and persistence.

- Tool: Develop an online interface to facilitate access by State and Federal agencies to the range-wide integrated population model to inform sage-grouse management actions.

Sagebrush and Sage-Grouse Science Need #6: Identify seasonal habitats for sage-grouse across their entire range.

Subtopic: Seasonal Habitat; Associated Strategy Tasks: 7(b)iv and vi, and Crosscut 2

Background

Sagebrush habitats continue to be fragmented and degraded by natural factors, such as wildfire and climate, and human-induced changes, such as energy development, land use conversion, and invasive plant species. An added complication is that the characteristics of some natural factors also are human-influenced. As a result, sage-grouse populations have decreased in numbers (Garton et al., 2011) and distribution (Schroeder et al., 2004). To aid in management of sagebrush habitats and the conservation of sage-grouse, the BLM has included habitat monitoring in the agency's revised and amended land use plans to better characterize the regional habitat requirements for sage-grouse populations, including identifying seasonal habitat requirements at the broad and mid-range scales following guidelines outlined within the Habitat Assessment Framework (HAF; Stiver et al., 2015). To help with range-wide management of sage-grouse habitats, a consistent approach to identifying important seasonal habitat is necessary. Ideally, seasonal habitats would be identified using sage-grouse telemetry data to drive spatial models, following similar processes to those recently completed for the State of Wyoming (see Fedy et al., 2014). However, these empirically based models would take several years to develop and complete, and the BLM needs consistent maps delineating seasonal models as soon as possible to begin implementing management actions. With a set of west-wide shrub-mapping products (Homer et al., 2012;



Photo credit: Tatiana Gettelman, USGS

Xian et al., 2015) becoming readily available covering the years 2015 to 2017, there is a unique opportunity to use these consistent, range-wide mapping products to help identify seasonal sage-grouse habitats for conservation and management across the sagebrush ecosystem. Such an effort could directly facilitate the BLM's landscape approaches and management planning.

Summary of recent science and syntheses

Site-scale habitat requirements (Stiver et al., 2015) have been measured in numerous individual studies across the range of sage-grouse (see Hagen et al., 2007, for a review of nesting and brood-rearing habitats). Recently, individual studies have assessed sage-grouse habitat selection across larger areas, evaluating resource needs for nesting (Aldridge and Boyce, 2007; Kirol et al., 2015), brood-rearing (Aldridge and Boyce, 2007; Kirol et al., 2015), and winter habitat (Carpenter et al., 2010). However, these modeling efforts typically include a single study site, preventing the modeling and mapping of resource needs and connectivity across populations, management zones, or range-wide. In each study, a base model or map depicting habitat classifications was required to model sage-grouse resource selection, and ultimately, map habitat predictions. The lack of high-resolution maps predicting cover components (percent cover) across large areas for sagebrush habitats has limited the ability to develop sage-grouse models over large landscapes. However, with the recent advancements in characterization of sagebrush-dominated ecosystems from remotely sensed imagery, evolving from categorical classes (cover types) to continuous field components (percent estimates of components such as sagebrush, bare ground, grass, etc., called fractional vegetation; Homer et al., 2012; Sant et al., 2014; Xian et al., 2015), there is an opportunity to combine multiple telemetry datasets to assess resource selection across broader landscapes, such as those developed for the State of Wyoming (Fedy et al., 2014). With new vegetation maps and range-wide telemetry studies, seasonal habitat models, similar to Fedy et al. (2014), could be accomplished range-wide. Several States are working on some form of seasonal habitat model, but a collaboration to develop a consistent range-wide approach to compile all existing data and newly collected telemetry data would allow for better management of sage-grouse habitats and provide a more succinct understanding of regional variation in resource requirements. Without a collaborative effort, the use of disparately different habitat models (based on different statistical assumptions, scales, and approaches) would likely prove difficult for monitoring and addressing populations and connectivity of those populations.

Existing science gaps

The BLM is supporting work to develop coarse seasonal habitat models based on habitat objectives identified in planning documents and associated environmental compliance documents. These models will be applied as thresholds to the shrub map products. However, these products are limited by the application of literature-based thresholds and habitat objectives, rather than empirically derived responses. Also, winter habitat models cannot currently be developed due to a variety of data limitations. Efforts are underway to bring together all telemetry datasets range-wide, and collaborate on establishing new telemetry studies to have improved regional data to develop empirically based range-wide seasonal habitat models.

Next steps

Short-term (1 to 3 years)

- New Research: Compile and summarize habitat objectives from land use plans across the range of sage-grouse, and summarize literature to develop regional functional responses that link site-scale habitat objectives to fine- or mid-scale shrub map products, which will be used for seasonal habitat models range-wide.
- New Research: Collect existing telemetry data throughout the sage-grouse range and evaluate threshold-based seasonal habitat maps to evaluate sage-grouse resource selection models.
- New Research: Develop empirically based seasonal habitat models for sage-grouse range-wide using existing telemetry data (above) and new data collected as part of a multi-partner population and habitat monitoring framework.

- Tool: Develop approaches to apply habitat objectives to shrub map products that allow the development of thresholded seasonal habitat models (several methods being pursued).

Long-term (greater than 3 years)

- New Research: Integrate seasonal habitat models into a large, spatially explicit population-viability modeling approach that encompasses the range of sage-grouse.
- New Research: Develop spatially explicit simulations to evaluate the effects of land use change (energy development, climate-induced habitat changes, fires, restoration, etc.) on sage-grouse seasonal habitat, and thus population viability.
- Tool: Use results from work above to support multiple management applications across spatial and management hierarchies.
- Tool: Develop a modeling process to enable frequent updates of seasonal models to account for habitat lost due to fire and other disturbance, and gained through conservation and restoration actions.

Sagebrush and Sage-Grouse Science Need #7: Develop sagebrush ecosystem-wide models identifying conditions necessary to support sagebrush-associated species, other than sage-grouse, using an individual species approach or species groups when necessary.

Subtopic: Other Species; Associated Strategy Task: 7(b)iv and vi, and Crosscut 3

Background

Management of the sagebrush ecosystem has recently been predominantly focused on sage-grouse, primarily because of the potential for listing the species under the Endangered Species Act and also because of its value as a game species in many States. While concerns relative to single-species ecosystem management are common, the general presumption is that sage-grouse serve as an umbrella species for other sagebrush-obligates. While limited research supports this assumption for some sagebrush-associated species (e.g., wintering mule deer [*Odocoileus hemionus*]), more rigorous analyses suggest that not all sagebrush-associated species are well served by management for sage-grouse (Rowland et al., 2006; Hanser and Knick, 2011).

The development of an understanding of sage-grouse habitat across the sagebrush ecosystem (Knick and Connelly 2011; Doherty et al., *in press*) and the development of appropriate management strategies to conserve and restore those conditions have highlighted the need to understand the needs of other species that live in sagebrush habitats. Detailed, multi-scale analyses of habitat selection and quality have been conducted for some species, such as the Brewer's sparrow (*Spizella breweri*; Chalfoun and Martin, 2007, 2009), but are rare for most non-game sagebrush-associated wildlife. Developing ecosystem-wide models for other sagebrush-obligates and associated species will clarify key habitat needs and allow for development of a comprehensive sagebrush conservation strategy.

Summary of recent science and syntheses

Development of models for sagebrush-associated species, other than sage-grouse, has primarily been limited by a lack of field data and coordinated efforts to collect such data. The lack of field data has led to the use of modeling approaches involving expert opinion to establish a baseline distribution of these species through the USGS Gap Analysis Program (2016) and other modeling efforts. More recently, sagebrush-associated species have been the subject of regional assessments in the Great Basin and Wyoming Basins (Wisdom et al., 2005a; Hanser et al., 2011). These efforts have resulted in important information about the habitat needs and relative sensitivity of these species to surface-disturbing activities (Hanser et al., 2011). Recently, data from the U.S. Breeding Bird Survey was used to develop models for three sagebrush-obligate species: Brewer's sparrow, sagebrush sparrow (*Artemisiospiza nevadensis*), and

sage thrasher (*Oreoscoptes montanus*; Donnelly et al., *in press*). Several other national programs exist for the bird species, including the Christmas Bird Count and the citizen science effort, eBird. Responses (density and nesting success) of the three sagebrush-obligate songbird species to natural gas density has been explored in western Wyoming (Gilbert and Chalfoun, 2011; Hethcoat and Chalfoun, 2015a, b), revealing key information about how and why habitat changes due to energy extraction activities can influence sagebrush-associated wildlife.

Existing science gaps

Information on many sagebrush-obligate and associated species, including basic data about range, habitat use, and individual species' vital rates, is lacking or inferred from other similar species in dissimilar habitats. There are no data, except for a few charismatic species, regarding population and habitat connectivity. Yet these data are essential for understanding population and potential species persistence. Many species or taxa (e.g., small mammals) lack a standardized monitoring strategy and protocols.

Next steps

Short-term (1 to 3 years)

- New research: Update existing expert opinion and habitat suitability models using current land-cover and human-disturbance mapping products.
- New research: Develop empirically based models for those species where suitable and sufficient data exist.
- New research: Initiate data collection to develop the information necessary to model those sagebrush-associated species that lack sufficient existing data to develop models.
- Synthesis: Conduct a comprehensive review and synthesis of available information for sagebrush-obligate and associated species to identify information that can inform modeling efforts.
- Synthesis: Develop standard monitoring strategies and protocols for priority species lacking current baseline habitat information.
- Synthesis: Identify and resolve information gaps for sagebrush-obligates and ecosystem management.

Long-term (greater than 3 years)

- New research: Develop empirical models for sagebrush-associated species as data become available.
- Tool: Develop decision-support tools to inform management actions for individual or groups of sagebrush-associated species.

Sagebrush and Sage-Grouse Science Need #8: Develop thresholds for the extent and magnitude of a threat (e.g., cover of pinyon and juniper, density of oil and gas wells, road density, etc.) above which the habitat can no longer support sagebrush-obligate species.

Subtopic: Threats; Associated Strategy Tasks: 7(b)iv and vi, Crosscut 2 and 3

Background

The sagebrush ecosystem is continuously modified by natural processes, such as plant succession, and anthropogenic activities, such as energy development, livestock grazing, and recreation. Changes in habitats can affect sagebrush-obligate species, with impacts ranging from temporary disturbance to altered vital rates or local species extirpation. One well-studied example is the impact of non-renewable resource extraction on sage-grouse, where intensive development can reduce lek persistence, negatively

affect female and chick survival, and result in habitat loss and fragmentation (Connelly et al., 2004; Holloran, 2005; Aldridge and Boyce, 2007; Doherty et al., 2008). Similar impacts are seen with conifer expansion into the overstory of sagebrush ecosystems (Doherty et al., 2008; Baruch-Mordo et al., 2013). Actual impacts depend on the intensity of development and recreational activities, necessary pertinent resources, timing of impacts, amount of functional habitat modification, and impacts to habitat and population connectivity, etc., and may vary by location within the sagebrush ecosystem due to climatic conditions. Responses to development, recreational activities, and natural ecological processes also vary by sagebrush-obligate species. The understanding of actual impacts to individual sagebrush-obligate species is limited, underlying mechanisms are poorly understood, and cumulative assessments are lacking. Given the great variability in species' responses, land managers struggle to apply allowable thresholds for development, recreation activities, and management actions that will minimize the impact of such activities on sagebrush-obligate species.

Summary of recent science and syntheses

The development of thresholds for managing human development and recreational activities in sagebrush ecosystems has historically been focused on single species, such as mule deer and sage-grouse. Development of thresholds for other sagebrush-obligate and sagebrush-associated species has been limited due to a lack of basic ecological information about other species. Additionally, many sagebrush-associated species have not been prioritized for management due to their management designation as non-game and lack of economic value and impact. Sagebrush-associated species have been the subject of regional assessments in the Great Basin and Wyoming Basins (Wisdom et al., 2005a; Hanser et al., 2011). These efforts have resulted in important information about the habitat needs and relative sensitivity of some sagebrush-associated species to surface-disturbing activities (Hanser et al., 2011), but there is limited information on responses to recreational activities or plant succession. The recently formed WAFWA Sagebrush Science Initiative has identified information gaps for select sagebrush "focal" species and will soon be releasing a request for proposals to address these gaps. The Great Basin LCC has also solicited research proposals to address the impacts of removal of junipers for sage-grouse conservation on non-target species. State wildlife agencies also have identified focal species through state wildlife action plans. While not all of these efforts will directly address management thresholds, the insight gained will help inform future management of selected species.

Existing science gaps

Information about many sagebrush-obligate species, including basic data about range, habitat use, and vital rates, is lacking or inferred from similar species in dissimilar habitats. There are no data outside a few charismatic species for population and habitat connectivity and movement patterns. Additionally, because of the lack of information for many of these species, the types of responses, the magnitude of those responses, and the underlying mechanisms are unknown. Without these data, establishment of acceptable species-specific thresholds for management activities and resource development within the sagebrush ecosystem is not possible. Lack of basic information and consistent monitoring of many sagebrush-obligate species precludes an evaluation of these species relative to thresholds established in the 2016 BLM and USFS revisions to land use plans.

Next steps

Short-term (1 to 3 years)

- New research: Assess efficacy of current management strategies for conservation of sagebrush-obligates, and identify recommended changes using this information.
- New research: Initiate additional research on the effects of habitat management and modification on pinyon-juniper-associated species, such as the juniper titmouse (*Baeolophus ridgwayi*) and the pinyon jay (*Gymnorhinus cyanocephalus*), to identify potential irreversible impacts to these species resulting from habitat management geared towards the restoration of sagebrush-steppe and sagebrush-obligates.

- New research: Develop or refine monitoring protocols and initiate systematic monitoring for sagebrush-obligates and other sagebrush-associated species to develop data necessary for evaluation of thresholds established for sage-grouse conservation.
- Synthesis: Conduct a comprehensive review of data and literature for sagebrush-obligate species to identify types of responses to various disturbance factors and habitat change, the magnitude of those responses, and the underlying mechanisms.

Long-term (greater than 3 years)

- New research: Evaluate the responses of sagebrush-obligate species relative to various disturbance factors and habitat change and the magnitude of those responses, and determine the underlying causal mechanisms for those responses.
- New research: Continue research to identify habitat needs, connectivity, vital rates, etc. of sagebrush-obligate and sagebrush-associated species.

Sagebrush and Sage-Grouse Science Need #9: Conduct long-term monitoring to assess development of community structure, community function, dynamics in native seedlings, as well as suitability of resulting communities in meeting specific management goals, such as sage-grouse habitat restoration.

Subtopic: Monitoring; Associated Strategy Tasks: Crosscut 2 and 3

Background

Conservation and restoration of a healthy sagebrush ecosystem are priorities for Federal and State agencies to reverse losses of habitat for sage-grouse. Despite decades of sagebrush restoration efforts that span millions of acres, little is known about what contributes to successful establishment of sagebrush stands and associated perennial grasses and forbs. Many factors affect sagebrush seeding success, such as rangeland condition, weather, soil characteristics, herbivory, seed sources, and seeding rates. Coordinated long-term monitoring of sagebrush habitats, both within management treatments and the surrounding landscape, will provide the information necessary to inform changes to future management of this landscape. Monitoring uses repeat observations to understand how habitat metrics change relative to climate, disturbance, and management actions. These observations drive the adaptive management cycle, and in the absence of monitoring data, managers may lack the information to assess if they are meeting their objectives and to determine corrective actions. Monitoring needs to provide information about the ecological status and trends of the landscape and help in understanding how well treatments or project areas are meeting objectives.

Summary of recent science and syntheses

Recently, the BLM and USFS completed the Greater Sage-Grouse Monitoring Framework (Interagency Greater Sage-Grouse Disturbance and Monitoring Subteam, 2014). This provides a multi-scale approach for monitoring sage-grouse habitat and disturbances (both natural and anthropogenic). In 2015, the BLM and WAFWA released HAF (Stiver et al., 2015). This provides managers with a tool to assess whether conditions are suitable for sage-grouse. Several years of research addressing the response of post-fire sagebrush communities to seeding treatments have been conducted in the Great Basin (USGS SageSuccess and Chronosequence Projects, Knutson et al., 2014). This recent work should help inform future efforts to improve the success of sagebrush in seeding and live planting treatments, and inform post-treatment monitoring methods and adjustments to management actions. Research on resistance and resilience of sagebrush ecosystems (Chambers et al., 2014a) can inform specific management objectives relative to the site where a project is being implemented. Use of remote sensing is an additional important tool for long-term monitoring of sagebrush ecosystem communities. The Grass/Shrub Stewardship Mapping being developed by the USGS (Homer et al., 2013) provides “all lands” information for



sagebrush vegetation components, and this mapping is currently being expanded to the entire sagebrush biome. Building on these products, analytical techniques using the Landsat archive now provide map products of sagebrush ecosystem components back to 1984 (Homer et al., 2015). Compilation of past treatment data is critical for both retrospective assessment and analyses of cumulative effects of past treatment. The Land Treatment Digital Library (Pilliod and Welty, 2013) has been developed to compile and deliver this information.

Existing science gaps

The identification and adoption of a standardized set of indicators and protocols for collecting those indicators has been an impediment to aggregation of datasets, which are critical for development of large-scale assessment and comparison between projects and multiple environmental gradients. Standardized indicators measured with consistent protocols enable these data to be scaled up from the site level to landscapes, making data useful for multiple purposes and analysis. In addition to the vegetation monitoring data, high-quality environmental and human disturbance metrics are lacking. These data are necessary for developing an in-depth understanding of drivers of community structure and function and the potential limits for seeding success. These datasets include range-wide high-resolution mapping of infrastructure, soil characteristics, precipitation patterns, and temperature. Development of new techniques to enable more efficient collection of monitoring data could help facilitate consistent collection of monitoring data, which has been lacking in the past. An in-depth evaluation of monitoring metrics to ensure that data collected provide the information necessary to detect changes in habitat conditions can improve monitoring efficiency. This evaluation should include a test of the large number of metrics developed to assess sage-grouse habitat at multiple spatial scales. Also, monitoring of management treatments has been a short-term endeavor, with the assumption of long-term success if short-term objectives were met. Information is needed to help inform which short-term monitoring objectives, if met, indicate long-term success.

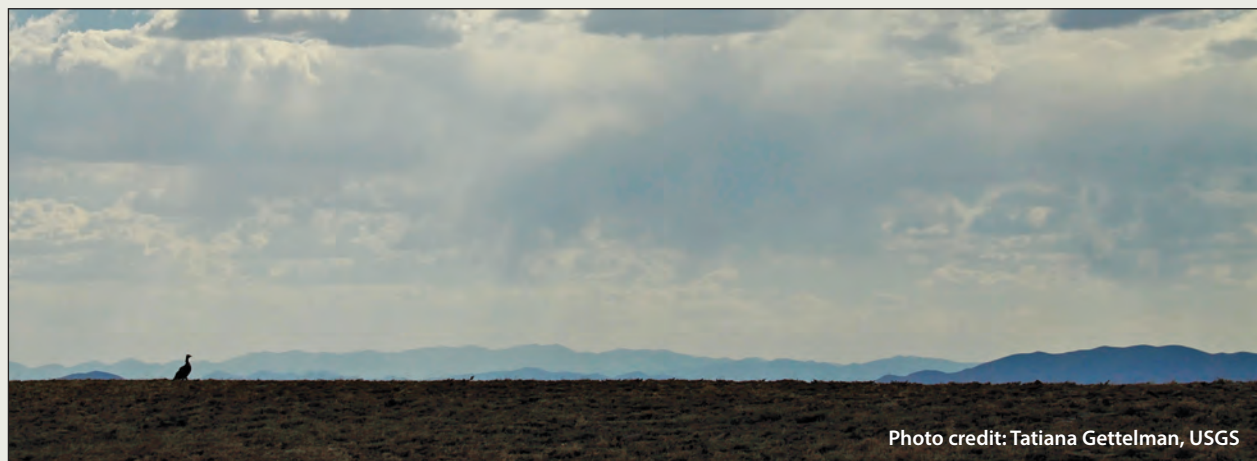
Next steps

Short-term (1 to 3 years)

- New research: Identify and assess a standardized set of monitoring indicators and protocols, and evaluate their success for measuring efforts to meet habitat conservation and restoration goals.
- New research: Develop high-quality geospatial information for environmental and human disturbance metrics including soil characteristics, temperature, precipitation, and infrastructure.
- New research: Develop and assess new monitoring methods to improve monitoring efficiency (e.g., use of tablets and other devices, photo points, remote sensing, and LIDAR).
- New research: Use radio-telemetry and spatially explicit simulation (population) modeling to evaluate the potential gains and losses of sage-grouse associated with alternative sagebrush restoration approaches.
- New research: Use long-term temporally stamped sagebrush mapping products currently being developed (See Sagebrush and Sage-Grouse Science Need #4) to construct temporal data series of changes in sagebrush vegetation components (1984–2016) for evaluation of the time to recovery of sagebrush vegetation given the various treatments, disturbances, and restoration practices.
- Tool: Develop decision-support tools to enable managers to evaluate potential outcomes of planned treatments using information about similar treatments conducted under equivalent environmental conditions, including pre-treatment vegetation, ecological site, weather, and disturbance.

Long-term (greater than 3 years)

- New research: Complete evaluation of monitoring indicators and adopt those that provide clear information to detect community structure and function, evaluate success of management treatments, and detect habitat changes critical to sage-grouse and other sagebrush-obligate species.
- New research: Use improved soil maps, maps and models of topography and climate, and information about post-disturbance vegetation response to refine and describe community responses to treatments across environmental gradients.
- New research: Develop a set of long-term monitoring sites across the sagebrush ecosystem, stratified by ecological site conditions, resistance and resilience, and other environmental characteristics to facilitate evaluation of long-term community dynamics.
- New research: Refer to Invasives Science Need #1 Short-Term Next Step #5 (Table 3).
- Tool: Work with the NRCS to complete and improve soil surveys and maps for public lands across the West.



Climate and Weather

This topic covers a range of priority science needs related to climate and weather (Table 6). These include developing predictive models for plant species used for restoration under climate-change scenarios, improving the collection of climate-appropriate seeds, developing native plant materials resilient to climate change, and understanding the complex set of variables that controls seeding success.

Table 6. Science needs and next steps in the Climate and Weather topic. Next steps include new research, syntheses, and tools that are needed to fill the identified science gaps. The list separates those steps that could be accomplished in the short term (1 to 3 years), followed by those that are considered long term (accomplished in more than 3 years).

#	Need	Timing	Type	Next step
1	Improve understanding of the complex set of variables that controls seeding success and improve accuracy of predictive meteorological data and models to identify years when the potential for seeding success is high or low	Short-term	New research	Quantify the expected future short- and long-term trajectories in the variables (weather, soil moisture, etc.) that are recognized as important for successful regeneration of big sagebrush.
			Tool	Develop a decision-support tool to help resource managers identify when and where weather and soil moisture conditions are predicted to be unfavorable for seedling establishment. Consider if it is advisable to wait for better conditions to seed or adjust techniques to accommodate poor predicted weather conditions.
		Long-term	New research	<p>Develop new techniques for establishing desired vegetation that buffer propagules from poor post-fire weather or long-term climate conditions.</p> <p>Identify the thresholds in plant responses to environmental conditions and the precise variables (e.g., mid-summer temperatures, winter temperatures, minimum or maximum temperatures, soil moisture, etc.) that desired restoration plants respond to best.</p> <p>Conduct distributed manipulative experiments to determine (1) whether mixes or blends of seed provenances can mitigate against climate uncertainty and (2) how that mitigation potential varies across the range of climate and soil conditions that exist within big sagebrush ecosystems.</p> <p>Prioritize geographic areas that will best respond to seeding given current factors (existing vegetation, soils, land use, fire history, etc.) and projected future climate conditions.</p>

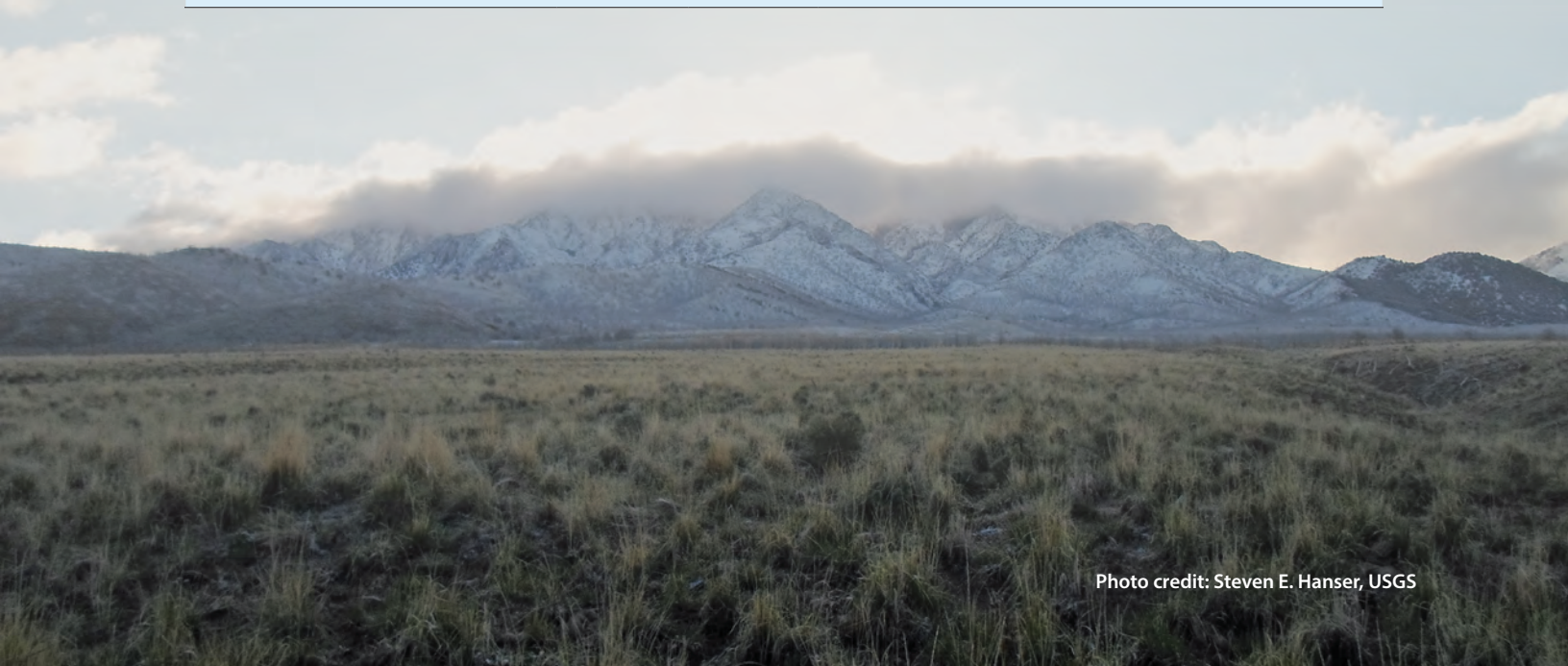


Table 6. Science needs and next steps in the Climate and Weather topic. Next steps include new research, syntheses, and tools that are needed to fill the identified science gaps. The list separates those steps that could be accomplished in the short term (1 to 3 years), followed by those that are considered long term (accomplished in more than 3 years).—Continued

#	Need	Timing	Type	Next step
2	Study the propagation and production of native plant materials to identify species or genotypes that may be resilient to climate change	Short-term	New research	Identify native species attributes that provide resiliency under warming climates, are competitive against invasive plants, and can be easily propagated. This may include continuation of ongoing research. Continue studies to model species and plant communities under changing climates.
		Long-term	New research	Conduct assisted migration trials to evaluate the capacity of species and population to establish, grow, and reproduce under varied environments. Investigate new techniques to improve drought tolerance of nursery seedlings and develop innovative ways to outplant them to leverage biotic and abiotic site factors toward increased survival.
			Synthesis	Develop a list of candidate species and ecotypes that are conducive for seed germination and seedling increase under projected mid-century climates.
3	Identify areas for seed collection across elevational and latitudinal ranges of target species to protect and maintain high-quality sources for native seeds	Short-term	New research	Conduct common garden studies to identify variation in adaptive traits and their associated climate drivers. Conduct population genetic studies for warranted species.
			Synthesis	Identify critical species needed in restoration. (Also see Climate and Weather Science Need #2.)
		Long-term	New research	Develop seed-transfer zones for contemporary and future climates. (Refer to Restoration Science Need #4). If necessary, conduct assisted migration trials.
			Tool	Publish seed-zone maps. (Refer to Restoration Science Need #4, Table 4.)
4	Develop predictive models of climate change effects, targeting restoration species, including regionally suitable culturally significant species, and genetic diversity using 20-year or mid-century climate models	Short-term	New research	Characterize high-temporal resolution patterns of ecological drought across the sagebrush biome and use newly developed drought indices (e.g., soil moisture drought index) to quantify how climate change will alter the occurrence and severity of ecological drought and the overall probability of observing conditions that support successful restoration.
			Synthesis	Review the literature to synthesize existing knowledge about environmental controls over regeneration of native plant species other than big sagebrush. Quantify the level of certainty in the magnitude and direction of changing climate for sagebrush steppe ecosystems by synthesizing forecasts from statistically and dynamically downscaled global and regional climate models and multiple representative concentration pathways.
		Long-term	New research	Conduct field experiments that manipulate environmental conditions and quantify how regeneration, mortality, and plant community dynamics respond to variation in precipitation, temperature, snowpack, and soil moisture. Experiments can be modest in complexity at each site but should be distributed across sites that represent broad climate gradients as well as edaphic variation in soil texture and depth.

Climate and Weather Science Need #1: Improve understanding of the complex set of variables that controls seeding success and improve accuracy of predictive meteorological data and models to identify years when the potential for seeding success is high or low.

Subtopic: Weather pattern and influence; Associated Strategy Tasks: 7(b)iv, v, viii, and ix

Background

Sagebrush ecosystem managers often seed areas that have been burned or are otherwise degraded to stabilize soils, re-establish native perennial plant cover, increase habitat for wildlife, and reduce the probability of invasion by nonnative annual grasses (Knutson et al., 2014). However, in the semi-arid Great Basin, regeneration success relies heavily on weather and soil moisture conditions after seeding (Schlaepfer et al., 2014a), long-term mean annual precipitation, and the origin of the seeds themselves (Germino, 2014; Knutson et al., 2014). Improving the accuracy of predictive ecological models that use short- to medium-term meteorological forecasts to identify years when the potential for seeding and outplanting success is high or low is vital to maximize the probability of successfully restoring burned and degraded sagebrush ecosystems.

Summary of recent science and syntheses

A recent synthesis of the long-term outcomes of seeding after wildfire at 88 Great Basin shrubland sites revealed that in many post-fire seeding treatments, native perennial grasses generally did not increase cover relative to burned areas that were not seeded (Knutson et al., 2014). Factors such as how seeds were sown (i.e., drill or aerial seeding), whether nonnative perennials were included in the seed mix, and seeding at high or low elevations (which correlates with annual precipitation) were important determinants of seeding success or failure. Germino (2014) found a high sensitivity of sagebrush seedings to post-fire weather as well as to seed source. Failed efforts could be traced to seeds that originated from colder sites than those into which they were planted, whereas successful seedings resulted from seeds from sites having the same minimum temperatures. Pinto et al. (2016) examined responses of seedlings to drought under various spatial and temporal conditions. Schlaepfer et al. (2014b) reviewed the literature relating to natural regeneration of big sagebrush and identified a small set of important variables relating to soil moisture, temperature, and snowpack. Together, these results suggest that seed source, seeding techniques, production and use of appropriate seedlings, and post-fire weather conditions are key factors in the climate adaptation of sagebrush ecosystem plant species.

Existing science gaps

The patchy nature of weather systems in arid environments will still be a factor at the scale of an individual seeding even if predictive meteorological models are generally accurate. As a result, new techniques for establishing vegetation are needed that buffer propagules from poor climatic conditions. A more tailored approach to post-fire rehabilitation is needed, not only in terms of plant species, but in terms of plant establishment techniques. Importantly, there is a need to identify the thresholds in plant responses to climate and weather. Studies are needed that will reveal mechanisms and identify the precise climate variables (e.g., mid-summer temperatures, winter temperatures, and minimum/maximum temperatures) that native perennials or nonnative plants that perform desired functions such as soil stabilization respond to best. Knowing these variables and their associated mechanisms of action will increase restoration success in a future climate.

Prioritization of areas that will best respond to seeding and outplanting materials, given factors such as vegetation, soils, land use, and fire history, should be completed prior to fires occurring so that when fires do occur, resources are concentrated in areas that have a higher chance of being recovered. This will require determining what combinations of soil type, topography, pre-existing vegetation, and treatments result in successful establishment under different weather and climate scenarios.

Next steps

Short-term (1 to 3 years)

- New research: Quantify the expected future short- and long-term trajectories in the variables (weather, soil moisture, etc.) that are recognized as important for successful regeneration of big sagebrush.
- Tool: Develop a decision-support tool to help resource managers identify when and where weather and soil moisture conditions are predicted to be unfavorable for seedling establishment. Consider if it is advisable to wait for better conditions to seed or adjust techniques to accommodate poor predicted weather conditions.

Long-term (greater than 3 years)

- New research: Develop new techniques for establishing desired vegetation that buffer propagules from poor post-fire weather or long-term climate conditions.
- New research: Identify the thresholds in plant responses to environmental conditions and the precise variables (e.g., mid-summer temperatures, winter temperatures, minimum or maximum temperatures, soil moisture, etc.) that desired restoration plants respond to best.
- New research: Conduct distributed manipulative experiments to determine (1) whether mixes or blends of seed provenances can mitigate against climate uncertainty and (2) how that mitigation potential varies across the range of climate and soil conditions that exist within big sagebrush ecosystems.
- New research: Prioritize geographic areas that will best respond to seeding given current factors (existing vegetation, soils, land use, fire history, etc.) and projected future climate conditions.

Climate and Weather Science Need #2: Study the propagation and production of native plant materials to identify species or genotypes that may be resilient to climate change.

Subtopic: Climate adaptation; Associated Strategy Tasks: 7(b)iv, viii, and ix

Background

Climate change is projected to result in warmer temperatures and more variable precipitation in the western United States. These changes will, in turn, affect plant communities. Mid-century (2050s) bioclimatic modeling of plant communities supports substantial vegetation changes, especially between warm (Mojave) and cold (Great Basin) deserts (Rehfeldt et al., 2012). While there is uncertainty about the pace at which these changes will occur, it is likely that disturbances (e.g., fire and drought) will be influential in ushering changes in plant communities and providing further opportunities for invasive plant species to expand their range. To foster resilient native plant communities, land management agencies will have to be strategic in choosing plant species and populations for propagation of seedlings and seedling out-plantings that have the life history strategies and traits necessary to be successful under warmer, drier climates. Multi-disciplinary research that includes nursery managers, climatologists, ecologists, and geneticists will be needed to guide the choices in use of native plants to foster resilient and diverse native ecosystems.

Summary of recent science and syntheses

Identifying native plants and their ecotypes that likely will be winners under warmer climates remains understudied. Studies of adaptive genetic variation are a foundation for developing understanding of which species and traits will be favored. To date, much of the work regarding adaptive genetic variation and climate change impact in the sagebrush ecosystem has involved grasses (Johnson et al., 2012; St. Clair et al., 2013) and shrubs (Richardson et al., 2014; Schlaepfer et al., 2015; Still and Richardson, 2015). Another necessary area of research is identifying native plant species that have traits compatible

for seed or seedling increase (e.g., Gunnell and Stettler, 2014; Jensen, 2014; Tilley, 2014) and identifying the most effective ways of re-establishing them on the landscape. A summary of native sagebrush plant propagation in the context of a changing climate is presented in Finch et al. (2016).

Existing science gaps

Climate change will determine winners and losers among species and populations. It will be critical to devote limited resources to those native species that have attributes that provide resiliency under warming climates, are competitive against invasive plants, and can be easily propagated. The major science gaps involve (1) understanding how climate change will impact individual species, (2) developing a list of candidate species and ecotypes that are conducive to propagation and production, (3) developing a list of species and ecotypes that meet the following criteria: resilient under climate change and conducive to propagation, and (4) conducting assisted migration trials to assess how candidate species and ecotypes perform under differing environmental conditions.

Next steps

Short-term (1 to 3 years)

- New research: Identify native species attributes that provide resiliency under warming climates, are competitive against invasive plants, and can be easily propagated. This may include continuation of ongoing research.
- New research: Continue studies to model species and plant communities under changing climates.

Long-term (greater than 3 years)

- New research: Conduct assisted migration trials to evaluate the capacity of species and population to establish, grow, and reproduce under varied environments.
- New research: Investigate new techniques to improve drought tolerance of nursery seedlings and develop innovative ways to outplant them to leverage biotic and abiotic site factors toward increased survival.
- Synthesis: Develop a list of candidate species and ecotypes that are conducive for seed germination and seedling increase under projected mid-century climates.



Photo credit: Tom Koerner, USFWS

Climate and Weather Science Need #3: Identify areas for seed collection across elevational and latitudinal ranges of target species to protect and maintain high-quality sources for native seeds.

Subtopic: Climate adaptation; Associated Strategy Tasks: 7(b)iv, viii, and ix

Background

Climate is the predominant driver of adaptation within plant species. Genecology is the study of adaptive genetic patterns in relation to the environment and the development of seed-transfer zones. In the past, genecological research used climate surrogates, such as latitude and elevation, to associate with different adaptive traits observed in common gardens. However, the development of climate surfaces, which are the interpolation of precipitation and temperature from weather stations, has provided a more accurate and informative procedure to assess putative drivers of adaptation. Variation in adaptive traits and their associated climate drivers can be used to define seed-transfer zones. Climate surfaces also have allowed researchers to make predictions of future climate by updating temperature and precipitation surfaces based on general circulation models (Rehfeldt et al., 2014; Richardson et al., 2014). Climate variables affecting patterns of adaptive genetic variation can then be modeled to predict how climate change will affect the adaptive patterns. These models can be coupled with bioclimatic niche models to assess changes in both species distribution and seed zones.

Summary of recent science and syntheses

Genecological studies and empirical seed-transfer zones have been completed for several of the predominant grasses (Johnson et al., 2012; St. Clair et al., 2013) and shrubs (Richardson et al., 2014) in the Intermountain West. Few forb species have been studied; however, see Johnson et al. (2013). These studies have focused on providing seed-transfer zones for contemporary climates with the exception of Richardson et al. (2014) who also examined mid-century projections. For species where genecological studies have not been completed or have not been practical, provisional seed zones can be used (Bower et al., 2014). Provisional seed-transfer zones use a standard range of precipitation and temperature to make recommendations about the limits of seed transfer. However, empirical seed-transfer zones are preferred because each species has unique adaptive genetic strategies. (Refer to Restoration Science Need #4 for more information [Table 4].) Population genetics offers another approach to evaluate areas for conservation and maintain high genetic diversity of seed sources. Population genetic studies have been essential in understanding the complex evolution of shrub species (Richardson et al., 2012) and the genetic structure and diversity of grass (Larson et al., 2004) and forb species (Bhattarai et al., 2010). An overview of sagebrush ecosystem seed science is presented in Finch et al. (2016).

Existing science gaps

Identifying areas for seed collection requires addressing the following science gaps: (1) identify the critical species necessary for restoration, (2) conduct genecological studies on these species, (3) develop seed zones for contemporary and future climates, (4) use a web-based platform to display maps of seed-transfer zones in formats accessible to land managers, and (5) conduct population genetics studies for species where taxonomic, genetic diversity and structure are lacking.

Next steps

Short-term (1 to 3 years)

- New research: Conduct common garden studies to identify variation in adaptive traits and their associated climate drivers.
- New research: Conduct population genetic studies for warranted species.
- Synthesis: Identify critical species needed in restoration. (Also see Climate and Weather Science Need #2.)



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Long-term (greater than 3 years)

- New research: Develop seed-transfer zones for contemporary and future climates. (Refer to Restoration Science Need #4, Table 4.)
- New research: If necessary, conduct assisted migration trials.
- Tool: Publish seed-zone maps. (Refer to Restoration Science Need #4, Table 4.)

Climate and Weather Science Need #4: Develop predictive models of climate change effects, targeting restoration species, including regionally suitable culturally significant species, and genetic diversity using 20-year or mid-century climate models.

Subtopic: Weather pattern and influence; Associated Strategy Tasks: 7(b)viii and ix

Background

Observations and models confirm that global climate cycles are changing and that climate variability is intensifying (Marvel and Bonfils, 2013; Wu et al., 2015). This includes increases in the frequency and intensity of extreme heat waves, droughts, fires, and large precipitation events (Cayan et al., 2010; MacDonald, 2010; Seager and Vecchi, 2010; Cook et al., 2015). These changes will have a substantial influence on ecosystems and plant communities. In water-limited regions like sagebrush ecosystems of the Great Basin, many of these impacts can be understood by examining changes in ecological drought, e.g., the magnitude and severity of the deficit soil water experienced by plants (Noy-Meir, 1973; Sala et al., 1988). Consequences will be particularly dramatic for plant regeneration, which is already a highly episodic response to varying drought conditions.

Summary of recent science and syntheses

Twenty global climate models downscaled for Oregon, Washington, Idaho, and western Montana project end-of-century temperatures to be 2–15 degrees Fahrenheit warmer than average temperatures for 1950 to 1999 (Mote et al., 2014). These models agree that by mid-century, the Northwest will experience wetter winters and drier summers, a far greater probability of precipitation falling as rain rather than snow, and a high probability of larger, more severe, and more frequent droughts and fires (Mote et al., 2014). More specific to the sagebrush ecosystem, a recent literature review by Schlaepfer et al. (2014b) identified the specific climate and soil variables that exert important control over germination and establishment of

big sagebrush. These insights were integrated with an ecohydrological model to develop a framework for estimating how the occurrence of suitable conditions responds to weather and soil conditions (Schlaepfer et al., 2014a).

Existing science gaps

Assessing the management-relevant consequences of changing and more variable climate conditions requires integrating near- and medium-term (e.g., 10–50 years) climate forecasts with appropriate ecological models that estimate impacts to specific drought or pluvial conditions that inhibit or promote restoration, respectively. In particular, there remains a need to quantify future expectations for both long-term aridity and the extreme drought events that drive plant mortality, restrict regeneration, limit restoration success, and influence long-term plant community composition and vegetation structure (Dobrowolski and Ewing, 1990; Allen et al., 2015). Because the Great Basin, and the sagebrush ecosystem in general, encompasses dramatic variation in climate, topography, and soil conditions, this analysis needs to occur across the entire range of interest. Furthermore, to provide appropriate perspective on the magnitude and importance of uncertainty in climate forecasts, these analyses should (1) represent the range of predictions being developed by the climatology community and (2) focus on climate models that performed best in hindcast comparisons with observed weather for the region of interest.

Next steps

Short-term (1 to 3 years)

- New research: Characterize high-temporal resolution patterns of ecological drought across the sagebrush biome and use newly developed drought indices (e.g., soil moisture drought index) to quantify how climate change will alter the occurrence and severity of ecological drought and the overall probability of observing conditions that support successful restoration.
- Synthesis: Review the literature to synthesize existing knowledge about environmental controls over regeneration of native plant species other than big sagebrush.
- Synthesis: Quantify the level of certainty in the magnitude and direction of changing climate for sagebrush steppe ecosystems by synthesizing forecasts from statistically and dynamically downscaled global and regional climate models and multiple representative concentration pathways.

Long-term (greater than 3 years)

- New research: Conduct field experiments that manipulate environmental conditions and quantify how regeneration, mortality, and plant community dynamics respond to variation in precipitation, temperature, snowpack, and soil moisture. Experiments can be modest in complexity at each site but should be distributed across sites that represent broad climate gradients as well as edaphic variation in soil texture and depth.

Implementation

A goal of broad participation by Federal and State management and research agencies, universities, and non-governmental organizations, funding entities, and partnership programs is hoped for in the implementation of this shared vision. Implementation integrated across the community of stakeholders will ensure the greatest chance of success in meeting the identified science needs. The construct of this Plan recognizes that individual agencies and organizations interested in sagebrush ecosystems have specific missions and goals that will result in differences in how they address the Plan. The broad range of topics and science needs in this Plan will provide opportunities for teamwork in developing integrated and complementary approaches including the integration of data and expertise among Federal and State agencies and non-government organizations.

Within the DOI, and hopefully among agency and other partners, science and management partnerships will be the norm to ensure science needs are addressed efficiently and expertly and in a manner that results in management-relevant science outcomes. These partnerships also will be useful in proposal preparation and sponsorship of projects of mutual interest, and to ensure that data collection and syntheses are well-documented, validated, and readily available for analysis and application.

Implementing Priorities

This Plan's set of high-priority science needs and next steps (Tables 2–6) form the basis for multi-year planning for science and research in the areas of fire, invasive plant species, restoration, sagebrush and sage-grouse, and climate and weather. Implementing the identified science and research activities will require an integrated approach. It is recommended that DOI agencies focus on accomplishing these priority science needs and integrate emerging science into the Science Framework for the Conservation and Restoration Strategy (Action Item 7(b)iv, #1 of the Strategy). In addition, clearly identified research priorities can offer funding organizations an opportunity to select and coordinate on projects they might jointly fund.

Sequencing research to maximize the knowledge gained is particularly important given limited research budgets. Short-term actions may be the first step in multi-step processes to address complex issues. Long-term actions may require that other actions occur first or may require more than 3 years to obtain results. Sequencing actions will be influenced by which actions are selected initially.



Funding Suggestions and Opportunities

Action Item 7(b)viii, #5 of the Strategy states “Identify available funding sources to support the action plan and implement new research in 2017 and beyond” (DOI, 2015). It is the intent that publication of this Actionable Science Plan is the first step in achieving this outcome. Within the DOI, it is recommended that funding and other resources be devoted to the high-priority science in this Plan.

Developing an organized process for communicating ongoing research and funding sources will improve efficiency and effectiveness. Therefore, it is recommended that the research and management communities collaboratively develop integrated budgets that reflect ongoing research activities and needs in the sagebrush biome, determine funding sources for the priority needs in the action plan, identify opportunities for cost-sharing, and identify any priorities not supported with existing budgets. This plan can also be used to develop specific requests for implementation funding within individual agencies. With increased certainty in strategically aligned funding resulting from such a process, the science organizations and individual researchers could be able to focus research programs to fill the existing knowledge gaps and assist partners in developing decision support tools for application of that science.

The clear set of priority science needs and tangible next steps (Tables 2–6) in this Plan are guidance tools to achieve this process for the sagebrush biome. The Plan outlines priority science needs that funding organizations can use to select and coordinate projects they might jointly fund in the coming years.

Coordination

These science needs and next steps are designed for use in science planning and the development of Requests for Proposals (RFPs) by a wide variety of organizations, including the LCCs, JFSP, DOI Climate Science Centers, USDA Climate Hubs, USGS USFWS Science Support Partnership, National Fire Plan, NRCS Sage-Grouse Initiative, WAFWA Initiatives, Collaborative Forest Landscape Restoration Program (CFLRP), and others. These organizations and initiatives all present opportunities to coordinate focused funding for these priorities. For instance, the Great Basin LCC and JFSP have indicated they will consider the topics and next steps articulated



Photo credit: Matthew J. Germino, USGS

in this plan, in conjunction with other relevant sources of information, to inform possible future funding opportunity notices and associated task statements. Also, individual agencies have research funding that can be important for filling additional gaps that are of particular importance to those agencies. However, coordination will be necessary to alleviate the potential for unnecessary overlap with research funded via RFPs and allow scaling up of local research activities to develop syntheses and landscape-scale analyses.

Annual meetings provide ideal venues for coordination of activities, presentation of science and next steps identified in this Plan, information about ongoing implementation and adaptive management efforts, and development of local and regional collaborations to support co-production, integration, and scaling of data. Important coordination activities include construction and maintenance of a database to track implementation of the plan and development of an annual multi-agency work plan based on review and acquisition of prior research, current priorities, and funding availability. As science needs and next steps are addressed, the management and research community will have the opportunity to identify new and emerging science needs as these will form the basis for the Plan update scheduled for 2019.

Agency leadership and program managers who are familiar with the “next-steps” section of each narrative can take action to assure (i) synthesis of existing knowledge is easily accessible and applicable in a management context; (ii) tools are available (either existing or developed as necessary) to put new or existing knowledge in the hands of on-the-ground managers and resource specialists; (iii) new research is initiated where information is lacking or questions still remain; and (iv) similar proposals are reviewed for overlap or redundancy.

Recognition of timing constraints is also an issue that must be highlighted. Many of the next steps will rely on data collected over a long time period and across large geographic areas; therefore, starting those efforts today will reduce delays in obtaining those data. Also, solving problems that have plagued the management community often requires new knowledge and breakthroughs that come from the collection of new data and application of new and innovative analysis techniques. These efforts can take time to unfold, and acknowledging the time and effort required can determine timelines for initiating and completing those projects and establish appropriate expectations for timeliness of results.

Outreach

A key step in the science life-cycle and in the facilitation of adaptive management is communication of new knowledge to the management community. Use of science in day-to-day management decisions will be enhanced by increasing dissemination, interpretation, and application of new science and research through an improved system for science delivery. The Strategy identified the Great Basin Fire Science Exchange (GBFSE) as the primary online science delivery system to allow easier access to published science products and information. The GBFSE was selected because it provides an expert web-based delivery system for the Strategy’s targeted audience. Ensuring that science information is aggregated up to the GBFSE will enable efficient science-informed decision making. A

single point of access will help managers find information and science materials currently provided by a large number of groups (such as the Great Basin Consortium, Great Basin Research and Management Partnership, and the Great Basin, Great Northern, and Southern Rockies LCCs, the Great Basin Native Plant Project, the WAFWA Sagebrush Science Initiative, and the Sagebrush-Steppe Evaluation Project), as well as universities, land grant colleges, and Federal research agencies, like the USGS, involved in similar research. These entities as well as individual scientists will also communicate findings through annual meetings of their organizations, professional society meetings, webinars, agency and individual websites, and within-agency and interagency workshops. An important goal will be to ensure information distributed through these other avenues are incorporated into the GBFSE website (<http://greatbasinfirescience.org/>).

Effective outreach is a multi-faceted process. Regular exchange of information between the research and management communities is the foundation of science delivery and science/management coordination. The combination of the GBFSE and other communication tools, including annual meetings, webinars, field tours, etc., will continue to strengthen science and management partnerships and provide a venue to communicate the outcomes of activities outlined in this Plan.



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Appendix

Table 1. List of Federal and State reports and strategy documents reviewed to identify existing science needs.

Document	Year	Citation	URL
Collaborative management and research in the Great Basin—examining the issues and developing a framework for action	2008	Chambers, J.C., Devoe, N., and Evenden, A., eds., 2008, Collaborative management and research in the Great Basin—examining the issues and developing a framework for action. Gen. Tech. Rep. RMRS-GTR-204. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 66 p.	http://www.fs.fed.us/rm/pubs/rmrs_gtr204.html
A Dynamic Invasive Species Research Vision: Opportunities and Priorities 2009–29	2009	Dix, M.E., and Britton, K., eds., 2010, A Dynamic Invasive Species Research Vision: Opportunities and Priorities 2009–29. Gen. Tech. Rep. WO-GTR-79. Arlington, VA: U.S. Department of Agriculture, Forest Service, Research and Development. 138 p.	http://www.fs.fed.us/research/docs/invasive-species/gtr_wo79_83.pdf
JFSP final report for project #05-2-1-94	2009	Fleishman, E., Chambers, J., Dobkin, D., Dickson, B., and Bradley, B., 2009, Response of birds, butterflies, and their habitats to management of wildland fuels and fire regimes.	http://www.firescience.gov/projects/05-2-1-94/project/05-2-1-94_05-2-1-94_final_report.pdf
JFSP final report for project #07-1-3-10	2010	Meyer, S.E., Allen, P.S., and Beckstead, J., 2010, Annual brome biocontrol after wildfire using a native fungal seed pathogen.	https://www.firescience.gov/projects/07-1-3-10/project/07-1-3-10_jfs5_final_report_2007-1-3-10.pdf
Geomorphology, hydrology, and ecology of Great Basin meadow complexes—implications for management and restoration.	2011	Chambers, J.C., and Miller, J.R., eds., 2011, Geomorphology, hydrology, and ecology of Great Basin meadow complexes—implications for management and restoration. Gen. Tech. Rep. RMRS-GTR-258. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 125 p.	http://www.fs.fed.us/rm/pubs/rmrs_gtr258.html
JFSP final report for project #07-1-3-18	2011	Paschke, M.W., Meiman, P.J., Romme, W.H., and Brown, C.S., 2011, Using native annual plant species to suppress weedy invasive species in post-fire habitats.	https://www.firescience.gov/projects/07-1-3-18/project/07-1-3-18_final_report.pdf
JFSP final report for project #07-1-3-12	2011	Shaw, N., Newingham, B., Ganguli, A.C., Hild, A.L., Cox, R.D., Truax, J., Pellant, M., and Pyke, D., 2011, Equipment and strategies to enhance the post-wildfire establishment and persistence of Great Basin native plants.	https://www.firescience.gov/projects/07-1-3-12/project/07-1-3-12_final_report.pdf
JFSP final report for project #05-S-08	2011	McIver, J.D., Barrett, H., Brunson, M., Bunting, S., Chambers, J., D’Antonio, C., Doescher, P., Johnson, D., Karl, S., Knick, S., Miller, R., Pellant, M., Pierson, F., Pyke, D., Rollins, K., Roundy, B., Schupp, G., Tausch, R., Turner, D., and Wisdom M., 2011, A regional experiment to evaluate effects of fire and fire surrogate treatments in the sagebrush biome.	https://www.firescience.gov/projects/05-S-08/project/05-S-08_final_report.pdf

Table 1. List of Federal and State reports and strategy documents reviewed to identify existing science needs.—Continued

Document	Year	Citation	URL
Identifying Science Priorities: 2013–2018 (Intermountain West Joint Venture)	2012	Intermountain West Joint Venture, 2012, Identifying Science Priorities: 2013–2018.	http://iwjv.org/resource/iwjv-identifying-science-priorities-2013-2018
National Fish, Wildlife, and Plants Climate Adaptation Strategy	2012	National Fish, Wildlife, and Plants Climate Adaptation Partnership, 2012, National Fish, Wildlife, and Plants Climate Adaptation Strategy, Association of Fish and Wildlife Agencies, Council on Environmental Quality, Great Lakes Indian Fish and Wildlife Commission, National Oceanic and Atmospheric Administration, and U.S. Fish and Wildlife Service. Washington, DC.	http://www.wildlifeadaptationstrategy.gov/
JFSP final report for project #08-1-5-20	2012	Bakker, J.D., Dunwiddie, P.W., Hall, S.A., Evans, J.R., Davies, G.M., and Dettweiler-Robinson, E., 2012, Vegetation impacts of recurring fires on sagebrush ecosystems in Washington: Implications for conservation and rehabilitation.	https://www.firescience.gov/projects/08-1-5-20/project/08-1-5-20_final_report.pdf
USGS Greater Sage-Grouse National Research Strategy	2013	Hanser, S.E., and Manier, D.J., 2013, Greater Sage-Grouse National Research Strategy: U.S. Geological Survey Scientific Investigations Report 2013–5167, 46 p.	http://pubs.usgs.gov/sir/2013/5167/
WAFWA Wildfire and Invasive Species in the West: Challenges that Hinder Current Future Management and Protection of the Sagebrush-Steppe Ecosystem—A Gap Report	2013	Mayer, K.E., Anderson, P., Chambers, J., Boyd, C., Christiansen, T., Davis, D., Espinosa, S., Havlina, D., Ielmini, M., Kemner, D., and Kurth, L., 2013, Wildfire and invasive species in the west: challenges that hinder current and future management and protection of the sagebrush-steppe ecosystem: a Gap Report. Western Association of Fish and Wildlife Agencies. Unpublished Report. Cheyenne, Wyoming.	http://www.wafwa.org/Documents%20and%20Settings/37/Site%20Documents/Initiatives/Sage%20Grouse/Wildfire-Invasive-WG-Final-Gap-Analysis-Report-Final.pdf
Nevada Wildlife Action Plan (Nevada Department of Wildlife)	2013	Wildlife Action Plan Team, 2012, Nevada Wildlife Action Plan. Nevada Department of Wildlife, Reno.	http://www.ndow.org/Nevada_Wildlife/Conservation/Nevada_Wildlife_Action_Plan/
Forest Service National Strategic Framework for Invasive Species Management 2013–2018	2013	Framework Development Team, 2013, Forest Service National Strategic Framework for Invasive Species Management 2013–2018. Forest Service Report 1017. Washington, D.C.	http://www.fs.fed.us/foresthealth/management/fhm-invasives.shtml
JFSP final report for project #09-1-08-4	2013	Fleishman, E., Chambers, J., Dobkin, D., and Dickson, B., 2013, Decision support tools for conserving Greater-Sage Grouse during fire and fuels management in pinyon and juniper woodlands. JFSP Final report #09-1-08-4	https://www.firescience.gov/projects/09-1-08-4/project/09-1-08-4_final_report.pdf
JFSP final report for project #09-S-02-1	2013	Pyke, D.A., Pilliod, D.S., Chambers, J.C., Brooks, M.L., and Grace, J., 2013, Fire rehabilitation effectiveness: A chronosequence approach for the Great Basin.	https://www.firescience.gov/projects/09-S-02-1/project/09-S-02-1_final_report.pdf

Table 1. List of Federal and State reports and strategy documents reviewed to identify existing science needs.—Continued

Document	Year	Citation	URL
JFSP Fuel Treatment Science Plan	2014	Zimmerman, T., Lasko, R., and Kaufmann, M., 2014, Fuel Treatment Science Plan. Joint Fire Science Program. Boise, ID.	http://www.firescience.gov/documents/fuels/FTSP_093014_v3.pdf
WAFWA Fire and Fuels Management Contributions to Sage-Grouse Conservation	2014	Havlina, D.W., Anderson, P., Kurth, L., Mayer, K.E., Chambers, J.C., Boyd, C., Christiansen, T., Davis, D., Espinosa, S., Ielmini, M., Kemner, D., Maestas, J.D., Mealor, B., Pellant, M., Tague, J., and Vernon, J., 2015, Fire and Fuels Management Contributions to Sage-Grouse Conservation: A Status Report: Unpublished Report, Western Association of Fish and Wildlife Agencies, Cheyenne, Wyoming, 73 p.	http://www.nifc.gov/fireandsagegrouse/docs/WAFWA_FireReport_v1.01.pdf
WAFWA Invasive Plant Management and Greater Sage-Grouse Conservation Report	2015	Ielmini, M., Hopkins, T., Mayer, K.E., Goodwin, K., Boyd, C., Mealor, B., Pellant, M., and Christensen, T., 2015, Invasive plant management and greater sage-grouse conservation: a review and status report with strategic recommendations for improvement: Unpublished Report, Western Association of Fish and Wildlife Agencies, Cheyenne, Wyoming, 47 p.	http://www.wafwa.org/Documents%20and%20Settings/37/Site%20Documents/Initiatives/Sage%20Grouse/WAFWA%20Invasive%20Plant%20Management%20and%20Greater%20Sage-Grouse%20Report%20FINAL%203-28-15.pdf
BLM/USGS sagebrush restoration/rehabilitation research needs workshop	2015	Unpublished workshop report.	None
Advancing Science in the BLM: An Implementation Strategy	2015	Kitchell, K., Cohn, S., Falise, R., Hadley, H., Herder, M., Libby, K., Muller, K., Murphy, T., Preston, M., Rugwell, M.J., and Schlanger, S., 2015, Advancing Science in the BLM: An Implementation Strategy. Department of the Interior, Bureau of Land Management, Washington, DC.	http://www.blm.gov/style/medialib/blm/wo/blm_library/BLM_pubs.Par.38337.File.dat/BLMAdvSciImpStratFINAL032515.pdf
National Seed Strategy for Rehabilitation and Restoration 2015–2020	2015	Plant Conservation Alliance, 2015, National Seed Strategy for Rehabilitation and Restoration 2015–2020, accessed September 25, 2015. U.S. Department of the Interior, Bureau of Land Management, Washington, DC.	http://www.blm.gov/style/medialib/blm/wo/Planning_and_Renewable_Resources/fish_wildlife_and/plants/seedstrategy.Par.66250.File.dat/SeedStrategy081215.pdf
Sage-Grouse Habitat Assessment Framework: A Multiscale Assessment Tool	2015	Stiver, S., Rinkes, E.T., Naugle, D., Makela, P., Nance, D., and Karl, J., 2015. Sage-grouse habitat assessment framework: multi-scale habitat assessment tool. Bureau of Land Management and Western Association of Fish and Wildlife Agencies Technical Reference 6710-1. Bureau of Land Management and Western Association of Fish and Wildlife Agencies, Denver, Colorado.	http://www.blm.gov/style/medialib/blm/wo/blm_library/tech_refs.Par.34086.File.dat/TR_6710-01.pdf

Table 1. List of Federal and State reports and strategy documents reviewed to identify existing science needs.—Continued

Document	Year	Citation	URL
Great Basin LCC Science and Traditional Ecological Knowledge Strategic Plan	2015	Great Basin LCC Science and Traditional Ecological Knowledge Strategic Plan. 2015	https://greatbasinlcc.blob.core.windows.net/media/Default/Priorities/2015_0624_GBLCC_S-TEK_Plan_FINAL.PDF
Central Basin and Range Rapid Ecoregional Assessment	2015	Comer, P., Crist, P., Reid, M., Hak, J., Hamilton, H., Braun, D., Kittel, G., Varley, I., Unnasch, B., Auer, S., Creutzburg, M., Theobald, D., and Kutner, L., 2013, Central Basin and Range Rapid Ecoregional Assessment Report. Prepared for the U.S. Department of the Interior, Bureau of Land Management. 168 p. + Appendixes	http://www.blm.gov/wo/st/en/prog/more/Landscape_Approach/reas/cbasinrange.html
Northern Basin and Range Rapid Ecoregional Assessment	2015	Science Applications International Corporation, 2013, Northern Great Basin Rapid Ecoregional Assessment, Prepared for the U.S. Bureau of Land Management. 135 p. + Appendixes	http://www.blm.gov/wo/st/en/prog/more/Landscape_Approach/reas/nbasinrange.html
USFS Sage-Grouse Conservation Science Strategy	2015	Finch, D., Boyce, D., Chambers, J., Colt, C., McCarthy, C., Kitchen, S., Richardson, B., Rowland, M., Rumble, M., Schwartz, M., and Tomosy, M., 2015, USDA Forest Service Sage-Grouse Conservation Science Strategy, 2015–2020. USDA Forest Service. Washington, DC.	http://www.fs.fed.us/research/docs/wildlife-fish/sage-grouse-conservation-strategy.pdf
Utah Wildlife Action Plan	2015	Utah Wildlife Action Plan Joint Team, 2015, Utah Wildlife Action Plan: A plan for managing native wildlife species and their habitats to help prevent listing under the Endangered Species Act. Publication number 15–14. Utah Division of Wildlife Resources, Salt Lake City, Utah, USA.	http://wildlife.utah.gov/learn-more/wap2015.html
Conservation and Restoration of Sagebrush Ecosystems and Sage-Grouse: An Assessment of USDA Forest Service Science	2016	Finch, Deborah M.; Boyce, Douglas A., Jr.; Chambers, Jeanne C.; Colt, Chris J.; Dumroese, R. Kasten; Kitchen, Stanley G.; McCarthy, Clinton; Meyer, Susan E.; Richardson, Bryce A.; Rowland, Mary M.; Rumble, Mark A.; Schwartz, Michael K.; Tomosy, Monica S.; and Wisdom, Michael J., 2016, Conservation and restoration of sagebrush ecosystems and sage-grouse: An assessment of USDA Forest Service Science. Gen. Tech. Rep. RMRS-GTR-348. Fort Collins, CO; U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, 54 p.	http://www.fs.fed.us/rm/pubs/rmrs_gr348.pdf?

Table 2. Complete list of science needs organized by topic: Fire; Invasives; Restoration; Sagebrush and Sage-Grouse; and Climate and Weather. The list was prioritized in open sessions during which a large group of managers and researchers provided input. High-priority science needs are those that were selected by more than 20 percent of participants during these sessions and also were selected in follow-up prioritization. Moderate-priority science needs were those remaining that were selected by more than 10 percent of participants. Low-priority science needs are those that remained.

Topic	Rank	Need
Fire	High	<p>Develop and assess novel management approaches for breaking the connection between cheatgrass and higher frequency fire regime that may permit the continued persistence of species that are vulnerable to more frequent fires.</p> <p>Determine the relationship between fire and the sagebrush ecosystem, including fire-return intervals, post-fire recovery, fire behaviors, fuel accumulation, ignition sources, frequency of ignition events, and patterns of variation in all of these factors among regions to help inform habitat management and conservation.</p> <p>Assess changes in greater sage-grouse demographic rates, including (i) survival, reproductive success, and movement patterns in response to burned areas and (ii) the interactive effects of fire or treatment size and timing on the response of sage-grouse individuals and populations.</p> <p>Develop spatial risk analysis relative to conservation of greater sage-grouse habitat through mapped projections of fire probability to develop strategic approaches and aid in targeting of pre-suppression and suppression efforts.</p> <p>Determine the community and species-specific responses to fuels management treatments (e.g., conifer removal) in both a short- and long-term context.</p> <p>Assess the effects of fuel treatments, installation of fire breaks, and similar manipulation of fuels and (or) landscape patterns intended to reduce wildfire spread and burn intensities on greater sage-grouse habitat use, movement patterns, and population trends to help minimize the potential detrimental effects of fire-risk-reduction measures to the species.</p> <p>Assess the long-term effects of sagebrush reduction treatments on hydrology, geochemical cycling, vegetation, wildlife (e.g., greater sage-grouse), fuels, fire behavior, and economics.</p> <p>Conduct analysis of wildfire suppression activities to determine their effects on sage-grouse habitat quality and identify potential mechanisms to minimize detrimental effects.</p> <p>Assess the role of fire in maintaining healthy sagebrush communities by identifying the balance between loss of intact sagebrush and recovery of young sagebrush required for habitat maintenance for different regions, communities, and ecological types.</p> <p>Determine which fuel breaks have met the objective of preventing fire spread or fire severity, and determine the characteristics of those that are successful, including synthesis of the literature, critical evaluation of techniques and plant materials used in fire breaks (species, structure, placement, and native versus nonnative species), and economic tradeoffs.</p> <p>Develop models of shrub and grass fuels in the sagebrush shrub-steppe as a function of abiotic conditions, disturbance history, and plant community composition.</p>
Fire	Medium	<p>Assess fire history to understand effectiveness of pro-active fuels management techniques, including how pre-treatment condition and ecological site potential affect the outcomes of both small- and large-scale treatments.</p> <p>Determine the amount of high-quality, seasonally important sagebrush/sage-grouse habitat being lost annually to fire and the rates of success of sagebrush restoration efforts in terms of number of acres in various successional states.</p> <p>Develop improved techniques for measuring and characterizing the fuel load of shrublands and grasslands encroached by woody plants for long-term monitoring.</p>
Fire	Low	<p>Assess the response of rare and vulnerable species to implementation of wildfire, prescribed fire, and fire surrogates.</p> <p>Assess fire frequency, size, and distribution relative to landscape features and disturbance in the sagebrush biome.</p> <p>Improve landscape simulation models (e.g., data and parameterization) to inform risk-based approaches to fire management in sage-grouse habitat.</p>

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Topic	Rank	Need
Fire— Continued	Low	<p>Assess soil redistribution effects on ants, pollinators, and small mammals following wildfire and drill seeding and their influence on drill-seeding success.</p> <p>Determine how sage-grouse populations respond when large portions of seasonal habitat burn within a population boundary.</p> <p>Investigate the effectiveness of fuel treatments before fires occur (such as green-stripping) on burn-potentials and area burned to help inform future treatment implementation.</p> <p>Assess the net impacts of controlled grazing on wildfire management and ecosystem response to determine the differences in impact and contribution of different species of ungulates.</p> <p>Evaluate the effectiveness of grazing as a fuel treatment in shrubland and grassland vegetation types.</p> <p>Examine effects of mastication treatments on grass production, rearrangement of fuels, change in surface fuel structure and composition, and resultant effects on wildfire behavior.</p> <p>Study the ecological response of prescribed fire treatments in pinyon-juniper woodlands over long timeframes.</p>
Invasives	High	<p>Improve understanding of the natural and anthropogenic factors that influence invasive plant species distributions, including invasion history, surface disturbance, habitat condition, and fire history, and determine whether those factors can help identify tradeoffs among alternative management approaches.</p> <p>Implement long-term, ecosystem-based research to determine how to restore the function and structure of affected ecosystems, enhance endemic biological control agents, foster natural recovery, and improve the resiliency of ecosystems to unexpected future threats.</p> <p>Improve measures for prevention, eradication, and control of invasive plant species, and use risk assessments to weigh potential benefits and deleterious effects of different measures on native plant species.</p> <p>Conduct invasive plant inventory, including spatial data on infestations and current range maps, to improve the ability for managers to prioritize actions to prevent and control nonnative plant populations before they become established and spread.</p> <p>Assess effectiveness of targeted grazing with livestock to reduce nonnative annual grasses and understand the impact on native plants in the sagebrush ecosystem.</p> <p>Conduct detailed optimization studies on production and delivery systems of biocontrol agents, followed by evaluation in scaled-up field inoculation trials.</p> <p>Investigate cheatgrass die-off and potential biocontrols for cheatgrass to provide effective tools for site preparation.</p>
Invasives	Medium	<p>Determine the interactions of current or altered biotic and abiotic factors on the establishment, spread, and effects of invasive species over time and space.</p> <p>Develop increased capacity to recognize and identify species and variants of current and future invasive pathogens, hosts, microorganisms, and vectors through the use of classical and molecular taxonomy, fungal and plant systematics, and molecular diagnostic tools.</p> <p>Examine environmental and genetic factors that contribute to variation in virulence expression of the biocontrol properties among and within strains.</p> <p>Assess the influence of livestock and feral horse grazing on invasive annual grasses and its influence on fire behavior and spread patterns at landscape scales.</p> <p>Develop new prediction and ecological risk assessment tools and conduct risk assessments for priority invasive species and habitats.</p>

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Topic	Rank	Need
Invasives	Low	<p>Assess the biocontrol effectiveness of agents and improve traits using traditional methods and modern techniques, including marker-assisted selection.</p> <p>Assess costs of invasive species to society through integrated economic and social science research.</p> <p>Identify ecological processes and services affected by invasive weeds and prioritize control based on the potential for range degradation.</p> <p>Conduct research on geographic variation of invasive species to increase the understanding of the spread of these species after they are established.</p> <p>Develop a synthesis of existing research and conduct new research to increase resilience and resistance of sagebrush stands with an understory of invasive annuals.</p> <p>Assess the role of interspace plant species to survive fire and reduce fine-fuel loads (i.e., cheatgrass).</p>
Restoration	High	<p>Develop methods for “jumpstarting” growth and recovery of sagebrush and native grasses and forbs to encourage rapid re-establishment of sagebrush and enable re-colonization by sage-grouse as soon as possible to help offset effects of wildfire and help mitigate potential effects of future fires.</p> <p>Develop and improve seeding methods, seed mixes, and equipment used for post-fire rehabilitation or habitat restoration to improve native plant (especially sagebrush) reestablishment.</p> <p>Determine the criteria and thresholds that indicate restoration and rehabilitation success or failure across the range of environmental conditions that characterize sage-grouse habitat. Develop decision support tools that define success or failure and the need for follow-up actions.</p> <p>Develop new techniques needed to restore invaded landscapes to functioning sage-grouse habitat and minimize the risk of reinfestation after treatment.</p> <p>Complete a generalized seed-zone map and determine (1) if it is more effective to develop seed-transfer zones by species or subspecies, (2) which climate parameters are most useful in developing transfer zones, (3) thresholds in climate adaptations, and (4) effects of using seed collected throughout a specified transfer zone versus seed collected from the local area to restore sagebrush habitats. Also demonstrate that actual planting success is improved for a given seed-transfer specification.</p> <p>Conduct retrospective studies of selected native plant restoration projects to evaluate short- and long-term responses of plant communities to these treatments and to biotic and abiotic conditions.</p> <p>Develop site preparation and seeding and transplanting strategies that improve plant establishment and community diversity.</p> <p>Assess the long-term effects of conifer removal treatments on hydrology, geochemical cycling, vegetation, wildlife, fuels, fire behavior, and economics.</p> <p>Evaluate the effectiveness of various rehabilitation or restoration activities in sage-grouse habitat to help determine if offsite mitigation is a viable option, because if restoration of sites to conditions useful for sage-grouse is not possible (for near-term benefits), then mitigation procedures might warrant reevaluation.</p> <p>Develop decision-support tools to assist in planning and implementing conifer removal treatments that will maximize maintenance of sagebrush systems, greater sage-grouse, and other sensitive species.</p> <p>Assess soil degradation and develop treatments, soil amendments, and other site-preparation techniques that enhance germination, establishment, and development of healthy sagebrush communities capable of resisting invasion by nonnative plant species.</p>

Table 2. Complete list of science needs organized by topic: Fire; Invasives; Restoration; Sagebrush and Sage-Grouse; and Climate and Weather. The list was prioritized in open sessions during which a large group of managers and researchers provided input. High-priority science needs are those that were selected by more than 20 percent of participants during these sessions and also were selected in follow-up prioritization. Moderate-priority science needs were those remaining that were selected by more than 10 percent of participants. Low-priority science needs are those that remained.—Continued

Topic	Rank	Need
Restoration	Medium	<p>Determine the appropriate timeframe for removal or reduction of livestock grazing to promote ecosystem recovery and reduce cheatgrass invasion risk after wildfire and rehabilitation/restoration treatments. Assessments should provide information in relation to aspect, precipitation, and elevation gradients.</p> <p>Determine the appropriate size and location of conifer treatments, characteristics of the pre-treatment target community, effective removal methods that reduce the immediate negative effects of treatment, and the timeframe for reuse by sage-grouse populations following treatment.</p> <p>Develop methods and techniques for increasing seed and native plant material availability with each ecoregion.</p> <p>Refine propagation (e.g., seedlings and transplants) techniques for increased plant materials development.</p> <p>Identify inter- and intraspecific variation in seed characteristics and plant functional traits that may enhance germination, emergence, and establishment under stressful biotic and abiotic conditions.</p> <p>Determine the cover percentages of native perennial herbaceous plants that provide for natural site recovery without emergency stabilization and rehabilitation seeding and how these differ over temperature/precipitation gradients.</p> <p>Determine best deployment of native plants on the landscape, including appropriate species and subspecies, plant spacing, and patch configuration.</p> <p>Develop new practices or improve existing practices to reduce or eliminate the spread of invasive species and to restore sagebrush that is affected by invasive plant species.</p> <p>Evaluate the effectiveness of current management guidelines and practices and identify new alternatives to improve habitat conditions using sage-grouse population responses.</p> <p>Evaluate the effects of historical and modern habitat treatments on current habitat conditions, use by sage-grouse, or value to sage-grouse to help adapt management practices and refine treatment techniques.</p> <p>Develop and deploy techniques to diversify species composition in monoculture or near monoculture stands of seeded nonnative plants (e.g., crested wheatgrass).</p> <p>Increase understanding of the effects of seed mixtures (native, introduced; life form, etc.) and spatial patterns of seeding on community development and biological diversity.</p> <p>Develop and improve state-transition models to inform future decisionmaking processes.</p> <p>Investigate effectiveness of habitat rehabilitation techniques following large fires to help inform efforts to reduce threats of long-term conversion to nonnative grasslands and improve success of rehabilitation efforts.</p> <p>Assess the role of post-fire soil conditions in influencing the success of native seed treatments.</p> <p>Develop multi-scale assessment of treatment distributions in relation to sage-grouse habitat use patterns, population dynamics, and landscape connectivity. Build upon previous work (Wisdom et al., 2005b; Meinke et al., 2009) to further the understanding of correct spatial distribution and prioritization of treatments.</p> <p>Test the effectiveness of new technologies for successfully revegetating damaged areas using native seedling and plant materials.</p> <p>Assess species and seeding practices necessary to prevent reoccurrence of undesirable species, including consideration of the effects of variability in species viability and differences between seed sources among regions on restoration success.</p> <p>Within seed zones, investigate the capacity of native plant materials to establish and persist with invasive species, while maintaining plant diversity/function.</p>

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Topic	Rank	Need
Restoration— Continued	Medium	<p>Determine restoration-suitable culturally significant plant properties appropriate for different management objectives (e.g., fire-tolerance for fuel breaks, invasive competitive ability, etc.).</p> <p>Develop an analytical process that looks at the cost/success tradeoff of applying seed versus transplanting live seedlings (mainly for shrubs and forbs).</p> <p>Investigate the influence of planting different sagebrush subspecies on establishment success and the impact of big sagebrush subspecies palatability on use of habitat by sage-grouse and other sagebrush-associated species.</p>
Restoration	Low	<p>Conduct a cost-benefit assessment of conifer treatments in different regions, successional stages, and environmental conditions to help determine the long-term efficacy of these management actions.</p> <p>Determine effective techniques for restoration of perennial herbaceous understory in areas following conifer removal.</p> <p>Determine cultural significance of, and values produced by, conifer communities and sagebrush communities to Great Basin tribes.</p> <p>Examine how the degree of tree encroachment changes emergency stabilization and rehabilitation seeding success relationships.</p> <p>Evaluate effectiveness of emergency stabilization and rehabilitation seeding projects in areas that have burned once versus those with varying numbers of fires.</p> <p>Develop a tool for assessing suitability of burned areas for re-establishment of native communities and determination of appropriate seeding equipment and methods.</p> <p>Determine the effects of livestock grazing on long-term effectiveness of post-wildfire rehabilitation efforts.</p> <p>Determine the effect of modern grazing on the long-term resilience and resistance of the sagebrush plant community, including species being grazed, intensity, season of use, etc.</p> <p>Develop and test the effectiveness of techniques used to diversify the understory species composition and age classes of sagebrush stands.</p> <p>Examine seed placement and movement within the soil profile over time due to soil wetting and drying.</p> <p>Examine seedling emergence for species commonly used in wildland rehabilitation in the face of soil chemical or physical crusts.</p> <p>Investigate and improve effectiveness of restoration practices through identification of traditional practices and associated ecological understanding.</p> <p>Determine where lands are most effectively conserved (e.g., Conservation Reserve Program) to benefit sage-grouse; the appropriate size, configuration, connectivity, and juxtaposition of these set-aside lands; and the effectiveness of various habitat modifications on set-aside lands.</p> <p>Evaluate the attainability of the management recommendations and their effectiveness for maintaining sage-grouse populations. This includes a critical evaluation of the proposed optimal ratio of 70 to 30 percent, mature to early-phase, sagebrush communities both for its effectiveness for sage-grouse conservation and the attainability.</p> <p>Determine the relative importance of improved connectivity of habitats or subpopulations versus increased habitat area.</p> <p>Evaluate multi-scale effects of land management treatments on sage-grouse and sagebrush ecosystems.</p> <p>Develop methods to classify land-cover types and landscape features according to their potential for restoration or reconstruction.</p> <p>Develop a stand treatment prioritization process in sagebrush habitats that weighs the degree of invasiveness of a stand against its relative habitat value.</p>

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Topic	Rank	Need
Restoration— Continued	Low	<p>Investigate the relationship between resistance to invasion, sagebrush ecosystem health, and the occurrence of biological soil crusts.</p> <p>Examine efficacy of recommended mitigation to help avoid, minimize, or reduce the effects of surface-disturbing activities onsite, or replace or enhance suitable habitat offsite.</p> <p>Develop and validate a drill-seeding risk assessment framework based on soil chemical and physical properties to improve seeding efficacy and reduce detrimental effects of seeding activities.</p> <p>Determine whether or not native annuals provide benefits in post-fire seeding across a broad range of sites.</p> <p>Investigate modifications of seeding equipment to provide increased flexibility in creating appropriate microsite conditions for an array of native plant species.</p> <p>Test the effectiveness of new technologies, including soil pathogens, to counter cheatgrass.</p> <p>Develop an understanding of how to prevent the establishment of invasive plant species in areas where soils have been disturbed and distinguish between disturbance types.</p> <p>Advance investigations to diversify depleted native communities to improve structure and function and to replace nonnative monocultures with native communities.</p> <p>Investigate the effects of post-drilling soil movement on seedbed properties.</p> <p>Evaluate effectiveness of minimum-tillage techniques that reduce disruption of soil aggregates and physical soil crusting.</p> <p>Determine optimal seeding strategies to maximize success and minimize risk when seed is a limiting factor.</p> <p>Develop new techniques to improve field identification of big sagebrush subspecies to improve restoration practices using the right seed sources.</p> <p>Develop techniques for restoration of sagebrush communities at the periphery of current sage-grouse range, including plant communities at the current climate envelope for sagebrush.</p> <p>Evaluate potential pathways and transitions between ecosystem and habitat conditions to inform the potential for natural recovery of a system following disturbance, potentially negating the need for restoration or mitigation.</p> <p>Conduct genetic research to develop seed zones for key restoration species.</p> <p>Conduct seed germination studies and develop seed testing protocols for key restoration species.</p> <p>Develop species-specific protocols for seed and seedling production practices that maintain genetic diversity.</p> <p>Develop storage guidelines for restoration species to improve maintenance of seed viability.</p> <p>Compile a database of revegetation species' characteristics pertinent to germination, establishment, functional traits, and life cycles that will aid in selection of materials for development of native seed mixes.</p> <p>Identify restoration-suitable culturally significant (RSCS) plant species for restoration and propagation.</p> <p>Develop propagation protocols for restoration-suitable culturally significant plant species to enhance seeding quality, installation and treatment success.</p> <p>Determine appropriate stock types of restoration-suitable culturally significant plants to mitigate post-planting conditions and limiting factors (including drought, cold, herbivory, and soils).</p> <p>Determine if optimal seeding rates, mixtures, and methods exist for establishing both native and non-native perennial plants in areas where inadequate perennial herbaceous species exist for site recovery.</p> <p>Quantify major short- and long-term ecological and economic costs and benefits of planting native or nonnative plants on public lands (e.g., value to pollinators, biodiversity, and ecosystem functions).</p>

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Topic	Rank	Need
Restoration— Continued	Low	<p>Examine inter- and intra-specific competition among restoration species and between restoration species and exotic weeds to aid in developing more effective seed mixes and strategies.</p> <p>Determine optimal seed mixtures appropriate for the soils, climate, and landform of an area.</p> <p>Investigate how crested wheatgrass or forage kochia dominated seeding affect fuels and fire behavior and wildlife (e.g., sage-grouse, pollinators) use. Determine if there are differences in fuels and fire behavior and wildlife use between seedings dominated by introduced vs native species. Determine the potential for transitioning from alternative plant sources to native species.</p> <p>Determine the ratio of plants killed by fire and density of surviving plants that should trigger re-seeding (by site potential [Ecological Site], vegetation community/condition, and precipitation).</p> <p>Evaluate the influence of sagebrush plant chemistry on sage-grouse habitat use to improve selection of plant species for restoration.</p>
Sagebrush and sage- grouse	High	<p>Investigate sage-grouse movement patterns, the habitat characteristics that are conducive, restrictive, or preventive to those movements, and the genetic structure of populations to help inform management practices to improve or maintain connections.</p> <p>Conduct a series of large-scale, replicated grazing studies that address how different livestock species, grazing systems, disturbance histories, and other environmental conditions affect sage-grouse habitat.</p> <p>Identify thresholds beyond which effects on sage-grouse behavior, population response(s), or habitat use are minimized relative to different types of disturbances and related activities, for example, effects of wildfire, energy development, and other surface-disturbing activities.</p> <p>Develop next-generation mapping techniques to provide regular interval updates and continue to enhance grassland and shrubland vegetation mapping (e.g., every 2–5 years).</p> <p>Develop spatially explicit sage-grouse population models that incorporate biological processes and habitat dynamics and investigate scenarios that reflect local management possibilities (options, opportunities, and obstacles).</p> <p>Identify seasonal habitats for sage-grouse across their entire range.</p> <p>Develop sagebrush ecosystem-wide models identifying conditions necessary to support sagebrush-associated species, other than sage-grouse, using an individual species approach or species groups when necessary.</p> <p>Develop thresholds for the extent and magnitude of a threat (e.g., cover of pinyon and juniper, density of oil and gas wells, road density, etc.) above which the habitat can no longer support sagebrush-obligate species.</p> <p>Conduct long-term monitoring to assess development of community structure, community function, and dynamics in native seedings, as well as suitability of resulting communities in meeting specific management goals, such as sage-grouse habitat restoration.</p>
Sagebrush and sage- grouse	Medium	<p>Conduct long-term research and monitoring to examine the response of forbs and native plant diversity to grazing to address grazing effects on sage-grouse and the effectiveness of habitat guidelines in the context of current grazing practices.</p> <p>Establish experimental sites that will be continually monitored to obtain long-term data on restoration and fuel treatment effectiveness.</p> <p>Test of the ability of restored habitats to support sage-grouse population connectivity through dispersal and migration.</p> <p>Develop high-resolution, landscape-scale, seasonal habitat models for sage-grouse that incorporate physical and chemical attributes of sagebrush and understory characteristics.</p> <p>Determine the best methods for surveying leks and (or) best methods for use in Before-After-Control-Impact (BACI) designs to assess development impacts on sage-grouse.</p>

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Topic	Rank	Need
Sagebrush and sage-grouse— Continued	Medium	<p>Assess the condition and configuration of habitat patches within priority habitat management areas relative to habitats outside the priority areas.</p> <p>Determine best indicators that indicate resistance and resilience to invasive annuals by using models and large-scale experiments to evaluate relationships between resistance to invasion and associated environmental and biological characteristics of sagebrush ecosystems over the environmental gradients that characterize sagebrush ecosystems. Examples include cover of perennial herbaceous species needed to facilitate recovery and resist invaders, soil characteristics that are not conducive to invaders, climate limitations of invaders, etc.</p> <p>Assess the links between infrastructure, predator population size, and subsequent changes in predation rates on sage-grouse to inform management and mitigation strategies.</p>
Sagebrush and sage-grouse	Low	<p>Develop spatially explicit maps of rangeland condition as established in the rangeland health standards and guidelines to help understand impact on sagebrush vegetation and sage-grouse habitat.</p> <p>Develop monitoring and assessment protocols for post-fire monitoring of soil stability, and early detection of sagebrush recovery within ESR Project periods.</p> <p>Evaluate the effectiveness of the Habitat Assessment Framework to adequately assess habitat conditions across sagebrush landscapes and document changes in those conditions through time.</p> <p>Determine how migratory movement patterns vary by sex, age, region, habitat, landscape, and weather to implement actions to address or avert problems with population connectivity.</p> <p>Identification of greater sage-grouse seasonal movement pathways and habitat characteristics across their entire range.</p>
Climate and weather	High	<p>Improve understanding of the complex set of variables that controls seeding success and improve accuracy of predictive meteorological data and models to identify years when the potential for seeding success is high or low.</p> <p>Study the propagation and production of native plant materials to identify species or genotypes that may be resilient to climate change.</p> <p>Identify areas for seed collection across elevational and latitudinal ranges of target species to protect and maintain high-quality sources for native seeds.</p> <p>Develop predictive models of climate change effects, targeting restoration species, including regionally suitable culturally significant species, and genetic diversity using 20-year or mid-century climate models.</p>
Climate and weather	Low	<p>Develop protocols for use of propagation techniques to rebuild abundance and genetic diversity for particularly at-risk plant and animal species in the face of climate change.</p> <p>Conduct a study on the influence of climate patterns on resiliency of soil crusts and links to resilience of sagebrush ecosystems, particularly in light of invasives.</p>

Table 3. List of agencies and organizations provided opportunity to review the Plan.

Agency or organization
Bureau of Land Management
Department of the Interior
Integrated Rangeland Fire Management Strategy Action Item Teams
Office of Wildland Fire
U.S. Fish and Wildlife Service
U.S. Geological Survey
USDA Agricultural Research Service
USDA Forest Service
USDA Natural Resources Conservation Service
Western Association of Fish and Wildlife Agencies (WAFWA) Rangeland Interagency Sagebrush Conservation Team
WAFWA Sagebrush Executive Oversight Committee
WAFWA Sagebrush Science Strategy Team

