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Integrated Rangeland Fire Management Strategy Actionable Science Plan Completion Assessment: Restoration Topic, 2015–20

Open-File Report 2023–1004

U.S. Department of the Interior
U.S. Geological Survey

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By Christopher R. Anthony, Matthew J. Holloran, Mark A. Ricca, Steven E. Hanser, Sue L. Phillips, Paul F. Steblein, and Lief A. Wiechman

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Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
	Length	
mile (mi)	1.609	kilometer (km)
	Area	
acre	4,047	square meter (m^2)
acre	0.4047	hectare (ha)
acre	0.4047	square hectometer (hm^2)

International System of Units to U.S. customary units

Multiply	By	To obtain
	Length	
kilometer (km)	0.6214	mile (mi)
	Area	
square meter (m^2)	0.0002471	acre
hectare (ha)	2.471	acre
square hectometer (hm^2)	2.471	acre

Abbreviations

BLM	Bureau of Land Management
DOI	U.S. Department of the Interior
IRFMS	Integrated Rangeland Fire Management Strategy
MZ	WAFWA Sage-grouse Management Zone
OFR	Open-File Report
USGS	U.S. Geological Survey
WAFWA	Western Association of Fish and Wildlife Agencies

Species names

Basin big sagebrush	*Artemisia tridentata* spp. *tridentata*
Cheatgrass	*Bromus tectorum*
Crested wheatgrass	*Agropyron cristatum*
Greater sage-grouse	*Centrocercus urophasianus*
Mountain big sagebrush	*Artemisia tridentata* spp. *vaseyana*
Sagebrush	*Artemisia* spp.
Wyoming big sagebrush	*Artemisia tridentata* spp. *wyomingensis*

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Abstract

Loss and degradation of sagebrush rangelands due to an accelerated invasive annual grass-wildfire cycle and other stressors are substantial management, conservation, and economic issues in the western United States. These sagebrush rangelands comprise a unique biome spanning 11 states, support over 350 wildlife species, and provide important ecosystem services that include stabilizing the economies of western communities. Impacts to sagebrush ecosystem processes over large areas due to the annual grass-wildfire cycle necessitated the development of a coordinated, science-based strategy for improving efforts to achieve long-term protection, conservation, and restoration of sagebrush rangelands, which was framed in 2015 under the Integrated Rangeland Fire Management Strategy (IRFMS). Central to this effort was the development of an Actionable Science Plan (Plan) that identified 37 priority science needs (Needs) for informing the actions proposed under the 5 topics (Fire, Invasives, Restoration, Sagebrush and Sage-Grouse, Climate and Weather) that were part of the collective focus of the IRFMS. Notable keys to this effort were identification of the Needs co-produced by managers and researchers, and a focus on resulting science being “actionable.”

Substantial investments aimed at fulfilling the Needs identified in the Plan have been made since its release in 2016. While the state of the science has advanced considerably, the extent to which knowledge gaps remain relative to identified Needs is relatively unknown. Moreover, new Needs have likely emerged since the original strategy as results from actionable science reveal new questions, and possible (yet untested) solutions. A quantifiable assessment of the progress made on the original science Needs can identify unresolved gaps and new information that can help inform prioritization of future research efforts.

This report details a systematic literature review that evaluated how well peer-reviewed journal articles and formal technical reports published between January 1, 2015, and December 31, 2020, addressed 10 needs (hereinafter “Needs”) identified under the Restoration topic in the Plan. The topic outlined research Needs for improving restoration success in degraded sagebrush rangelands. We established the level of progress towards addressing each Need following a standardized set of criteria, and developed summaries detailing how research objectives nested within Needs identified in the Plan (“Next Steps”) were either addressed well, partially addressed or remain outstanding (that is, addressed poorly) in the literature through 2020. Our searches resulted in the inclusion of 371 science products that at least partially addressed a Need identified in the Restoration topic. The Needs that were well and partially addressed included:

(1) the development of methods to improve seeding success of native plants after fire;

(2) evaluation of short- and long-term plant responses relative to biotic and abiotic factors following restoration treatments;

(3) assessments of long-term effects on ecosystem processes following conifer removal treatments and development of decision support tools to aid in conifer management;

(4) determination of the costs of restoration treatments relative to the benefits to sage-grouse occupancy, survival, and populations; and

(5) assessments of the factors which contribute to soil degradation and development of soil enhancement methods that enhance seed germination and seedling survival while resisting nonnative plants.

Needs that were not addressed well included:

(1) the development of methods for the rapid recovery of sagebrush and native herbaceous plants following wildfire and determination of whether treatments benefit sage-grouse and mitigate impacts from fires;

(2) determination of thresholds for successful restoration across a range of environmental conditions and development of decision support tools to assist with restoration effectiveness monitoring; and

(3) development and evaluation of the utility of seed transfer zones.

The information provided in this assessment will assist updating the Plan along with other science strategies.

Introduction

Stemming the cumulative loss and degradation of sagebrush (*Artemisia* spp.) rangelands that comprise a unique biome across western North America represents a challenge to land managers and applied researchers in the 21st century. Functioning and viable sagebrush rangelands not only support over 350 plant and animal species of conservation concern (Suring and others, 2005), these landscapes are also essential for agricultural and recreational industries and thereby play a vital role in stabilizing the economies of western communities. This is of particular importance given dramatic fluctuations resulting from the traditional dependence of these communities on energy development (Western Governors' Association, 2017; Bureau of Land Management [BLM], 2020). Approximately 55–60 percent of sagebrush rangelands of the western U.S. have been lost (direct conversion) or degraded (alteration of understory vegetation or fragmentation) since European settlement (Knick and others, 2003; Miller and others, 2011). Sagebrush rangelands are currently distributed across 160 million acres of 14 western states (Remington and others, 2021; fig. 1).

Arresting downward trends in sagebrush ecosystems is complex owing to multiple and often interacting stressors, including conversion to agricultural crops or non-native perennial grasses (for example, crested wheatgrass [*Agropyron cristatum*]), energy development, improper livestock grazing, expansion of native conifers, and other anthropogenic surface-disturbing activities (for example, roads, transmission lines, exurban development; Hanser and others, 2018; Shinneman, 2019; BLM, 2020). However, altered wildfire regimes driven largely by positive feedbacks from invasive annual grasses (Miller and Eddleman, 2001; Balch and others, 2013) are perhaps the most immediate and pervasive threat to sagebrush rangelands (U.S. Fish and Wildlife Service [USFWS], 2013; fig. 2). The proliferation of invasive annual grasses (for example, cheatgrass [*Bromus tectorum*]) and resulting increases in fire frequency and extent can ultimately result in long-term and often permanent loss of fire-intolerant species of sagebrush along with deep rooted bunchgrass and soil microbial communities that normally promote resilience to disturbance and resistance to invasion in sagebrush ecosystems (Chambers and others, 2014; Germino and others, 2016). The threat from the annual grass-wildfire cycle is greatest throughout western portions of the sagebrush biome (that is, Great Basin and Snake River Plain), where trends in proportion of larger fires and fire season length have increased since the mid-1980s and fire frequency has increased substantially compared to historic frequencies (Brooks and others, 2015). Over the next 20 years, median annual total area burned in western states supporting sagebrush is projected to increase (from a 1961–2004 baseline period; Kitzberger and others, 2017), suggesting that increasing trends in sagebrush rangelands fires are likely to continue.

The increasing frequency and impact of wildfires prompted the development of an enhanced strategy for addressing rangeland fire across sagebrush-dominated regions. A significant milestone in this effort was the drafting of the Integrated Rangeland Fire Management Strategy (hereinafter IRFMS; U.S. Department of the Interior [DOI], 2015) following the issuance of Secretarial Order 3336. The IRFMS outlined coordinated, science-based approaches for improving the efficiency and efficacy of actions to better prevent and suppress rangeland fire and to improve efforts to achieve long-term protection, conservation, and restoration of the sagebrush biome. Inherent in the IRFMS was the recognition that a strong science foundation was fundamental to successful rangeland fire prevention and suppression, and to management and restoration of sagebrush rangelands and wildlife populations reliant on those rangelands. Therefore, the IRFMS further called for the development of an Actionable Science Plan (hereinafter, Plan) that identified the priority science needed to inform another generation of management strategies and tools (Integrated Rangeland Fire Management Strategy Actionable Science Plan Team [IRFMS], 2016). Critical elements to the Plan's success were:

(1) the collaborative identification of knowledge gaps by managers and researchers which, when filled, would break down barriers to successful implementation of management actions; and

(2) a focus on the resultant priority science having "actionable" traits by:

(i) immediately filling knowledge gaps;

(ii) directly informing management action aimed at protecting, conserving, or restoring sagebrush ecosystems; and

(iii) facilitating funding mechanisms for effective research and communication of results to management audiences.

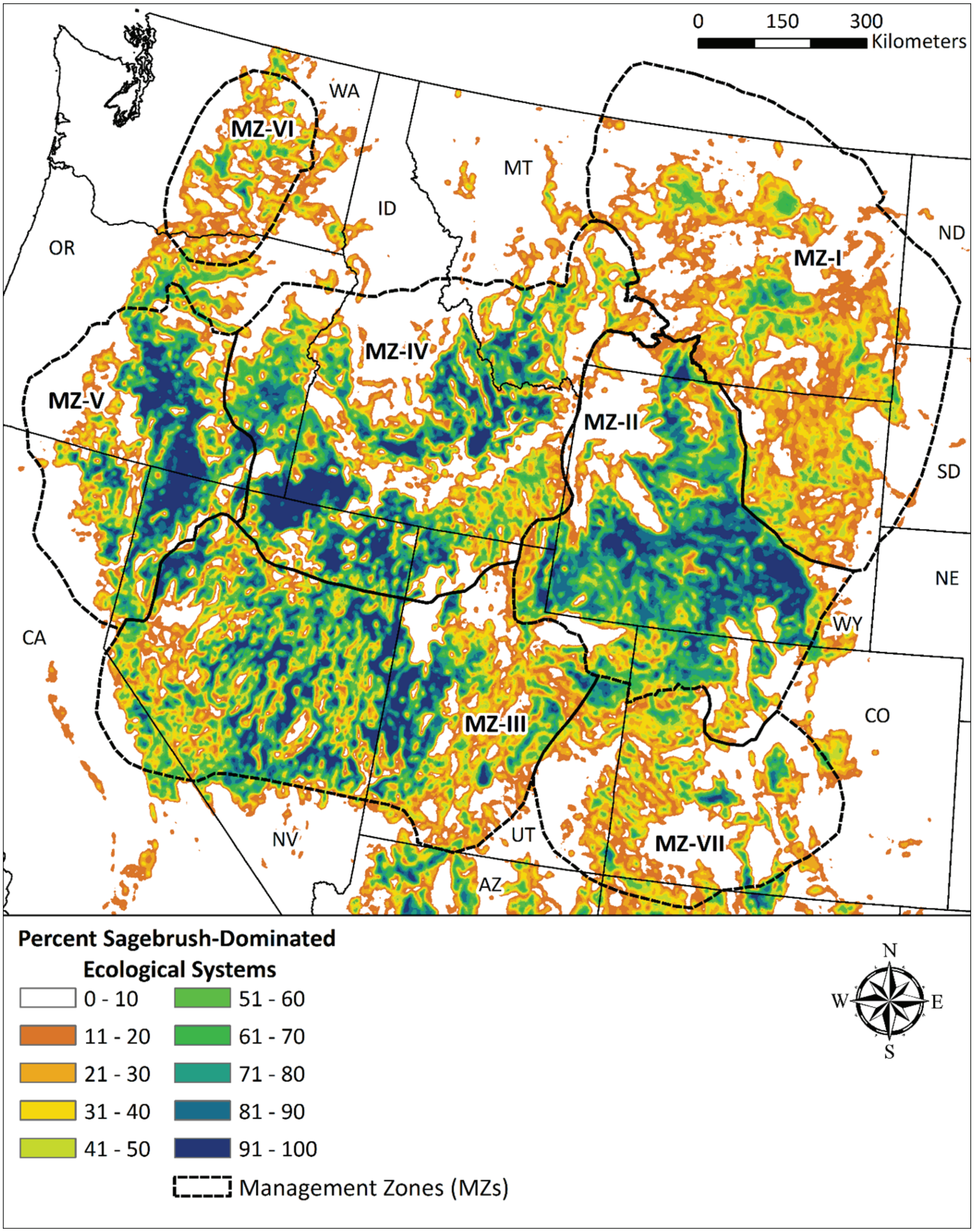

Figure 1. Map showing the landscape cover of sagebrush-dominated ecological systems in the western United States. Figure is taken from Chambers and others (2017, fig. 28).

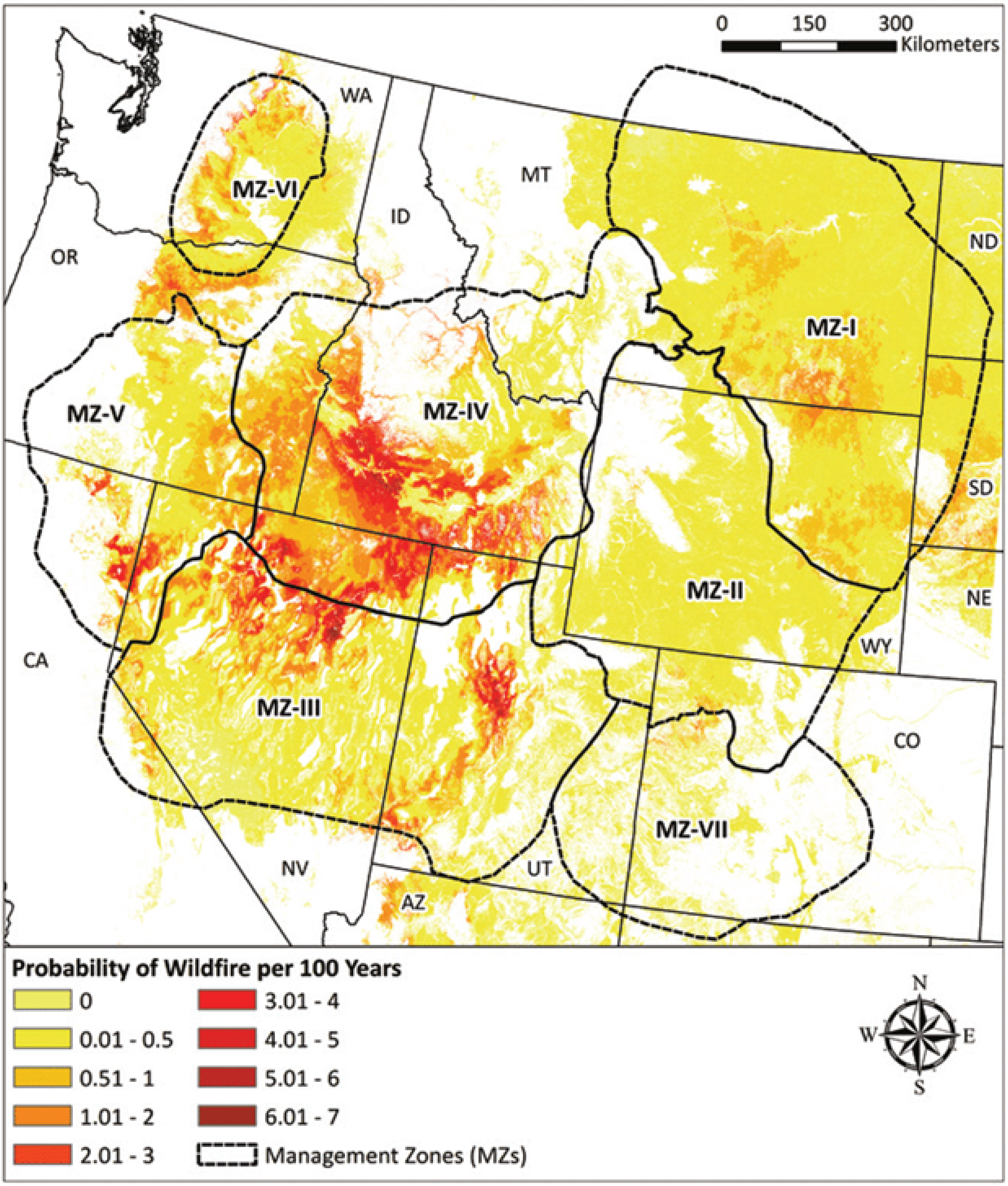

Figure 2. Large fire probability for the sagebrush biome in the western United States. Figure taken from Chambers and others (2017, fig. 34).

Accordingly, needed science was identified by considering planning and prioritization efforts conducted in the previous 5 years by Federal and State agencies. The resulting comprehensive list was prioritized with engagement of the broader research and management communities. The 37 highest-priority science needs (hereinafter, Needs) identified through these efforts were then organized under five topics outlined in the IRFMS: (1) Fire, (2) Invasives (plant species), (3) Restoration, (4) Sagebrush and Sage-Grouse, and (5) Climate and Weather. A multi-disciplinary team of experts developed narratives describing these highest-priority Needs and outlined a series of research objectives (hereinafter, Next Steps) to help guide the development of new knowledge, syntheses, and decision-support tools for addressing each Need.

Conservation strategies depend on the consideration and application of the best available science and ongoing efforts to address gaps in that scientific knowledge to achieve management success. While the state of the science has ostensibly advanced owing to substantial research investments since the Plan's release in 2016, the extent to which knowledge gaps remain relative to identified Needs is largely unknown. Several annotated bibliographies have made strides towards making results from research efforts in the sagebrush biome available and tractable for management audiences (for example, Carter and others, 2020; Poor and others, 2021). However, many knowledge gaps likely remain, and an assessment of progress made on achieving previously identified priorities is needed to help focus the next prioritization on unresolved gaps in the science and new science needs that have arisen since development of the original strategy. A quantifiable and targeted assessment of progress made towards meeting the original Needs under the Plan's five topics can help identify unresolved gaps and prioritize future actionable research efforts for new questions and possible (yet untested) solutions.

The Restoration topic in the Plan identified 10 Needs focused on maintaining sagebrush ecosystem integrity in the face of multiple threats. The priorities identified across the 10 Needs broadly encompassed:

(1) determination of biotic and abiotic factors that lead to successful restoration (short- and long-term) following disturbance, and develop decision support tools to assist adaptive management;

(2) improvement of restoration applications to offset negative effects of disturbances on sage-grouse and other sagebrush-obligate species; and

(3) evaluation of seed-transfer zones relative to changing climate and development of a strategic plan for integrating the appropriate seeds into restoration projects.

This report details a literature review that quantified how well peer-reviewed journal articles and formal technical reports published between January 1, 2015, and December 31, 2020, addressed 10 Needs identified under the Restoration topic in the Plan. Five years was considered an adequate time period for implementation of science projects that coincided with or were inspired by the Plan and, as such, a suitably defined interval for completing this assessment and updating priority science and management needs. Our objective was to comprehensively summarize the scientific literature generated since the release of the Plan. Leveraging advances in bibliographic search-engine tools, we developed a quantitative "scorecard" to assess progress towards addressing each Need following a standardized set of criteria. The scorecard informed summaries detailing how Next Steps were addressed in the literature as well as those that remain unresolved. The summaries are intended to provide information for stakeholder-driven efforts aimed at identifying the next set of science needs in a forthcoming updated version of the Plan.

Methods

We organized literature reviews on the five overarching topics included in the Plan (that is, [1] Fire, [2] Invasives (plant species), [3] Restoration, [4] Sagebrush and Sage-Grouse, and [5] Climate and Weather). For the Restoration topic, we initially searched the reference databases Web of Science and Scopus using broad search terms (for example, sagebrush restoration) to capture the bulk of the relevant literature in USGS BiblioSearch—a python tool designed for compiling literature across multiple databases (Kleist and Enns, 2022). We then conducted a series of literature searches using search terms specific to the Next Steps (for example, sagebrush AND seed transfer) to capture the science products that may have been excluded by the broad search terms (table 1). We examined all papers included in the resulting lists of literature for relevance to the Needs identified in the Restoration topic. Products searched included published literature and peer-reviewed Federal research reports (for example, Open-File Reports released by the U.S. Geological Survey [USGS]). Data releases, popular articles, "gray" literature, and other lower-tier publications were not included in search results (Kleist and Enns, 2022), although some of these types of literature (for example, data releases) were summarized in the annotated bibliographies we accessed (for example, Carter and others, 2020; Poor and others, 2021) and included in our review when pertinent. In situations where a research report was later published in the peer-reviewed literature, we only considered the published manuscript; in situations where the research report included pertinent information not included in the manuscript, we considered both.

We established how well Needs (that is, priority science required to inform the next generation of management strategies) listed in the Plan were addressed in the literature by independently "scoring" each Need from Next Steps (that is, science objectives required to address a Need) associated with the Restoration topic. Papers that were relevant to a Next Step were considered when scoring that Next Step. Our review approach initially focused on a paper's abstract. If this information suggested that the research was related to a Next Step,

Table 1. Search results for the Restoration topic in the Integrated Rangeland Fire Management Strategy Actionable Science Plan establishing the terms searched, the number of unique articles resulting from that search (Unique Results), and general descriptions of each search (Comment).

[**Search terms:** We used a search algorithm (Kleist and Enns, 2022) during early stages of tool development, and at that time the entire term between the word AND in the search terms was not searched (for example, “sagebrush” and “restoration” searched, not “sagebrush restoration”). **Unique results:** This resulted in broader and more inclusive lists of literature. The number of papers associated with each search term represent the number of unique papers resulting from that search but are not necessarily unique to the search (for example, the same paper could be included in the count of both the “sagebrush restoration” and “restoration AND sagebrush” searches). **Comment:** Need 4, development and evaluation of the utility of seed transfer zones; Need 10, assessments of factors contributing to soil degradation and development of soil enhancement methods that enhance restoration success]

Search terms	Unique results	Comment
sagebrush restoration	187	2015–20; broad search term
restoration AND sagebrush[1]	227	2015–20; broad search term
sagebrush AND soils	272	2015–20; broad search term
sagebrush AND seed zone map	1	2015–20; Need 4; targeted search term
sagebrush AND seed transfer	6	2015–20; Need 4; targeted search term
sagebrush sage AND wind erosion	9	2015–20; Need 10; targeted search term

[1]The search algorithm (Kleist and Enns, 2022) used was updated to include the entire search term between the word AND for these searches.

we focused our in-depth examination on research objectives, study area descriptions, and data collection and analysis methods. Because the objective of this project was to assess if Next Steps had been addressed, we did not systematically summarize results although we considered results when necessary to determine if the research addressed a Next Step. A given paper could be relevant to more than one Next Step in a Need, more than one Need, and more than one topic.

Each Next Step was scored based on the relevant literature following a set of criteria (table 2). Scores were scaled from 0.00 to 1.00 with 0.00 indicating that the Next Step had not been considered (that is, no papers were reviewed that considered the objective(s) detailed in the Next Step) and 1.00 indicating that the Next Step had been considered at the full spatial extent of the issue being investigated. Scores progressively decreased as the applicability of the research associated with a Next Step became more regional or localized. The scale of inference for Next Steps that were pertinent to the entire sagebrush biome was based on Western Association of Fish and Wildlife Agencies Management Zones (WAFWA; MZ) for sage-grouse (Stiver and others, 2006; fig. 1). If studies were distributed in one MZ or less than or equal to three adjoining MZs, the scale of inference was considered local or regional, respectively. “NA” was assigned when a Next Step could not be evaluated with the literature review approach we used (for example, data releases, online tools), and that Next Step was not scored. A Next Step that could be addressed adequately following our approach but that had no relevant literature identified was scored 0.00 (not “NA”). Each Need was scored as the proportion of the Next

Table 2. Criteria used to score Next Steps established for the Needs included in the Restoration topic in the Integrated Rangeland Fire Management Strategy Actionable Science Plan.

Scoring description	Score
Next Step addressed across the sagebrush range, or at the full spatial extent of the issue being investigated	1.00
Next Step addressed and was scale independent (for example, literature summaries)	1.00
Next Step partially addressed across the sagebrush range, or at the full spatial extent of the issue being investigated	0.75
Next Step partially addressed and was scale independent	0.75
Next Step fully addressed at the local or regional level	0.50
Next Step partially addressed at the local or regional level	0.25
Next Step not addressed	0.00
Next Step could not be assessed through literature review approach used (for example, development of databases)	NA[1]

[1]Next Step not included in scoring of Need

Steps associated with that Need that received a score greater than or equal to (≥) 0.75 (table 2). We categorized each Need based on the scores as addressed well by the literature (scores ≥0.67; that is, a majority of the Next Steps associated with that Need received a score of 0.75 or greater), partially addressed by the literature (scores 0.50–0.66) or addressed poorly by the literature (scores less than or equal to [≤] 0.49). We did not distinguish between Next Steps identified in the Plan as accomplishable within 3 years (short-term) and longer than 3 years (long-term) because 5 years had elapsed between plan formulation and this report.

For each Need, we developed a summary of the Next Steps. Summaries were organized by Need and describe Next Steps or portions of a Next Step that had been "Addressed" and those that had not (that is, "Outstanding") based on the details in the Next Steps rather than each Need in entirety. As such, descriptions of the research related to a given Next Step could be included in both the summaries of the science that had been Addressed as well as what remains Outstanding for a Need. These summaries provide details of how well specific science objectives established in the Plan were addressed and are important for evaluating the scores and informing the next set of science needs in the updated Plan.

Research relevant to the science Needs identified in the Plan continues to be conducted and published. However, because we are not privy to all the research being conducted throughout the sagebrush biome and we did not want to bias assessments to internal research efforts, products released after 2020 and interim updates of ongoing research were not discussed in this report. As such, the completion scores provided in this assessment are snapshots, and should be augmented with knowledge of newly published and on-going research programs using the search and scoring methods described in this report when updating the Plan.

Results and Summary

We reviewed 702 products that were identified by the literature searches conducted for the Restoration topic (table 1). Of those, 371 unique products were directly related to at least one of the 10 Needs. Most (78 percent) of the 50 Next Steps included in the topic had greater than or equal to one ≥ 1 published product that at least partially addressed the science objective(s) detailed by that Next Step. Nine Next Steps could not be effectively assessed with the evaluation approach we used and were not scored (NA; table 2). The 11 Next Steps that could be effectively assessed but had no related products (that is, were scored as 0.00 not as NA) included:

(1) investigations of sage-grouse and other sagebrush-obligate use of restoration treatments (three Next Steps under Need 1);

(2) seven Next Steps pertaining to investigations of seed transfer zone applications (Need 4); and

(3) studies of the impacts of fire on conifer seed banks (Need 9).

Table 3 provides the completion scores for each Need and summaries of the literature evaluated for Next Steps. Literature citations are provided in Appendix 1, organized by Next Step.

The Needs that were addressed well (scores ≥ 0.67) included the development of methods to improve seeding success of native plants after fire (Need 2); evaluations of short- and long-term responses of plant communities to restoration treatments (Need 5); development of site preparation and seeding strategies to improve plant establishment and diversity (Need 6); assessments of long-term effects on ecosystem processes of conifer removal treatments (Need 7) and development of decision support tools to aid in conifer management within the sagebrush biome (Need 9); determination of the mitigation potential of restoration treatments relative to the benefits to sage-grouse populations (Need 8); and assessments of factors contributing to soil degradation and development of soil enhancement methods that enhance restoration success (Need 10). A substantial amount of research conducted throughout the sagebrush biome, at local and regional scales, has investigated associations between seeding ecology (germination, emergence, seedling establishment, seedling survival) and biotic and abiotic factors such as invasive annual grasses, weather, livestock grazing (within experimental exclosures), and the timing of seeding. Short-term and long-term plant responses to mechanical, chemical, and prescribed fire treatments have been investigated at local and regional scales. Approaches for controlling invasive annual grasses without producing negative impacts to native plants have been investigated at predominantly local scales. Numerous studies distributed throughout the sagebrush biome have investigated the response of vegetation communities (including native and non-native plants) and wildlife to various conifer and sagebrush removal treatment methods. Many of these studies have been used to develop tools to help managers set expectations when planning restoration treatments and to develop monitoring metrics (leveraging information from similar legacy treatments) for informing adaptive management and improving restoration success.

Table 3. Priority science Needs detailed under the Restoration topic in the Integrated Rangeland Fire Management Strategy Actionable Science Plan establishing the completion score (score), and a summary of science objectives addressed and not addressed (Outstanding) in the scientific literature published 2015–20.

Need	Score	Summary of 2015–20 literature
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.	0.25	***Addressed***: Several tools and guidelines have been developed to identify priority sagebrush restoration areas based on resistance and resilience, soils data, restoration costs, and benefits to sage-grouse populations across their range, including tools that identify and prioritize sagebrush areas to restore for sage-grouse after fire. Throughout the Great Basin, methods for rapidly re-establishing sagebrush have been identified through several studies including studies that link the costs to the ecological benefits of restoring sage-grouse habitat post-wildfire. Sagebrush patch and other environmental characteristics (for example, cumulative burned area) required by sage-grouse have been identified at local and regional scales through examinations of nest site selection and survival, and adult survival post-fire. Methods for restoring sagebrush (that is, seedings or seedlings) have been evaluated and linked to environmental factors and site characteristics in western portions of the sagebrush biome. ***Outstanding***: The effects of post-fire habitat restoration efforts have not been explicitly linked to sage-grouse occupancy or population dynamics except at the regional scale in western portion of the species' range. The minimum sagebrush cover and patch size and other environmental requirements for sage-grouse occupancy, survival, and population persistence are poorly understood in post-fire landscapes. The response of sagebrush-obligate and sagebrush-dependent species other than sage-grouse to post-fire restoration treatments has not been studied.
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.	0.88	***Addressed***: A substantial amount of research has investigated associations between seeding ecology (germination, emergence, seedling establishment, seedling survival) and biotic and abiotic factors such as invasive annual grasses, weather, livestock grazing (within experimental exclosures), and the timing of seeding at local and regional scales across the sagebrush biome. The plant species that have been evaluated under various restoration conditions are diverse and fit within the three dominant plant life-forms (shrubs, grasses, forbs). Comparisons of drill and aerial seeding, elevation and precipitation gradients, rangeland drills (conventional and minimum till), other seed delivery techniques, and the timing and rate of seed application have been done at local and regional scales primarily in western portions of the sagebrush biome. Advancements in identifying big sagebrush to subspecies in seed lots have been achieved through assessments of seed weight and spectrophotometry. Seed coating techniques that (1) increase soil water availability, (2) enhance seedling emergence in crusting soil, (3) control the timing of seed germination, (4) enhance seed coverage of broadcasted seeds, (5) improve plantability and emergence of small-seeded species, and (6) protect seedlings from pre-emergent herbicides have been developed and tested at local and regional scales. ***Outstanding***: Basin and Wyoming big sagebrush seed-zone maps and seed-transfer guidelines regarding climate change across most of the sagebrush biome are lacking. Investigations are needed to understand how interactions between the selective use of livestock and various seeding methods influences seeding success across multiple ecological sites and conditions. There remains a need to synthesize and centralize restoration species data and provide links to tools and databases required for all aspects of restoration planning.

Table 3. Priority science Needs detailed under the Restoration topic in the Integrated Rangeland Fire Management Strategy Actionable Science Plan establishing the completion score (score), and a summary of science objectives addressed and not addressed (Outstanding) in the scientific literature published 2015–20.—Continued

Need	Score	Summary of 2015–20 literature
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.	0.25	***Addressed***: Numerous local and regional scale studies throughout the sagebrush biome have quantified the responses of newly seeded or planted seedlings of sagebrush and perennial bunchgrass species and identified thresholds in these responses as a function of biotic and abiotic factors. Practical applications for restoration in the sagebrush biome have been reviewed and synthesized in the context of restoration planning, including assessing restoration success of past practices and approaches to prioritizing future restoration practices. Frameworks with range-wide applicability have been proposed for restoration effectiveness monitoring. ***Outstanding***: Information from land treatment effectiveness monitoring on operational restoration projects (for example, Bureau of Land Management [BLM] Emergency, Stabilization, and Rehabilitation) has not been synthesized to establish criteria and determine thresholds. Spatial replication is needed to determine when seedlings and native plants can tolerate grazing by large herbivores and provide resistance to invasive annual grasses after fire and restoration.
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.	0.27	***Addressed***: Several local, regional and range-wide scale studies investigated adaption and population dynamics of Wyoming, mountain, and basin big sagebrush seedlings within and across seed-transfer zones in relation to local weather parameters, post-fire restoration treatments, and invasive annual grasses in common gardens and operational restoration projects. Seed-zone investigations of native forb and a limited number of bunchgrass species common in sagebrush habitat restoration efforts have been conducted at local and range-wide scales. Seed-zone maps for big sagebrush have been refined range-wide based on genetic variation, environmental effects, and adaptive breadth of populations grown in common gardens. ***Outstanding***: Seed-zone models and seed transfer tools that incorporate uncertainty and evaluate risk are limited. Seed-zone maps for common understory species used in sagebrush habitat restoration need to be refined and existing seed-zone models for all restoration species (including sagebrush and other shrubs) need to be evaluated across restoration areas in the sagebrush biome. Meta-analyses have not been completed to determine patterns and thresholds between perennial bunchgrasses and climate variables or to test generalities of seed transfer for other functional plant groups used for restoration. A synthesis of common garden studies to determine adaptive trends and a review of seed-zone construction methods to identify best practices for seed-zone modelling have not been completed. Molecular-marker studies to support seed-zone development are lacking.
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.	0.67	***Addressed***: Short-term and long-term plant responses to restoration treatments have been investigated by numerous local and regional scale studies distributed throughout the sagebrush biome. Several studies examined the response of vegetation following sagebrush removal, sagebrush removal and seeding, and seeding after fire. Tools to help managers set expectations when planning restoration treatments and to develop monitoring metrics (leveraging information from similar legacy treatments) for informing adaptive management and improving restoration success that has range-wide relevance have been developed. ***Outstanding***: Short-term and long-term information linking vegetation responses to biotic and abiotic conditions following treatments in fire affected areas is lacking replication, especially for the Great Basin. Most studies that investigated vegetation responses to restoration treatments are local and the identification of regional and range-wide consistencies and differences in temporal trajectories of vegetation responses have not been synthesized. Predictive models of revegetation trajectories have not been validated.

Table 3. Priority science Needs detailed under the Restoration topic in the Integrated Rangeland Fire Management Strategy Actionable Science Plan establishing the completion score (score), and a summary of science objectives addressed and not addressed (Outstanding) in the scientific literature published 2015–20.—Continued

Need	Score	Summary of 2015–20 literature
Need 6: Develop site preparation and seeding and transplanting strategies that improve plant establishment and community diversity.	0.67	***Addressed***: A substantial number of greenhouse, field, and operational restoration studies conducted at local and regional scales and replicated range-wide have investigated the effects of site specific biotic and abiotic factors on the establishment and success of commonly used plant species in restoration. Approaches for controlling invasive annual grasses without producing negative impacts to native plants have been investigated at predominantly local scales by a substantial number of studies distributed throughout the sagebrush biome. ***Outstanding***: Investigations of different potential species for incorporation into the "pool" of available species for restoration is lacking. Syntheses of information on site preparation and seeding and transplanting strategies for sagebrush communities across the biome have not been fully developed.
Need 7: Assess the long-term effects of conifer removal treatments on hydrology, geochemical cycling, vegetation, wildlife, fuels, fire behavior, and economics.	1.00	***Addressed***: A substantial number of local and regional scale studies distributed throughout the sagebrush biome have investigated the response of vegetation communities (including native and non-native plants) and wildlife to various conifer removal treatment methods in Wyoming and mountain big sagebrush communities. Many studies have evaluated hydrological process, and to a lesser degree carbon fluxes in response to conifer removal treatments. Studies examining long-term vegetation responses to conifer removal treatments in relation to the biophysical setting have been replicated across the sagebrush biome. Associations between conifer removal and fire and fuel dynamics have been described (see also Fire topic Need 3). The costs and benefits of implementing mechanical versus prescribed fire have been evaluated. Several reviews and syntheses have been completed describing the effects of conifer removal on wildlife, hydrology, and climate change. ***Outstanding***: Studies investigating the effects of conifer removal treatments on the biogeochemical cycle are lacking. Although studied extensively, the long-term hydrologic, vegetation, and wildlife responses to conifer removal treatments across the array of biophysical settings being treated is a broad topic that could benefit from additional research.
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.	0.75	***Addressed***: Numerous local and regional scale studies have examined the effectiveness of land treatment projects, including various conifer or sagebrush removal treatments, for providing habitat for sage-grouse. Local scale studies in eastern portions of the sagebrush biome have quantified the response of sage-grouse to mitigation efforts at energy development sites. Guidelines and tools to inform sagebrush restoration efforts based on state-and-transition models, threat-based models, and ecological site potential that have relevance informing sage-grouse mitigation efforts have been completed. ***Outstanding***: Syntheses or meta-analyses of sagebrush habitat response to the suite of restoration treatments across the sagebrush biome have not been completed. Unified metrics for quantifying changes in sagebrush habitat suitability and quality for sage-grouse in response to restoration activities and sage-grouse population or demographic trends have not been developed limiting the ability to evaluate mitigation success and assess whether mitigation is a viable option.
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.	0.75	***Addressed***: Vegetation community succession following mechanical and prescribed fire treatments of conifers has been investigated through numerous local scale studies distributed throughout the sagebrush biome. Reviews describing the socioecological aspects of woodland expansion and management actions taken to reduce threats to sage-grouse have been completed. Several decision-support tools have been developed to identify areas where conifer removal would be most effective based on criteria such as treatment costs, benefits to sage-grouse, livestock forage, and resistance and resilience of plant communities. See also Restoration topic Need 7 summary. ***Outstanding***: Studies investigating the effects of fire on conifer seedbanks within sagebrush communities have not been completed. Further syntheses are needed to better understand how variability in site characteristics and treatment methods throughout the sagebrush biome influence vegetation responses to restoration treatments.

Table 3. Priority science Needs detailed under the Restoration topic in the Integrated Rangeland Fire Management Strategy Actionable Science Plan establishing the completion score (score), and a summary of science objectives addressed and not addressed (Outstanding) in the scientific literature published 2015–20.—Continued

Need	Score	Summary of 2015–20 literature
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.	0.67	***Addressed***: Numerous local and regional scale studies distributed across the sagebrush biome evaluated the effects of disturbances including fire, grazing, conifer treatments, herbicides, and conifer and invasive annual grass invasion on soil degradation (for example, biological soil crusts, microbial community, soil nutrients, and soil moisture and temperature). Relationships between post-fire restoration treatments and wind erosion have been investigated at local scales. Regional-scale studies linking soil moisture and temperature to sagebrush restoration success after fire have been conducted in the Great Basin. Several local scale water and wind-erosion models have been developed. Restoration tools that incorporate soil properties in assessments of the reestablishment of plant communities after fire have been explored and tested range-wide. See also Restoration topic Need 2 summary. ***Outstanding***: A synthesis describing the effects of fire and invasive annual grasses on soil biogeochemistry for the sagebrush biome has not been completed. Studies investigating plant establishment in response to differences in soil water and chemistry after fire need to be replicated outside the Great Basin. The effects of grazing heterogeneity on biological soil crusts need evaluated. Wind and water-erosion models have not been developed for post-fire sagebrush communities in eastern portions of the sagebrush biome.

None of the Needs in the topic were partially addressed (scores 0.50–0.66). The Needs that were addressed poorly (scores ≤0.49) included the development of methods for the rapid recovery of sagebrush and native herbaceous plants following wildfire to benefit sage-grouse and mitigate impacts from future fires (Need 1); determination of thresholds for successful restoration of sagebrush habitats and development of decision support tools to assist with restoration effectiveness monitoring (Need 3); and development and evaluation of the utility of seed transfer zones (Need 4). The effects of post-fire habitat restoration efforts (for example, sagebrush seedings) have not been explicitly linked to sage-grouse occupancy or population dynamics except in the western portion of the species' range. Information from land treatment effectiveness monitoring on operational restoration projects (for example, BLM Emergency, Stabilization, and Rehabilitation) has not been synthesized to establish criteria and determine thresholds. Replication is needed to determine when sagebrush seedlings and recovering native herbaceous species can tolerate grazing by large herbivores and provide resistance to invasive annual grasses after fire and restoration across multiple ecological sites. Seed-zone models and seed transfer tools that incorporate uncertainty and evaluate risk are limited. Meta-analyses have not been completed to determine patterns and thresholds between perennial bunchgrasses and climate variables or to test generalities of seed transfer for other functional plant groups used for restoration.

There were several Next Steps identified under the Restoration topic that were addressed poorly, even when the overall Need was addressed well. There remains a need to develop, synthesize and centralize restoration seed-zone maps, seed-transfer guidelines and species' data and provide links to tools and databases required for all aspects of restoration planning (Need 2). Most studies that investigated vegetation responses to different restoration techniques, including restoration of areas affected by wildfire, are local and the broader-scale applicability and transferability of findings have not been investigated or validated (Need 5). Syntheses of information on site preparation, seeding and transplanting strategies, and identification of different potential species for the restoration of sagebrush communities across the biome have not been fully developed (Need 6). Studies investigating the effects of conifer removal treatments on soil biogeochemistry and the biogeochemical cycle are lacking (Needs 7, 10). Syntheses of sagebrush habitat response to the suite of restoration treatment options across the biome, and unified metrics for quantifying the response of sagebrush-dependent species to these restoration activities have not been developed; this is contributing to limitations evaluating mitigation success and establishing whether mitigation is a viable option (Need 8). Studies investigating the effects of fire on conifer seedbanks within sagebrush communities have not been completed (Need 9).

The completion scores and summaries in this report provide the basis to identify new actionable science priorities that are needed to address the issues continuing to drive the loss, degradation, restoration, and conservation of sagebrush habitats in the western United States. The resulting information can directly inform an update to the Plan, as well as other highly relevant science planning documents including, but not limited to: Parts 1 and 2 of the Science Framework (Chambers and others, 2017; Crist and others, 2019), the WAFWA Sagebrush Conservation Strategy (Remington and others, 2021), and online science portals for managers in various stages of development. Because actionable science production continues to move forward quickly, Needs and Next Steps likely to be addressed by science released after 2020 will require consideration in Plan updates.

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Glossary

Addressed Objective detailed in a Next Step that was addressed in the literature published between January 1, 2015, and December 31, 2020

Fire frequency The recurrence of fire in a given area over time

Need A shared vision among researchers and managers of priority science required to fill knowledge gaps and inform the next generation of management strategies and tools

Next step Science objectives (that is, new research, syntheses, and tools) required to address a Need

Objective Science or research goals detailed as Next Steps in the Plan

Outstanding Objective detailed in a Next Step that was not addressed in the literature published between January 1, 2015, and December 31, 2020

Plan IRFMS Actionable Science Plan (Integrated Rangeland Fire Management Strategy Actionable Science Plan Team, 2016)

Score Relative measure of the level of progress towards addressing the Next Steps established in a Need

Topic One of five science themes identified in the Plan relevant to the management of sagebrush ecosystems

Appendix 1. Literature Included in Scoring Next Steps for the Restoration Topic in the Actionable Science Plan

The literature in this appendix is organized by Need and Next Step. Needs are defined as a shared vision among researchers and managers of priority science required to fill knowledge gaps and inform the next generation of management strategies and tools. Next Steps are defined as science objectives (that is, new research, syntheses, and tools) required to address a Need. Next Steps scored as 0.00 in table 2 are described as "Not addressed." Next Steps that could not be assessed through literature review approach used (for example, development of databases) are described as "NA."

Restoration 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.

Next Step 1a

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.

Foster, L.J., Dugger, K.M., Hagen, C.A., and Budeau, D.A., 2019, Greater sage-grouse vital rates after wildfire—Sage-grouse wildfire response: The Journal of Wildlife Management, v. 83, no. 1, p. 121–134.

Lockyer, Z.B., Coates, P.S., Casazza, M.L., Espinosa, S., and Delehanty, D.J., 2015, Nest-site selection and reproductive success of greater sage-grouse in a fire-affected habitat of northwestern Nevada: The Journal of Wildlife Management, v. 79, no. 5, p. 785–797.

O'Neil, S.T., Coates, P.S., Brussee, B.E., Ricca, M.A., Espinosa, S.P., Gardner, S.C., and Delehanty, D.J., 2020, Wildfire and the ecological niche—Diminishing habitat suitability for an indicator species within semi-arid ecosystems: Global Change Biology, v. 26, no. 11, p. 6296–6312.

Next Step 1b

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.

Davidson, B.E., Germino, M.J., Richardson, B., and Barnard, D.M., 2019, Landscape and organismal factors affecting sagebrush-seedling transplant survival after megafire restoration: Restoration Ecology, v. 27, no. 5, p. 1008–1020.

Pyke, D.A., Shriver, R.K., Arkle, R.S., Pilliod, D.S., Aldridge, C.L., Coates, P.S., Germino, M.J., Heinrichs, J.A., Ricca, M.A., and Shaff, S.E., 2020, Postfire growth of seeded and planted big sagebrush—Strategic designs for restoring greater sage-grouse nesting habitat: Restoration Ecology, v. 28, no. 6, p. 1495–1504.

Next Step 1c

Monitor and analyze the use of re-vegetated treatments by sage-grouse and quantify their seasonal survival and reproductive success at those sites.

Not addressed.

Next Step 1d

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.

Ricca, M.A., Coates, P.S., Gustafson, K.B., Brussee, B.E., Chambers, J.C., Espinosa, S.P., Gardner, S.C., Lisius, S., Ziegler, P., Delehanty, D.J., and Casazza, M.L., 2018, A conservation planning tool for greater sage-grouse using indices of species distribution, resilience, and resistance: Ecological Applications, v. 28, no. 4, p. 878–896.

Next Step 1e

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.

Vander Haegen, W.M., Schroeder, M.A., Chang, W.-Y., and Knapp, S.M., 2015, Avian abundance and reproductive success in the intermountain west—Local-scale response to the conservation reserve program: Wildlife Society Bulletin, v. 39, no. 2, p. 276–291.

Next Step 1f

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.

Ricca, M.A., Coates, P.S., Gustafson, K.B., Brussee, B.E., Chambers, J.C., Espinosa, S.P., Gardner, S.C., Lisius, S., Ziegler, P., Delehanty, D.J., and Casazza, M.L., 2018, A conservation planning tool for greater sage-grouse using indices of species distribution, resilience, and resistance: Ecological Applications, v. 28, no. 4, p. 878–896.

Next Step 1g

Synthesize the results of continued sagebrush and sage-grouse responses to develop post-fire sagebrush restoration guidelines for revegetating sage-grouse habitat.

Not addressed.

Next Step 1h

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.

Chambers, J.C., Beck, J.L., Bradford, J.B., Bybee, J., Campbell, S., Carlson, J., Christiansen, T.J., Clause, K.J., Collins, G., Crist, M.R., Dinkins, J.B., Doherty, K.E., Edwards, F., Espinosa, S., Griffin, K.A., Griffin, P., Haas, J.R., Hanser, S.E., Havlina, D.W., Henke, K.F., Hennig, J.D., Joyce, L.A., Kilkenny, F.M., Kulpa, S.M., Kurth, L.L., Maestas, J.D., Manning, M., Mayer, K.E., Mealor, B.A., McCarthy, C., Pellant, M., Perea, M.A., Prentice, K.L., Pyke, D.A., Wiechman, L.A., and Wuenschel, A., 2017a, Science framework for conservation and restoration of the sagebrush biome—Linking the Department of the Interior's Integrated Rangeland Fire Management Strategy to long-term strategic conservation actions—Part 1. Science basis and applications: Fort Collins, Colorado, U.S. Forest Service, Rocky Mountain Research Station, Gen. Tech. Rep. RMRS-GTR360, 213 p. [Also available at https://doi.org/10.2737/RMRS-GTR-360.]

Chambers, J.C., Beck, J.L., Campbell, S., Carlson, J., Christiansen, T.J., Clause, K.J., Dinkins, J.B., Doherty, K.E., Griffin, K.A., Havlina, D.W., Mayer, K.F., Hennig, J.D., Kurth, L.L., Maestas, J.D., Manning, M., Mealor, B.A., McCarthy, C., Perea, M.A., and Pyke, D.A., 2016, Using resilience and resistance concepts to manage threats to sagebrush ecosystems, Gunnison sage-grouse, and greater sage-grouse in their eastern range—A strategic multi-scale approach: U.S. Forest Service, Rocky Mountain Research Station, General Technical Report RMRS-GTR-356, 143 p. [Also available at https://doi.org/10.2737/RMRS-GTR-356.]

Chambers, J.C., Maestas, J.D., Pyke, D.A., Boyd, C.S., Pellant, M., and Wuenschel, A., 2017b, Using resilience and resistance concepts to manage persistent threats to sagebrush ecosystems and greater sage-grouse: Rangeland Ecology and Management, v. 70, no. 2, p. 149–164.

Crist, M.R., Chambers, J.C., Phillips, S.L., Prentice, K.L., and Wiechman, L.A., eds., 2019, Science framework for conservation and restoration of the sagebrush biome—Linking the Department of the Interior's Integrated Rangeland Fire Management Strategy to long-term strategic conservation actions—Part 2. Management applications: Fort Collins, Colorado, U.S. Forest Service, Rocky Mountain Research Station, Gen. Tech. Rep. RMRS-GTR-389, 237 p. [Also available at https://doi.org/10.2737/RMRS-GTR-389.]

Maestas, J.D., Campbell, S.B., Chambers, J.C., Pellant, M., and Miller, R.F., 2016, Tapping soil Survey information for rapid assessment of sagebrush ecosystem resilience and resistance: Rangelands, v. 38, no. 3, p. 120–128.

Ricca, M.A., Coates, P.S., Gustafson, K.B., Brussee, B.E., Chambers, J.C., Espinosa, S.P., Gardner, S.C., Lisius, S., Ziegler, P., Delehanty, D.J., and Casazza, M.L., 2018, A conservation planning tool for greater sage-grouse using indices of species distribution, resilience, and resistance: Ecological Applications, v. 28, no. 4, p. 878–896.

Studies Related to Need 1, But Not Any of the Next Steps

Davies, K.W., Bates, J.D., and Hulet, A., 2017, Attempting to restore mountain big sagebrush (*Artemisia tridentata* ssp. *vaseyana*) four years after fire—Attempting sagebrush restoration: Restoration Ecology, v. 25, no. 5, p. 717–722.

Germino, M.J., Barnard, D.M., Davidson, B.E., Arkle, R.S., Pilliod, D.S., Fisk, M.R., and Applestein, C., 2018, Thresholds and hotspots for shrub restoration following a heterogeneous megafire: Landscape Ecology, v. 33, no. 7, p. 1177–1194.

Restoration 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.

Next Step 2a

Synthesize ecological and restoration-related data for commonly seeded or planted native species of the sagebrush ecosystem, including seed and seedling production data.

Leger, E.A., and Baughman, O.W., 2015, What seeds to plant in the Great Basin? Comparing traits prioritized in native plant cultivars and releases with those that promote survival in the field: Natural Areas Journal, v. 35, no. 1, p. 54–68.

Pyke, D.A. and Wirth, T.A. 2017, Compilation of Bureau of Land Management monitoring reports assessing post-wildfire seeding of rangelands, 2001–09: U.S. Geological Survey data release, [Also available at https://doi.org/10.5066/F7445JPQ.]

Pyke, D.A. and Wirth, T.A., 2017, Compilation of studies assessing post-wildfire seeding of rangelands worldwide, 1965–2010: U.S. Geological Survey data release, [Also available at https://doi.org/10.5066/F7MW2F9B.]

Next Step 2b

Centralize synthesized species data and links to tools and databases required for all aspects of restoration planning.

NA.

Next Step 2c

Identify priority equipment needs and support modification of existing equipment or development of new equipment by agricultural engineers.

Ott, J.E., Cox, R.D., and Shaw, N.L., 2017, Comparison of postfire seeding practices for Wyoming big sagebrush: Rangeland Ecology and Management, v. 70, no. 5, p. 625–632.

Ott, J.E., Cox, R.D., Shaw, N.L., Newingham, B.A., Ganguli, A.C., Pellant, M., Roundy, B.A., and Eggett, D.L., 2016, Postfire drill-seeding of Great Basin plants—Effects of contrasting drills on seeded and nonseeded species: Rangeland Ecology and Management, v. 69, no. 5, p. 373–385.

Next Step 2d

Update Seed Lot Selection Tool.

NA.

Next Step 2e

Develop a protocol for identifying subspecies composition of big sagebrush seed lots.

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Next Step 2f

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.

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Next Step 2g

Complete the planning tool component of the Land Treatment Digital Library.

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Next Step 2h

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.

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Germino, M.J., Fisk, M.R., and Applestein, C., 2019, Bunchgrass root abundances and their relationship to resistance and resilience of burned shrub-steppe landscape: Rangeland Ecology and Management, v. 72, no. 5, p. 783–790.

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Next Step 2i

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.

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Next Step 2j

Complete, synthesize, and test results of ongoing studies of sagebrush seed-lot handling, seed and seedling ecology, establishment requirements, and seeding methods.

Clenet, D.R., Davies, K.W., Johnson, D.D., and Kerby, J.D., 2019, Native seeds incorporated into activated carbon pods applied concurrently with indaziflam—A new strategy for restoring annual-invaded communities?: Activated carbon improves restoration: Restoration Ecology, v. 27, no. 4, p. 738–744.

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Next Step 2j

Update the Revegetation Equipment Catalog and add a synthesis of research-based recommendations for selection of equipment to meet specific needs.

NA.

Studies Related to Need 2, but Not Any of the Next Steps

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Metier, E.P., Rew, L.J., and Rinella, M.J., 2018, Establishing Wyoming big sagebrush in annual brome-invaded landscapes with deeding and herbicides: Rangeland Ecology and Management, v. 71, no. 6, p. 705–713.

Restoration 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.

Next Step 3a

Evaluate newly developed criteria and thresholds of treatment success across the range of sage-grouse to determine the efficacy.

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Herriman, K.R., Davis, A.S., Apostol, K.G., Kildisheva, O.A., Ross-Davis, A.L., and Dumroese, R.K., 2016, Do container volume, site preparation, and field fertilization affect restoration potential of Wyoming big sagebrush?: Natural Areas Journal, v. 36, no. 2, p. 194–201.

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Wainwright, C.E., Davies, G.M., Dettweiler-Robinson, E., Dunwiddie, P.W., Wilderman, D., and Bakker, J.D., 2020, Methods for tracking sagebrush-steppe community trajectories and quantifying resilience in relation to disturbance and restoration: Restoration Ecology, v. 28, no. 1, p. 115–126.

Wilder, L., Veblen, K.E., Schupp, E.W., and Monaco, T.A., 2019, Seedling emergence patterns of six restoration species in soils from two big sagebrush plant communities: Western North American Naturalist, v. 79, no. 2, p. 233–246.

Next Step 3b

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.

Fulbright, T.E., Davies, K.W., and Archer, S.R., 2018, Wildlife responses to brush management—A contemporary evaluation: Rangeland Ecology and Management, v. 71, no. 1, p. 35–44.

Hardegree, S.P., Sheley, R.A., Brunson, M.W., Taylor, M.H., and Moffet, C.A., 2019, Forum—Iterative-adaptive management and contingency-based restoration planning in variable environment: Rangeland Ecology and Management, v. 72, no. 2, p. 217–224.

Svejcar, T., Boyd, C., Davies, K., Hamerlynck, E., and Svejcar, L., 2017, Challenges and limitations to native species restoration in the Great Basin, USA: Plant Ecology, v. 218, no. 1, p. 81–94.

Next Step 3c

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.

Davies, K.W., Bates, J.D., and Boyd, C.S., 2020, Response of planted sagebrush seedlings to cattle grazing applied to decrease fire probability: Rangeland Ecology and Management, v. 73, no. 5, p. 629–635.

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Next Step 3d

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.

NA.

Next Step 3e

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.

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Studies Related to Need 3, but Not Any of the Next Steps

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Dittel, J.W., Sanchez, D., Ellsworth, L.M., Morozumi, C.N., and Mata-Gonzalez, R., 2018, Vegetation response to juniper reduction and grazing exclusion in sagebrush-steppe habitat in eastern Oregon: Rangeland Ecology and Management, v. 71, no. 2, p. 213–219.

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Restoration 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.

Next Step 4a

Conduct meta-analyses of existing datasets, such as bunchgrasses, to determine generalities and thresholds for climatic variables in the sagebrush ecosystem.

Not addressed.

Next Step 4b

Test the efficacy of existing seed-zone models in operational-scale restoration projects.

Brabec, M.M., Germino, M.J., and Richardson, B.A., 2017, Climate adaption and post-fire restoration of a foundational perennial in cold desert—Insights from intraspecific variation in response to weather: Journal of Applied Ecology, v. 54, no. 1, p. 293–302.

Next Step 4c

Review and synthesize all common garden studies related to the sagebrush ecosystem to find general, adaptive trends.

Not addressed.

Next Step 4d

Review seed-zone construction methods to determine best practices for seed-zone modeling.

Not addressed.

Next Step 4e

Develop statistical tools to incorporate variation and uncertainty into seed-zone models.

Not addressed.

Next Step 4f

Refine generalized seed-zone maps for the sagebrush ecosystem.

Munson, S.M., and Sher, A.A., 2015, Long-term shifts in the phenology of rare and endemic Rocky Mountain plants: American Journal of Botany, v. 102, no. 8, p. 1268–1276.

Richardson, B.A., and Chaney, L., 2018, Climate-based seed transfer of a widespread shrub—Population shifts, restoration strategies, and the trailing edge: Ecological Applications, v. 28, no. 8, p. 2165–2174.

Next Step 4g

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.

NA.

Nest Step 4h

Perform molecular-marker studies on all taxa undergoing seed-zone development.

Not addressed.

Next Step 4i

Develop and improve empirical seed-zones for those species commonly used in restoration and rehabilitation actions that are widespread, intraspecifically diverse, and locally dominant.

Barga, S.C., Dilts, T.E., and Leger, E.A., 2018, Contrasting climate niches among co-occurring subdominant forbs of the sagebrush steppe: Diversity & Distributions, v. 24, no. 9, p. 1291–1307.

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Chaney, L., Richardson, B.A., and Germino, M.J., 2017, Climate drives adaptive genetic responses associated with survival in big sagebrush (*Artemisia tridentata*): Evolutionary Applications, v. 10, no. 4, p. 313–322.

Davidson, B.E., and Germino, M.J., 2020, Spatial grain of adaptation is much finer than ecoregional-scale common gardens reveal: Ecology and Evolution, v. 10, no. 18, p. 9920–9931.

Ferguson, S.D., Leger, E.A., Li, J., and Nowak, R.S., 2015, Natural selection favors root investment in native grasses during restoration of invaded fields: Journal of Arid Environments, v. 116, p. 11–17.

Lazarus, B.E., Germino, M.J., and Richardson, B.A., 2019, Freezing resistance, safety margins, and survival vary among big sagebrush populations across the western United States: American Journal of Botany, v. 106, no. 7, p. 922–934.

Next Step 4j

Conduct a meta-analysis of new studies of seed transfer to test generalities.

Not addressed.

Next Step 4k

Develop dynamic “on-the-fly” seed-transfer tools that use underlying data structures and models to include uncertainty and acceptable risk.

Not addressed.

Next Step 4l

Further refine generalized seed-zone maps based on new knowledge.

Richardson, B.A., and Chaney, L., 2018, Climate-based seed transfer of a widespread shrub—Population shifts, restoration strategies, and the trailing edge: Ecological Applications, v. 28, no. 8, p. 2165–2174.

Studies Related to Need 4, but Not Any of the Next Steps

Germino, M.J., Moser, A.M., and Sands, A.R., 2019, Adaptive variation, including local adaptation, requires decades to become evident in common gardens: Ecological Applications, v. 29, no. 2, p. 1–7.

Richardson, B.A., Chaney, L., Shaw, N.L., and Still, S.M., 2017, Will phenotypic plasticity affecting flowering phenology keep pace with climate change?: Global Change Biology, v. 23, no. 6, p. 2499–2508.

Restoration 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.

Next Step 5a

Evaluate and synthesize outcomes of restoration projects that are underway or moving forward.

NA.

Next Step 5b

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.

Davies, K.W., Boyd, C.S., Bates, J.D., Hamerlynck, E.P., and Copeland, S.M., 2020, Restoration of sagebrush in crested wheatgrass communities—Longer-term evaluation in northern Great Basin: Rangeland Ecology and Management, v. 73, no. 1, p. 1–8.

Grant-Hoffman, M.N., Lincoln, A., and Dollerschell, J., 2018, Post-fire native seed use in western Colorado—A look at burned and unburned vegetation communities: Natural Areas Journal, v. 38, no. 4, p. 286–297.

Johnston, A.N., Beever, E.A., Merkle, J.A., and Chong, G., 2018, Vegetation responses to sagebrush-reduction treatments measured by satellites: Ecological Indicators, v. 87, p. 66–76.

Hanna, S.K., and Fulgham, K.O., 2015, Post-fire vegetation dynamics of a sagebrush steppe community change significantly over time: California Agriculture, v. 69, no. 1, p. 36–42.

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Ripplinger, J., Franklin, J., and Edwards, T.C., Jr., 2015, Legacy effects of no-analogue disturbances alter plant community diversity and composition in semi-arid sagebrush steppe: Journal of Vegetation Science, v. 26, no. 5, p. 923–933.

Seipel, T., Rew, L.J., Taylor, K.T., Maxwell, B.D., and Lehnhoff, E.A., 2018, Disturbance type influences plant community resilience and resistance to *Bromus tectorum* invasion in the sagebrush steppe: Applied Vegetation Science, v. 21, no. 3, p. 385–394.

Shriver, R.K., Andrews, C.M., Pilliod, D.S., Arkle, R.S., Welty, J.L., Germino, M.J., Duniway, M.C., Pyke, D.A., and Bradford, J.B., 2018, Adapting management to a changing world—Warm temperatures, dry soil, and interannual variability limit restoration success of a dominant woody shrub in temperate drylands: Global Change Biology, v. 24, no. 10, p. 4972–4982.

Wilder, L.E., Veblen, K.E., Gunnell, K.L., and Monaco, T.A., 2019, Influence of fire and mechanical sagebrush reduction treatments on restoration seedings in Utah, United States—Sagebrush reduction and seeding success: Restoration Ecology, v. 27, no. 2, p. 308–319.

Next Step 5c

Create a searchable 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.

Barker, B.S., Pilliod, D.S., Welty, J.L., Arkle, R.S., Karl, M.G., and Toevs, G.R., 2018, An introduction and practical guide to use of the soil-vegetation inventory method (SVIM) data: Rangeland Ecology and Management, v. 71, no. 6, p. 671–680.

Pilliod, D.S., Welty, J.L., Jeffries, M.I., Schueck, L.S., and Zarriello, T.J., 2018, Land treatment exploration tool—(rev. 1.1, October 2018): U.S. Geological Survey Fact Sheet 2018–3042, 2 p. [Also available at https://doi.org/10.3133/fs20183042.]

Next Step 5d

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.

Avirmed, O., Lauenroth, W.K., Burke, I.C., and Mobley, M.L., 2015, Sagebrush steppe recovery on 30–90-year-old abandoned oil and gas wells: Ecosphere, v. 6, no. 1–10.

Barnard, D.M., Germino, M.J., Pilliod, D.S., Arkle, R.S., Applestein, C., Davidson, B.E., and Fisk, M.R., 2019, Cannot see the random forest for the decision trees—Selecting predictive models for restoration ecology: Restoration Ecology, v. 27, no. 5, p. 1053–1063.

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Love, B.G., and Cane, J.H., 2019, Mortality and flowering of Great Basin perennial forbs after experimental burning—Implications for wild bees: Rangeland Ecology and Management, v. 72, no. 2, p. 310–317.

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Waller, E.K., Villarreal, M.L., Poitras, T.B., Nauman, T.W., and Duniway, M.C., 2018, Landsat time series analysis of fractional plant cover changes on abandoned energy development sites: International Journal of Applied Earth Observation and Geoinformation, v. 73, p. 407–419.

Wood, D.J.A., Seipel, T., Irvine, K.M., Rew, L.J., and Stoy, P.C., 2019, Fire and development influences on sagebrush community plant groups across a climate gradient in northern Nevada: Ecosphere, v. 10, no. 12, p. 1–20.

Restoration Need 6

Develop site preparation and seeding and transplanting strategies that improve plant establishment and community diversity.

Next Step 6a

Develop assessment of species biology, interactions with other species, and species response to specific site conditions for management-relevant species.

Adler, P.B., Kleinhesselink, A., Hooker, G., Taylor, J.B., Teller, B., and Ellner, S.P., 2018, Weak interspecific interactions in a sagebrush steppe? Conflicting evidence from observations and experiments: Ecology, v. 99, no. 7, p. 1621–1632.

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Barnard, D.M., Germino, M.J., Arkle, R.S., Bradford, J.B., Duniway, M.C., Pilliod, D.S., Pyke, D.A., Shriver, R.K., and Welty, J.L., 2019, Soil characteristics are associated with gradients of big sagebrush canopy structure after disturbance: Ecosphere, v. 10, no. 6, 12 p.

Bishop, T.B.B., Nusink, B.C., Lee Molinari, R., Taylor, J.B., and St. Clair, S.B., 2020, Earlier fall precipitation and low-severity fire impacts on cheatgrass and sagebrush establishment: Ecosphere, v. 11, no. 1, p. 1–13.

Blank, R.R., Mackey, B., and Morgan, T., 2016, Do a native and two exotic grasses respond differently in soils conditioned by native vegetation versus an exotic grass?: Rhizosphere, v. 2, p. 38–47.

Clements, C.D., Harmon, D.N., Blank, R.R., and Weltz, M., 2017, Improving seeding success on cheatgrass-infested rangelands in northern Nevada: Rangelands, v. 39, no. 6, p. 174–181.

Davies, K.W., Bates, J.D., and Clenet, D., 2020, Improving restoration success through microsite selection—An example with planting sagebrush seedlings after wildfire: Restoration Ecology, v. 28, no. 4, p. 859–868.

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Haight, J.D., Reed, S.C., and Faist, A.M., 2019, Seed bank community and soil texture relationships in a cold desert: Journal of Arid Environments, v. 164, p. 46–52.

Hamerlynck, E.P., and Davies, K.W., 2019, Changes in abundance of 8 sagebrush-steppe bunchgrass species 13 years after coplanting: Rangeland Ecology and Management, v. 72, no. 1, p. 23–27.

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Herget, M.E., Hufford, K.M., Mummey, D.L., Mealor, B.A., and Shreading, L.N., 2015, Effects of competition with *Bromus tectorum* on early establishment of *Poa secunda* accessions—Can seed source impact restoration success?: Restoration Ecology, v. 23, no. 3, p. 277–283.

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Holthuijzen, M.F., and Veblen, K.E., 2015, Grass-shrub associations over a precipitation gradient and their implications for restoration in the Great Basin, USA: PLoS One, v. 10, no. 12, 19 p. [Also available at https://doi.org/10.1371/journal.pone.0143170.]

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James, J.J., Sheley, R.L., Leger, E.A., Adler, P.B., Hardegree, S.P., Gornish, E.S., and Rinella, M.J., 2019, Increased soil temperature and decreased precipitation during early life stages constrain grass seedling recruitment in cold desert restoration: Journal of Applied Ecology, v. 56, no. 12, p. 2609–2619.

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Next Step 6b

Synthesize available data on site preparation and seeding and transplanting strategies for sagebrush communities.

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Next Step 6c

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.

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Next Step 6d

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.

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Next Step 6e

Expand existing databases such as the Land Treatment Digital Library to include seed sources, seed quality and seedling production specifications, planting details (for example, annotated plans, equipment, weather, and site conditions), and long-term monitoring data.

NA.

Studies Related to Need 6, but Not Any of the Next Steps

NA.

Restoration Need 7

Assess the long-term effects of conifer removal treatments on hydrology, geochemical cycling, vegetation, wildlife, fuels, fire behavior, and economics.

Next Step 7a

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

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Gallo, T., Stinson, L.T., and Pejchar, L., 2017, Mitigation for energy development fails to mimic natural disturbance for birds and mammals: Biological Conservation, v. 212, p. 39–47.

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Next Step 7b

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.

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Throop, H.L., and Lajtha, K., 2018, Spatial and temporal changes in ecosystem carbon pools following juniper encroachment and removal: Biogeochemistry, v. 140, no. 3, p. 373–388.

Next Step 7c

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.

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Williams, C.J., Pierson, F.B., Kormos, P.R., Al-Hamdan, O.Z., Nouwakpo, S.K., and Weltz, M.A., 2019, Vegetation, hydrologic, and erosion responses of sagebrush steppe 9 years following mechanical tree removal: Rangeland Ecology and Management, v. 72, no. 1, p. 47–68.

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Next Step 7d

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.

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Bombaci, S.P., Gallo, T., and Pejchar, L., 2017, Small-scale woodland reduction practices have neutral or negative short-term effects on birds and small mammals: Rangeland Ecology and Management, v. 70, no. 3, p. 363–373.

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Donnelly, J.P., Tack, J.D., Doherty, K.E., Naugle, D.E., Allred, B.W., and Dreitz, V.J., 2017, Extending conifer removal and landscape protection strategies from sage-grouse to songbirds, a range-wide assessment: Rangeland Ecology and Management, v. 70, no. 1, p. 95–105.

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Niemeyer, R.J., Link, T.E., Seyfried, M.S., and Flerchinger, G.N., 2016, Surface water input from snowmelt and rain throughfall in western juniper—Potential impacts of climate change and shifts in semi-arid vegetation: Hydrological Processes, v. 30, no. 17, p. 3046–3060.

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Sandford, C.P., Kohl, M.T., Messmer, T.A., Dahlgren, D.K., Cook, A., and Wing, B.R., 2017, Greater sage-grouse resource selection drives reproductive fitness under a conifer removal strategy: Rangeland Ecology and Management, v. 70, no. 1, p. 59–67.

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Next Step 7e

Use results from retrospective vegetation studies to determine economic viability of different treatment options based on treatment lifetime and cost of application.

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Next Step 7f

Synthesize findings from ongoing studies addressing the long-term effects of mechanical and fire-based conifer treatments on ecosystem properties.

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Studies Related to Need 7, but Not Any of the Next Steps

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Severson, J.P., Hagen, C.A., Maestas, J.D., Naugle, D.E., Forbes, J.T., and Reese, K.P., 2017, Restoring sage-grouse nesting habitat through removal of early successional conifer: Restoration Ecology, v. 25, no. 6, p. 1026–1034.

Restoration 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.

Next Step 8a

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.

Bates, J.D., Davies, K.W., Hulet, A., Miller, R.F., and Roundy, B., 2017, Sage-grouse groceries—Forb response to piñon-juniper treatments: Rangeland Ecology and Management, v. 70, no. 1, p. 106–115.

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Next Step 8b

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.

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Next Step 8c

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Next Step 8d

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.

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Restoration 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.

Next Step 9a

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.

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Next Step 9b

Study the impacts of fire on conifer seed banks.
NA.

Next Step 9c

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.

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Next Step 9d

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.

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Restoration 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.

Next Step 10a

Assess soil degradation across sagebrush ecosystems with regards to fire, nonnative annual grass invasion, grazing, and other disturbances.

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Next Step 10f

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