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

Open-File Report 2023–1009

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

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By Matthew J. Holloran, Christopher R. Anthony, 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
FTEM	Fuels Treatment Effectiveness Monitoring
IRFMS	Integrated Rangeland Fire Management Strategy
MZ	WAFWA Sage-grouse Management Zone
OFR	Open-File Report
SageSTEP	Sagebrush Steppe Treatment Evaluation Project
USGS	U.S. Geological Survey
WAFWA	Western Association of Fish and Wildlife Agencies

Species names

Basin big sagebrush	*A. t. tridentata*
Big sagebrush	*A. tridentata* spp.
Cheatgrass	*Bromus tectorum*
Crested wheatgrass	*Agropyron cristatum*
Greater sage-grouse	*Centrocercus urophasianus*
Kochia	*Kochia scoparia*
Mountain big sagebrush	*A. t. vaseyana*
Sagebrush	*Artemisia* spp.
Wyoming big sagebrush	*A. t. 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 significant 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 eight needs (hereinafter known as "Needs") identified under the Fire topic in the Plan, defined as any non-structure fire that occurs in vegetation or natural fuels, including wildfires and prescribed fires. The topic outlined research Needs broadly focused on understanding the mechanisms and management of threats posed to the maintenance of large, contiguous sagebrush rangelands by fire. 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 (in other words., addressed poorly) in the literature through 2020. Our searches resulted in the inclusion of 156 science products that at least partially addressed a Need identified in the Fire topic. The Needs that were well and partially addressed included:

(1) studies of relationships between fire and the sagebrush ecosystem (Need 1);

(2) investigations of the responses of sage-grouse to burned area characteristics (Need 2);

(3) spatial modeling of fire risk (Need 3);

(4) studies of the effects of fuels management treatments (Need 4);

(5) sagebrush reduction treatments on multiple characteristics of the sagebrush ecosystem (Need 6); and

(6) assessments of the role of fire in maintaining healthy sagebrush communities (Need 7).

Needs addressed poorly included:

(1) assessments of the effects of fuel breaks on sage-grouse (Need 5); and

(2) investigations of characteristics associated with the effectiveness of fuel breaks (Need 8).

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, 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 (for example, 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 rangeland 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, 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.

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.

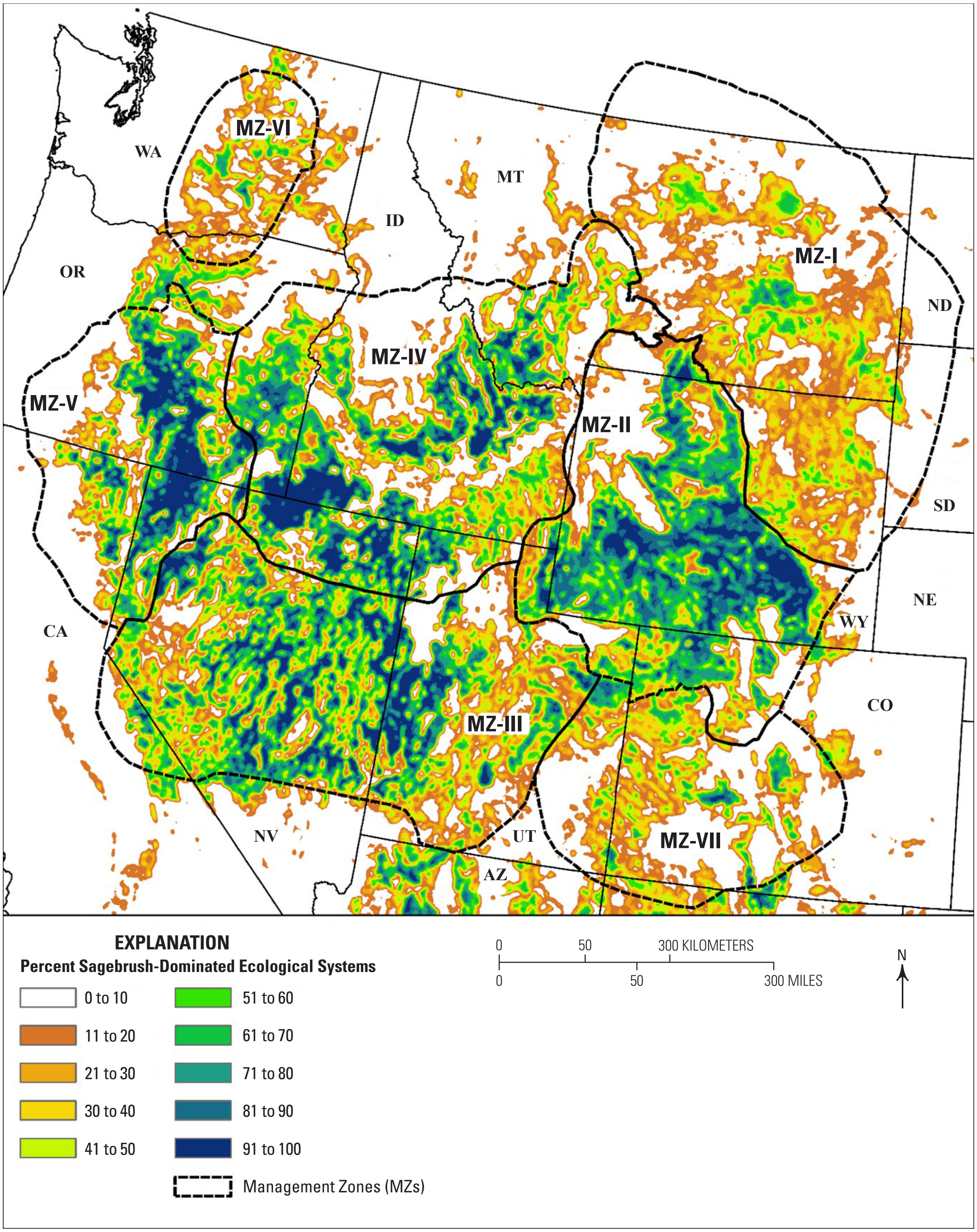

Figure 1. Map showing the landscape cover of sagebrush-dominated ecological systems in the western United States (fig. 28 from Chambers and others, 2017).

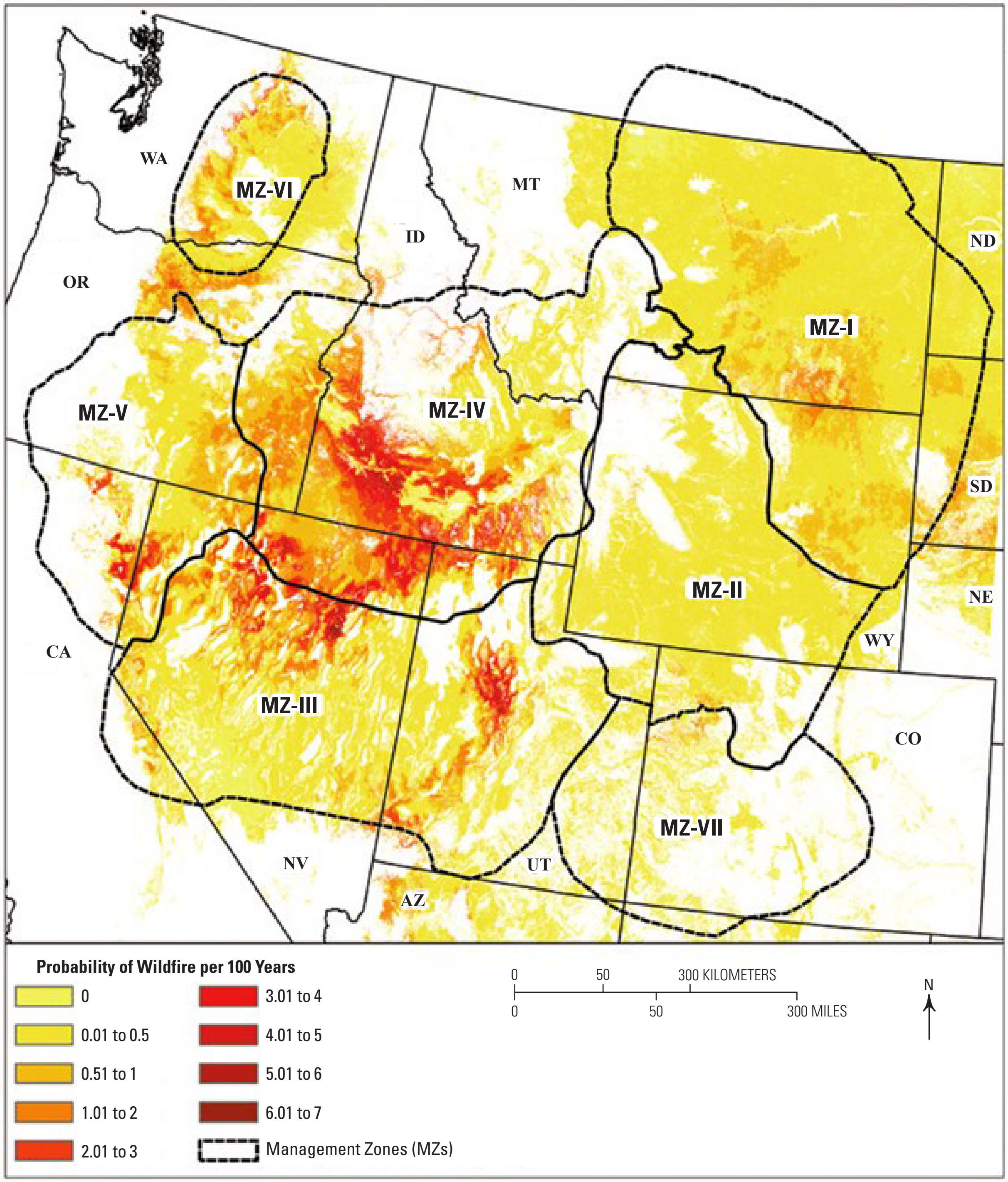

Figure 2. Map showing large fire probability for the sagebrush biome in the western United States (fig. 34 from Chambers and others, 2017).

Conservation strategies depend on the consideration and application of the best available science, and on-going 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 the 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 Fire topic in the Plan identified eight Needs focused on understanding the mechanisms and management of threats posed to the maintenance of large, contiguous sagebrush rangelands by fire, defined as wildland fire—any non-structure fire that occurs in vegetation or natural fuels, including wildfires and prescribed fires (Steblein and others, 2021). The priorities identified across the eight Needs broadly encompassed:

(1) studies of the effectiveness of fuel treatments (including fuel breaks);

(2) assessments of the effects of these fuel treatments on greater sage-grouse (*Centrocercus urophasianus*; hereinafter sage-grouse) and other sagebrush-dependent wildlife populations and habitats;

(3) investigations of fire regimes in the sagebrush ecosystem including the role of fire in degrading and maintaining healthy sagebrush communities; and

(4) the development of enhanced, spatially-explicit approaches to understanding fire risk.

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 eight Needs identified under the Fire 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 Fire topic, we initially searched the reference databases Web of Science and Scopus using broad search terms (for example, fire AND sagebrush) 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, fire suppression AND sagebrush) 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 Fire 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 Fire 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, 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.

Table 1. Search results for the Fire 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, “fire” and “suppression” searched, not “fire suppression”). This resulted in broader and more inclusive lists of literature. **Unique results:** 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 “fuel AND sagebrush” and “treatment AND sagebrush” searches).**Comments:** Need 1, studies of relationships between fire and the sagebrush ecosystem; Need 2, investigations of the responses of sage-grouse to burned area characteristics; Need 3, spatial modeling of fire risk; Need 4, studies of the effects of fuels management treatments; Need 5, assessments of the effects of fuel breaks on sage-grouse; Need 6, sagebrush reduction treatments on multiple characteristics of the sagebrush ecosystem; Need 7, assessments of the role of fire in maintaining healthy sagebrush communities; Need 8, investigations of characteristics associated with the effectiveness of fuel breaks]

Search terms	Unique results	Comment
fire AND sagebrush[1]	277	2015–20; broad search term
fuel AND sagebrush	65	2015–20; broad search term
treatment AND sagebrush	214	2015–20; broad search term
fire regimes AND sagebrush	60	2015–20; Need 1; targeted search term
fire history AND sagebrush	31	2015–20; Need 1; targeted search term
burn severity AND sagebrush[1]	10	2015–20; Need 1; targeted search term
fire AND sage-grouse	28	October 2019–20; Need 2; targeted search term to capture papers in our timeframe not captured by Carter and others (2020)
fire suppression AND sagebrush	12	2015–20; Need 3; targeted search term
fire behavior model AND sagebrush	13	2015–20; Need 3; targeted search term
wildfire risk AND sagebrush	26	2015–20; Need 3; targeted search term
fire AND risk AND sagebrush	37	2015–20; Need 3; targeted search term
next generation physics-based fire model AND sagebrush	0	2015–20; Need 3; targeted search term
fuel reduction treatments AND sagebrush	16	2015–20; Need 4; targeted search term
fuel breaks AND sagebrush	4	2015–20; Needs 5 and 8; targeted search term
sagebrush removal	88	2015–20; Need 6; targeted search term
sagebrush reduction treatments	40	2015–20; Need 6; targeted search term
livestock grazing AND fire behavior AND sagebrush	2	2015–20; Need 7; targeted search term
sagebrush recovery AND fire	75	2015–20; Need 7; 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.

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 (in other words, no papers were reviewed that considered the objective(s) detailed in the Next Step) and 1.0 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) and included in the scoring of the Need. Each Need was scored as the proportion of the Next 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

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

[NA, Next Step not included in scoring of Need]

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 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

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 (in other words, “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 ongoing research programs using the search and scoring methods described in this report when updating the Plan.

Results and Summary

We reviewed 998 products that were identified by the literature searches conducted for the Fire topic (table 1). Of those, 156 unique products were directly related to at least one of the eight Needs. Most (73 percent) of the 48 Next Steps included in the topic had greater than or equal to one published product that at least partially addressed the science objective(s) of that Next Step. Five Next Steps could not be effectively assessed with the evaluation approach we used and were not scored (“NA”; table 2). The eight 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 the regional variation in the magnitude of behavioral and demographic responses of sage-grouse populations to fire (Need 2);

(2) validation of fire behavior models using field-derived data (Need 3); and

(3) detailed assessments of fuel breaks, including investigations of effectiveness, longevity, maintenance requirements, economic tradeoffs, and impacts to sage-grouse behavior and demographics, and development and assessment of decision support tools to inform the strategic placement of fuel breaks (Needs 5 and 8).

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.

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

Need	Score	Summary of 2015–20 literature
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 these factors among regions to help inform habitat management and conservation.	0.75	***Addressed***: Fire data mapped from 1984 to 2013 have been used to estimate fire return intervals, fire size, fire rotation (time needed to burn the entire area of interest), and fire season timing and length across the sagebrush biome. Fire perimeter and burn severity data have been compiled from 2006, and mapping techniques updated across the sagebrush biome. Several regional scale studies, primarily in the Great Basin, investigated relationships between fine fuels (for example, invasive annual grasses) and fire occurrence probabilities, size, frequency, seasonality, and ignition source. Numerous local and regional scale studies distributed throughout the sagebrush biome investigated up to 75-year (although most were <20-year) post-fire chronosequences of vegetative response to fire in mountain, basin, and Wyoming big sagebrush communities. Local and regional scale studies in western portions of the sagebrush biome combined field and remotely sensed information into investigations of long-term post-fire recovery of sagebrush habitats. ***Outstanding***: Range wide historical estimates of fire severity are lacking. Although patterns may be discernable from the numerous local scale investigations of sagebrush response to fire published, a systematic assessment of the variation in fire characteristics and sagebrush recovery patterns post-fire by region and by vegetation type range wide has not been completed. Detailed investigations of post-fire recovery rates in eastern portions of the sagebrush biome are lacking.
Need 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.	0.57	***Addressed***: A framework for targeting sagebrush conservation and restoration activities based on resistance and resilience concepts that has range wide applicability has been developed. Several spatially-explicit conservation planning tools have been developed focusing on prioritizing the treatment of conifer expansion and restoring burned areas to protect and enhance sagebrush habitats. A limited number of local and regional scale studies directly investigating sage-grouse short-term and long-term population dynamics, nesting and brood-rearing habitat selection, and nesting success response to fire in sagebrush habitats using lek count, brood flush count, telemetry, and fire history data have been conducted. The sage-grouse literature has been comprehensively synthesized numerous times, including research on the species' response to fire (see also Sagebrush and Sage-Grouse topic Need 5). ***Outstanding***: Fine grained sagebrush conservation and restoration planning tools that have regional specificity are unavailable for much of the sagebrush biome. Information on the effects of fire in sagebrush habitats on sage-grouse short and long-term population dynamics, seasonal habitat selection, and demographics is limited to a few local and regional scale studies; spatial replication of these studies is needed. Local and regional variation in the magnitude of behavioral and demographic response of sage-grouse populations to fire in sagebrush habitats has not been established.

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

Need	Score	Summary of 2015–20 literature
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.	0.63	***Addressed***: Numerous local, regional and range wide approaches to mapping fine fuel loads (especially cheatgrass) in sagebrush habitats have been developed and used to assess annual wildfire risk at regional scales primarily in western portions of the sagebrush biome (although the mapped layers have range wide applicability). Ecoregional differences in wildfire ignition sources predicted from range wide wildfire risk models have been investigated. A series of lab experiments investigating sagebrush fire spread behavior relative to fuel moisture (and other fuel characteristics) have been conducted. ***Outstanding***: Validation of predictive wildfire risk models has not been accomplished and predictive fire behavior (for example, intensity, spread and severity) models have not been developed for the range of ecological communities and fuel environments found across the sagebrush biome. Different modeling approaches for assessing wildfire risk in sagebrush habitats have not been compared or contrasted. Science on the response of sage-grouse populations and habitats to fire has not been incorporated into wildfire risk assessments. Physics-based wildfire risk models have not been developed. The incorporation of fuels projection information into sagebrush habitat management tools (for example, state-and-transition models) has not occurred. Spatially explicit fuel moisture data (and other fuel characteristics) other than fine fuel phenology projections have not been integrated into fire behavior models to improve fire risk predictions.
Need 4: Determine the community and species-specific responses to fuels management treatments (for example, conifer removal) in both a short- and long-term context.	0.80	***Addressed***: Numerous local and regional scale studies conducted throughout the sagebrush biome have compared wildlife and vegetative response to conifer treatments (primarily prescribed fire and mastication) across a gradient of pre-treatment conifer dominance in sagebrush habitats (see also Restoration topic Needs 7, 8 and 9). Long-term (greater than 10 years post-treatment) vegetative response to conifer treatments has been investigated in several local and regional scale studies in western portions of the sagebrush biome (see also Restoration topic Needs 7, 8 and 9). Several local scale studies investigated hydrologic, erosion, and soil carbon response to the treatment of conifer expansion into sagebrush habitats in western portions of the sagebrush range. Studies of the long-term wildlife and vegetation response to conifer removal treatments in sagebrush habitats have been synthesized (see also Sagebrush and Sage-Grouse topic Need 8 and Restoration topic Need 7). ***Outstanding***: Spatial replication of investigations of the ecological mechanisms of responses to conifer treatments observed throughout the sagebrush biome is needed. Replication of studies of the long-term (greater than 10 years post-treatment) response of various wildlife and sagebrush communities to conifer removal treatments is needed especially outside of western portions of the sagebrush biome.

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

Need	Score	Summary of 2015–20 literature
Need 5: Assess the effects of fuel treatments, installation of fire breaks, and similar manipulation of fuels and 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.	0.13	***Addressed***: An evaluation and summarization of literature describing the characteristics, effectiveness at changing fire behavior, and effects on sagebrush habitat suitability for sagebrush associated wildlife (for example, potential facilitated spread of invasive species into surrounding sagebrush habitats) of fuel breaks across the sagebrush biome has been completed. A few local studies have examined vegetation and soil property responses to different approaches to constructing fuel breaks in sagebrush habitats. ***Outstanding***: 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 has not been completed. Fuel break spatial optimization models and decision support tools incorporating fire risk and ignition zone assessments, wildlife habitat suitability, economics, and suppression response to inform the strategic placement of fire breaks need to be developed for sagebrush systems. Studies of the effects of different approaches to constructing fuel breaks on vegetation, soils, and other biotic and abiotic characteristics in sagebrush habitats are limited. Although the potential effects of fuel breaks on sage-grouse have been summarized from the literature, field research on the effects of the addition of fuel breaks to existing sagebrush habitats on sage-grouse movement patterns, habitat use, demographics, and habitat suitability have not been conducted. Literature pertaining to the potential effects of fuel breaks of spreading invasive plant species (for example, forage kochia) into sagebrush habitats has been summarized, but studies directly investigating the spread of nonnative plants into adjacent sagebrush communities as a result of the construction of fuel breaks have not been conducted. See also Fire topic Need 8 summary.
Need 6: Assess the long-term effects of sagebrush reduction treatments on hydrology, geochemical cycling, vegetation, wildlife (for example, greater sage-grouse), fuels, fire behavior, and economics.	0.75	***Addressed:*** Several local scale studies distributed throughout the sagebrush biome examined the effects of different sagebrush removal techniques (in other words, fire, mowing, herbicide treatment, and seeding) on vegetation and wildlife, and to a lesser extent hydrological processes. Several studies quantified long-term (>10 years and up to 50 years post treatment) vegetation responses to sagebrush removal treatments. Syntheses on the effects of shrub management and fire on sagebrush rangelands and wildlife have been completed. ***Outstanding***: The effects of sagebrush removal on geochemical cycling, fuels, and to a lesser extent hydrology have not been studied. Studies describing the long-term (>15 years) effects of sagebrush removal treatments on sagebrush obligate wildlife, fuels, hydrology, geochemical cycling, and vegetation need to be replicated across the sagebrush biome. The literature on the effects of the variety of sagebrush removal treatments on ecological and economic attributes other than wildlife needs to be synthesized.

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

Need	Score	Summary of 2015–20 literature
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.	0.75	***Addressed***: Responses of the vegetation community, including invasive annual grasses, native perennial species, fire and fuel behavior, and biological soil crusts, have been investigated in relation to interactions between livestock grazing and prescribed fire and wildfire at local and regional scales primarily in western portions of the sagebrush biome (see also Invasives topic Need 4, and Restoration topic Needs 3). A few studies characterized vegetation community responses over a period of >10 years after fire, with local scale descriptions of associations between pre-fire and post-fire conditions (see also Fire topic Need 4). Although a comprehensive synthesis describing the risk of fire, sagebrush loss, post-fire vegetation responses, and benefits of fire for wildlife and plant community structure and function has not been done, several reviews have been conducted that are related to this objective (see Restoration topic Needs 3 and 5). ***Outstanding***: The role of fire in managing sagebrush communities that are resistant to invasive annual grasses and resilient to disturbances while balancing the loss of intact sagebrush and allowing natural processes to occur is poorly understood across the range of different regions, communities, and ecological types within the sagebrush biome. Studies investigating if prescribed and natural fire play similar ecological roles are lacking. Investigations of the effects of livestock grazing at management-relevant scales (for example, distribution and activity at the scale of a pasture or ranch) in relation to fire behavior and fuels, and post-fire restoration success, have not been conducted. Studies investigating interactions between pre-fire conditions and post-fire management need replication. Evaluations of existing treatment effectiveness monitoring data (for example, from BLM, Natural Resources Conservation Service) to quantify native herbaceous cover and functional diversity thresholds needed to resist invasion of nonnative annual grasses have not been completed.
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.	0.00	***Addressed***: None ***Outstanding***: Detailed assessments of fuel breaks, including their effectiveness at reducing fire severity, intensity and spread long-term, economic tradeoffs among different types, longevity, and maintenance requirements have not been published. Research analyzing Fuels Treatment Effectiveness Monitoring (FTEM) data has not been published.

The Needs that were addressed well (scores ≥0.67) included studies of relationships and patterns of variation between fire and the sagebrush ecosystem (Need 1); investigations of community and species-specific responses to fuels management treatments (for example, conifer removal) (Need 4); investigations of the effects of sagebrush reduction treatments on multiple characteristics of the sagebrush ecosystem (for example, wildlife, hydrology, geochemical cycling, etc.) (Need 6); and assessments of the role of fire in maintaining healthy sagebrush communities (Need 7). Historic fire and fine fuels data have been used to estimate fire size, frequency, seasonality, occurrence probabilities, and ignition source across most of the sagebrush biome. Post-fire chronosequences (up to 75 years) have been used to assess long-term vegetative, hydrologic, erosion, and soil carbon responses to fire and conifer treatments in sagebrush communities. Wildlife and vegetative response to conifer treatments across a gradient of pre-treatment conifer dominance in sagebrush habitats have been studied and synthesized. The short and long-term effects of different sagebrush removal techniques (in other words, fire, mowing, herbicide treatment, and seeding) on vegetation and wildlife, and to a lesser extent hydrological processes, have been examined. Responses of vegetative communities (including invasive annual grasses, native perennial species, and biological soil crusts) and fire behavior and fuel treatments have been investigated in relation to interactions between livestock grazing and fire at local and regional scales primarily in western portions of the sagebrush biome.

The Needs that were partially addressed (scores 0.50–0.66) included investigations of demographic and behavioral responses of sage-grouse populations and individuals to burned area characteristics (Need 2); and the development of spatial fire potential assessments (for example, mapped projections of fire probability) for informing sagebrush habitat management and fire suppression efforts (Need 3). Frameworks for targeting sagebrush conservation, restoration, and conifer treatment activities based on resistance and resilience concepts linked to sage-grouse habitat suitability have been developed, and some local and regional scale studies have directly investigated sage-grouse response to fire. Numerous approaches to mapping fine fuel loads in sagebrush habitats have been developed and used to assess wildfire risk primarily in western portions of the sagebrush biome.

The Needs that were addressed poorly (scores ≤0.49) included assessments of the effects of fuel manipulation treatments (for example, fuel breaks) on sage-grouse habitat use, movement patterns, and population trends (Need 5); and investigations of characteristics (for example, placement, plant material used) that increase the effectiveness of fuel breaks (Need 8). Detailed assessments of fuel breaks, including spatial optimization models incorporating fire risk and ignition zone information, effectiveness at reducing fire severity, intensity and spread, impacts on wildlife habitat suitability, economics, longevity, and maintenance requirements have not been published. Studies of the effects of different approaches to constructing fuel breaks on vegetation, soils, and other biotic and abiotic characteristics of sagebrush habitats are limited.

There were several Next Steps identified under the Fire topic that were addressed poorly, even when the overall Need was well or partially addressed. There remains a need for systematic assessments of the variation in fire characteristics and sagebrush recovery patterns post-fire by region and by vegetation type across the sagebrush biome (Need 1). Information on the effects of fire on sage-grouse population dynamics, seasonal habitat selection, and demographics is limited to a few local and regional scale studies and replication of this research remains a need (Need 2). Predictive fire potential and behavior models have not been validated, data input requirements have not been assessed, and fuel characteristics data (for example, fuel moisture) and wildlife response projections (for example, sage-grouse response to fire) have not been incorporated into these models (Need 3). Studies describing the long-term effects of sagebrush and conifer removal treatments on sagebrush obligate wildlife, fuels, hydrology, geochemical cycling, and vegetation remain to be replicated across the sagebrush biome (Needs 4 and 6). The assessment of the effectiveness of fuel treatments, especially as related to response of sage-grouse populations to the implementation of these measures, also requires replication across the sagebrush biome (Need 5). 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 (Need 5). The role of fire in managing resistant and resilient sagebrush communities while balancing the loss of intact sagebrush is poorly understood (Need 7). Evaluations of existing treatment effectiveness monitoring data (for example, from BLM, Natural Resources Conservation Service) to quantify native herbaceous cover and functional diversity thresholds needed to resist invasion of nonnative annual grasses are needed. Lastly, studies of the effects of herbivory at management-relevant scales (for example, livestock distribution and activity at the scale of a pasture) in relation to fire behavior and fuels, and post-fire restoration success, are lacking (Need 7).

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 fragmentation 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 Defined as wildland fire—any non-structure fire that occurs in vegetation or natural fuels including wildfires and prescribed fires

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

Fire potential The likelihood of a wildland fire event measured in terms of anticipated occurrence of fire(s) and management's capability to respond; influenced by factors including fuel conditions, ignition triggers, significant weather triggers, and resource capability

Fire risk The chance of fire starting, as determined by the presence and activity of causative agents, and consequences of in terms of loss of life, damage, etc.

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 (in other words, 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 Fire 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."

Fire 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.

Next Step 1a

Initiate fire history studies to understand historical and contemporary fire regimes (for example, fire frequency, intensity, severity, seasonality, size distribution, and patchiness) across the sagebrush ecosystem.

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Requena-Mullor, J.M., Maguire, K.C., Shinneman, D.J., and Caughlin, T.T., 2019, Integrating anthropogenic factors into regional-scale species distribution models—A novel application in the imperiled sagebrush biome: Global Change Biology, v. 25, no. 11, p. 3844–3858.

Next Step 1b

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.

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Duniway, M.C., Palmquist, E., and Miller, M.E., 2015, Evaluating rehabilitation efforts following the Milford Flat Fire—Successes, failures, and controlling factors: Ecosphere, v. 6, no. 5, article 80, 33 p.

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Shriver, R.K., Andrews, C.M., Arkle, R.S., Barnard, D.M., Duniway, M.C., Germino, M.J., Pilliod, D.S., Pyke, D.A., Welty, J.L., and Bradford, J.B., 2019, Transient population dynamics impede restoration and may promote ecosystem transformation after disturbance: Ecology Letters, v. 22, no. 9, p. 1357–1366.

Swanson, J.C., Murphy, P.J., Swanson, S.R., Schultz, B.W., and McAdoo, J.K., 2018, Plant community factors correlated with Wyoming big sagebrush site responses to fire: Rangeland Ecology and Management, v. 71, no. 1, p. 67–76.

Weiner, N.I., Strand, E.K., Bunting, S.C., and Smith, A.M.S., 2016, Duff distribution influences fire severity and post-fire vegetation recovery in sagebrush steppe: New York, New York, Ecosystems, v. 19, no. 7, p. 1196–1209.

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, article e02990, 20 p.

Next Step 1c

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).

See also Sagebrush and Sage-Grouse topic Need 4.

Barker, B.S., Pilliod, D.S., Rigge, M., and Homer, C.G., 2019, Pre-fire vegetation drives post-fire outcomes in sagebrush ecosystems—Evidence from field and remote sensing data: Ecosphere v. 10, no. 11, article e02929, 29 p.

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.

Rodhouse, T.J., Irvine, K.M., and Bowersock, L., 2020, Post-fire vegetation response in a repeatedly burned low-elevation sagebrush steppe protected area provides insights about resilience and invasion resistance: Frontiers in Ecology and Evolution, v. 8, article 584726, 14 p.

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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.

Next Step 1d

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.

Board, D.I., Chambers, J.C., Miller, R.F., and Weisberg, P.J., 2018, Fire patterns in piñon and juniper land cover types in the Semiarid Western United States from 1984 through 2013: U.S. Forest Service, Rocky Mountain Research Station, General Technical Report RMRS-GTR-372, 57 p, accessed January 26, 2022, at https://www.fs.usda.gov/treesearch/pubs/55663.

Limb, R.F., Fuhlendorf, S.D., Engle, D.M., and Miller, R.F., 2016, Synthesis paper—Assessment of research on rangeland fire as a management practice: Rangeland Ecology and Management, v. 69, no. 6, p. 415–422.

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

Boyd, C.S., Davies, K.W., and Hulet, A., 2015, Predicting fire-based perennial bunchgrass mortality in big sagebrush plant communities: International Journal of Wildland Fire, v. 24, no. 4, p. 527–533.

Fire Need 2

Assess changes in greater sage-grouse demographic rates, including: (1) survival, reproductive success, and movement patterns in response to burned areas and (2) the interactive effects of fire or treatment size and timing on the response of sage-grouse individuals and populations.

Next Step 2a

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.

Foster, L.J., Dugger, K.M., Hagen, C.A., and Budeau, D.A., 2019, Greater sage-grouse vital rates after wildfire: 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 2b

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.

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.

Dahlgren, D.K., Larsen, R.T., Danvir, R., Wilson, G., Thacker, E.T., Black, T.A., Naugle, D.E., Connelly, J.W., and Messmer, T.A., 2015, Greater sage-grouse and range management—Insights from a 25-year case study in Utah and Wyoming: Rangeland Ecology and Management, v. 68, no. 5, p. 375–382.

Davis, D.M., and Crawford, J.A., 2015, Case study—Short-term response of greater sage-grouse habitats to wildfire in mountain big sagebrush communities: Wildlife Society Bulletin, v. 39, no. 1, p. 129–137.

Fremgen-Tarantino, M.R., Pena, J.J., Connelly, J.W., and Forbey, J.S., 2020, Winter foraging ecology of greater sage-grouse in a post-fire landscape: Journal of Arid Environments, v. 178, article 104154, 10 p.

Pennington, V.E., Schlaepfer, D.R., Beck, J.L., Bradford, J.B., Palmquist, K.A., and Lauenroth, W.K., 2016, Sagebrush, greater sage-grouse, and the occurrence and importance of forbs: Western North American Naturalist, v. 76, no. 3, p. 298–312.

Smith, K.T., and Beck, J.L., 2018, Sagebrush treatments influence annual population change for greater sage-grouse: Restoration Ecology, v. 26, no. 3, p. 497–505.

Steenvoorden, J., Meddens, A.J.H., Martinez, A.J., Foster, L.J., and Kissling, W.D., 2019, The potential importance of unburned islands as refugia for the persistence of wildlife species in fire-prone ecosystems: Ecology and Evolution, v. 9, no. 15, p. 8800–8812.

Next Step 2c

Review and synthesize information about sage-grouse habitat selection, behavior (for example, 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.

See Sagebrush and Sage-Grouse topic Needs 3, 5, 6, 8, and 9.

Next Step 2d

Improve decision-support tools to inform prioritization of suppression and fuels management activities to maximize protection of sage-grouse habitat.

See also Sagebrush and Sage-Grouse topic Need 9; Restoration topic Need 9.

Boyd, C.S., Kerby, J.D., Svejcar, T.J., Bates, J.D., Johnson, D.D., and Davies, K.W., 2017, The sage-grouse habitat mortgage—Effective conifer management in space and time: Rangeland Ecology and Management, v. 70, no. 1, p. 141–148.

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., 2017, 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. General Technical Report RMRS-GTR360, p. 213.

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.

Chambers, J.C., Brooks, M.L., Germino, M.J., Maestas, J.D., Board, D.I., Jones, M.O., and Allred, B.W., 2019, Operationalizing resilience and resistance concepts to address invasive grass-fire cycles: Frontiers in Ecology and Evolution, v. 7, article 185, 25 p.

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, General Technical Report RMRS-GTR-389, 237 p.

Farzan, S., Young, D.J.N., Dedrick, A.G., Hamilton, M., Porse, E.C., Coates, P.S., and Sampson, G., 2015, Western juniper management—Assessing strategies for improving greater sage-grouse habitat and rangeland productivity: Environmental Management, v. 56, no. 3, p. 675–683.

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 2e

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.

Coates, P.S., Ricca, M.A., Prochazka, B.G., Brooks, M.L., Doherty, K.E., Kroger, T., Blomberg, E.J., Hagen, C.A., and Casazza, M.L., 2016, Wildfire, climate, and invasive grass interactions negatively impact an indicator species by reshaping sagebrush ecosystems: Proceedings of the National Academy of Sciences of the United States of America, v. 113, no. 45, p. 12745–12750.

Dahlgren, D.K., Larsen, R.T., Danvir, R., Wilson, G., Thacker, E.T., Black, T.A., Naugle, D.E., Connelly, J.W., and Messmer, T.A., 2015, Greater sage-grouse and range management—Insights from a 25-year case study in Utah and Wyoming: Rangeland Ecology and Management, v. 68, no. 5, p. 375–382.

Next Step 2f

Analyze wildfire monitoring data to determine the effects of rangeland fire (for example, severity and patchiness), vegetation, or other factors on sage-grouse population dynamics.

Coates, P.S., Ricca, M.A., Prochazka, B.G., Brooks, M.L., Doherty, K.E., Kroger, T., Blomberg, E.J., Hagen, C.A., and Casazza, M.L., 2016, Wildfire, climate, and invasive grass interactions negatively impact an indicator species by reshaping sagebrush ecosystems: Proceedings of the National Academy of Sciences of the United States of America, v. 113, no. 45, p. 12745–12750.

Smith, K.T., and Beck, J.L., 2018, Sagebrush treatments influence annual population change for greater sage-grouse: Restoration Ecology, v. 26, no. 3, p. 497–505.

Steenvoorden, J., Meddens, A.J.H., Martinez, A.J., Foster, L.J., and Kissling, W.D., 2019, The potential importance of unburned islands as refugia for the persistence of wildlife species in fire-prone ecosystems: Ecology and Evolution, v. 9, no. 15, p. 8800–8812.

Next Step 2g

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.

Not addressed.

Fire 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.

Next Step 3a

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.

Bateman, T.M., Villalba, J.J., Ramsey, R.D., and Sant, E.D., 2020, A multi-scale approach to predict the fractional cover of medusahead: Rangeland Ecology and Management, v. 73, no. 4, p. 538–546.

Boyte, S.P., and Wylie, B.K., 2016, Near-real-time cheatgrass percent cover in the northern Great Basin, USA, 2015: Rangelands, v. 38, no. 5, p. 278–284.

Boyte, S.P., Wylie, B.K., and Major, D.J., 2016, Cheatgrass percent cover change—Comparing recent estimates to climate change–driven predictions in the northern Great Basin: Rangeland Ecology and Management, v. 69, no. 4, p. 265–279.

Boyte, S.P., Wylie, B.K., Major, D.J., and Brown, J.F., 2015, The integration of geophysical and enhanced Moderate Resolution Imaging Spectroradiometer Normalized Difference Vegetation Index data into a rule-based, piecewise regression-tree model to estimate cheatgrass beginning of spring growth: International Journal of Digital Earth, v. 8, no. 2, p. 118–132.

Bradley, B.A., Curtis, C.A., Fusco, E.J., Abatzoglou, J.T., Balch, J.K., Dadashi, S., and Tuanmu, M.N., 2018, Cheatgrass (*Bromus tectorum*) distribution in the intermountain western United States and its relationship to fire frequency, seasonality, and ignitions: Biological Invasions, v. 20, no. 6, p. 1493–1506.

Brummer, T.J., Taylor, K.T., Rotella, J., Maxwell, B.D., Rew, L.J., and Lavin, M., 2016, Drivers of *Bromus tectorum* abundance in the western North American sagebrush steppe: New York, New York, Ecosystems, v. 19, no. 6, p. 986–1000.

Fusco, E.J., Finn, J.T., Balch, J.K., Nagy, R.C., and Bradley, B.A., 2019, Invasive grasses increase fire occurrence and frequency across US regions: Proceedings of the National Academy of Sciences of the United States of America, v. 116, no. 47, p. 23594–23599.

Hak, J.C., and Comer, P.J., 2020, Modeling invasive annual grass abundance in the cold desert ecoregions of the interior western United States: Rangeland Ecology and Management, v. 73, no. 1, p. 171–180.

Pastick, N.J., Dahal, D., Wylie, B.K., Parajuli, S., Boyte, S.P., and Wu, Z., 2020, Characterizing land surface phenology and exotic annual grasses in dryland ecosystems using Landsat and Sentinel-2 data in harmony: Remote Sensing, v. 12, no. 4, article 725, 17 p.

Pastick, N.J., Wylie, B.K., and Wu, Z.T., 2018, Spatiotemporal analysis of Landsat-8 and Sentinel-2 data to support monitoring of dryland ecosystems: Remote Sensing, v. 10, no. 5, article 791, 15 p.

Pilliod, D.S., Welty, J.L., and Arkle, R.S., 2017, Refining the cheatgrass-fire cycle in the Great Basin—Precipitation timing and fine fuel composition predict wildfire trends: Ecology and Evolution, v. 7, no. 19, p. 8126–8151.

Sparks, A.M., Boschetti, L., Smith, A.M.S., Tinkham, W.T., Lannom, K.O., and Newingham, B.A., 2015, An accuracy assessment of the MTBS burned area products for shrub-steppe fires in the northern Great Basin, United States: International Journal of Wildland Fire, v. 24, no. 1, p. 70–78.

Young, K.R., Roundy, B.A., Bunting, S.C., and Eggett, D.L., 2015, Utah juniper and two-needle pinon reduction alters fuel loads: International Journal of Wildland Fire, v. 24, no. 2, p. 236–248.

Next Step 3b

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.

See Next Step 3a and 3c.

Next Step 3c

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.

Bradley, B.A., Curtis, C.A., Fusco, E.J., Abatzoglou, J.T., Balch, J.K., Dadashi, S., and Tuanmu, M.N., 2018, Cheatgrass (*Bromus tectorum*) distribution in the intermountain western United States and its relationship to fire frequency, seasonality, and ignitions: Biological Invasions, v. 20, no. 6, p. 1493–1506.

Fusco, E.J., Abatzoglou, J.T., Balch, J.K., Finn, J.T., and Bradley, B.A., 2016, Quantifying the human influence on fire ignition across the western USA: Ecological Applications, v. 26, no. 8, p. 2390–2401.

Link, S.O., Hill, R.W., and Bansal, S., 2019, Fire risk in revegetated bunchgrass communities infested with *Bromus tectorum*: Rangeland Ecology and Management, v. 72, no. 3, p. 539–541.

Pilliod, D.S., Welty, J.L., and Arkle, R.S., 2017, Refining the cheatgrass-fire cycle in the Great Basin—Precipitation timing and fine fuel composition predict wildfire trends: Ecology and Evolution, v. 7, no. 19, p. 8126–8151.

Next Step 3d

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.

Qi, Y., Jolly, W.M., Dennison, P.E., and Kropp, R.C., 2016, Seasonal relationships between foliar moisture content, heat content and biochemistry of lodgepole pine and big sagebrush foliage: International Journal of Wildland Fire, v. 25, no. 5, p. 574–578.

Shen, C., and Fletcher, T.H., 2015, Fuel element combustion properties for live wildland Utah shrubs: Combustion Science and Technology, v. 187, no. 3, p. 428–444.

Shen, C., Gallacher, J.R., Prince, D.R., Fletcher, T.H., and Weise, D.R., 2015, Experiments and modeling of fire spread in shrubs in a wind tunnel: Cincinnati, Ohio, Proceedings 9th U.S. National Combustion Meeting, Combustion Institute, 10 p.

Shen, C., Prince, D.R., Gallacher, J., Fletcher, M.E., and Fletcher, T.H., 2017, Semi-empirical model for fire spread in chamise and big sagebrush shrubs with spatially-defined fuel elements and flames: College Park, Maryland, Proceedings 10th U.S. National Combustion Meeting, Combustion Institute, 6 p.

Next Step 3e

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 (for example, state-and-transition models, fire behavior models).

Boyte, S.P., Wylie, B.K., and Major, D.J., 2019, Validating a time series of annual grass percent cover in the sagebrush ecosystem: Rangeland Ecology and Management, v. 72, no. 2, p. 347–359.

Frost, S.M., Alexander, M.E., DeRose, R.J., and Jenkins, M.J., 2020, Fire-environment analysis—An example of army garrison Camp Williams, Utah: Fire, v. 3, no. 1, article 6, 20 p.

Li, Z., Shi, H., Vogelmann, J.E., Hawbaker, T.J., and Peterson, B., 2020, Assessment of fire fuel load dynamics in shrubland ecosystems in the western United States using MODIS products: Remote Sensing, v. 12, no. 12, article 1911, 17 p.

Weiner, N.I., Strand, E.K., Bunting, S.C., and Smith, A.M.S., 2016, Duff distribution influences fire severity and post-fire vegetation recovery in sagebrush steppe: New York, New York, Ecosystems, v. 19, no. 7, p. 1196–1209.

Next Step 3f

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.

Not addressed, but see Next Steps 3a and 3b.

Next Step 3g

Incorporate new science on fire effects on sage-grouse habitat and populations into new wildfire risk assessments.

Davis, D.M., and Crawford, J.A., 2015, Case study—Short-term response of greater sage-grouse habitats to wildfire in mountain big sagebrush communities: Wildlife Society Bulletin, v. 39, no. 1, p. 129–137.

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.

Pennington, V.E., Schlaepfer, D.R., Beck, J.L., Bradford, J.B., Palmquist, K.A., and Lauenroth, W.K., 2016, Sagebrush, greater sage-grouse, and the occurrence and importance of forbs: Western North American Naturalist, v. 76, no. 3, p. 298–312.

Smith, K.T., and Beck, J.L., 2018, Sagebrush treatments influence annual population change for greater sage-grouse: Restoration Ecology, v. 26, no. 3, p. 497–505.

Steenvoorden, J., Meddens, A.J.H., Martinez, A.J., Foster, L.J., and Kissling, W.D., 2019, The potential importance of unburned islands as refugia for the persistence of wildlife species in fire-prone ecosystems: Ecology and Evolution, v. 9, no. 15, p. 8800–8812.

Next Step 3h

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.

Boyte, S.P., Wylie, B.K., Major, D.J., and Brown, J.F., 2015, The integration of geophysical and enhanced Moderate Resolution Imaging Spectroradiometer Normalized Difference Vegetation Index data into a rule-based, piecewise regression-tree model to estimate cheatgrass beginning of spring growth: International Journal of Digital Earth, v. 8, no. 2, p. 118–132.

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., 2017, 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. General Technical Report RMRS-GTR360, p. 213.

Chambers, J.C., Brooks, M.L., Germino, M.J., Maestas, J.D., Board, D.I., Jones, M.O., and Allred, B.W., 2019, Operationalizing resilience and resistance concepts to address invasive grass-fire cycles: Frontiers in Ecology and Evolution, v. 7, article 185, 25 p.

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, General Technical Report RMRS-GTR-389, 237 p.

Filippelli, S.K., Falkowski, M.J., Hudak, A.T., Fekety, P.A., Vogeler, J.C., Khalyani, A.H., Rau, B.M., and Strand, E.K., 2020, Monitoring pinyon-juniper cover and aboveground biomass across the Great Basin: Environmental Research Letters, v. 15, no. 2, article 025004, 11 p.

Hawbaker, T.J., Vanderhoof, M.K., Beal, Y.J., Takacs, J.D., Schmidt, G.L., Falgout, J.T., Williams, B., Fairaux, N.M., Caldwell, M.K., Picotte, J.J., Howard, S.M., Stitt, S., and Dwyer, J.L., 2017, Mapping burned areas using dense time-series of Landsat data: Remote Sensing of Environment, v. 198, p. 504–522.

Rideout, D.B., Wei, Y., Epps, J.R., Mueller, D., and Kernohan, N., 2017, Sustainable development and the great sage-grouse: International Journal of Safety and Security Engineering, v. 7, no. 1, p. 31–40.

Next Step 3i

As next generation physics-based models become validated for operational use, incorporate their use into methods for assessing wildfire risk.

NA.

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

Balzotti, C.S., Kitchen, S.G., and McCarthy, C., 2016, Beyond the single species climate envelope—A multifaceted approach to mapping climate change vulnerability: Ecosphere, v. 7, no. 9, article e01444, 23 p.

Pennington, V.E., Schlaepfer, D.R., Beck, J.L., Bradford, J.B., Palmquist, K.A., and Lauenroth, W.K., 2016, Sagebrush, greater sage-grouse, and the occurrence and importance of forbs: Western North American Naturalist, v. 76, no. 3, p. 298–312.

Fire Need 4

Determine the community and species-specific responses to fuels management treatments (for example, conifer removal) in both a short- and long-term context.

Next Step 4a

Analyze collected data on effects of different conifer removal treatments (for example, mastication, fire, lop and scatter) on various plant and animal species and ecological communities at different spatial scales.

See also Sagebrush and Sage-Grouse topic Needs 7 and 8; Restoration topic Needs 7 and 9.

Bates, J.D., and Davies, K.W., 2016, Seasonal burning of juniper woodlands and spatial recovery of herbaceous vegetation: Forest Ecology and Management, v. 361, p. 117–130.

Bates, J.D., and Davies, K.W., 2017, Effects of conifer treatments on soil nutrient availability and plant composition in sagebrush steppe: Forest Ecology and Management, v. 400, p. 631–644.

Bates, J.D., Davies, K.W., Bournoville, J., Boyd, C., O'Connor, R., and Svejcar, T.J., 2019, Herbaceous biomass response to prescribed fire in juniper-encroached sagebrush steppe: Rangeland Ecology and Management, v. 72, no. 1, p. 28–35.

Bates, J.D., Svejcar, T., Miller, R., and Davies, K.W., 2017, Plant community dynamics 25 years after juniper control: Rangeland Ecology and Management, v. 70, no. 3, p. 356–362.

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.

Bernau, C.R., Strand, E.K., and Bunting, S.C., 2018, Fuel bed response to vegetation treatments in juniper-invaded sagebrush steppe: Fire Ecology, v. 14, no. 2, article s42408, 13 p.

Ellsworth, L.M., and Kauffman, J.B., 2017, Plant community response to prescribed fire varies by pre-fire condition and season of burn in mountain big sagebrush ecosystems: Journal of Arid Environments, v. 144, p. 74–80.

Havrilla, C.A., Faist, A.M., and Barger, N.N., 2017, Understory plant community responses to fuel-reduction treatments and seeding in an upland piñon-juniper woodland: Rangeland Ecology and Management, v. 70, no. 5, p. 609–620.

Stephens, G.J., Johnston, D.B., Jonas, J.L., and Paschke, M.W., 2016, Understory responses to mechanical treatment of pinyon-juniper in northwestern Colorado: Rangeland Ecology and Management, v. 69, no. 5, p. 351–359.

Williams, R.E., Roundy, B.A., Hulet, A., Miller, R.F., Tausch, R.J., Chambers, J.C., Matthews, J., Schooley, R., and Eggett, D., 2017, Pretreatment tree dominance and conifer removal treatments affect plant succession in sagebrush communities: Rangeland Ecology and Management, v. 70, no. 6, p. 759–773.

Wozniak, S.S., Strand, E.K., Johnson, T.R., Hulet, A., Roundy, B.A., and Young, K., 2020, Treatment longevity and changes in surface fuel loads after pinyon-juniper mastication: Ecosphere, v. 11, no. 8, article e03226, 18 p.

Young, K.R., Roundy, B.A., Bunting, S.C., and Eggett, D.L., 2015, Utah juniper and two-needle pinon reduction alters fuel loads: International Journal of Wildland Fire, v. 24, no. 2, p. 236–248.

Next Step 4b

Revisit treatments to evaluate long-term (greater than 10 years) effects of conifer removal on various species and ecological communities at different spatial scales.

Roundy, B.A., Chambers, J.C., Pyke, D.A., Miller, R.F., Tausch, R.J., Schupp, E.W., Rau, B., and Gruell, T., 2018, Resilience and resistance in sagebrush ecosystems are associated with seasonal soil temperature and water availability: Ecosphere, v. 9, no. 9, article e02417, 27 p.

Roundy, B.A., Miller, R.F., Tausch, R.J., Chambers, J.C., and Rau, B.M., 2020, Long-term effects of tree expansion and reduction on soil climate in a semiarid ecosystem: Ecosphere, v. 11, no. 9, article e03241, 18 p.

Williams, C.J., Johnson, J.C., Pierson, F.B., Burleson, C.S., Polyakov, V.O., Kormos, P.R., and Nouwakpo, S.K., 2020, Long-term effectiveness of tree removal to re-establish sagebrush steppe vegetation and associated spatial patterns in surface conditions and soil hydrologic properties: Water, v. 12, no. 8, article 2213, 35 p.

Next Step 4c

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.

Ernst-Brock, C., Turner, L., Tausch, R.J., and Leger, E.A., 2019, Long-term vegetation responses to pinyon-juniper woodland reduction treatments in Nevada, USA: Journal of Environmental Management, v. 242, p. 315–326.

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.

Wozniak, S.S., Strand, E.K., Johnson, T.R., Hulet, A., Roundy, B.A., and Young, K., 2020, Treatment longevity and changes in surface fuel loads after pinyon-juniper mastication: Ecosphere, v. 11, no. 8, article e03226, 18 p.

Next Step 4d

Conduct mechanistic studies that reveal relationships between treatments and system responses to conifer removal and the underlying ecological basis for changes observed.

Abdallah, M.A.B., Mata-Gonzalez, R., Noller, J.S., and Ochoa, C.G., 2020, Ecosystem carbon in relation to woody plant encroachment and control—Juniper systems in Oregon, USA: Agriculture, Ecosystems, and Environment, v. 290, article 106762, 10 p.

Nouwakpo, S.K., Williams, C.J., Pierson, F.B., Weitz, M.A., Kormos, P.R., Arslan, A., and Al-Hamdan, O.Z., 2020, Effectiveness of prescribed fire to re-establish sagebrush steppe vegetation and ecohydrologic function on woodland-encroached sagebrush rangelands, Great Basin, USA—Part II—Runoff and sediment transport at the patch scale: Catena, v. 185, article 104301, 15 p.

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.

Urza, A.K., Weisberg, P.J., Chambers, J.C., Dhaemers, J.M., and Board, D., 2017, Post-fire vegetation response at the woodland—Shrubland interface is mediated by the pre-fire community: Ecosphere, v. 8, no. 6, article e01851, 20 p.

Warren, S.D., St. Clair, L.L., Johansen, J.R., Kugrens, P., Baggett, L.S., and Bird, B.J., 2015, Biological soil crust response to late season prescribed fire in a Great Basin juniper woodland: Rangeland Ecology and Management, v. 68, no. 3, p. 241–247.

Williams, C.J., Pierson, F.B., Nouwakpo, S.K., Al-Hamdan, O.Z., Kormos, P.R., and Weltz, M.A., 2020, Effectiveness of prescribed fire to re-establish sagebrush steppe vegetation and ecohydrologic function on woodland-encroached sagebrush rangelands, Great Basin, USA—Part I—Vegetation, hydrology, and erosion responses: Catena, v. 185, article 103477, 26 p.

Next Step 4e

Synthesize findings on long-term species and community responses to conifer removal at different spatial scales.

Bombaci, S., and Pejchar, L., 2016, Consequences of pinyon and juniper woodland reduction for wildlife in North America: Forest Ecology and Management, v. 365, p. 34–50.

Hartsell, J.A., Copeland, S.M., Munson, S.M., Butterfield, B.J., and Bradford, J.B., 2020, Gaps and hotspots in the state of knowledge of pinyon-juniper communities: Forest Ecology and Management, v. 455, article 117628, 23 p.

Knick, S.T., Hanser, S.E., Grace, J.B., Hollenbeck, J.P., and Leu, M., 2017, Response of bird community structure to habitat management in pinon-juniper woodland-sagebrush ecotones: Forest Ecology and Management, v. 400, p. 256–268.

Limb, R.F., Fuhlendorf, S.D., Engle, D.M., and Miller, R.F., 2016, Synthesis paper—Assessment of research on rangeland fire as a management practice: Rangeland Ecology and Management, v. 69, no. 6, p. 415–422.

Miller, R.F., Chambers, J.C., Evers, L., Williams, C.J., Snyder, K.A., Roundy, B.A., and Pierson, F.B., 2019, The ecology, history, ecohydrology, and management of pinyon and juniper woodlands in the Great Basin and Northern Colorado Plateau of the western United States: Fort Collins, Colorado, U.S. Forest Service, Rocky Mountain Research Station, General Technical Report RMRS-GTR-403, 284 p.

Miller, R.F., Chambers, J.C., and Pellant, M., 2015, A field guide for rapid assessment of post-wildfire recovery potential in sagebrush and piñon-juniper ecosystems in the Great Basin—Evaluating resilience to disturbance and resistance to invasive annual grasses and predicting vegetation response: Fort Collins, Colorado, U.S. Forest Service, Rocky Mountain Research Station, General Technical Report RMRS-GTR-338, 70 p.

Williams, C.J., Snyder, K.A., and Pierson, F.B., 2018, Spatial and temporal variability of the impacts of pinyon and juniper reduction on hydrologic and erosion processes across climatic gradients in the western US—A regional synthesis: Water, v. 10, no. 11, article 1607, 44 p.

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

Clark, P.E., Williams, C.J., and Pierson, F.B., 2018, Factors affecting efficacy of prescribed fire for Western Juniper control: Rangeland Ecology and Management, v. 71, no. 3, p. 345–355.

Fire Need 5

Assess the effects of fuel treatments, installation of fire breaks, and similar manipulation of fuels and 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.

Next Step 5a

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.

Not addressed.

Next Step 5b

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.

Porensky, L.M., Perryman, B.L., Williamson, M.A., Madsen, M.D., and Leger, E.A., 2018, Combining active restoration and targeted grazing to establish native plants and reduce fuel loads in invaded ecosystems: Ecology and Evolution, v. 8, no. 24, p. 12533–12546.

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.

Next Step 5c

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.

Shinneman, D.J., Aldridge, C.L., Coates, P.S., Germino, M.J., Pilliod, D.S., and Vaillant, N.M., 2018, A conservation paradox in the Great Basin—Altering sagebrush landscapes with fuel breaks to reduce habitat loss from wildfire: U.S. Geological Survey Open-File Report 2018–1034, 70 p.

Shinneman, D.J., Germino, M.J., Pilliod, D.S., Aldridge, C.L., Vaillant, N.M., and Coates, P.S., 2019, The ecological uncertainty of wildfire fuel breaks—Examples from the sagebrush steppe: Frontiers in Ecology and the Environment, v. 17, no. 5, p. 279–288.

Next Step 5d

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.

Not addressed.

Next Step 5e

A synthesis to determine the applicability of past research on fragmentation and treatment effects to inform proposed strategy actions.

Hulet, A., Boyd, C.S., Davies, K.W., and Svejcar, T.J., 2015, Prefire (preemptive) management to decrease fire-induced bunchgrass mortality and reduce reliance on postfire seeding: Rangeland Ecology and Management, v. 68, no. 6, p. 437–444.

Shinneman, D.J., Aldridge, C.L., Coates, P.S., Germino, M.J., Pilliod, D.S., and Vaillant, N.M., 2018, A conservation paradox in the Great Basin—Altering sagebrush landscapes with fuel breaks to reduce habitat loss from wildfire: U.S. Geological Survey Open-File Report 2018–1034, 70 p.

Shinneman, D.J., Germino, M.J., Pilliod, D.S., Aldridge, C.L., Vaillant, N.M., and Coates, P.S., 2019, The ecological uncertainty of wildfire fuel breaks—Examples from the sagebrush steppe: Frontiers in Ecology and the Environment, v. 17, no. 5, p. 279–288.

Next Step 5f

Long-term assessment of effects of fuel breaks on sage-grouse movement patterns, habitat use, and population trends.

NA.

Next Step 5g

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.

Gray, M.E., and Dickson, B.G., 2016, Applying fire connectivity and centrality measures to mitigate the cheatgrass-fire cycle in the arid West, USA: Landscape Ecology, v. 31, no. 8, p. 1681–1696.

Next Step 5h

Long-term assessment of effects of fuel breaks on adjacent sagebrush communities, especially through spread of nonnative plants used in the fuel breaks (for example, kochia [*Bassia scoparia*]).

Aryal, P., and Islam, M.A., 2018, Effect of forage kochia on seedling growth of cheatgrass (*Bromus tectorum*) and perennial grasses: Invasive Plant Science and Management, v. 11, no. 4, p. 201–207.

Shinneman, D.J., Germino, M.J., Pilliod, D.S., Aldridge, C.L., Vaillant, N.M., and Coates, P.S., 2019, The ecological uncertainty of wildfire fuel breaks—Examples from the sagebrush steppe: Frontiers in Ecology and the Environment, v. 17, no. 5, p. 279–288.

Next Step 5i

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.

Not addressed.

Fire Need 6

Assess the long-term effects of sagebrush reduction treatments on hydrology, geochemical cycling, vegetation, wildlife (for example, greater sage-grouse), fuels, fire behavior, and economics.

Next Step 6a

Analyze data already collected to gain new understanding of effects of sagebrush removal on fuels, wildlife species, and hydrology.

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. 7, article 115, 10 p.

Chandler, D.G., Cheng, Y., Seyfried, M.S., Madsen, M.D., Johnson, C.E., and Williams, C.J., 2018, Seasonal wetness, soil organic carbon, and fire influence soil hydrological properties and water repellency in a sagebrush-steppe ecosystem: Water Resources Research, v. 54, no. 10, p. 8514–8527.

Day, J.D., Birrell, J.H., Terry, T.J., Clark, A., Allen, P., and St. Clair, S.B., 2019, Invertebrate community response to fire and rodent activity in the Mojave and Great Basin deserts: Ecology and Evolution, v. 9, no. 10, p. 6052–6067.

Day, J.D., Bishop, T.B.B., and St. Clair, S.B., 2018, Fire and plant invasion, but not rodents, alter ant community abundance and diversity in a semi-arid desert: Ecosphere, v. 9, no. 7, article e02344, 14 p.

Flerchinger, G.N., Seyfried, M.S., and Hardegree, S.P., 2016, Hydrologic response and recovery to prescribed fire and vegetation removal in a small rangeland catchment: Ecohydrology, v. 9, no. 8, p. 1604–1619.

Gasch, C.K., Huzurbazar, S.V., and Stahl, P.D., 2016, Description of vegetation and soil properties in sagebrush steppe following pipeline burial, reclamation, and recovery time: Geoderma, v. 265, p. 19–26.

Holbrook, J.D., Pilliod, D.S., Arkle, R.S., Rachlow, J.L., Vierling, K.T., and Wiest, M.M., 2016, Transition of vegetation states positively affects harvester ants in the Great Basin, United States: Rangeland Ecology and Management, v. 69, no. 6, p. 449–456.

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.

Love, B.G., and Cane, J.H., 2016, Limited direct effects of a massive wildfire on its sagebrush steppe bee community: Ecological Entomology, v. 41, no. 3, p. 317–326.

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.

Monroe, A.P., Aldridge, C.L., O’Donnell, M.S., Manier, D.J., Homer, C.G., and Anderson, P.J., 2020, Using remote sensing products to predict recovery of vegetation across space and time following energy development: Ecological Indicators, v. 110, article 105872, 11 p.

Riginos, C., Veblen, K.E., Thacker, E.T., Gunnell, K.L., and Monaco, T.A., 2019, Disturbance type and sagebrush community type affect plant community structure after shrub reduction: Rangeland Ecology and Management, v. 72, no. 4, p. 619–631.

Rohde, A.T., Pilliod, D.S., and Novak, S.J., 2019, Insect communities in big sagebrush habitat are altered by wildfire and post-fire restoration seeding: Insect Conservation and Diversity, v. 12, no. 3, p. 216–230.

Root, H.T., Miller, J.E.D., and Rosentreter, R., 2020, Grazing disturbance promotes exotic annual grasses by degrading soil biocrust communities: Ecological Applications, v. 30, no. 1, article e02016, 10 p.

Rottler, C.M., Burke, I.C., Palmquist, K.A., Bradford, J.B., and Lauenroth, W.K., 2018, Current reclamation practices after oil and gas development do not speed up succession or plant community recovery in big sagebrush ecosystems in Wyoming: Restoration Ecology, v. 26, no. 1, p. 114–123.

Smith, K.T., and Beck, J.L., 2018, Sagebrush treatments influence annual population change for greater sage-grouse: Restoration Ecology, v. 26, no. 3, p. 497–505.

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.

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: Restoration Ecology, v. 27, no. 2, p. 308–319.

Williams, C.J., Pierson, F.B., Kormos, P.R., Al-Hamdan, O.Z., Hardegree, S.P., and Clark, P.E., 2016, Ecohydrologic response and recovery of a semi-arid shrubland over a five year period following burning: Catena, v. 144, p. 163–176.

Next Step 6b

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.

Condon, L.A., and Gray, M.L., 2020, Not all fuel-reduction treatments degrade biocrusts—Herbicides cause mostly neutral to positive effects on cover of biocrusts: Land Degradation & Development, v. 31, no. 13, p. 1727–1734.

Copeland, S.M., Munson, S.M., Bradford, J.B., Butterfield, B.J., and Gunnell, K.L., 2019, Long-term plant community trajectories suggest divergent responses of native and non-native perennials and annuals to vegetation removal and seeding treatments: Restoration Ecology, v. 27, no. 4, p. 821–831.

Roundy, B.A., Chambers, J.C., Pyke, D.A., Miller, R.F., Tausch, R.J., Schupp, E.W., Rau, B., and Gruell, T., 2018, Resilience and resistance in sagebrush ecosystems are associated with seasonal soil temperature and water availability: Ecosphere, v. 9, no. 9, article e02417, 27 p.

Summers, D.D., and Roundy, B.A., 2018, Evaluating mechanical treatments and seeding of a Wyoming big sagebrush community 10 year post treatment: Rangeland Ecology and Management, v. 71, no. 3, p. 298–308.

Swanson, S.R., Swanson, J.C., Murphy, P.J., McAdoo, J.K., and Schultz, B., 2016, Mowing Wyoming big sagebrush (*Artemisia tridentata* ssp. *wyomingensis*) cover effects across northern and central Nevada: Rangeland Ecology and Management, v. 69, no. 5, p. 360–372.

Next Step 6c

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.

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.

Next Step 6d

Synthesize findings of long-term effects of sagebrush removal treatments on a variety of ecological attributes.

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.

Limb, R.F., Fuhlendorf, S.D., Engle, D.M., and Miller, R.F., 2016, Synthesis paper—Assessment of research on rangeland fire as a management practice: Rangeland Ecology and Management, v. 69, no. 6, p. 415–422.

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

Nouwakpo, S.K., Williams, C.J., Pierson, F.B., Weitz, M.A., Kormos, P.R., Arslan, A., and Al-Hamdan, O.Z., 2020, Effectiveness of prescribed fire to re-establish sagebrush steppe vegetation and ecohydrologic function on woodland-encroached sagebrush rangelands, Great Basin, USA—Part II—Runoff and sediment transport at the patch scale: Catena, v. 185, article 104301, 15 p.

Williams, C.J., Pierson, F.B., Nouwakpo, S.K., Al-Hamdan, O.Z., Kormos, P.R., and Weltz, M.A., 2020, Effectiveness of prescribed fire to re-establish sagebrush steppe vegetation and ecohydrologic function on woodland-encroached sagebrush rangelands, Great Basin, USA—Part I—Vegetation, hydrology, and erosion responses: Catena, v. 185, article 103477, 26 p.

Fire 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.

Next Step 7a

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.

NA.

Next Step 7b

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 Invasives Science Need 1 and Need 4.)

Chambers, J.C., Board, D.I., Roundy, B.A., and Weisberg, P.J., 2017, Removal of perennial herbaceous species affects response of Cold Desert shrublands to fire: Journal of Vegetation Science, v. 28, no. 5, p. 975–984.

Clark, P.E., Lee, J., Ko, K., Nielson, R.M., Johnson, D.E., Ganskopp, D.C., Pierson, F.B., and Hardegree, S.P., 2016, Prescribed fire effects on resource selection by cattle in mesic sagebrush steppe—Part 2—Mid-summer grazing: Journal of Arid Environments, v. 124, p. 398–412.

Clark, P.E., Williams, C.J., Kormos, P.R., and Pierson, F.B., 2018, Postfire grazing management effects on mesic sagebrush-steppe vegetation—Mid-summer grazing: Journal of Arid Environments, v. 151, p. 104–112.

Clark, P.E., Williams, C.J., Pierson, F.B., and Hardegree, S.P., 2016, Postfire grazing management effects on mesic sagebrush-steppe vegetation—Spring grazing: Journal of Arid Environments, v. 132, p. 49–59.

Condon, L.A., and Pyke, D.A., 2018, Fire and grazing influence site resistance to Bromus tectorum through their effects on shrub, bunchgrass and biocrust communities in the Great Basin (USA): New York, New York, Ecosystems, v. 21, no. 7, p. 1416–1431.

Connell, L.C., Scasta, J.D., and Porensky, L.M., 2018, Prairie dogs and wildfires shape vegetation structure in a sagebrush grassland more than does rest from ungulate grazing: Ecosphere, v. 9, no. 8, article 02390, 19 p.

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, General Technical Report RMRS-GTR-389, 237 p.

Davies, K.W., and Boyd, C.S., 2018, Longer-term evaluation of revegetation of medusahead-invaded sagebrush steppe: Rangeland Ecology and Management, v. 71, no. 3, p. 292–297.

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.

Davies, K.W., Bates, J.D., Boyd, C.S., and Svejcar, T.J., 2016a, Prefire grazing by cattle increases postfire resistance to exotic annual grass (*Bromus tectorum*) invasion and dominance for decades: Ecology and Evolution, v. 6, no. 10, p. 3356–3366.

Davies, K.W., Boyd, C.S., and Bates, J.D., 2018, Eighty years of grazing by cattle modifies sagebrush and bunchgrass structure: Rangeland Ecology and Management, v. 71, no. 3, p. 275–280.

Davies, K.W., Boyd, C.S., Bates, J.D., and Hulet, A., 2015a, Dormant season grazing may decrease wildfire probability by increasing fuel moisture and reducing fuel amount and continuity: International Journal of Wildland Fire, v. 24, no. 6, p. 849–856.

Davies, K.W., Boyd, C.S., Bates, J.D., and Hulet, A., 2015b, Winter grazing can reduce wildfire size, intensity and behaviour in a shrub-grassland: International Journal of Wildland Fire, v. 25, no. 2, p. 191–199.

Davies, K.W., Boyd, C.S., Bates, J.D., and Hulet, A., 2016b, Winter grazing decreases the probability of fire-induced mortality of bunchgrasses and may reduce wildfire size—A response to Smith et al. (this issue): International Journal of Wildland Fire, v. 25, no. 4, p. 489–493.

Davies, K.W., Gearhart, A., Boyd, C.S., and Bates, J.D., 2017, Fall and spring grazing influence fire ignitability and initial spread in shrub steppe communities: International Journal of Wildland Fire, v. 26, no. 6, p. 485–490.

Davies, K.W., Nafus, A.M., Boyd, C.S., Hulet, A., and Bates, J.D., 2016c, Effects of using winter grazing as a fuel treatment on Wyoming big sagebrush plant communities: Rangeland Ecology and Management, v. 69, no. 3, p. 179–184.

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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Next Step 7c

Evaluate existing treatment effectiveness monitoring data (for example, from BLM, Natural Resources Conservation Service) to quantify native herbaceous cover and functional diversity thresholds needed to resist invasion of nonnative annual grasses.

Not addressed.

Next Step 7d

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 Sagebrush and Sage-Grouse science Need 9.)

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Next Step 7e

Summarize science about potential risks (for example, partial to complete loss of sagebrush and other native plant species, extensive post-fire recovery period, and incursion of nonnative plant species) and benefits (for example, improved habitat structural conditions for sage-grouse and enhanced grass-forb cover) of fire and how these benefits differ across the sagebrush ecosystem.

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

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

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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Fire 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.

Next Step 8a

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.

Not addressed.

Next Step 8b

Analysis of the economic tradeoffs between fuel-break types, as affected by different fuel types, and in comparison to other non-fuel break alternatives.

Not addressed.

Next Step 8c

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.

Not addressed.

Next Step 8d

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.

Not addressed.

Next Step 8e

Develop a database and standardized protocol for entry of information that allows for assessment of treatment effectiveness across fuel types.

NA.

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For more information concerning the research in this report, contact the
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Box 25046, Mail Stop 415
Denver, CO 80225
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