Prepared in cooperation with the Bureau of Land Management and the
U.S. Fish and Wildlife Service

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

Open-File Report 2023–1003

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

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The findings and conclusions in this report are those of the authors and do not necessarily represent the views of the Bureau of Land Management and U.S. Fish and Wildlife Service.

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Contents

Figures

Tables

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
EIS	Environmental Impact Statement
IRFMS	Integrated Rangeland Fire Management Strategy
MZ	WAFWA Sage-grouse Management Zone
OFR	Open-File Report
USGS	U.S. Geological Survey
WAFWA	Western Association of Fish and Wildlife Agencies

Species names

Cheatgrass	*Bromus tectorum*
Crested wheatgrass	*Agropyron cristatum*
Dyer’s woad	*Isatis tinctoria*
Greater sage-grouse	*Centrocercus urophasianus*
Hoary cress	*Lepidium draba*
Knapweed	*Centaurea* spp.
Kochia	*Kochia scoparia*
Leafy spurge	*Euphorbia esula*
Mediterranean sage	*Salvia aethiopis*
Medusahead	*Taeniatherum caput-medusae*
Perennial pepperweed	*Lepidium latifolium*
Rush skeletonweed	*Chondrilla juncea*
Sagebrush	*Artemisia* spp.
Thistle	*Cirsium* spp.
Ventenata	*Ventenata dubia*
Yellow starthistle	*Centaurea solstitialis*

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

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

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 six needs (hereinafter “Needs”) identified under the Invasives topic in the Plan. The topic outlined research Needs related to the control of invasive plant species in sagebrush rangelands, with a special emphasis on invasive annual grasses. We established the level of progress towards addressing each Need following a standardized set of criteria, and developed summaries detailing how research objectives nested within Needs identified in the Plan (“Next Steps”) were either addressed well, partially addressed, or remain outstanding (that is, addressed poorly) in the literature through 2020. Our searches resulted in the inclusion of 198 science products that at least partially addressed a Need identified in the Invasives topic. The Needs that were well and partially addressed included:

1. studies of natural and anthropogenic factors influencing the distribution and spread;
2. methods of preventing, eradicating and controlling invasive plant species;
3. development of mapping techniques that provide regularly updated annual grass and fine fuel projections; and
4. assessment of the efficacy of potential cheatgrass biocontrol agents.

Needs that were addressed poorly included (1) investigations of livestock grazing as a tool for managing invasive plants and (2) investigations of cheatgrass die-offs and identification and subsequent study of potential biocontrol agents associated with those die-offs. 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). Roughly 55–60 percent of sagebrush rangelands of the western United States 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 (that is, Great Basin and Snake River Plain), where trends in proportion of larger fires and fire season length have increased since the mid-1980s and fire frequency has increased substantially compared to historic frequencies (Brooks and others, 2015). Over the next 20 years, median annual total area burned in western states supporting sagebrush is projected to increase (from a 1961–2004 baseline period; Kitzberger and others, 2017), suggesting that increasing trends in sagebrush 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 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.

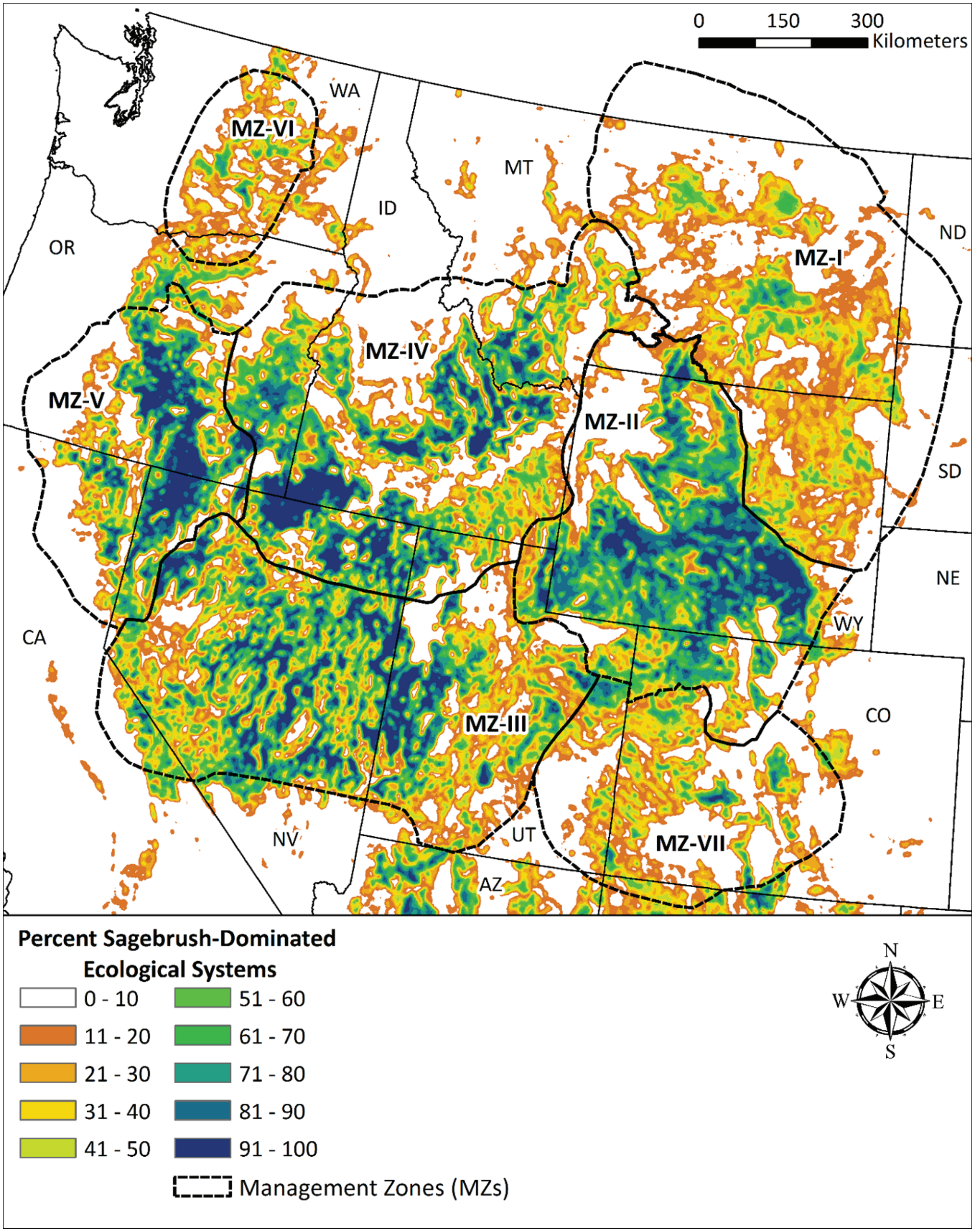

Figure 1. Map showing the landscape cover of sagebrush-dominated (*Artemisia* ssp.) ecological systems in the western United States. Figure is taken from Chambers and others (2017, fig. 28).

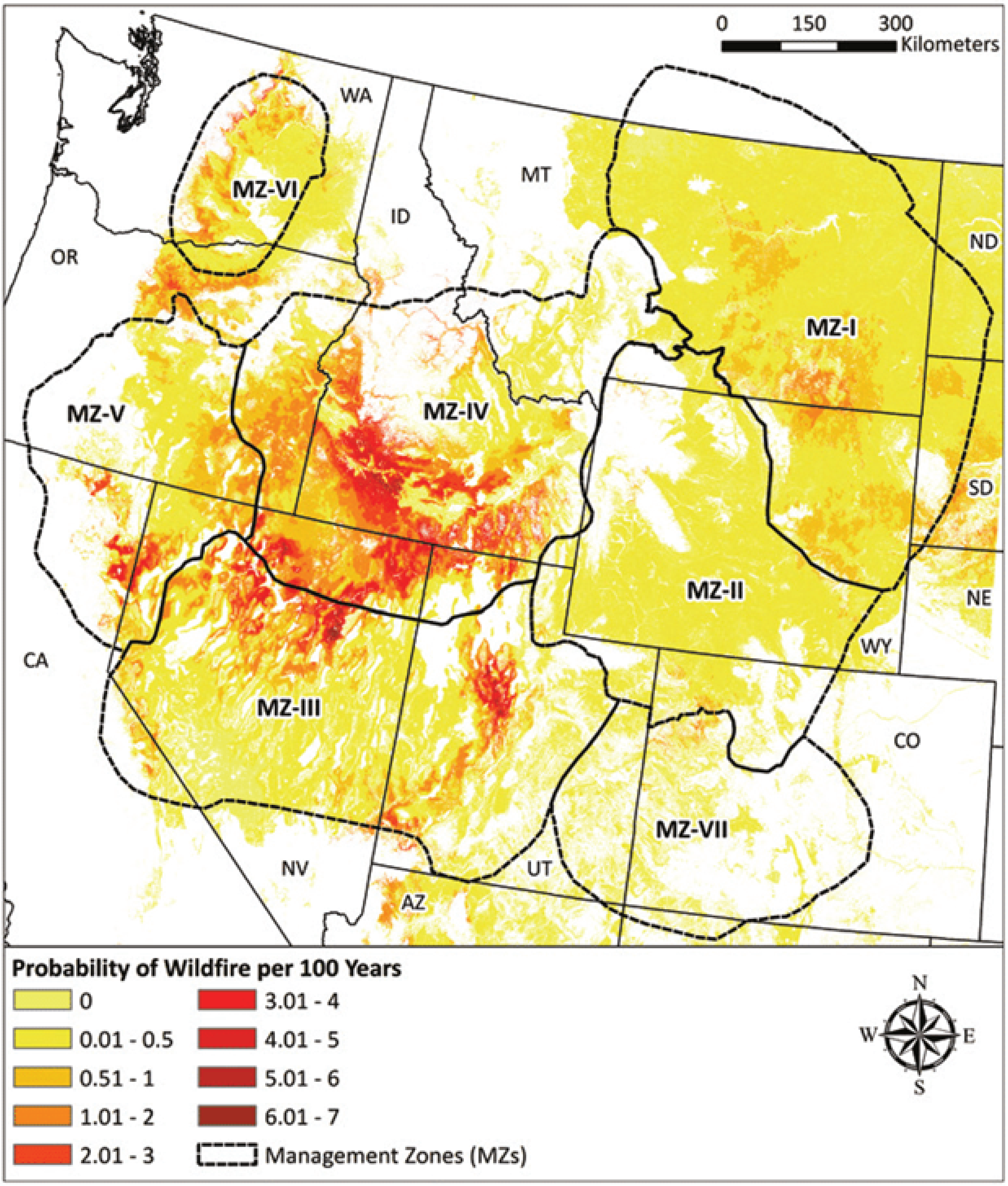

Figure 2. Map showing large fire probability for the sagebrush biome in the western United States. Figure taken from Chambers and others (2017, fig. 34).

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

The Invasives topic in the Plan identified six Needs focused on understanding components of exotic plant species invasions and approaches to manage them, with an emphasis on invasive annual grasses, especially cheatgrass (fig. 3). The priorities identified across the six Needs broadly encompassed:

(1) determining the factors that influence invasive plant species distributions and spread;

(2) improving prevention, eradication, and control measures for invasive plant species;

(3) developing high-resolution maps and monitoring tools to inform early detection and invasive plant control efforts;

(4) assessing the effectiveness of targeted livestock grazing to reduce invasive annual grasses; and

(5) investigating potential biocontrol agents for cheatgrass and developing approaches for improving the production and delivery of successful biocontrol agents.

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 six Needs identified under the Invasives 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.

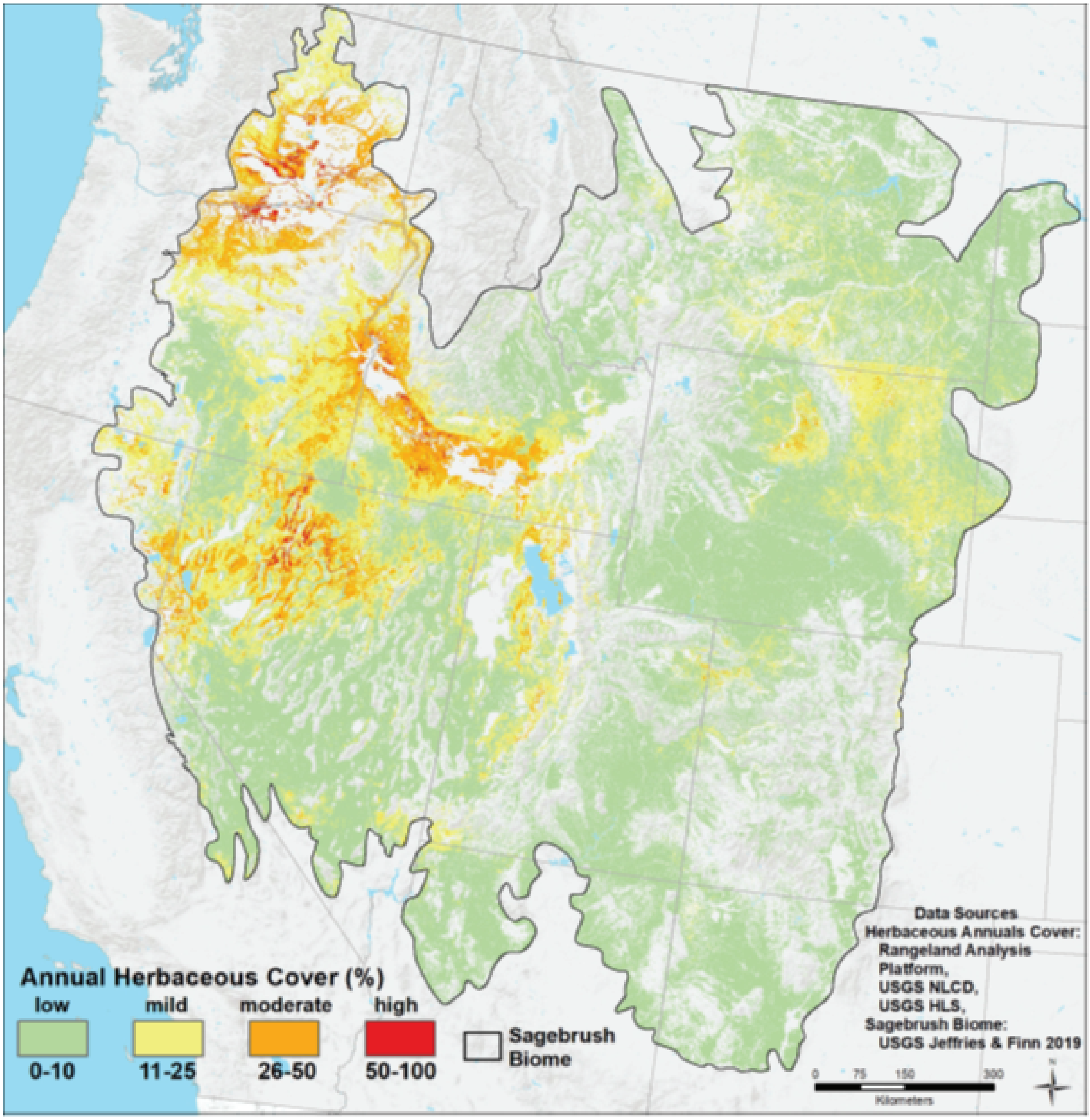

Figure 3. Map showing percent cover of herbaceous annuals across the sagebrush biome from 2016 to 2018 (Western Governors' Association Toolkit, 2020).

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 Invasives topic, we initially reviewed the invasive plant species literature that was included in broad searches for literature pertaining to cheatgrass, medusahead (*Taeniatherum caput-medusae*) and ventenata (*Ventenata dubia*) provided by Poor and others (2021). We then used USGS BiblioSearch (Kleist and Enns, 2022) to search the reference databases Web of Science and Scopus using broad search terms (for example, cheatgrass) then search terms specific to the Next Steps (for example, rush skeletonweed 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 science Needs identified in the Invasives 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.

Table 1. Search results for the Invasives 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).

[For more information on the individual Needs, please see Needs 1–6 described in the report. **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, "invasive" and "species" searched, not "invasive species"). 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 "cheatgrass" and "invasive species AND sagebrush" searches).]

Search terms	Unique results	Comment
cheatgrass OR cheat grass OR downy brome OR *Bromus tectorum*	345	2015–20; broad search term
medusahead OR medusa head	115	2015–20; broad search term
ventenata OR *Ventenata dubia*	27	2015–20; broad search terms captured in Poor and others (2021)
invasive species AND sagebrush[1]	88	2015–20; broad search term
soil mapping AND sagebrush	12	2015–20; Need 1; targeted search term
leafy spurge AND sagebrush[1]	0	2015–20; Needs 1–3; targeted search term
knapweed AND sagebrush[1]	1	2015–20; Needs 1–3; targeted search term
thistle AND sagebrush[1]	2	2015–20; Needs 1–3; targeted search term
kochia AND sagebrush[1]	7	2015–20; Needs 1–3; targeted search term
mediterranean sage AND sagebrush[1]	0	2015–20; Needs 1–3; targeted search term
hoary cress AND sagebrush[1]	0	2015–20; Needs 1–3; targeted search term
perennial pepperweed AND sagebrush[1]	0	2015–20; Needs 1–3; targeted search term
rush skeletonweed AND sagebrush[1]	0	2015–20; Needs 1–3; targeted search term
yellow starthistle AND sagebrush[1]	0	2015–20; Needs 1–3; targeted search term
dyer's woad AND sagebrush[1]	0	2015–20; Needs 1–3; targeted search term
feral horses AND sagebrush	6	2015–20; Need 4; targeted search term
livestock grazing AND fuel AND sagebrush	3	2015–20; Need 4; targeted search term
livestock grazing AND invasive grass	48	2015–20; Need 4; targeted search term
livestock grazing AND sagebrush treatment	10	2015–20; Need 4; targeted search term
targeted livestock grazing AND economics AND sagebrush	0	2015–20; Need 4; targeted search term
biocontrol AND cheatgrass	6	2015–20; Needs 5 and 6; targeted search term

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

We 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 Invasives topic. Papers that were relevant to a Next Step were considered when scoring that Next Step. Our review approach initially focused on summaries provided in Poor and others (2021), or 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.

Each Next Step was scored based on the relevant literature following a set of criteria (table 2). Scores were scaled from 0.00 to 1.00 with 0.00 indicating that the Next Step had not been considered (that is, no papers were reviewed that considered the objective(s) detailed in the Next Step) and 1.00 indicating that the Next Step had been considered at the full spatial extent of the issue being investigated. Scores progressively decreased as the applicability of the research associated with a Next Step became more regional or localized. The scale of inference for Next Steps that were pertinent to the entire sagebrush biome was based on Western Association of Fish and Wildlife Agencies Management Zones (WAFWA; MZ) for sage-grouse (Stiver and others, 2006; fig. 1). If studies were distributed in one MZ or less than or equal to three adjoining MZs, the scale of inference was considered local or regional, respectively. "NA" was assigned when a Next Step could not be evaluated with the literature review approach we used (for example, data releases, online tools), and that Next Step was not scored. A Next Step that could be addressed adequately following our approach but that had no relevant literature identified was scored 0.00 (not NA) 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 identified in the Plan as accomplishable within 3 years (short-term) and longer than 3 years (long-term) because 5 years had elapsed between plan formulation and this report.

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

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

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

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

[1] Next Step not included in scoring of Need

Results and Summary

We reviewed 670 products that were identified by the literature searches conducted for the Invasives topic (table 1). Of those, 198 unique products were directly related to at least one of the six Needs. Most (84 percent) of the 44 Next Steps included in the topic had greater than or equal to one published product that at least partially addressed the science objective(s) detailed by that Next Step. Seven Next Steps could not be effectively assessed with the evaluation approach we used and were not scored ("NA"; table 2). The seven Next Steps that could be effectively assessed but had no related products (that is, were scored as 0.00 not as NA) included:

(1) a meta-analysis of literature addressing the distribution, spread, and environmental associations of cheatgrass (although a meta-analysis of changes in plant community structure in response to exotic vegetation not including cheatgrass has been conducted; Need 1);

(2) a synthesis of the effectiveness and economic efficiencies of using livestock to create and maintain fire breaks and for targeted fuel treatments (two Next Steps under Need 4);

(3) study designs developed to assess the impacts to non-target plant, animal and microbial communities of biocontrol agents being considered for broad-scale application (two Next Steps under Need 5); and

(4) approaches to measuring pathogen loads in soils and identification of locations for conducting study trials on cheatgrass die-offs (two Next Steps under Need 6).

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

The Needs that were addressed well (scores ≥0.67) included the development of biome-wide mapping and inventory techniques that can provide regularly updated, spatially-explicit invasive annual grass and fine fuel projections from remotely sensed data (Need 3). Further, although the Next Steps associated with improving production and delivery of cheatgrass biocontrol agents (Need 5) were not expressly addressed, the lack of replication of Kennedy's (2018) results across the sagebrush range indicated low efficacy of currently formulated agents. Hence, several of these Next Steps appear no longer relevant and Need 5 can be considered to have been addressed well.

Two Needs that were partially addressed by the literature (scores 0.50–0.66), included investigations of the natural and anthropogenic factors influencing the distribution and spread of invasive plants (Need 1); and the identification of improved methods of prevention, eradication, and control for invasive plant species (Need 2). Numerous local and regional scale studies have investigated relationships among various biotic and abiotic ecosystem characteristics and invasive plant distributions. Additionally, sagebrush ecosystem responses to a suite of invasive annual grass management measures throughout the sagebrush biome have been investigated.

The Needs that were addressed poorly (scores ≤0.49) were studies which examined the effectiveness of targeted livestock grazing as a management tool for invasive annual grasses and evaluations of impacts of these activities on native plants (Need 4); and investigations of cheatgrass die-offs and identification and subsequent study of potential biocontrol agents associated with those die-offs (Need 6). Although several local scale studies have investigated different aspects of livestock grazing on fine fuel loads, assessments of the effectiveness of using livestock to maintain fuel load objectives and create fuel discontinuity (for example, fuel breaks) require spatial replication across the sagebrush biome. Further, several local scale or greenhouse studies have investigated the effects of different soil pathogens on cheatgrass, but links between pathogen soil loading, invasive annual grass survival, and the potential for broad applicability of these pathogens as biocontrol agents or management tools have not been made.

There were several Next Steps identified under the Invasives topic that were addressed poorly, even when the overall Need was well or partially addressed. There remains a paucity of studies related to natural and anthropogenic processes influencing invasive plant species other than invasive annual grasses (for example, leafy spurge [*Euphorbia esula*], knapweed [*Centaurea* spp.], kochia [*Kochia scoparia*]) across the range of these other species in the sagebrush biome (Needs 1 and 2). Assessments of the effectiveness of potential control measures for these other invasive species are also lacking. Risk assessments for establishing cost-benefit estimates of different invasive annual grass management measures have not been conducted (Need 2). Strategies for minimizing or interrupting major vectors (that is, seed dispersal mechanisms) contributing to the spread of invasive annual grasses are needed (Need 2). Investigations into the effects of biocontrol agents on soil microbial communities, best management practices for the use of biocontrols, and delivery mechanisms of bacteria applications over large areas are lacking (Need 5).

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.

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

Need	Score	Summary of 2015–20 literature
Need 1: Improve understanding of the natural and anthropogenic factors that influence invasive plant species distributions, including invasion history, surface disturbance, habitat condition, and fire history, and determine whether those factors can help identify tradeoffs among alternative management approaches.	0.78	***Addressed:*** Substantial numbers of local and regional scale studies distributed throughout the sagebrush biome have investigated ecosystem responses to different invasive annual grass management options and post-disturbance habitat recovery rates have been studied predominantly in the context of investigating sagebrush habitat restoration efforts (see also Restoration topic Needs 5, 6, 7, 8, and 9 summaries). Literature reviews regarding the influence of weather and climate on the spread of cheatgrass have been completed, and multiple local scale studies have investigated relationships between weather, climate, and other biotic and abiotic conditions on the spread of invasive annual grasses including cheatgrass and medusahead (see also Invasives topic Need 2 summary). The distribution and percent cover of cheatgrass has been mapped at local, regional, and range-wide scales, and several automated tools have been developed to estimate cheatgrass cover through time to characterize seasonal and annual variation across the sagebrush biome. Probability of occurrence modeling (climate suitability models) for 15 invasive plant species has been conducted range wide. Soil properties have been mapped at local, regional, and range-wide scales and these maps have been used to inform invasive annual grass decision support tools. ***Outstanding:*** Studies linking biotic and abiotic variables with the distribution and invasion of medusahead and ventenata have not been replicated across the range of these two species. A meta-analysis investigating the distribution, spread, environmental associations and management of cheatgrass has not been completed. Literature reviews for nonnative annual grasses other than cheatgrass are lacking. Maps and remote sensing monitoring tools for invasive annual grasses other than cheatgrass (for example, medusahead and ventenata) are lacking across much of these species' ranges. Range-wide soil mapping products lack local specificity limiting management relevance in certain areas of the sagebrush biome.
Need 2: Improve measures for prevention, eradication, and control of invasive plant species, and use risk assessments to weigh potential benefits and deleterious effects of different measures on native plant species.	0.40	***Addressed:*** A substantial number of predominantly local-scale studies distributed throughout the sagebrush biome have investigated relationships among various biotic and abiotic ecosystem characteristics and invasive annual grass response to vegetation management. The ecology of invasive annual grass seed dispersal in the context of treating invaded sites has been investigated at local scales. Frameworks for managing invasive annual grasses through the identification of areas resistant to invasion for targeting conservation and restoration actions have been developed at local and range-wide scales. ***Outstanding:*** Risk assessments for generating cost-benefit estimates of different invasive annual grass management measures have not been conducted. Guidelines for evaluating causes of cheatgrass and medusahead invasion and expansion have not been developed. Strategies to minimize or interrupt major vectors contributing to the dispersal of invasive annual grasses are needed. Investigations of the ecology of invasive annual grass seed dispersal to inform strategies for preventing invasion are limited.

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

Need	Score	Summary of 2015–20 literature
Need 3: Conduct invasive plant inventory, including spatial data on infestations and current range maps, to improve the ability for managers to prioritize actions to prevent and control nonnative plant populations before they become established and spread.	1.00	***Addressed:*** Spatially-explicit invasive annual grass datasets, mapping products, and early detection monitoring approaches that rely on remotely sensed data have been developed at local, regional and range-wide scales across the sagebrush biome. Fine fuels projections for informing wildfire risk have been developed in relation to climatic conditions and used to predict future cheatgrass and other invasive annual grass distributions range wide (see also Invasives topic Need 1 and Fire topic Need 3 summaries). ***Outstanding:*** Although this Need is scored as being addressed, note that the level of completion of the initiation of standardized field collection protocols for informing early detection of invasive annual grasses, and the development of a centralized clearinghouse of invasive annual grass occurrence data (two objectives associated with this Need) are unknown because these types of products or efforts would not be identified consistently by the literature search approach we used. These Next Steps were not included in the scoring of this Need.
Need 4: Assess effectiveness of targeted grazing with livestock to reduce non-native annual grasses and understand the impact on native plants in the sagebrush ecosystem.	0.27	***Addressed:*** Local scale studies investigating different aspects of livestock grazing on fine fuel loads and flammability, and fire behavior have been completed. A large number of local, regional and range-wide studies investigating the restoration of sagebrush habitats dominated by invasive annual grasses, including studies that assessed the seeding of a variety of native and introduced vegetative species, have been conducted throughout the sagebrush biome (see also Restoration topic Needs 2, 6, and 8 summaries). Several local, regional and range-wide studies have investigated long-term, interactive responses of sagebrush habitats to restoration options combined with livestock grazing pre- and post-treatment (see also Fire topic Need 7 summary). Local scale fire behavior fuel models incorporating precipitation variables and dynamic fuel estimates have been developed. Several local scale studies investigating relationships between livestock grazing, herbaceous cover and sage-grouse habitat suitability have been conducted throughout the sagebrush biome (see also Sagebrush and Sage-grouse topic Need 2 summary). Relationships between livestock grazing and invasive annual grass occurrence and probabilities of invasion have been investigated by local scale studies distributed throughout the sagebrush biome. A limited number of feeding trial studies investigating approaches to promote high herbaceous biomass utilization of invasive annual grasses by livestock have been conducted. Literature pertaining to the ecological effects of feral horses on rangelands has been summarized. ***Outstanding:*** Assessments of the effectiveness of using livestock to manage fine fuel loads, including evaluations of the rate, frequency, and timing of grazing events required to maintain fuel load objectives, require spatial replication across the sagebrush biome. Using livestock to create fire breaks has not been investigated. Investigations of chemical and mechanical fuels treatments in combination with livestock grazing are lacking. Economic studies of targeted livestock grazing as a fuel treatment have not been conducted. Studies explicitly linking livestock grazing to manage fuel loads and habitat suitability for sage-grouse and other sagebrush associated wildlife are limited. Studies investigating approaches to managing livestock to ameliorate the spread of invasive annual grasses are lacking. Specific guidance for implementing fuels management programs using livestock have not been published. The effects of feral horses on the proliferation of invasive annual grasses requires further study across the sagebrush biome.

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

Need	Score	Summary of 2015–20 literature
Need 5: Conduct detailed optimization studies on production and delivery systems of biocontrol agents, followed by evaluation in scaled-up field inoculation trials.	0.60	***Addressed:*** The effectiveness of weed-suppressive bacteria treatments at reducing cheatgrass has been assessed through a series of spatially-replicated studies attempting to replicate the results of successful suppression of invasive annual grasses by biocontrol agents published by Kennedy (2018). These studies investigating the effectiveness of biocontrol agents have been summarized in a special issue of Rangeland Ecology and Management (vol. 73; 2020). ***Outstanding:*** Studies assessing the impacts to non-target plant, animal and soil microbial communities of biocontrol agent use across broad spatial scales have not been published. However, the lack of replication of Kennedy's (2018) results across the sagebrush range indicated low efficacy of currently formulated agents, and several of the Next Steps not addressed in Need 5 (and included in the scoring) appear no longer relevant. Functionally, Need 5 can be considered to have been addressed.
Need 6: Investigate cheatgrass die-off and potential biocontrols for cheatgrass to provide effective tools for site preparation.	0.29	***Addressed:*** Numerous local scale or greenhouse studies have been conducted investigating the effects on cheatgrass of several different potential soil pathogens. Local and regional studies presenting cheatgrass die-off geospatial mapping approaches have been conducted in the Great Basin. Several experimental local scale studies have investigated cheatgrass seed survival in combination with manipulated environmental conditions in response to different soil pathogens. Local scale studies have been conducted investigating seedling survival and productivity of restoration treatments using native seeds (perennial grasses, forbs, and shrubs) in cheatgrass die-offs. ***Outstanding:*** The link between pathogen soil loading, invasive annual grass survival, and using pathogens as a management approach to prepare for restoration seeding have not been investigated. Predictive spatial models of cheatgrass die-offs need to be spatially replicated across the Great Basin. Spatial replication of studies assessing restoration success of seeding cheatgrass die-off areas and non-target species response to cheatgrass pathogens is lacking. Molecular-genetic techniques for measuring pathogen loads in soils and approaches to predicting seedbed pathogen loading for informing study designs have not been published.

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Brooks, M.L., Matchett, J.R., Shinneman, D.J., and Coates, P.S., 2015, Fire patterns in the range of greater sage-grouse, 1984–2013—Implications for conservation and management: U.S. Geological Survey Open-File Report 2015–1167, 66 p. [Also available at https://doi.org/10.3133/ofr20151167.]

Bureau of Land Management (BLM), 2020, Final programmatic EIS for fuels reduction and rangeland restoration in the Great Basin: BLM Idaho State Office, Boise, Idaho, 153 p. [Also available at https://eplanning.blm.gov/eplanning-ui/project/122968/570.]

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Miller, R.F., and Eddleman, L.L., 2001, Spatial and temporal changes of sage-grouse habitat in the sagebrush biome: Oregon State University Agricultural Experiment Station Technical Bulletin, no. 151, 39 p. [Also available at https://catalog.extension.oregonstate.edu/tb151.]

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Poor, E.E., Kleist, N.J., Bencin, H.L., Foster, A.C., and Carter, S.K., 2021, Annotated bibliography of scientific research on *Ventenata dubia* published from 2010 to 2020: U.S. Geological Survey Open-File Report 2021–1031, 26 p. [Also available at https://doi.org/10.3133/ofr20211031.]

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U.S. Fish and Wildlife Service, 2013, Greater sage-grouse (*Centrocercus urophasianus*) Conservation objectives—Final report: Denver, Colorado, U.S. Fish and Wildlife Service, 115 p. [Also available at http://www.sagegrouseinitiative.com/wp-content/uploads/2013/07/USFWS_ConservationObjectives-report.pdf.]

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Western Governors' Association, 2020, A toolkit for invasive annual grass management in the West: Denver, Colorado, Western Governors Association, 8 p. [Also available at https://westgov.org/images/editor/FINAL_Cheatgrass_Toolkit_July_2020.pdf.]

Glossary

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

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

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

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

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

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

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

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

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

Appendix 1. Literature Included in Scoring Next Steps for the Invasives 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."

Invasives Need 1

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

Next Step 1a

Develop high-resolution maps of the current distribution of cheatgrass (*Bromus tectorum*), and create mechanisms or geospatial tools to update the maps regularly.

Anderson, K.E., Glenn, N.F., Spaete, L.P., Shinneman, D.J., Pilliod, D.S., Arkle, R.S., McIlroy, S.K., and Derryberry, D.R., 2018, Estimating vegetation biomass and cover across large plots in shrub and grass dominated drylands using terrestrial lidar and machine learning: Ecological Indicators, v. 84, p. 793–802.

Barnett, D.T., Jarnevich, C., Chong, G.W., Stohlgren, T.J., Kumar, S., and Holcombe, T., 2017, Ecology and space—A case study in mapping harmful invasive species, *in* Brunn, S., and Dodge, M., eds., Mapping across academia: Dordrecht, Springer, p. 63–81. [Also available at https://doi.org/10.1007/978-94-024-1011-2_4.]

Bishop, T.B.B., Munson, S., Gill, R.A., Belnap, J., St Clair, S.B., and Petersen, S.L., 2019, Spatiotemporal patterns of cheatgrass invasion in Colorado Plateau National Parks: Landscape Ecology, v. 34, p. 925–941.

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., Gu, Y., and Major, D.J., 2020, Estimating abiotic thresholds for sagebrush condition class in the western United States: Rangeland Ecology and Management, v. 73, no. 2, p. 297–308.

Boyte, S.P., Wylie, B.K., Rigge, M.B., and Dahal, D., 2018, Fusing MODIS with Landsat 8 data to downscale weekly normalized difference vegetation index estimates for central Great Basin rangelands, USA: GIScience & Remote Sensing, v. 55, no. 3, p. 376–399.

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.

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.

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.

Horning, N., Fleishman, E., Ersts, P.J., Fogarty, F.A., and Wohlfeil Zillig, M., 2020, Mapping of land cover with open-source software and ultra-high-resolution imagery acquired with unmanned aerial vehicles: Remote Sensing in Ecology and Conservation, v. 6, no. 4, p. 487–497.

Irvine, K.M., Wright, W.J., Shanahan, E.K., and Rodhouse, T.J., 2019, Cohesive framework for modelling plant cover class data: Methods in Ecology and Evolution, v. 10, no. 10, p. 1749–1760.

Jarnevich, C.S., Talbert, M., Morisette, J., Aldridge, C., Brown, C.S., Kumar, S., Manier, D., Talbert, C., and Holcombe, T., 2017, Minimizing effects of methodological decisions on interpretation and prediction in species distribution studies—An example with background selection: Ecological Modelling, v. 363, p. 48–56.

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, article 725, 17 p. [Also available at https://doi.org/10.3390/rs12040725.]

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Rigge, M., Homer, C., Cleeves, L., Meyer, D.K., Bunde, B., Shi, H., Xian, G., Schell, S., and Bobo, M., 2020, Quantifying western U.S. rangelands as fractional components with multi-resolution remote sensing and in situ data: Remote Sensing, v. 12, no. 3, article 412, 26 p. [Also available at https:// doi.org/10.3390/rs12030412.]

West, A.M., Evangelista, P.H., Jarnevich, C.S., and Schulte, D., 2018, A tale of two wildfires—Testing detection and prediction of invasive species distributions using models fit with topographic and spectral indices: Landscape Ecology, v. 33, no. 6, p. 969–984.

West, A.M., Evangelista, P.H., Jarnevich, C.S., Kumar, S., Swallow, A., Luizza, M.W., and Chignell, S.M., 2017, Using multi-date satellite imagery to monitor invasive grass species distribution in post-wildfire landscapes—An iterative, adaptable approach that employs open-source data and software: International Journal of Applied Earth Observation and Geoinformation, v. 59, p. 135–146.

Next Step 1b

Create high-resolution maps of the current distributions of other invasive nonnative annual grasses such as medusahead rye (*Taeniatherum caput-medusae*) and ventenata (*Ventenata dubia*).

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.

Bradley, B.A., 2016, Predicting abundance with presence-only models: Landscape Ecology, v. 31, no. 1, p. 19–30.

Dronova, I., Spotswood, E.N., and Suding, K.N., 2017, Opportunities and constraints in characterizing landscape distribution of an invasive grass from very high resolution multi-spectral imagery: Frontiers in Plant Science, v. 8, article 890, 17 p. [Also available at https://doi.org/10.3389/fpls.2017.00890.]

Next Step 1c

Conduct a meta-analysis of literature addressing the distribution, spread, and environmental associations of cheatgrass. Focus on relationship between disturbance events and activities that affect cheatgrass abundance, including wildfire, prescribed fire, grazing, roads, industrial activities and infrastructure, habitat treatments, and environmental conditions associated with cheatgrass abundance and dominance.

James, J.J., Gornish, E.S., DiTomaso, J.M., Davy, J., Doran, M.P., Becchetti, T., Lile, D., Brownsey, P., and Laca, E.A., 2015, Managing medusahead (*Taeniatherum caput-medusae*) on rangeland—A meta-analysis of control effects and assessment of stakeholder needs: Rangeland Ecology and Management, v. 68, no. 3, p. 215–223.

Scasta, J.D., Engle, D.M., Fuhlendorf, S.D., Redfearn, D.D., and Bidwell, T.G., 2015, Meta-analysis of exotic forages as invasive plants in complex multi-functioning landscapes: Invasive Plant Science and Management, v. 8, no. 3, p. 292–306.

Next Step 1d

Map and model additional invasive plants. Prioritization of this work should consider potential of an invasive plant to negatively affect ecosystems, habitats, or both.

Bradley, B.A., 2016, Predicting abundance with presence-only models: Landscape Ecology, v. 31, no. 1, p. 19–30.

Next Step 1e

Develop locally specific spatially-explicit soil maps, including soil temperature and moisture estimates, to inform spatial models and decision support tools at management-relevant scales.

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, 23 p.

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.

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Palmquist, K.A., Schlaepfer, D.R., Bradford, J.B., and Lauenroth, W.K., 2016a, Mid-latitude shrub steppe plant communities—Climate change consequences for soil water resources: Ecology, v. 97, no. 9, p. 2342–2354.

Palmquist, K.A., Schlaepfer, D.R., Bradford, J.B., and Lauenroth, W.K., 2016b, Spatial and ecological variation in dryland ecohydrological responses to climate change—Implications for management: Ecosphere, v. 7, no. 11, 20 p.

Next Step 1f

Review the literature about the role of weather and climate in facilitating the spread of nonnative annual grasses.

Belnap, J., Stark, J.M., Rau, B.M., Allen, E.B., and Phillips, S., 2016, Soil moisture and biogeochemical factors influence the distribution of annual *Bromus* species, *in* Germino, M.J., Chambers, J.C., and Brown, C.S., eds., Exotic brome-grasses in arid and semiarid ecosystems of the western U.S: Switzerland, Springer International Publishing, p. 227–256.

Bradley, B.A., Curtis, C.A., and Chambers, J.C., 2016, *Bromus* response to climate and projected changes with climate change, *in* Germino, M.J., Chambers, J.C., and Brown, C.S., eds., Exotic brome-grasses in arid and semiarid ecosystems of the western U.S: Switzerland, Springer International Publishing, p. 257–274.

Hufft, R.A., and Zelikova, T.J., 2016, Ecological genetics, local adaptation, and phenotypic plasticity in *Bromus tectorum* in the context of a changing climate, *in* Germino, M.J., Chambers, J.C., and Brown, C.S., eds., Exotic brome-grasses in arid and semiarid ecosystems of the western U.S: Switzerland, Springer International Publishing, p. 133–154.

Reeves, M.C., Manning, M.E., DiBenedetto, J.P., Palmquist, K.A., Lauenroth, W.K., Bradford, J.B., and Schlaepfer, D.R., 2018, Effects of climate change on rangeland vegetation in the Northern Rockies, *in* Halofsky, J., and Peterson, D., eds., Climate change and Rocky Mountain ecosystems v. 63: Advances in Global Change Research, p. 97–114.

Zefferman, E., Stevens, J.T., Charles, G.K., Dunbar-Irwin, M., Emam, T., Fick, S., Morales, L.V., Wolf, K.M., Young, D.J.N., and Young, T.P., 2015, Plant communities in harsh sites are less invaded—A summary of observations and proposed explanations: AoB Plants, v. 7, 21 p. [Also available at https://doi.org/10.1093/aobpla/plv056.]

Next Step 1g

Initiate treatment and restoration experiments using cooperative efforts between management and research. Distribute study areas across the region using environmental gradients to capture and explain variability in response, seeking single or combined treatments that “mimic” positive effects of disturbance on habitat quality, and that minimize stimulation of nonnative annual grasses, annual forbs, and perennial invaders.

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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Next Step 1h

Conduct studies aimed at understanding the distribution, spread, and environmental associations of other rapidly spreading nonnative annual grasses (for example, medusahead rye and ventenata), including the effects of weather and climate.

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Next Step 1i

Conduct integrated landscape (remote-sensing) and local (field-based) assessment of post-disturbance recovery rates to assess differences in rates and composition due to climate, soils herbivory, land use, and other environmental patterns. Assess implications of recovered areas for wildlife use, fuel dynamics and fire potential, and ecosystem services.

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Next Step 1j

Also refer to Invasives Science Need 4, long-term next steps.

NA.

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Invasives Need 2

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

Next Step 2a

Investigate the complex interrelationships among various components within ecosystems that create multiple, indirect responses by invasive plant species to specific vegetation-management actions.

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Davies, K.W., and Johnson, D.D., 2017, Established perennial vegetation provides high resistance to reinvasion by exotic annual grasses: Rangeland Ecology and Management, v. 70, no. 6, p. 748–754.

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Next Step 2b

Develop guidelines to evaluate causes of invasion, succession, and retrogression (for example, cheatgrass die-off).

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Next Step 2c

Investigate strategies for prevention of new plant invasions that are based on the ecology of seed dispersal.

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Next Step 2d

Investigate the potential for integrating invasive plant management within a systems approach to facilitate problem solving and the attainment of well-defined goals, rather than practice-based outcomes.

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Smith, B.S., and Sheley, R.L., 2015, Implementing strategic weed prevention programs to protect rangeland ecosystems: Invasive Plant Science and Management, v. 8, no. 2, p. 233–242.

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.

Next Step 2e

Develop a conceptual framework and associated tools that assist in identifying which vectors are major contributors to invasive plant species dispersal. Then develop dispersal-management strategies to minimize or interrupt these major vectors.

Spackman, C.N., Monaco, T.A., Stonecipher, C.A., and Villalba, J.J., 2020, Plant silicon as a factor in medusahead (*Taeniatherum caput-medusae*) invasion: Invasive Plant Science and Management, v. 13, no. 3, p. 143–154.

Strickland, C., Dangelmayr, G., Shipman, P.D., Kumar, S., and Stohlgren, T.J., 2015, Network spread of invasive species and infectious diseases: Ecological Modelling, v. 309–310, p. 1–9.

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

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

Hergert, H.J., Mealor, B.A., and Kniss, A.R., 2015, Inter- and intraspecific variation in native restoration plants for herbicide tolerance: Ecological Restoration, v. 33, no. 1, p. 74–81.

Jabran, K., and Dogan, M.N., 2018, High carbon dioxide concentration and elevated temperature impact the growth of weeds but do not change the efficacy of glyphosate: Pest Management Science, v. 74, no. 3, p. 766–771.

Johnston, D.B., 2015, Downy brome (Bromus tectorum) control for pipeline restoration: Invasive Plant Science and Management, v. 8, no. 2, p. 181–192.

Rinella, M.J., Knudsen, A.D., Jacobs, J.S., and Mangold, J.M., 2020, Seeding causes long-term increases in grass forage production in invaded rangelands: Rangeland Ecology and Management, v. 73, no. 2, p. 329–333.

Invasives Need 3

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

Next Step 3a

Initiate standardized early-season field collection to inform early detection efforts and map development.

See Next Step 3b citations.

Next Step 3b

Develop nonnative annual grass spatial datasets to inform annual predictive fire models and identify of potential treatment areas.

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., 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.

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.

Next Step 3c

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

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

Next Step 3d

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

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., 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.

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.

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

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.

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, Ecosystems, v. 19, no. 6, p. 986–1000.

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, 17 p. [Also available at https://doi.org/10.3390/rs12040725.]

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, article 791, 15 p. [Also available at https://doi.org/10.3390/rs10050791.]

Invasives Need 4

Assess effectiveness of targeted grazing with livestock to reduce nonnative annual grasses and understand the impact on native plants in the sagebrush ecosystem.

Next Step 4a

Implement and intensively monitor landscape-level, targeted-grazing demonstration projects to strategically reduce fine fuels.

Davies, K.W., Boyd, C.S., Bates, J.D., and Hulet, A., 2015, 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.

Lehnhoff, E.A., Rew, L.J., Mangold, J.M., Seipel, T., and Ragen, D., 2019, Integrated management of cheatgrass (*Bromus tectorum*) with sheep grazing and herbicide: Agronomy, v. 9, 21 p. [Also available at https://doi.org/10.3390/agronomy9060315.]

Montes-Sánchez, J.J., Van Miegroet, H., and Villalba, J.J., 2017, Effects of energy supplementation and time on use of medusahead by grazing ewes with their lambs: Rangeland Ecology and Management, v. 70, no. 3, p. 380–387.

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.

Rinella, M.J., and Bellows, S.E., 2016, Evidence-targeted grazing benefits to invaded rangelands can increase over extended time frames: Rangeland Ecology and Management, v. 69, no. 3, p. 169–172.

Next Step 4b

Implement and assess several projects to establish grazed “fire breaks” in combination with other fuel treatment methods, determining relative importance of targeted grazing versus other treatments.

NA.

Next Step 4c

Determine thresholds of residual herbaceous fuels required to alter fire behavior and facilitate suppression under various weather conditions.

Davies, K.W., Bates, J.D., Boyd, C.S., and Svejcar, T.J., 2016, 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., 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, 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., 2016, Winter grazing decreases the probability of fire-induced mortality of bunchgrasses and may reduce wildfire size—A response to Smith et al.: 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. no. 6, p. 485–490.

Davies, K.W., Nafus, A.M., Boyd, C.S., Hulet, A., and Bates, J.D., 2016, 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.

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, 17 p. [Also available at https:// doi.org/10.3390/rs12121911.]

Smith, M.S.A., Talhelm, A.F., Kolden, C.A., Newingham, B.A., Adams, H.D., Cohen, J.D., Yedinak, K.M., and Kremens, R.L., 2016, The ability of winter grazing to reduce wildfire size and fire-induced plant mortality was not demonstrated—A comment on Davies et al. (2015): International Journal of Wildland Fire, v. 25, no. 4, p. 484–488.

Next Step 4d

Evaluate the economic efficiencies of using targeted grazing as a short-term wildland fuel treatment.

NA.

Next Step 4e

Evaluate the potential role of livestock grazing to reduce fuel loads in mixed shrub and grass vegetation types in the short-term.

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., Boyd, C.S., Bates, J.D., and Hulet, A., 2015, 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.

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.

Veblen, K.E., Nehring, K.C., McGlone, C.M., and Ritchie, M.E., 2015, Contrasting effects of different mammalian herbivores on sagebrush plant communities: PLoS ONE, v. 10, no. 2, 19 p. [Also available at https://doi.org/10.1371/journal.pone.0118016.]

Next Step 4f

Evaluate the rate, frequency, and timing of grazing events necessary to maintain targeted fuel levels.

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., 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.

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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. 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.

Smith, M.S.A., Talhelm, A.F., Kolden, C.A., Newingham, B.A., Adams, H.D., Cohen, J.D., Yedinak, K.M., and Kremens, R.L., 2016, The ability of winter grazing to reduce wildfire size and fire-induced plant mortality was not demonstrated—A comment on Davies et al. (2015): International Journal of Wildland Fire, v. 25, no. 4, p. 484–488.

Next Step 4g

Evaluate the interactions between the modifications of fine fuels by grazing and sage-grouse nesting and brood-rearing success, including measurement of the impacts of grass height on nesting cover and insect availability.

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, 19p.

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.

Cutting, K.A., Rotella, J.J., Schroff, S.R., Frisina, M.R., Waxe, J.A., Nunlist, E., and Sowell, B.F., 2019, Maladaptive nest-site selection by a sagebrush dependent species in a grazing-modified landscape: Journal of Environmental Management, v. 236, p. 622–630.

Davies, K.W., Nafus, A.M., Boyd, C.S., Hulet, A., and Bates, J.D., 2016, 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.

Elwell, S.L., Griswold, T., and Elle, E., 2016, Habitat type plays a greater role than livestock grazing in structuring shrubsteppe plant-pollinator communities: Journal of Insect Conservation, v. 20, no. 3, p. 515–525.

Hunter, H.E., Husby, P.O., Fidel, J., and Mosley, J.C., 2018, Ecological health of grasslands and sagebrush steppe on the northern Yellowstone Range: Rangelands, v. 40, no. 6, p. 212–223.

Rowland, M.M., 2019, The effects of management practices on grassland birds—Greater sage-grouse (*Centrocercus urophasianus*): chap. B of Johnson, D.H., Igl, L.D., Shaffer, J.A., and DeLong, J.P., eds., The effects of management practices on grassland birds, U.S. Geological Survey Professional Paper 1842, 50 p.

Veblen, K.E., Nehring, K.C., McGlone, C.M., and Ritchie, M.E., 2015, Contrasting effects of different mammalian herbivores on sagebrush plant communities: PLoS ONE, v. 10, no. 2, 19 p. [Also available at https://doi.org/10.1371/journal.pone.0118016.]

Next Step 4h

Evaluate the role of livestock in spreading invasive weeds, and explore methods to ameliorate the problem of the spread of invasive weeds.

Chuong, J., Huxley, J., Spotswood, E.N., Nichols, L., Mariotte, P., and Suding, K.N., 2016, Cattle as dispersal vectors of invasive and introduced plants in a California annual grassland: Rangeland Ecology and Management, v. 69, no. 1, p. 52–58.

Morton, H.L., 2015, Weed and brush control for range improvement: Range Research and Range Problems, v. 3, p. 55–74.

Perryman, B.L., Schultz, B.W., Burrows, M., Shenkoru, T., and Wilker, J., 2020, -grazing and grazing-exclusion effects on cheatgrass (*Bromus tectorum*) seed bank assays in Nevada, United States: Rangeland Ecology and Management, v. 73, no. 3, p. 343–347.

Porensky, L.M., McGee, R., and Pellatz, D.W., 2020, Long-term grazing removal increased invasion and reduced native plant abundance and diversity in a sagebrush grassland: Global Ecology and Conservation, v. 24, 13 p. [Also available at https://doi.org/10.1016/j.gecco.2020.e01267.]

Reisner, M.D., Doescher, P.S., and Pyke, D.A., 2015, Stress-gradient hypothesis explains susceptibility to *Bromus tectorum* invasion and community stability in North America's semi-arid *Artemisia tridentata wyomingensis* ecosystems: Journal of Vegetation Science, v. 26, no. 6, p. 1212–1224.

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, 10 p.

Veblen, K.E., Nehring, K.C., McGlone, C.M., and Ritchie, M.E., 2015, Contrasting effects of different mammalian herbivores on sagebrush plant communities: PLoS ONE, v. 10, no. 2, 19 p. [Also available at https://doi.org/10.1371/journal.pone.0118016.]

Williamson, M.A., Fleishman, E., Mac Nally, R.C., Chambers, J.C., Bradley, B.A., Dobkin, D.S., Board, D.I., Fogarty, F.A., Horning, N., Leu, M., and Zillig, M.W., 2020, Fire, livestock grazing, topography, and precipitation affect occurrence and prevalence of cheatgrass (*Bromus tectorum*) in the central Great Basin, USA: Biological Invasions, v. 22, no. 2, p. 663–680.

Next Step 4i

Develop science-based guidance for implementing and assessing effectiveness and resource and economic impacts of targeted grazing projects to manage wildland fuels.

Brownsey, P., James, J.J., Barry, S.J., Becchetti, T.A., Davy, J.S., Doran, M.P., Forero, L.C., Harper, J.M., Larsen, R.E., Larson-Proplan, S.R., Zhang, J., and Laca, E.A., 2017, Using phenology to optimize timing of mowing and grazing treatments for medusahead (*Taeniatherum caput-medusae*): Rangeland Ecology and Management, v. 70, no. 2, p. 210–218.

Next Step 4j

Develop management strategies to accomplish cost-effective high herbaceous biomass utilization.

Silva, L.G., Benedeti, P.D.B., Paula, E.M., Malekjahani, F., Amaral, P.M., Mariz, L.D.S., Shenkoru, T., and Faciola, A.P., 2017, Effects of carbohydrate and nitrogen supplementation on fermentation of cheatgrass (*Bromus tectorum*) in a dual-flow continuous culture system: Journal of Animal Science, v. 95, no. 3, p. 1335–1344.

Stonecipher, C.A., Panter, K.E., and Villalba, J.J., 2016, Effect of protein supplementation on forage utilization by cattle in annual grass-dominated rangelands in the Channeled Scablands of eastern Washington: Journal of Animal Science, v. 94, no. 6, p. 2572–2582.

Villalba, J.J., and Burritt, E.A., 2015, Intake of medusahead by sheep—Influence of supplements, silica, and individual animal variation: Invasive Plant Science and Management, v. 8, no. 2, p. 151–159.

Next Step 4k

Continue short-term monitoring and research studies in grazing demonstration areas to ensure that management practices are effective and sustainable.

Davies, K.W., Boyd, C.S., Bates, J.D., and Hulet, A., 2015, 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.

Lehnhoff, E.A., Rew, L.J., Mangold, J.M., Seipel, T., and Ragen, D., 2019, Integrated management of cheatgrass (*Bromus tectorum*) with sheep grazing and herbicide: Agronomy, v. 9, article 315, 21 p. [Also available at https://doi.org/10.3390/agronomy9060315.]

Montes-Sánchez, J.J., Van Miegroet, H., and Villalba, J.J., 2017, Effects of energy supplementation and time on use of medusahead by grazing ewes with their lambs: Rangeland Ecology and Management, v. 70, no. 3, p. 380–387.

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.

Rinella, M.J., and Bellows, S.E., 2016, Evidence-targeted grazing benefits to invaded rangelands can increase over extended time frames: Rangeland Ecology and Management, v. 69, no. 3, p. 169–172.

Next Step 4l

Evaluate the effects of grazing over large areas on fire intensity and patchiness, and extent of burned area.

Davies, K.W., Boyd, C.S., Bates, J.D., and Hulet, A., 2015, 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., 2016, 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.

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Smith, M.S.A., Talhelm, A.F., Kolden, C.A., Newingham, B.A., Adams, H.D., Cohen, J.D., Yedinak, K.M., and Kremens, R.L., 2016, The ability of winter grazing to reduce wildfire size and fire-induced plant mortality was not demonstrated—A comment on Davies et al. (2015): International Journal of Wildland Fire, v. 25, no. 4, p. 484–488.

Next Step 4m

Determine the ecological impact of “heavy utilization” to accomplish fuel reduction on the wildlife, plant, and soil microbial communities, especially those related to or dependent on native plants.

Davies, K.W., Nafus, A.M., Boyd, C.S., Hulet, A., and Bates, J.D., 2016, 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.

Next Step 4n

Investigate the effects of feral horses and burros, in combination with livestock, and as a single change agent.

Davies, K.W., and Boyd, C.S., 2019, Ecological effects of free-roaming horses in North American rangelands: Bioscience, v. 69, no. 7, p. 558–565.

King, S.R.B., Schoenecker, K.A., and Manier, D.J., 2019, Potential spread of cheatgrass and other invasive species by feral horses in western Colorado: Rangeland Ecology and Management, v. 72, no. 4, p. 706–710.

Next Step 4o

Develop strategies to replace nonnative annual grasses with grazing-tolerant and fire-resilient plant materials, particularly those that support sage-grouse nesting and brood-rearing, in targeted grazing demonstration areas.

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.

Barak, R.S., Fant, J.B., Kramer, A.T., and Skogen, K.A., 2015, Assessing the value of potential “native winners” for restoration of cheatgrass-invaded habitat: Western North American Naturalist, v. 75, no. 1, p. 58–69.

Blank, R.R., Morgan, T., and Allen, F., 2015, Suppression of annual *Bromus tectorum* by perennial *Agropyron cristatum*—Roles of soil nitrogen availability and biological soil space: AoB Plants, v. 7, 11 p. [Also available at https://doi.org/10.1093/aobpla/plv006.]

Cumberland, C., Jonas, J.L., and Paschke, M.W., 2017, Impact of grasshoppers and an invasive grass on establishment and initial growth of restoration plant species: Restoration Ecology, v. 25, no. 3, p. 385–395.

Davies, K.W., and Johnson, D.D., 2017, Established perennial vegetation provides high resistance to reinvasion by exotic annual grasses: Rangeland Ecology and Management, v. 70, no. 6, p. 748–754.

Davies, K.W., Boyd, C.S., Johnson, D.D., Nafus, A.M., and Madsen, M.D., 2015, Success of seeding native compared with introduced perennial vegetation for revegetating medusahead-invaded sagebrush rangeland: Rangeland Ecology and Management, v. 68, no. 3, p. 224–230.

Davies, K.W., Madsen, M.D., and Hulet, A., 2017, Using activated carbon to limit herbicide effects to seeded bunchgrass when revegetating annual grass-invaded rangelands: Rangeland Ecology and Management, v. 70, no. 5, p. 604–608.

Gibson, A., Nelson, C.R., and Atwater, D.Z., 2018, Response of bluebunch wheatgrass to invasion—Differences in competitive ability among invader-experienced and invader-naive populations: Functional Ecology, v. 32, no. 7, p. 1857–1866.

Harvey, A.J., Simanonok, S.C., Rew, L.J., Prather, T.S., and Mangold, J.M., 2020, Effect of *Pseudoroegneria spicata* (bluebunch wheatgrass) seeding date on establishment and resistance to invasion by *Bromus tectorum* (cheatgrass): Ecological Restoration, v. 38, no. 3, p. 145–152.

James, J.J., Gornish, E.S., DiTomaso, J.M., Davy, J., Doran, M.P., Becchetti, T., Lile, D., Brownsey, P., and Laca, E.A., 2015, Managing medusahead (*Taeniatherum caput-medusae*) on rangeland—A meta-analysis of control effects and assessment of stakeholder needs: Rangeland Ecology and Management, v. 68, no. 3, p. 215–223.

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

Leger, E.A., and Goergen, E.M., 2017, Invasive *Bromus tectorum* alters natural selection in arid systems: Journal of Ecology, v. 105, no. 6, p. 1509–1520.

Monaco, T.A., Mangold, J.M., Mealor, B.A., Mealor, R.D., and Brown, C.S., 2017, Downy brome control and impacts on perennial grass abundance—A systematic review spanning 64 years: Rangeland Ecology and Management, v. 70, no. 3, p. 396–404.

Mummey, D.L., Herget, M.E., Hufford, K.M., and Shreading, L., 2016, Germination timing and seedling growth of *Poa secunda* and the invasive grass, *Bromus tectorum*, in response to temperature—Evaluating biotypes for seedling traits that improve establishment: Ecological Restoration, v. 34, no. 3, p. 200–208.

Phillips, A.J., and Leger, E.A., 2015, Plastic responses of native plant root systems to the presence of an invasive annual grass: American Journal of Botany, v. 102, no. 1, p. 73–84.

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Schantz, M.C., Sheley, R.L., and James, J.J., 2015, Role of propagule pressure and priority effects on seedlings during invasion and restoration of shrub-steppe: Biological Invasions, v. 17, no. 1, p. 73–85.

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Walker, J.T., James, J.J., and Drenovsky, R.E., 2017, Competition from *Bromus tectorum* removes differences between perennial grasses in N capture and conservation strategies: Plant and Soil, v. 412, no. 1–2, p. 177–188.

Next Step 4p

Evaluate the potential role of livestock grazing to reduce fuel loads in mixed shrub and grass vegetation types over long time frames; include type of livestock (cattle versus sheep), pre-grazing condition, seasonal precipitation (amount and timing), and interactions with other treatment methods, including fire, chemical, and mechanical treatments conducted individually or in combinations.

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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, Ecosystems, v. 21, no. 7, p. 1416–1431.

Davies, K.W., Bates, J.D., Boyd, C.S., and Svejcar, T.J., 2016, 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.

Perryman, B.L., Schultz, B.W., McAdoo, J.K., Alverts, R.L., Cervantes, J.C., Foster, S., McCuin, G., and Swanson, S., 2018, Viewpoint—An alternative management paradigm for plant communities affected by invasive annual grass in the Intermountain West: Rangelands, v. 40, no. 3, p. 77–82.

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

NA.

Invasives Need 5

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

Next Step 5a

Develop a study design and protocols that can be used in a U.S. Department of the Interior (DOI) pilot study to ensure consistency in site selection, product application, data collection, and data management to evaluate efficacy and impacts to non-target species across a broad geographical area.

NA.

Next Step 5b

Develop and conduct improved trials of the effectiveness and effects of ACK55 to address requirements for EPA registration.

Kennedy, A.C., 2018, Selective soil bacteria to manage downy brome, jointed goatgrass, and medusahead and do no harm to other biota: Biological Control, v. 123, p. 18–27.

Reinhart, K.O., Carlson, C.H., Feris, K.P., Germino, M.J., Jandreau, C.J., Lazarus, B.E., Mangold, J., Pellatz, D.W., Ramsey, P., Rinella, M.J., and Valliant, M., 2020, Weed-suppressive bacteria fail to control *Bromus tectorum* under field conditions: Rangeland Ecology and Management, v. 73, no. 6, p. 760–765.

Next Step 5c

Evaluate the effectiveness of weed-suppressive bacteria treatments through time to reduce cheatgrass dominance over large areas.

Germino, M.J., and Lazarus, B.E., 2020b, Weed-suppressive bacteria have no effect on exotic or native plants in sagebrush-steppe: Rangeland Ecology and Management, v. 73, no. 6, p. 756–759.

Kennedy, A.C., 2018, Selective soil bacteria to manage downy brome, jointed goatgrass, and medusahead and do no harm to other biota: Biological Control, v. 123, p. 18–27.

Lazarus, B.E., Germino, M.J., Brabec, M., Peterson, L., Walker, R.N., and Moser, A., 2020, Post-fire management-scale trials of bacterial soil amendment MB906 show inconsistent control of invasive annual grasses: Rangeland Ecology and Management, v. 73, no. 6, p. 741–748.

Prevéy, J.S., and Seastedt, T.R., 2015, Increased winter precipitation benefits the native plant pathogen *Ustilago bullata* that infects an invasive grass: Biological Invasions, v. 17, no. 10, p. 3041–3047.

Pyke, D.A., Shaff, S.E., Gregg, M.A., and Conley, J.L., 2020, Weed-suppressive bacteria applied as a spray or seed mixture did not control *Bromus tectorum*: Rangeland Ecology and Management, v. 73, no. 6, p. 749–752.

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Tekiela, D.R., 2020, Effects of the bioherbicide pseudomonas fluorescens D7 on downy brome: Rangeland Ecology and Management, v. 73, no. 6, p. 753–755.

Next Step 5d

Complete a review of all open-source and non-open-source literature highlighting successful and unsuccessful applications of weed-suppressive bacteria as a nonnative annual grass biopesticide.

Germino, M.J., and Lazarus, B.E., 2020a, Synthesis of weed-suppressive bacteria studies in rangelands of the western United States—Special section of articles in Rangeland Ecology and Management provides little evidence of effectiveness: Rangeland Ecology and Management, v. 73, no. 6, p. 737–740.

Harding, D.P., and Raizada, M.N., 2015, Controlling weeds with fungi, bacteria and viruses—A review: Frontiers in Plant Science, v. 6, 14 p. [Also available at https://doi.org/10.3389/fpls.2015.00659.]

Next Step 5e

Develop a user-friendly centralized data management system to promote the exchange of information and facilitate investigation of efficacy and non-target effects of weed-suppressive bacteria.

NA.

Next Step 5f

Investigate effects of biocontrol agents on soil microbial communities.

NA.

Next Step 5g

Research and develop new delivery mechanisms (for example, pellets, granules) that will foster successful bacteria application over large areas.

NA.

Next Step 5h

Develop best management practices and associated guidance for proper use of biocontrols.

NA.

Studies Related to Need 5, but Not Any of the Next Steps

Cristofaro, M., Roselli, G., Marini, F., de Lillo, E., Petanovic, R.U., Augé, M., and Rector, B.G., 2020, Open field evaluation of *Aculodes altamurgensis*, a recently described eriophyid species associated with medusahead (*Taeniatherum caput-medusae*): Biocontrol Science and Technology, v. 30, no. 4, p. 339–350.

Lozano-Juste, J., Masi, M., Cimmino, A., Clement, S., Fernandez, M.A., Antoni, R., Meyer, S., Rodriguez, P.L., and Evidente, A., 2019, The fungal sesquiterpenoid pyrenophoric acid B uses the plant ABA biosynthetic pathway to inhibit seed germination: Journal of Experimental Botany, v. 70, no. 19, p. 5487–5494.

Invasives Need 6

Investigate cheatgrass die-off and potential biocontrols for cheatgrass to provide effective tools for site preparation.

Next Step 6a

Expand analysis of die-offs to include large expanses of cheatgrass-dominated desert valleys across the Great Basin, and use geospatial statistical tools to improve die-off predictive models.

Boyte, S.P., Wylie, B.K., and Major, D.J., 2015, Mapping and monitoring cheatgrass dieoff in rangelands of the northern Great Basin USA: Rangeland Ecology and Management, v. 68, no. 1, p. 18–28.

Weisberg, P.J., Dilts, T.E., Baughman, O.W., Meyer, S.E., Leger, E.A., Van Gunst, K.J., and Cleeves, L., 2017, Development of remote sensing indicators for mapping episodic die-off of an invasive annual grass (*Bromus tectorum*) from the Landsat archive: Ecological Indicators, v. 79, p. 173–181.

Next Step 6b

Develop technology to measure pathogen loads in soil using molecular-genetic techniques.

NA.

Next Step 6c

Carry out studies on small plots where pathogen load and environmental conditions are manipulated to determine how and where failure of cheatgrass can be induced by management as a site-preparation technique prior to restoration seeding.

Allen, P.S., Finch-Boekweg, H., and Meyer, S.E., 2018, A proposed mechanism for high pathogen-caused mortality in the seed bank of an invasive annual grass: Fungal Ecology, v. 35, p. 108–115.

Beckstead, J., Meyer, S.E., Ishizuka, T.S., McEvoy, K.M., and Coleman, C.E., 2016, Lack of host specialization on winter annual grasses in the fungal seed bank pathogen *Pyrenophora semeniperda*: PLoS ONE, v. 11, no. 3, 20 p. [Also available at https://doi.org/10.1371/journal.pone.0151058.]

Coleman, C.E., Meyer, S.E., and Ricks, N., 2019, Mating system complexity and cryptic speciation in the seed bank pathogen *Pyrenophora semeniperda*: Plant Pathology, v. 68, no. 2, p. 369–382.

Connolly, B.M., Carris, L.M., and Mack, R.N., 2018, Soil-borne seed pathogens—Contributors to the naturalization gauntlet in Pacific Northwest (USA) forest and steppe communities?: Plant Ecology, v. 219, no. 4, p. 359–368.

Ehlert, K.A., Miller, Z., Mangold, J.M., Menalled, F., and Thornton, A., 2019, Temperature effects on three downy brome (*Bromus tectorum*) seed collections inoculated with the fungal pathogen *Pyrenophora semeniperda*: Invasive Plant Science and Management, v. 12, no. 2, p. 150–154.

Masi, M., Meyer, S., Pescitelli, G., Cimmino, A., Clement, S., Peacock, B., and Evidente, A., 2017, Phytotoxic activity against *Bromus tectorum* for secondary metabolites of a seed-pathogenic Fusarium strain belonging to the *F. tricinctum* species complex: Natural Product Research, v. 31, no. 23, p. 2768–2777.

Next Step 6d

Determine the effects of cheatgrass pathogens on non-target hosts, including species likely to be included in restoration seeding mixes.

Baughman, O.W., Burton, R., Williams, M., Weisberg, P.J., Dilts, T.E., and Leger, E.A., 2017, Cheatgrass die-offs—A unique restoration opportunity in northern Nevada: Rangelands, v. 39, no. 6, p. 165–173.

Baughman, O.W., Meyer, S.E., Aanderud, Z.T., and Leger, E.A., 2016, Cheatgrass die-offs as an opportunity for restoration in the Great Basin, USA—Will local or commercial native plants succeed where exotic invaders fail?: Journal of Arid Environments, v. 124, p. 193–204.

Ehlert, K.A., Mangold, J.M., Menalled, F., Miller, Z., and Dyer, A., 2019, Seeding, herbicide, and fungicide impact on perennial grass establishment in cheatgrass infested habitats: Ecological Restoration, v. 37, no. 2, p. 67–70.

Next Step 6e

Continue and expand studies to assess effectiveness of restoration seedings in new die-offs (mapped in real-time), including reestablishment of deep-rooted perennial grasses and sagebrush.

Baughman, O.W., Burton, R., Williams, M., Weisberg, P.J., Dilts, T.E., and Leger, E.A., 2017, Cheatgrass die-offs—A unique restoration opportunity in northern Nevada: Rangelands, v. 39, no. 6, p. 165–173.

Baughman, O.W., Meyer, S.E., Aanderud, Z.T., and Leger, E.A., 2016, Cheatgrass die-offs as an opportunity for restoration in the Great Basin, USA—Will local or commercial native plants succeed where exotic invaders fail?: Journal of Arid Environments, v. 124, p. 193–204.

Next Step 6f

Use die-off predictive models and information about seed-bed pathogen loads to determine where to install study trials over large areas to evaluate induced die-offs with and without inoculum additions.

NA.

Next Step 6g

Carry out die-off induction trials over large geographic areas, and include post-die-off restoration seeding (using appropriate native plant materials) to determine how well this type of site preparation facilitates the establishment of seeded species across a range of site types in different environments.

Baughman, O.W., Burton, R., Williams, M., Weisberg, P.J., Dilts, T.E., and Leger, E.A., 2017, Cheatgrass die-offs—A unique restoration opportunity in northern Nevada: Rangelands, v. 39, no. 6, p. 165–173.

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Next Step 6h

Develop technology to scale up inoculum production for promising strains of potential biocontrol organisms.

NA.

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

Gehring, C.A., Hayer, M., Flores-Renteria, L., Krohn, A.F., Schwartz, E., and Dijkstra, P., 2016, Cheatgrass invasion alters the abundance and composition of dark septate fungal communities in sagebrush steppe: Botany, v. 94, no. 6, p. 481–491.

Masi, M., Meyer, S., Gorecki, M., Pescitelli, G., Clement, S., Cimmino, A., and Evidente, A., 2018, Phytotoxic activity of metabolites isolated from Rutstroemia sp.n., the causal agent of Bleach Blonde Syndrome on cheatgrass (*Bromus tectorum*): Molecules, v. 23, article 1734, 12 p.

Meyer, S.E., Beckstead, J., and Allen, P.S., 2018, Niche specialization in *Bromus tectorum* seed bank pathogens: Seed Science Research, v. 28, no. 3, p. 215–221.

Meyer, S.E., Beckstead, J., and Pearce, J., 2016, Community ecology of fungal pathogens on *Bromus tectorum, in* Germino, M.J., Chambers, J.C., and Brown, C.S., eds., Exotic brome-grasses in arid and semiarid ecosystems of the western U.S: Switzerland, Springer International Publishing, p. 193–223.

Ricks, K.D., and Koide, R.T., 2019, Biotic filtering of endophytic fungal communities in *Bromus tectorum*: Oecologia, v. 189, no. 4, p. 993–1003.

Salo, C., 2018, Army cutworm outbreak produced cheatgrass die-offs and defoliated shrubs in southwest Idaho in 2014: Rangelands, v. 40, no. 4, p. 99–105.

Smull, D.M., Pendleton, N., Kleinhesselink, A.R., and Adler, P.B., 2019, Climate change, snow mold and the *Bromus tectorum* invasion—Mixed evidence for release from cold weather pathogens: AoB Plants, v. 11, no. 5, 9 p.

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