

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

Open-File Report 2023–1035

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

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Conversion Factors

U.S. customary units to International System of Units

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

International System of Units to U.S. customary units

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

Abbreviations

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

Species names

Basin big sagebrush	<i>Artemisia tridentata</i> spp. <i>tridentata</i>
Big sagebrush	<i>Artemisia tridentata</i> spp.
Cheatgrass	<i>Bromus tectorum</i>
Crested wheatgrass	<i>Agropyron cristatum</i>
Sage-grouse	<i>Centrocercus urophasianus</i>
Juniper	<i>Juniperus</i> spp.
Mountain big sagebrush	<i>Artemisia tridentata</i> spp. <i>vaseyana</i>
Sagebrush	<i>Artemisia</i> spp.
Woodrat	<i>Neotoma</i> spp.
Wyoming big sagebrush	<i>Artemisia tridentata</i> spp. <i>wyomingensis</i>

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Abstract

Loss and degradation of sagebrush (*Artemisia* spp.) rangelands due to an accelerated invasive annual grass-wildfire cycle and other stressors are significant management, conservation, and economic issues in the western U.S. 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 (hereinafter, “Needs”) for informing the actions proposed under the five topics (Fire, Invasives, Restoration, Sagebrush and Sage-Grouse (*Centrocercus urophasianus*), 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 four Needs identified under the Climate and Weather topic in the Plan. The topic outlined

research Needs broadly focused on understanding the potential effects of climate change on vegetative resilience to inform restoration of sagebrush rangelands. We established the level of progress towards addressing each Need following a standardized set of criteria, and developed summaries detailing how research objectives nested within Needs identified in the Plan (hereinafter, “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 92 science products that at least partially addressed a Need identified in the Climate and Weather topic. The Needs that were well and partially addressed included:

- (1) studies of the complex set of climatic relationships that influence sagebrush rangeland restoration and seeding success;
- (2) the identification of seed collection areas across the range of environmental variability inhabited by target restoration species; and
- (3) develop predictive models to assess targeted restoration species’ responses to mid-century climatic conditions.

The Need addressed poorly was the identification of native plant species, genotypes and ecotypes, and seed mixes that may be resilient to a changing climate. The information provided in this assessment will assist updating the Plan, and can inform updates of other relevant science planning documents as needed.

Introduction

Stemming the cumulative loss and degradation of sagebrush (*Artemisia* spp.) rangelands 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

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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; BLM, 2020). Approximately 55–60 percent of sagebrush rangelands of the western U.S. have been lost (direct conversion) or degraded (alteration of understory vegetation or fragmentation) since European settlement (Knick and others, 2003; Miller and others, 2011). Sagebrush rangelands are currently distributed across 160 million acres of 14 western states (Remington and others, 2021; fig. 1).

Arresting downward trends in sagebrush ecosystems is complex owing to multiple and often interacting stressors, including conversion to agricultural crops or non-native perennial grasses (for example, crested wheatgrass [*Agropyron cristatum*]), energy development, improper livestock grazing, expansion of native conifers, and other anthropogenic surface disturbing activities (for example, roads, transmission lines, exurban development; Hanser and others, 2018; Shinneman, 2019; BLM, 2020). However, altered wildfire regimes driven largely by positive feedbacks from invasive annual grasses (Miller and Eddleman, 2001; Balch and others, 2013) are perhaps the most immediate and pervasive threat to sagebrush rangelands (U.S. Fish and Wildlife Service, 2013; fig. 2). The proliferation of invasive annual grasses (for example, cheatgrass [*Bromus tectorum*]) and resulting increases in fire frequency and extent can ultimately result in long-term and often permanent loss of fire-intolerant species of sagebrush along with deep rooted bunchgrass and soil microbial communities that normally promote resilience to disturbance and resistance to invasion in sagebrush ecosystems (Chambers and others, 2014; Germino and others, 2016). The threat from the annual grass-wildfire cycle is greatest throughout western portions of the sagebrush biome (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 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; 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, 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 5 topics outlined in the IRFMS: (1) Fire, (2) Invasives (plant species), (3) Restoration, (4) Sagebrush and Sage-Grouse, and (5) Climate and Weather. A multi-disciplinary team of experts developed narratives describing these highest-priority Needs and outlined a series of research objectives (hereinafter, Next Steps) to help guide the development of new knowledge, syntheses, and decision-support tools for addressing each Need.

Conservation strategies depend on the consideration and application of the best available science, and ongoing efforts to address gaps in that scientific knowledge, to achieve management success. While the state of the science has ostensibly advanced owing to substantial research investments since the Plan's release in 2016, the extent to which knowledge gaps remain relative to identified Needs is largely unknown. Several annotated bibliographies and literature reviews have made strides towards making results from research efforts in the sagebrush biome available and tractable for management audiences (for example, Hanser and others, 2018; Carter and others, 2020; Poor and others, 2021). However, many knowledge gaps likely remain, and an assessment of the progress made on achieving previously identified priorities is needed to help focus the next prioritization on unresolved gaps in the science and new science needs that have arisen since development of the original strategy. A quantifiable and targeted assessment of progress made towards meeting the original Needs under the Plan's five topics can help identify unresolved gaps and prioritize future actionable research efforts for new questions and possible (yet untested) solutions.

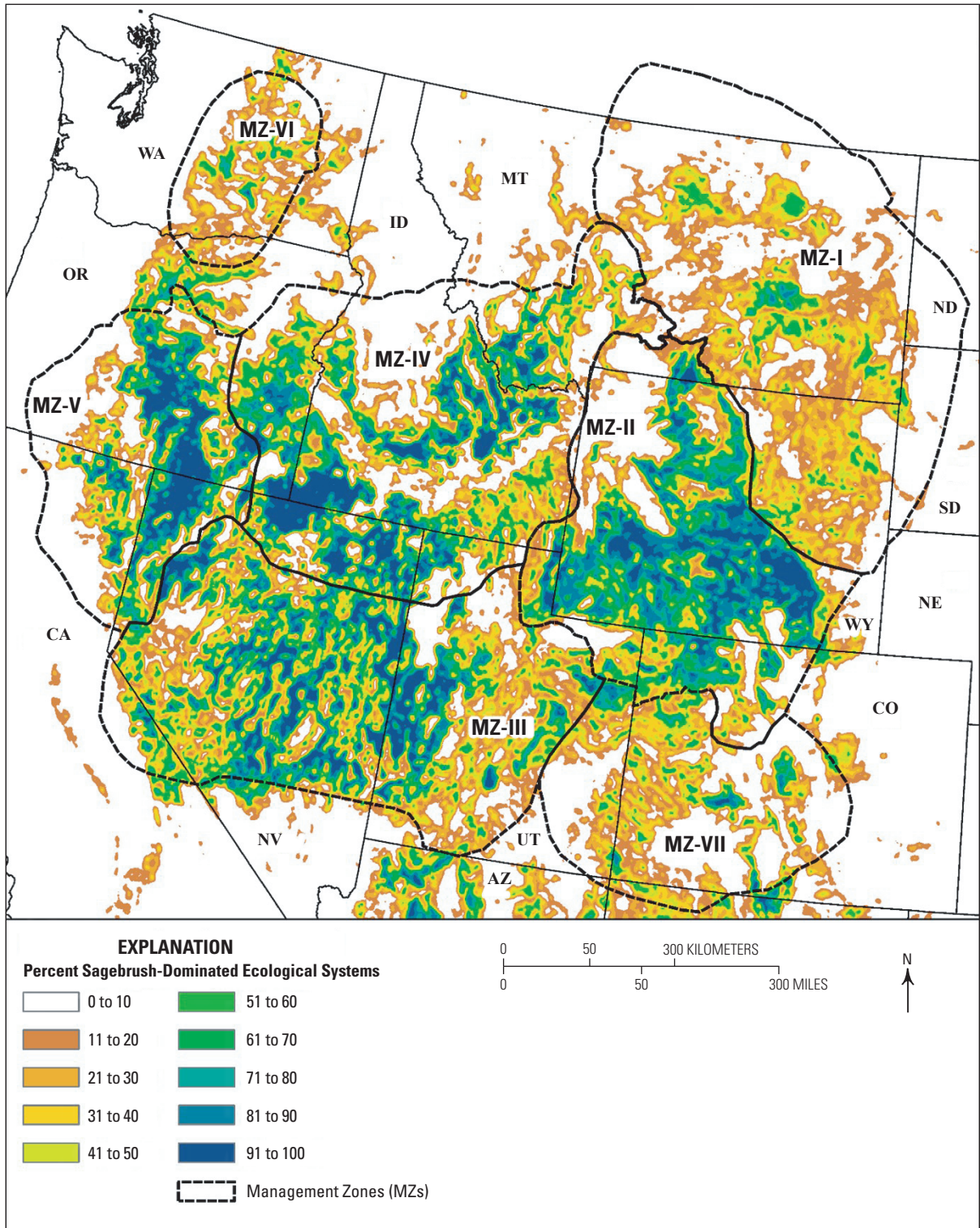


Figure 1. Landscape cover of sagebrush-dominated ecological systems in the western United States (fig. 28 from Chambers and others, 2017).

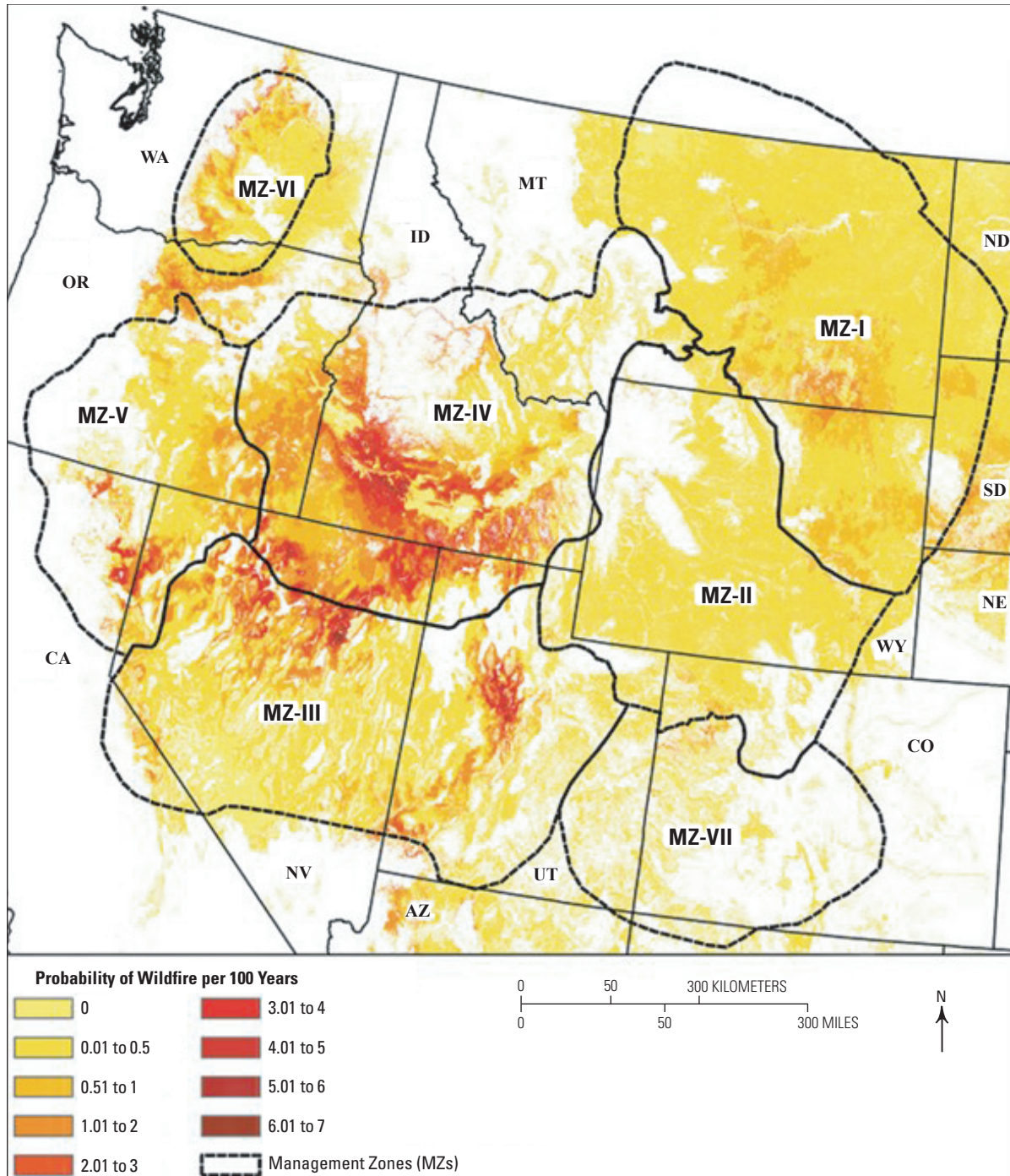


Figure 2. Large fire probability for the sagebrush biome in the western United States (fig. 34 from Chambers and others, 2017).

The Climate and Weather topic in the Plan identified four Needs focused on understanding the response of sagebrush rangeland plant species to climate change for informing restoration of the ecosystem. The priorities identified across the four Needs broadly encompassed:

- (1) the development of predictive models for plant species used for restoring sagebrush communities under mid-century climatic conditions;
- (2) identify areas to protect and maintain climate-appropriate native seeds;
- (3) the identification of native plant materials resilient to climate change; and
- (4) increasing the understanding of the complex set of variables that control the seeding success of native plant species.

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 four Needs identified under the Climate and Weather topic in the Plan. Five years was considered an adequate time period for implementation of science projects that coincided with or were inspired by the Plan and, as such, a suitably defined interval for completing this assessment and updating priority science and management needs. Our objective was to comprehensively summarize the scientific literature generated since the release of the Plan. Leveraging advances in bibliographic search-engine tools, we developed a quantitative “scorecard” to assess progress towards addressing each Need following a standardized set of criteria. The scorecard informed summaries detailing how Next Steps were addressed in the literature as well as those that remain unresolved. The summaries are intended to provide information for stakeholder-driven efforts aimed at identifying the next set of science needs in a forthcoming updated version of the Plan.

Methods

We organized literature reviews on the five overarching topics included in the Plan (that is, [1] Fire, [2] Invasives (plant species), [3] Restoration, [4] Sagebrush and Sage-Grouse, and [5] Climate and Weather). For the Climate and Weather topic, we used the USGS BiblioSearch (Kleist and Enns, 2022) to search the reference databases Web of Science and Scopus using broad search terms (for example, climate change AND sagebrush). We then conducted a series of literature searches using search terms specific to the Next Steps (for example, climate AND sagebrush restoration AND genotype) to capture the science products that may have been excluded by the broad search terms (table 1). We examined all papers included in the resulting lists of literature

for relevance to the Needs identified in the Climate and Weather topic. Products searched included published literature and peer-reviewed Federal research reports (for example, Open-file reports released by the U.S. Geological Survey). 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 also published in the peer-reviewed literature, we only considered the published manuscript; in situations where the research report included pertinent information not included in the manuscript, we considered both.

We established how well Needs (that is, priority science required to inform the next generation of management strategies) listed in the Plan were addressed in the literature by independently “scoring” each Need from Next Steps (that is, science objectives required to address a Need) associated with the Climate and Weather topic. Papers that were relevant to a Next Step were considered when scoring that Next Step. Our review approach initially focused on a paper’s abstract. If this information suggested that the research was related to a Next Step, we focused our in-depth examination on research objectives, study area descriptions, and data collection and analysis methods. Because the objective of this project was to assess if Next Steps had been addressed, we did not systematically summarize results although we considered results when necessary to determine if the research addressed a Next Step. A given paper could be relevant to more than one Next Step in a Need, more than one Need, and more than one topic.

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 (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” (not applicable) 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 (that is, not addressed) and included in the scoring of the

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

[**Search terms:** Used a search algorithm developed by Kleist and Enns (2022). **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 “climate AND restoration AND sagebrush” and “climate AND fire AND sagebrush” searches). **Comment:** Need 1, improve understanding of the complex set of variables that controls seeding success and improve accuracy of predictive meteorological data and models to identify years when the potential for seeding success is high or low; Need 2, study the propagation and production of native plant materials to identify species or genotypes that may be resilient to climate change; Need 3, identify areas for seed collection across elevational and latitudinal ranges of target species to protect and maintain high-quality sources for native seeds; Need 4, Develop predictive models of climate change effects, targeting restoration species, including regionally suitable culturally significant species, and genetic diversity using 20-year or mid-century climate models]

Search terms	Unique results	Comment
climate change AND sagebrush	161	2015–20; broad search term
climate AND restoration AND sagebrush	64	2015–20; broad search term
climate AND soils AND sagebrush	70	2015–20; broad search term
climate AND fire AND sagebrush	99	2015–20; broad search term
climate AND drought AND sagebrush	41	2015–20; broad search term
climate AND seeding AND sagebrush	19	2015–20; broad search term
weather AND fire AND sage-grouse	12	2015–20; Need 1; targeted search term
weather AND regeneration AND sagebrush	2	2015–20; Need 1; targeted search term
climate AND sagebrush restoration AND resilience	0	2015–20; Need 2; targeted search term
climate AND sagebrush restoration AND genotype	0	2015–20; Need 2; targeted search term
climate AND native restoration AND sagebrush	0	2015–20; Need 2; targeted search term
assisted migration AND sagebrush	1	2015–20; Need 2; targeted search term
drought tolerance AND sagebrush	4	2015–20; Need 2; targeted search term
climate AND sagebrush restoration AND adaptive traits	0	2015–20; Need 3; targeted search term
climate AND sagebrush restoration AND genetic	0	2015–20; Need 3; targeted search term
climate AND sagebrush restoration AND projection	1	2015–20; Need 4; targeted search term

Table 2. Criteria used to score Next Steps established for the Needs included in the Climate and Weather 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 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

¹Next Step not included in scoring of Need

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 (\geq) 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 [\leq] 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 critical for evaluating the scores and informing the next set of science needs in the updated Plan.

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

Results and Summary

We reviewed 474 products that were identified by the literature searches conducted for the Climate and Weather topic (table 1). We found 92 unique products that were directly related to at least one of the four Needs. Most (81 percent) of the 21 Climate and Weather Next Steps had greater than or equal to one published product that at least partially addressed the science objective(s) detailed by that Next Step. One Next Step could not be effectively assessed with the evaluation approach we used and was not scored (“NA”; table 2). The four Next Steps that could be effectively assessed but had no related products (that is, were scored as 0.00 not as NA; table 2) included:

- (1) investigations into whether different seed mixes, including mixes incorporating different seed provenances, can mitigate against climate uncertainty across the range of variability in sagebrush rangelands (Need 1);
- (2) assisted migration trials (Need 2); and
- (3) development of a list of critical plant species and ecotypes that are conducive for seed germination and restoration under projected mid-century climates (Needs 2 and 3).

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.

Need 1, studies addressing seed mixes and climate change, was addressed well (that is, score ≥ 0.67). We found several papers that evaluated restoration and seeding success in relation to a complex set of climate variables. Numerous studies have investigated relationships between variability in environmental factors (for example, precipitation timing, soil temperature and moisture, seasonal ambient temperatures) and native plant responses (for example, germination, emergence, seedling establishment, juvenile survival, seedlot differences) in sagebrush rangelands.

The Needs that were partially addressed (that is, scores 0.50–0.66) included the identification of seed collection areas across the range of environmental variability where target restoration species survive (Need 3); and assessments of important restoration species’ responses to mid-century climatic conditions (Need 4). Big sagebrush survival, growth, phenotypic plasticity, genetic variation, and adaptive breadth have been examined in relation to climatic variability throughout most of the sagebrush biome. The effects of climate change on drought indicators (soil temperature and moisture), snow accumulation, vegetation structure, and carbon fluxes in sagebrush rangelands have been modeled, and experimental field studies (primarily manipulation of the amount and timing of moisture) have been conducted to estimate effects of climate change on sagebrush plant community dynamics and ecosystem processes. State-and-transition models have been used to examine the potential effects of climate change on rangeland condition (for example, exotic annual grass abundance, conifer expansion) and to evaluate the likely effectiveness of restoration efforts under changing climatic conditions.

Need 2, identifying native plant species and genotypes that may be resilient to a changing climate, was addressed poorly (that is, score ≤ 0.49). Studies investigating resilience of native plant species in sagebrush rangelands under different climate change scenarios have not been replicated across the biome. Native plant species, ecotypes, and adaptive traits that will likely be successfully restored under mid-century climatic conditions have not been identified, and assisted migration studies have not been conducted.

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

Need	Score	Summary of 2015–20 literature
<p><i>Need 1:</i> Improve understanding of the complex set of variables that control seeding success and improve accuracy of predictive meteorological data and models to identify years when the potential for seeding success is high or low.</p>	0.83	<p>Addressed: Short- and long-term predictions of the bioclimatic factors (for example, soil temperature and moisture, weather) that contribute to successful regeneration and restoration of native plant species have been simulated under several climate change scenarios across the sagebrush biome. Numerous local, regional, and range wide studies have investigated associations and thresholds between environmental factors (for example, precipitation timing, soil temperature and moisture conditions, seasonal ambient temperatures) and native plant responses (for example, germination, emergence, seedling establishment, juvenile survival, seedlot differences) with many using this information to develop decision-support tools for informing restoration activities (for example, seedling establishment based on soil moisture, precipitation, and temperature trajectories). Several local-scale studies developed and tested various seed coating methods and demonstrated the benefits and limitations of these techniques for enhancing germination and seeding success of native vegetation in the restoration of annual grass-dominated and (or) burned sites (see also Restoration topic Need 2). Distributional shifts of big sagebrush in relation to climate envelopes have been mapped range wide.</p> <p>Outstanding: Spatial replication of experimental and (or) management trial studies of seeding enhancement products is needed across most the sagebrush biome. Techniques to distribute seed enhancement products efficiently and effectively across broad spatial scales have not been developed. Investigations into whether different seed mixes, including mixes incorporating different seed provenances, can mitigate against climate variability have not been conducted. Decision tools to spatially prioritize where seedings will be successful are needed for most native plant species, including sagebrush.</p>
<p><i>Need 2:</i> Study the propagation and production of native plant materials to identify species or genotypes that may be resilient to climate change.</p>	0.40	<p>Addressed: A few greenhouse studies investigating competition and functional trait differences between several perennial grass species and cheatgrass under variable temperature, nutrient availability and precipitation timing and amount have been completed. Associations between the recruitment of several sagebrush species and weather patterns, and sagebrush germination and seedling survival in relation to variable climatic and soil conditions at the edge of the species distribution have been investigated locally and range wide (see also Restoration topic Needs 2 and 4)</p> <p>Outstanding: Replication of studies investigating resilience of native plant species in the sagebrush biome under different climate change scenarios is needed. Experimental and field studies identifying the mechanisms by which native plant species are resilient to climate change are limited. Assisted migration studies have not been conducted. Techniques to enhance drought tolerance of seedlings have not been developed. Native plant species and ecotypes that will likely be successfully restored under mid-century climatic conditions have not been identified.</p>
<p><i>Need 3:</i> Identify areas for seed collection across elevational and latitudinal ranges of target species to protect and maintain high-quality sources for native seeds.</p>	0.60	<p>Addressed: Survival, growth and flowering phenology of Wyoming, mountain and basin big sagebrush collected from variable climates-of-origin have been examined among common gardens located throughout most of the sagebrush biome. Models have been developed to evaluate genetic variation, environmental effects, adaptive breadth, phenotypic plasticity in big sagebrush in relation to climatic factors. Seed transfer zones and seed zone maps for big sagebrush based on model predictions of survival and flowering phenology as a function of climatic variability have been developed for contemporary and future climates (see also Restoration topic Need 4).</p> <p>Outstanding: Adaptive traits and associated climatic drivers have not been identified for most of the native plants in the sagebrush biome other than big sagebrush. Native plant population genetic studies are generally lacking except for the regional-scale study of big sagebrush genetic variability to explain variability in flowering phenology across garden studies. Seed transfer zones or seed zone maps have not been completed for native plant species other than big sagebrush. Assisted migration studies have not been conducted. Native plant species that will likely be successfully restored under future climates have not been identified.</p>

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

Need	Score	Summary of 2015–20 literature
<p><i>Need 4:</i> Develop predictive models of climate change effects, targeting restoration species, including regionally suitable culturally significant species, and genetic diversity using 20-year or mid-century climate models.</p>	0.50	<p>Addressed: Several studies have developed models to quantify the effects of climate change on the severity of drought indicators such as soil temperature and water at local and range wide scales. Potential changes in snow accumulation, vegetation structure, and carbon fluxes in response to climatic variation have been examined at local scales. Numerous local-scale field experiments distributed throughout the sagebrush biome have manipulated environmental conditions (mostly the amount and timing of moisture availability) to investigate effects on plant community dynamics and ecosystem processes. Historic records (for example, pollen, fossilized woodrat middens, sagebrush growth rings) have been used to assess long-term shifts in vegetation and vertebrate communities in response to changing climates. State-and-transition models have been developed and used to examine the potential effects of climate change on rangeland condition (for example, exotic annual grass abundance, juniper expansion) and vegetation types, and to evaluate the likely effectiveness of restoration efforts under changing climatic conditions, at local scales.</p> <p>Outstanding: The level of certainty in the magnitude and direction of changing climates in sagebrush ecosystems has not been quantified across the biome. Existing knowledge about environmental controls over regeneration of native plant species (other than sagebrush) has not been synthesized. Manipulative experimental field studies need to be replicated at broader spatial scales to capture the variability inherent across the sagebrush biome.</p>

There were several Next Steps identified under the Climate and Weather topic that were addressed poorly, even when the overall Need was well or partially addressed. There remains a need for investigations of different seed mixes resilient to climate change and for tools that spatially prioritize areas where seedings of native species (including sagebrush) are expected to be successful (Need 1). Seed transfer zones have not been mapped for native species other than big sagebrush, and native plant populations genetics studies are generally lacking beyond regional-scale studies of big sagebrush (Need 3). The level of certainty in the magnitude and direction of changing climates in sagebrush ecosystems has not been quantified across the entire sagebrush biome, and syntheses of environmental controls over regeneration (for example, soil moisture) of native plant species (other than sagebrush) have not been published (Need 4).

The completion scores and summaries in this report provide the basis to identify new actionable science priorities that are needed to address the issues continuing to drive the loss, degradation, restoration, and conservation of sagebrush habitats in the western U.S. 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 Western Association of Fish and Wildlife Agencies 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 and beyond will require consideration in future Plan updates.

References Cited

- Balch, J.K., Bradley, B.A., D'Antonio, C.M., and Gómez-Dans, J., 2013, Introduced annual grass increases regional fire activity across the arid western USA (1980–2009): *Global Change Biology*, v. 19, no. 1, p. 173–183.
- 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: Boise, Idaho, Bureau of Land Management Idaho State Office, 153 p. [Also available at <https://eplanning.blm.gov/eplanning-ui/project/122968/570>.]
- Carter, S.K., Arkle, R.S., Bencin, H.L., Harms, B.R., Manier, D.J., Johnston, A.N., Phillips, S.L., Hanser, S.E., and Bowen, Z.H., 2020, Annotated bibliography of scientific research on greater sage-grouse published from 2015 to 2019: U.S. Geological Survey Open-File Report 2020–1103, 264 p. [Also available at <https://doi.org/10.3133/ofr20201103>.]
- Chambers, J.C., Beck, J.L., Bradford, J.B., Bybee, J., Campbell, S., Carlson, J., Christiansen, T.J., Clause, K.J., Collins, G., Crist, M.R., Dinkins, J.B., Doherty, K.E., Edwards, F., Espinosa, S., Griffin, K.A., Griffin, P., Haas, J.R., Hanser, S.E., Havlina, D.W., Henke, K.F., Hennig, J.D., Joyce, L.A., Kilkenny, F.M., Kulpa, S.M., Kurth, L.L., Maestas, J.D., Manning, M., Mayer, K.E., Meador, B.A., McCarthy, C., Pellant, M., Perea, M.A., Prentice, K.L., Pyke, D.A., Wiechman, L.A., and Wuenschel, A., 2017, Science framework for conservation and restoration of the sagebrush biome—Linking the Department of the Interior's Integrated Rangeland Fire Management Strategy to long-term strategic conservation actions—Part 1, Science basis and applications: Fort Collins, Colorado, U.S. Forest Service, Rocky Mountain Research Station, General Technical Report RMRS-GTR-360, 213 p. [Also available at <https://www.fs.usda.gov/treearch/pubs/53983>.]
- Chambers, J.C., Bradley, B.A., Brown, C.S., D'Antonio, C., Germino, M.J., Grace, J.B., Hardegree, S.P., Miller, R.F., and Pyke, D.A., 2014, Resilience to stress and disturbance, and resistance to *Bromus tectorum* L. invasion in cold desert shrublands of Western North America: *New York, Ecosystems*, v. 17, no. 2, p. 360–375.
- Crist, M.R., Chambers, J.C., Phillips, S.L., Prentice, K.L., and Wiechman, L.A., 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. [Also available at <https://doi.org/10.2737/RMRS-GTR-389>.]
- Germino, M.J., Belnap, J., Stark, J.M., Allen, E.B., and Rau, B.M., 2016, Ecosystem impacts of exotic annual invaders in the Genus *Bromus*, 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.—Springer Series on Environmental Management: Switzerland, Springer International Publishing, p. 61–95. [Also available at <https://link.springer.com/book/10.1007/978-3-319-24930-8>.]
- Hanser, S.E., Deibert, P.A., Tull, J.C., Carr, N.B., Aldridge, C.L., Bargsten, T.C., Christiansen, T.J., Coates, P.S., Crist, M.R., Doherty, K.E., Ellsworth, E.A., Foster, L.J., Herren, V.A., Miller, K.H., Moser, A., Naeve, R.M., Prentice, K.L., Remington, T.E., Ricca, M.A., Shinneman, D.J., Truex, R.L., Wiechman, L.A., Wilson, D.C., and Bowen, Z.H., 2018, Greater sage-grouse science (2015–17)—Synthesis and potential management implications: U.S. Geological Survey Open-File Report 2018–1017, 46 p. [Also available at <https://doi.org/10.3133/ofr20181017>.]
- Integrated Rangeland Fire Management Strategy Actionable Science Plan 2016, The integrated rangeland fire management strategy actionable science plan: Washington, D.C., U.S. Department of the Interior, 128 p. [Also available at <https://pubs.er.usgs.gov/publication/70178487>.]
- Kitzberger, T., Falk, D.A., Westerling, A.L., and Swetnam, T.W., 2017, Direct and indirect climate controls predict heterogeneous early mid-21st century wildfire burned area across western and boreal North America: *PLoS ONE*, v. 12, no. 12, 24 p. [Also available at <https://doi.org/10.1371/journal.pone.0188486>.]
- Kleist, N.J., and Enns, K.D., 2022, USGS BiblioSearch, Version 1.0.0: U.S. Geological Survey software release. [Also available at <https://doi.org/10.5066/P9EW8BO5>.]
- Knick, S.T., Dobkin, D.S., Rotenberry, J.T., Schroeder, M.A., Vander Haegen, W.M., and Van Riper, C., III, 2003, Teetering on the edge or too late?—Conservation and research issues for avifauna of sagebrush habitats: *The Condor*, v. 105, no. 4, p. 611–634.
- 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>.]

- Miller, R.F., Knick, S.T., Pyke, D.A., Meinke, C.W., Hanser, S.E., Wisdom, M.J., and Hild, A.L., 2011, Characteristics of sagebrush habitats and limitations to long-term conservation, *in* Knick, S.T., and Connelly, J.W., eds., Greater sage-grouse—Ecology and conservation of a landscape species and its habitats: Berkeley, University of California Press, Studies in Avian Biology, no. 38, p. 145–184.
- Poor, E.E., Kleist, N.J., Bencin, H.L., Foster, A.C., and Carter, S.K., 2021, Annotated bibliography of scientific research on *Ventanata 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>.]
- Remington, T.E., Deibert, P.A., Hanser, S.E., Davis, D.M., Robb, L.A., and Welty, J.L., 2021, Sagebrush conservation strategy—Challenges to sagebrush conservation: U.S. Geological Survey Open-File Report 2020–1125, 327 p. [Also available at <https://doi.org/10.3133/ofr20201125>.]
- Shinneman, D.J., 2019, North American sagebrush steppe and shrubland, *in* Goldstein, M.I., and DellaSala, D.A., eds., Encyclopedia of the World's Biomes, v. 3, no. 6, p. 505–515. [Also available at <https://doi.org/10.1016/B978-0-12-409548-9.11982-7>.]
- Stiver, S.J., Apa, A.D., Bohne, J.R., Bunnell, S.D., Deibert, P.A., Gardner, S.C., Hilliard, M.A., McCarthy, C.W., and Schroeder, M.A., 2006, Greater sage-grouse comprehensive conservation strategy—Unpublished report: Cheyenne, Wyoming, Western Association of Fish and Wildlife Agencies, 442 p. [Also available at <https://wdfw.wa.gov/publications/01317/wdfw01317.pdf>.]
- Suring, L.H., Rowland, M.M., and Wisdom, M.J., 2005, Identifying species of conservation concern, *in* Wisdom, M.J., Rowland, M.M., and Suring, L.H., eds., Habitat threats in the sagebrush ecosystem—Methods of regional assessment and applications in the Great Basin: Lawrence, KS, Alliance Communications Group, p. 150–162.
- U.S. Department of the Interior, [DOI], 2015, An integrated rangeland fire management strategy—The final report to the Secretary: Washington, D.C., U.S. Department of the Interior, 128 p. [Also available at https://www.forestsandrangelands.gov/documents/rangeland/IntegratedRangelandFireManagementStrategy_FinalReportMay2015.pdf.]
- 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 https://ir.library.oregonstate.edu/concern/technical_reports/02871197d.]
- Western Governors' Association, 2017, Western governors' national forest and rangeland management initiative—The chairman's initiative of Montana Governor Steve Bullock: Denver, CO, USA, 32 p. [Also available at http://westgov.org/images/files/2017_NFRMI_Report_for_Web.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, 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 Climate and Weather 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.”

Climate and Weather Need 1

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

Next Step 1a

Quantify the expected future short- and long-term trajectories in the variables (weather, soil moisture, etc.) that are recognized as important for successful regeneration of big sagebrush (*A. tridentata* spp.).

Bradford, J.B., Schlaepfer, D.R., Lauenroth, W.K., Palmquist, K.A., Chambers, J.C., Maestas, J.D., and Campbell, S.B., 2019, Climate-driven shifts in soil temperature and moisture regimes suggest opportunities to enhance assessments of dryland resilience and resistance: *Frontiers in Ecology and Evolution*, v. 7, article 358, 16 p.

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

Palmquist, K.A., Schlaepfer, D.R., Bradford, J.B., and Lauenroth, W.K., 2016, 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., 2016, Spatial and ecological variation in dryland ecohydrological responses to climate change—Implications for management: *Ecosphere*, v. 7, no. 11, article e01590, 20 p.

Snyder, K.A., Evers, L., Chambers, J.C., Dunham, J., Bradford, J.B., and Loik, M.E., 2019, Effects of changing climate on the hydrological cycle in cold desert ecosystems of the Great Basin and Columbia Plateau: *Rangeland Ecology and Management*, v. 72, no. 1, p. 1–12.

Svejcar, T., Angell, R., and James, J., 2016, Spatial and temporal variability in minimum temperature trends in the western US sagebrush steppe: *Journal of Arid Environments*, v. 133, p. 125–133.

Next Step 1b

Develop a decision-support tool to help resource managers identify when and where weather and soil moisture conditions are predicted to be unfavorable for seedling establishment. Consider if it is advisable to wait for better conditions to seed or adjust techniques to accommodate poor predicted weather conditions.

Boyte, S.T., 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.

Brown, M., and Bachelet, D., 2017, BLM sagebrush managers give feedback on eight climate web applications: *Weather, Climate, and Society*, v. 9, no. 1, p. 39–52.

Hardegee, S.P., Abatzoglou, J.T., Brunson, M.W., Germino, M.J., Hegewisch, K.C., Moffet, C.A., Pilliod, D.S., Roundy, B.A., Boehm, A.R., and Meredith, G.R., 2018, Weather-centric rangeland revegetation planning: *Rangeland Ecology and Management*, v. 71, no. 1, p. 1–11.

Hardegee, S.P., Sheley, R.L., Duke, S.E., James, J.J., Boehm, A.R., and Flerchinger, G.N., 2016, Temporal variability in microclimatic conditions for grass germination and emergence in the sagebrush steppe: *Rangeland Ecology and Management*, v. 69, no. 2, p. 123–128.

Hardegee, S.P., Walters, C.T., Boehm, A.R., Olsoy, P.J., Clark, P.E., and Pierson, F.B., 2015, Hydrothermal germination models—Comparison of two data-fitting approaches with Probit Optimization: *Crop Science*, v. 55, no. 5, p. 2276–2290.

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

- Richardson, W.C., Whitaker, D.R., Sant, K.P., Barney, N.S., Call, R.S., Roundy, B.A., Aanderud, Z.T., and Madsen, M.D., 2018, Use of auto-germ to model germination timing in the sagebrush-steppe: *Ecology and Evolution*, v. 8, no. 23, p. 11533–11542.
- Wilder, L., Veblen, K.E., Schupp, E.W., and Monaco, T.A., 2019, Seedling emergence patterns of six restoration species in soils from two big sagebrush plant communities: *Western North American Naturalist*, v. 79, no. 2, p. 233–246.
- Zanocco, C., Brown, M., Bachelet, D., Gough, M., Mutch, T., and Sheehan, T., 2018, Great Basin land managers provide detailed feedback about usefulness of two climate information web applications: *Climate Risk Management*, v. 20, p. 78–94.
- Hoose, B.W., Call, R.S., Bates, T.H., Anderson, R.M., Roundy, B.A., and Madsen, M.D., 2019, Seed conglomeration—A disruptive innovation to address restoration challenges associated with small-seeded species: *Restoration Ecology*, v. 27, no. 5, p. 959–965.
- Johnston, D.B., and Garbowski, M., 2020, Responses of native plants and downy brome to a water-conserving soil amendment: *Rangeland Ecology and Management*, v. 73, no. 1, p. 19–29.
- Madsen, M.D., Davies, K.W., Boyd, C.S., Kerby, J.D., and Svejcar, T.J., 2016, Emerging seed enhancement technologies for overcoming barriers to restoration: *Restoration Ecology*, v. 24, no. S2, p. S77–S84.
- Richardson, W.C., Badrakh, T., Roundy, B.A., Aanderud, Z.T., Petersen, S.L., Allen, P.S., Whitaker, D.R., and Madsen, M.D., 2019, Influence of an abscisic acid (ABA) seed coating on seed germination rate and timing of bluebunch wheatgrass: *Ecology and Evolution*, v. 9, no. 13, p. 7438–7447.
- Next Step 1c**
- Develop new techniques for establishing desired vegetation that buffer propagules from poor post-fire weather or long-term climate conditions.
- Clenet, D.R., Davies, K.W., Johnson, D.D., and Kerby, J.D., 2019, Native seeds incorporated into activated carbon pods applied concurrently with indaziflam—A new strategy for restoring annual-invaded communities?: *Restoration Ecology*, v. 27, no. 4, p. 738–744.
- Clenet, D.R., Davies, K.W., Johnson, D.D., and Kerby, J.D., 2020, Herbicide protection pods (HPPs) facilitate sagebrush and bunchgrass establishment under Imazapic control of exotic annual grasses: *Rangeland Ecology and Management*, v. 73, no. 5, p. 687–693.
- Davies, K.W., Boyd, C.S., Madsen, M.D., Kerby, J., and Hulet, A., 2018, Evaluating a seed technology for sagebrush restoration across an elevation gradient—Support for bet hedging: *Rangeland Ecology and Management*, v. 71, no. 1, p. 19–24.
- 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.
- Hardegee, S.P., Sheley, R.L., James, J.J., Reeves, P.A., Richards, C.M., Walters, C.T., Boyd, C.S., Moffet, C.A., and Flerchinger, G.N., 2020, Germination syndromes and their relevance to rangeland seeding strategies in the intermountain western United States: *Rangeland Ecology and Management*, v. 73, no. 2, p. 334–341.
- Next Step 1d**
- Identify the thresholds in plant responses to environmental conditions and the precise variables (for example, mid-summer temperatures, winter temperatures, minimum or maximum temperatures, soil moisture, etc.) that desired restoration plants respond to best.
- Bishop, T.B.B., Nusink, B.C., Lee Molinari, R., Taylor, J.B., and St. Clair, S.B., 2020, Earlier fall precipitation and low severity fire impacts on cheatgrass and sagebrush establishment: *Ecosphere*, v. 11, no. 1, article e03019, 13 p.
- Cline, N.L., Roundy, B.A., and Christensen, W.F., 2018, Using germination prediction to inform seeding potential—I—Temperature range validation of germination prediction models for the Great Basin, USA: *Journal of Arid Environments*, v. 150, p. 71–81.
- Cline, N.L., Roundy, B.A., Hardegee, S., and Christensen, W., 2018, Using germination prediction to inform seeding potential—II—Comparison of germination predictions for cheatgrass and potential revegetation species in the Great Basin, USA: *Journal of Arid Environments*, v. 150, p. 82–91.
- Gornish, E.S., Aanderud, S.T., Sheley, R.L., Rinella, M.J., Svejcar, T., Englund, S.D., and James, J.J., 2015, Altered snowfall and soil disturbance influence the early life stage transitions and recruitment of a native and invasive grass in a cold desert: *Oecologia*, v. 177, no. 2, p. 595–606.

- Holthuijzen, M.F., and Veblen, K.E., 2015, Grass-shrub associations over a precipitation gradient and their implications for restoration in the Great Basin, USA: *PLoS ONE*, v. 10, no. 12, article e0143170, 19 p.
- Hourihan, E., Schultz, B.W., and Perryman, B.L., 2018, Climatic influences on establishment pulses of four *Artemisia* species in Nevada: *Rangeland Ecology and Management*, v. 71, no. 1, p. 77–86.
- James, J.J., Sheley, R.L., Leger, E.A., Adler, P.B., Hardegree, S.P., Gornish, E.S., and Rinella, M.J., 2019, Increased soil temperature and decreased precipitation during early life stages constrain grass seedling recruitment in cold desert restoration: *Journal of Applied Ecology*, v. 56, no. 12, p. 2609–2619.
- Kleinhesselink, A.R., and Adler, P.B., 2018, The response of big sagebrush (*Artemisia tridentata*) to interannual climate variation changes across its range: *Ecology*, v. 99, no. 5, p. 1139–1149.
- 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.
- O'Connor, R.C., Germino, M.J., Barnard, D.M., Andrews, C.M., Bradford, J.B., Pilliod, D.S., Arkle, R.S., and Shriver, R.K., 2020, Small-scale water deficits after wildfires create long-lasting ecological impacts: *Environmental Research Letters*, v. 15, article 044001, 11 p.
- Pennington, V.E., Palmquist, K.A., Bradford, J.B., and Lauenroth, W.K., 2017, Climate and soil texture influence patterns of forb species richness and composition in big sagebrush plant communities across their spatial extent in the western U.S: *Plant Ecology*, v. 218, no. 8, p. 957–970.
- Renne, R.R., Bradford, J.B., Burke, I.C., and Lauenroth, W.K., 2019, Soil texture and precipitation seasonality influence plant community structure in North American temperate shrub steppe: *Ecology*, v. 100, no. 11, article e02824, 12 p.
- Roundy, B.A., and Madsen, M.D., 2016, Frost dynamics of sagebrush steppe soils: *Soil Science Society of America Journal*, v. 80, no. 5, p. 1403–1410.
- Shriver, R.K., Andrews, C.M., Pilliod, D.S., Arkle, R.S., Welty, J.L., Germino, M.J., Duniway, M.C., Pyke, D.A., and Bradford, J.B., 2018, Adapting management to a changing world—Warm temperatures, dry soil, and interannual variability limit restoration success of a dominant woody shrub in temperate drylands: *Global Change Biology*, v. 24, no. 10, p. 4972–4982.
- Vermeire, L.T., and Rinella, M.J., 2020, Fall water effects on growing season soil water content and plant productivity: *Rangeland Ecology and Management*, v. 73, no. 2, p. 252–258.

Next Step 1e

Conduct distributed manipulative experiments to determine (1) whether mixes or blends of seed provenances can mitigate against climate uncertainty and (2) how that mitigation potential varies across the range of climate and soil conditions that exist within big sagebrush ecosystems.

Not addressed.

Next Step 1f

Prioritize geographic areas that will best respond to seeding given current factors (existing vegetation, soils, land use, fire history, etc.) and projected future climate conditions.

Renwick, K.M., Curtis, C., Kleinhesselink, A.R., Schlaepfer, D., Bradley, B.A., Aldridge, C.L., Poulter, B., and Adler, P.B., 2018, Multi-model comparison highlights consistency in predicted effect of warming on a semi-arid shrub: *Global Change Biology*, v. 24, no. 1, p. 424–438.

Still, S.M., and Richardson, B.A., 2015, Projections of contemporary and future climate niche for Wyoming big sagebrush (*Artemisia tridentata* subsp. *wyomingensis*)—A guide for restoration: *Natural Areas Journal*, v. 35, no. 1, p. 30–43.

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

Hardegree, S.P., Roundy, B.A., Walters, C.T., Reeves, P.A., Richards, C.M., Moffet, C.A., Sheley, R.L., and Flerchinger, G.N., 2018, Hydrothermal germination models—Assessment of the wet-thermal approximation of potential field response: *Crop Science*, v. 58, no. 5, p. 2042–2049.

Kerns, B.K., Powell, D.C., Mellmann-Brown, S., Carnwath, G., and Kim, J.B., 2018, Effects of projected climate change on vegetation in the Blue Mountains ecoregion, USA: *Climate Services*, v. 10, p. 33–43.

Martyn, T.E., Bradford, J.B., Schlaepfer, D.R., Burke, I.C., and Lauenroth, W.K., 2016, Seed bank and big sagebrush plant community composition in a range margin for big sagebrush: *Ecosphere*, v. 7, no. 10, article e01453, 11 p.

Schlaepfer, D.R., Taylor, K.A., Pennington, V.E., Nelson, K.N., Martyn, T.E., Rottler, C.M., Lauenroth, W.K., and Bradford, J.B., 2015, Simulated big sagebrush regeneration supports predicted changes at the trailing and leading edges of distribution shifts: *Ecosphere*, v. 6, no. 1, article 3, 31 p.

Climate and Weather Need 2

Study the propagation and production of native plant materials to identify species or genotypes that may be resilient to climate change.

Next Step 2a

Identify native species attributes that provide resiliency under warming climates, are competitive against invasive plants, and can be easily propagated. This may include continuation of ongoing research.

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

He, H., Monaco, T.A., and Jones, T.A., 2018, Functional trait differences between native bunchgrasses and the invasive grass *Bromus tectorum*: *Frontiers of Agricultural Science and Engineering*, v. 5, no. 1, p. 139–147.

Larson, C.D., Lehnhoff, E.A., Noffsinger, C., and Rew, L.J., 2018, Competition between cheatgrass and bluebunch wheatgrass is altered by temperature, resource availability, and atmospheric CO₂ concentration: *Oecologia*, v. 186, no. 3, p. 855–868.

Zheng, W., Monaco, T., Jones, T., and Peel, M., 2019, Graphical partitioning of seedling phenotypic plasticity of seven cool-season grass species subjected to two watering frequencies: *Journal of Arid Environments*, v. 170, article 103986, 6 p.

Next Step 2b

Continue studies to model species and plant communities under changing climates.

Darrouzet-Nardi, A., Reed, S.C., Grote, E.E., and Belnap, J., 2018, Patterns of longer-term climate change effects on CO₂ efflux from biocrusted soils differ from those observed in the short term: *Biogeosciences*, v. 15, no. 14, p. 4561–4573.

Fernandes, A.C.M., Gonzalez, R.Q., Lenihan-Clarke, M.A., Trotter, E.F.L., and Arsanjani, J.J., 2020, Machine learning for conservation planning in a changing climate: *Sustainability*, v. 12, no. 18, article 7657, 28 p.

Hourihan, E., Schultz, B.W., and Perryman, B.L., 2018, Climatic influences on establishment pulses of four *Artemisia* species in Nevada: *Rangeland Ecology and Management*, v. 71, no. 1, p. 77–86.

Schlaepfer, D.R., Taylor, K.A., Pennington, V.E., Nelson, K.N., Martyn, T.E., Rottler, C.M., Lauenroth, W.K., and Bradford, J.B., 2015, Simulated big sagebrush regeneration supports predicted changes at the trailing and leading edges of distribution shifts: *Ecosphere*, v. 6, no. 1, article 3, 31 p.

Next Step 2c

Conduct assisted migration trials to evaluate the capacity of species and population to establish, grow, and reproduce under varied environments.

Not addressed.

Next Step 2d

Investigate new techniques to improve drought tolerance of nursery seedlings and develop innovative ways to outplant them to leverage biotic and abiotic site factors toward increased survival.

Boyd, C.S., Davies, K.W., and Lemos, J.A., 2017, Influence of soil color on seedbed microclimate and seedling demographics of a perennial bunchgrass: *Rangeland Ecology and Management*, v. 70, no. 5, p. 621–624.

Boyd, C.S., and Lemos, J.A., 2015, Evaluating winter/spring seeding of a native perennial bunchgrass in the sagebrush steppe: *Rangeland Ecology and Management*, v. 68, no. 6, p. 494–500.

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

Drenovsky, R.E., Thornhill, M.L., Knestrick, M.A., Dlugos, D.M., Svejcar, T.J., and James, J.J., 2016, Seed production and seedling fitness are uncoupled from maternal plant productivity in three aridland bunchgrasses: *Rangeland Ecology and Management*, v. 69, no. 3, p. 161–168.

Fund, A.J., Hulvey, K.B., Jensen, S.L., Johnson, D.A., Madsen, M.D., Monaco, T.A., Tilley, D.J., Arora, E., and Teller, B., 2019, Basalt milkvetch responses to novel restoration treatments in the Great Basin: *Rangeland Ecology and Management*, v. 72, no. 3, p. 492–500.

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

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

Leger, E.A., Atwater, D.Z., and James, J.J., 2019, Seed and seedling traits have strong impacts on establishment of a perennial bunchgrass in invaded semi-arid systems: *Journal of Applied Ecology*, v. 56, no. 6, p. 1343–1354.

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.

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.

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

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

Next Step 2e

Develop a list of candidate species and ecotypes that are conducive for seed germination and seedling increase under projected mid-century climates.

Not addressed.

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

Zorio, S.D., Williams, C.F., and Aho, K.A., 2016, Sixty-five years of change in montane plant communities in western Colorado, U.S.A: *Arctic, Antarctic, and Alpine Research*, v. 48, no. 4, p. 703–722.

Climate and Weather Need 3

Identify areas for seed collection across elevational and latitudinal ranges of target species to protect and maintain high-quality sources for native seeds.

Next Step 3a

Conduct common garden studies to identify variation in adaptive traits and their associated climate drivers.

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

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

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.

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

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

Next Step 3b

Conduct population genetic studies for warranted species.

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

Next Step 3c

Identify critical species needed in restoration. (Also see Climate and Weather Science Need 2).

Not addressed.

Next Step 3d

Develop seed-transfer zones for contemporary and future climates.

Brabec, M.M., Germino, M.J., Shinneman, D.J., Pilliod, D.S., McIlroy, S.K., and Arkle, R.S., 2015, Challenges of establishing big sagebrush (*Artemisia tridentata*) in rangeland restoration—Effects of herbicide, mowing, whole-community seeding, and sagebrush seed sources: *Rangeland Ecology and Management*, v. 68, no. 5, p. 432–435.

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

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

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

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

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

Next Step 3e

If necessary, conduct assisted migration trials.
NA.

Next Step 3f

Publish seed-zone maps.

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

Climate and Weather Need 4

Develop predictive models of climate change effects, targeting restoration species, including regionally suitable culturally significant species, and genetic diversity using 20-year or mid-century climate models.

Next Step 4a

Characterize high-temporal resolution patterns of ecological drought across the sagebrush biome and use newly developed drought indices (for example, soil moisture drought index) to quantify how climate change will alter the occurrence and severity of ecological drought and the overall probability of observing conditions that support successful restoration.

Bradford, J.B., Schlaepfer, D.R., Lauenroth, W.K., Palmquist, K.A., Chambers, J.C., Maestas, J.D., and Campbell, S.B., 2019, Climate-driven shifts in soil temperature and moisture regimes suggest opportunities to enhance assessments of dryland resilience and resistance: *Frontiers in Ecology and Evolution*, v. 7, article 358, 16 p.

Cartwright, J.M., Littlefield, C.E., Michalak, J.L., Lawler, J.J., and Dobrowski, S.Z., 2020, Topographic, soil, and climate drivers of drought sensitivity in forests and shrublands of the Pacific Northwest, USA: *Scientific Reports*, v. 10, article 18486, 13 p.

Devadoss, J., Falco, N., Dafflon, B., Wu, Y., Franklin, M., Hermes, A., Hinckley, E.L.S., and Wainwright, H., 2020, Remote sensing-informed zonation for understanding snow, plant and soil moisture dynamics within a mountain ecosystem: *Remote Sensing*, v. 12, no. 17, article 2733, 21 p.

Karban, R., and Pezzola, E., 2017, Effects of a multi-year drought on a drought-adapted shrub, *Artemisia tridentata*: *Plant Ecology*, v. 218, no. 5, p. 547–554.

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

Palmquist, K.A., Schlaepfer, D.R., Bradford, J.B., and Lauenroth, W.K., 2016, 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., 2016, Spatial and ecological variation in dryland ecohydrological responses to climate change—Implications for management: *Ecosphere*, v. 7, no. 11, article e01590, 20 p.

Snyder, K.A., Evers, L., Chambers, J.C., Dunham, J., Bradford, J.B., and Loik, M.E., 2019, Effects of changing climate on the hydrological cycle in cold desert ecosystems of the Great Basin and Columbia Plateau: *Rangeland Ecology and Management*, v. 72, no. 1, p. 1–12.

Next Step 4b

Review the literature to synthesize existing knowledge about environmental controls over regeneration of native plant species other than big sagebrush.

Leopold, E.B., and Zaborac-Reed, S., 2019, Pollen evidence of floristic turnover forced by cool aridity during the Oligocene in Colorado: *Geosphere*, v. 15, no. 1, p. 254–294.

Nowak, R.S., Nowak, C.L., and Tausch, R.J., 2017, Vegetation dynamics during last 35,000 years at a cold desert locale—Preferential loss of forbs with increased aridity: *Ecosphere*, v. 8, no. 7, article e01873, 23 p.

Snyder, K.A., Evers, L., Chambers, J.C., Dunham, J., Bradford, J.B., and Loik, M.E., 2019, Effects of changing climate on the hydrological cycle in cold desert ecosystems of the Great Basin and Columbia Plateau: *Rangeland Ecology and Management*, v. 72, no. 1, p. 1–12.

Next Step 4c

Quantify the level of certainty in the magnitude and direction of changing climate for sagebrush steppe ecosystems by synthesizing forecasts from statistically and dynamically downscaled global and regional climate models and multiple representative concentration pathways.

Flanary, S.J., and Keane, R.E., 2019, Whitebark pine encroachment into lower-elevation sagebrush grasslands in southwest Montana, USA: *Fire Ecology*, v. 15, article 42, 11 p.

Flerchinger, G.N., Fellows, A.W., Seyfried, M.S., Clark, P.E., and Lohse, K.A., 2020, Water and carbon fluxes along an elevational gradient in a sagebrush ecosystem: *New York, Ecosystems*, v. 23, no. 2, p. 246–263.

Michalak, J.L., Withey, J.C., Lawler, J.J., and Case, M.J., 2017, Future climate vulnerability—Evaluating multiple lines of evidence: *Frontiers in Ecology and the Environment*, v. 15, no. 7, p. 367–376.

Milling, C.R., Rachlow, J.L., Olsoy, P.J., Chappell, M.A., Johnson, T.R., Forbey, J.S., Shipley, L.A., and Thornton, D.H., 2018, Habitat structure modifies microclimate—An approach for mapping fine-scale thermal refuge: *Methods in Ecology and Evolution*, v. 9, no. 6, p. 1648–1657.

Renwick, K.M., Fellows, A., Flerchinger, G.N., Lohse, K.A., Clark, P.E., Smith, W.K., Emmett, K., and Poulter, B., 2019, Modeling phenological controls on carbon dynamics in dryland sagebrush ecosystems: *Agricultural and Forest Meteorology*, v. 274, p. 85–94.

Soulard, C.E., and Rigge, M., 2020, Application of empirical land-cover changes to construct climate change scenarios in federally managed lands: *Remote Sensing*, v. 12, no. 15, article 2360, 22 p.

Tredennick, A.T., Hooten, M.B., Aldridge, C.L., Homer, C.G., Kleinhesselink, A.R., and Adler, P.B., 2016, Forecasting climate change impacts on plant populations over large spatial extents: *Ecosphere*, v. 7, no. 10, article e01525, 16 p.

Next Step 4d

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

Apodaca, L.F., Devitt, D.A., and Fenstermaker, L.F., 2017, Assessing growth response to climate in a Great Basin big sagebrush (*Artemisia tridentata*) plant community: *Dendrochronologia*, v. 45, p. 52–61.

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

Campos, X., Germino, M.J., and de Graaff, M.A., 2017, Enhanced precipitation promotes decomposition and soil C stabilization in semiarid ecosystems, but seasonal timing of wetting matters: *Plant and Soil*, v. 416, no. 1–2, p. 427–436.

Gill, R.A., O'Connor, R.C., Rhodes, A., Bishop, T.B.B., Laughlin, D.C., and St. Clair, S.B., 2018, Niche opportunities for invasive annual plants in dryland ecosystems are controlled by disturbance, trophic interactions, and rainfall: *Oecologia*, v. 187, p. 755–765.

Huber, D.P., Lohse, K.A., Commendador, A., Joy, S., Aho, K., Finney, B., and Germino, M.J., 2019, Vegetation and precipitation shifts interact to alter organic and inorganic carbon storage in cold desert soils: *Ecosphere*, v. 10, no. 3, article e02655, 17 p.

Larson, C.D., Lehnhoff, E.A., and Rew, L.J., 2017, A warmer and drier climate in the northern sagebrush biome does not promote cheatgrass invasion or change its response to fire: *Oecologia*, v. 185, no. 4, p. 763–774.

- Loik, M.E., Griffith, A.B., Alpert, H., Concilio, A.L., Wade, C.E., and Martinson, S.J., 2015, Impact of intra- versus inter-annual snow depth variation on water relations and photosynthesis for two Great Basin Desert shrubs: *Oecologia*, v. 178, no. 2, p. 403–414.
- Reed, D.E., Ewers, B.E., Pendall, E., Naithani, K.J., Kwon, H., and Kelly, R.D., 2018, Biophysical factors and canopy coupling control ecosystem water and carbon fluxes of semiarid sagebrush ecosystems: *Rangeland Ecology and Management*, v. 71, no. 3, p. 309–317.
- Reinhardt, K., McAbee, K., and Germino, M.J., 2019, Changes in structure and physiological functioning due to experimentally enhanced precipitation seasonality in a widespread shrub species: *Plant Ecology*, v. 220, no. 2, p. 199–211.
- 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.
- Tredennick, A.T., Kleinhesselink, A.R., Taylor, J.B., and Adler, P.B., 2018, Ecosystem functional response across precipitation extremes in a sagebrush steppe: *PeerJ*, v. 6, article e4485, 19 p.
- Tucker, C.L., Tamang, S., Pendall, E., and Ogle, K., 2016, Shallow snowpack inhibits soil respiration in sagebrush steppe through multiple biotic and abiotic mechanisms: *Ecosphere*, v. 7, no. 5, article e01297, 18 p.
- Winkler, D.E., Belnap, J., Hoover, D., Reed, S.C., and Duniway, M.C., 2019, Shrub persistence and increased grass mortality in response to drought in dryland systems: *Global Change Biology*, v. 25, no. 9, p. 3121–3135.
- Studies Related to Need 4, But Not Any of the Next Steps**
- Creutzburg, M.K., Halofsky, J.E., Halofsky, J.S., and Christopher, T.A., 2015, Climate change and land management in the rangelands of central Oregon: *Environmental Management*, v. 55, no. 1, p. 43–55.
- Creutzburg, M.K., Henderson, E.B., and Conklin, D.R., 2015, Climate change and land management impact rangeland condition and sage-grouse habitat in southeastern Oregon: *AIMS Environmental Science*, v. 2, no. 2, p. 203–236.
- Emslie, S.D., and Meltzer, D.J., 2019, Late quaternary vertebrates from the upper Gunnison Basin, Colorado, and small-mammal community resilience to climate change since the last glacial maximum: *Quaternary Research*, v. 92, no. 2, p. 388–407.
- Homer, C.G., Xian, G., Aldridge, C.L., Meyer, D.K., Loveland, T.R., and O’Donnell, M.S., 2015, Forecasting sagebrush ecosystem components and greater sage-grouse habitat for 2050—Learning from past climate patterns and Landsat imagery to predict the future: *Ecological Indicators*, v. 55, p. 131–145.
- Lindquist, L.W., Palmquist, K.A., Jordan, S.E., and Lauenroth, W.K., 2019, Impacts of climate change on groundwater recharge in Wyoming big sagebrush ecosystems are contingent on elevation: *Western North American Naturalist*, v. 79, no. 1, p. 37–48.
- Palmquist, K.A., Bradford, J.B., Martyn, T.E., Schlaepfer, D.R., and Lauenroth, W.K., 2018, STEPWAT2—An individual-based model for exploring the impact of climate and disturbance on dryland plant communities: *Ecosphere*, v. 9, no. 8, article e02394, 23 p.
- 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.

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