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Conservation and Restoration of Sagebrush Ecosystems and Sage-Grouse:

An Assessment of USDA Forest Service Science

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Abstract

Sagebrush ecosystems are among the largest and most threatened ecosystems in North America. Greater sage-grouse has served as the bellwether for species conservation in these ecosystems and has been considered for listing under the Endangered Species Act eight times. In September 2015, the decision was made not to list greater sage-grouse, but to reevaluate its status in 5 years. Concerns over sage-grouse and associated habitats have set in motion sweeping Federal and State land management plan changes and proactive science-based conservation actions to address threats within the realm of management control.

For nearly a century, the Forest Service (FS), U.S. Department of Agriculture (USDA), has studied sagebrush ecosystems and for decades has focused on sage-grouse biology and habitat requirements. Our team of FS scientists and managers prepared this assessment to summarize FS strengths, capabilities, partners, past and current research, and potential future high-priority research areas for conservation and restoration of sagebrush ecosystems and sage-grouse. We identified research and science-based management needs of the National Forest System where lands are important for breeding and brood-rearing habitats for sage-grouse. We recommend expanded research and science delivery by FS scientists. This work will help meet continuing widespread concerns and calls for science-based conservation to mitigate threats to sagebrush ecosystems, conserve populations of sage-grouse and other sagebrush-obligate species, and restore sagebrush ecosystems throughout the western United States.

Keywords: sagebrush, sage-grouse, disturbance, fire, invasive species, restoration

Cover photos

Top left: A high elevation sagebrush hillside on the Uinta-Wasatch-Cache National Forest, Utah, after snowmelt in mid to late July. Photo by Teresa Prendusi, USDA Forest Service.

Top right: Female greater sage-grouse observed at a high-elevation mountain big sagebrush site, Inyo National Forest, California. Photo by Chris Balzotti, Stanford University, used with permission.

Bottom left: RMRS technicians monitoring a post-fire native grass, forb and sagebrush seeding in northern Utah. Photo by Matt Fisk, USDA Forest Service.

Bottom right: Wyoming big sagebrush, Owyhee County (southwest) Idaho. Photo by Matt Fisk, USDA Forest Service.

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Executive Summary

Sagebrush ecosystems are among the largest and most threatened ecosystems in North America. Greater sage-grouse (GRSG) has served as the bellwether for species conservation in these ecosystems and has been considered for listing under the Endangered Species Act (ESA) eight times. Most recently, in 2010, GRSG was warranted for listing under the ESA, but precluded by higher priority listing actions. In September 2015, the decision was made not to list GRSG, but to reevaluate the listing decision again in 5 years. Concerns over sage-grouse and associated habitats have set in motion sweeping Federal and State land management plan changes and proactive science-based conservation actions to address threats within the realm of management control. Nevertheless, persistent ecosystem threats, such as wildfire and invasive annual grasses, will continue to affect sagebrush ecosystems in the western portion of the GRSG range, and land development and land use activities will continue to affect sagebrush ecosystems in the eastern portion of the GRSG range. Science-driven management activities played a large role in preventing designation of GRSG as an endangered species in 2015. Ongoing management will be required to continue to mitigate threats to sagebrush ecosystems and to restore habitat for GRSG and other sagebrush-obligate species.

USDA Forest Service (FS) scientists have studied sagebrush ecosystems for nearly a century, and have focused on sage-grouse biology and habitat requirements for decades. This science has been included in many conservation and management plans produced by State and Federal agencies. Given FS science capacity, germane publications, research facilities and strategic locations, history of sagebrush science, and the importance of National Forest System (NFS) lands for breeding and brood-rearing habitats for sage-grouse, we recommend expanded research and science delivery by FS scientists. This work will help address continuing widespread concerns and calls for science-based conservation to mitigate threats to sagebrush ecosystems, conserve populations of sage-grouse and other sagebrush-obligate species, and restore sagebrush ecosystems throughout the western United States.

Our team of FS scientists and managers prepared this assessment to summarize the agency's strengths, capabilities, partners, past and current research, and potential future priority research areas for conservation and restoration of sagebrush ecosystems and sage-grouse. We identified four areas of strength, leadership, and knowledge development:

- Evaluating links among sage-grouse population ecology, monitoring, and habitat
- Understanding disturbances and stressors in sagebrush ecosystems
- Analyzing and designing landscapes to improve habitat connectivity
- Developing methods, models, and plant materials to restore sagebrush habitats.

Our assessment identifies high-priority research and science-based management needs of the NFS and contributes to preparation of the USDA Forest Service Sage-Grouse Conservation Science Strategy (Finch et al. 2015).

Contents

1.0—Overview

Greater sage-grouse (*Centrocercus urophasianus* (GRSG) (fig. 1) is a high-profile species facing many anthropogenic and persistent ecosystem threats; it has been considered for Federal regulatory protections under the Endangered Species Act (ESA 1973) eight times (U.S. Fish and Wildlife Service 2015). Sage-grouse and more than 350 other species rely on sagebrush (*Artemisia* spp.) ecosystems (Schroeder et al. 2004), which are among the largest and most imperiled systems in North America (Noss et al. 1995). State and Federal agencies, research institutions, and stakeholders across 11 States in the western United States have undertaken tremendous conservation and research efforts to reduce threats to sagebrush ecosystems and greater sage-grouse. In 2010, the U.S. Fish and Wildlife Service (FWS), Department of the Interior (DOI), determined that greater sage-grouse warranted protection under the ESA, but that action was precluded by higher priority listing actions. The FWS found that the bi-state population of GRSG bordering California and Nevada, considered a distinct population segment, did not warrant ESA protection as a threatened species (U.S. Fish and Wildlife Service 2015a). As part of a 2011 court settlement, FWS agreed to make an initial determination on whether to propose GRSG for listing by September 30, 2015. In the interim years, unprecedented conservation partnerships across the western United States have developed with the aim to significantly reduce threats to GRSG across 90 percent of its breeding habitat. Subsequently, after a thorough status review, FWS concluded that GRSG remains relatively abundant and well-distributed across its 70-million ha range and in the foreseeable future does not face the risk of extinction. Thus protection under the ESA was not warranted as of 2015, but the listing decision would be reevaluated in 5 years (U.S. Fish and Wildlife Service 2015b).

Questions remain, however, on whether these conservation partnerships and their GRSG conservation plans and requirements will be consistently upheld by agencies, remain intact

Figure 1—A displaying male greater sage-grouse on a lek in Butte County, South Dakota (photo by Steve Fairbairn, U.S. Fish and Wildlife Service).

if challenged by environmental groups, and mitigate threats to the bird and its habitat (Snodgrass and Jensen 2015). Two primary factors shaping the discussion of whether protection of GRSG was warranted under the ESA were threats to habitats important to sage-grouse populations and the lack of regulatory mechanisms, primarily in land use plans, to ensure protection for GRSG and its habitats. In response, the DOI's Bureau of Land Management (BLM) and the Department of Agriculture's Forest Service (FS), revised land use plans to incorporate measures to conserve, enhance, restore, or develop GRSG habitat and sagebrush ecosystems by reducing, eliminating, or minimizing threats, including climate change, that may force development of suitable GRSG habitat outside of its current range.

Sagebrush ecosystems remain threatened by a variety of stressors, and managers have called for science solutions to develop best practices for restoring damaged ecosystems. In January 2015, DOI released a Secretarial Order (SO 3666) for a comprehensive science-based policy to prevent and suppress rangeland fire and to restore sagebrush landscapes impacted by fire. Actions to prevent fire and restore habitats were deemed essential for conserving sagebrush ecosystems and GRSG habitat, particularly in the Great Basin (the Great Basin includes most of Nevada, half of Utah, and sections of Idaho, Wyoming, Oregon, and California). Continued collaboration and activities among State and Federal partners to proactively identify and implement actions to manage stressors and restore damaged sagebrush ecosystems remain necessary.

Scientists are recommending a holistic, multiscale approach for managing sagebrush habitats and sagebrush-obligate species (fig. 2) (Chambers et al. 2014d; Herrick et al. 2912; Knick and Connelly 2011; Rowland et al. 2006). At landscape scales, sage-grouse may serve as an "umbrella species" (species for which conservation indirectly protects other species) for other sagebrush-obligate species because of its requirement for large, contiguous areas of sagebrush (Rowland et al. 2006). For example, moderate to strong positive associations occur between GRSG and three sagebrush-obligate passerines (Brewer's sparrow [*Spizella breweri*], sage sparrow [*Amphispiza belli*], and sage thrasher [*Oreoscoptes montanus*]) whose populations have declined (Hanser and Knick 2011). This relationship indicates that

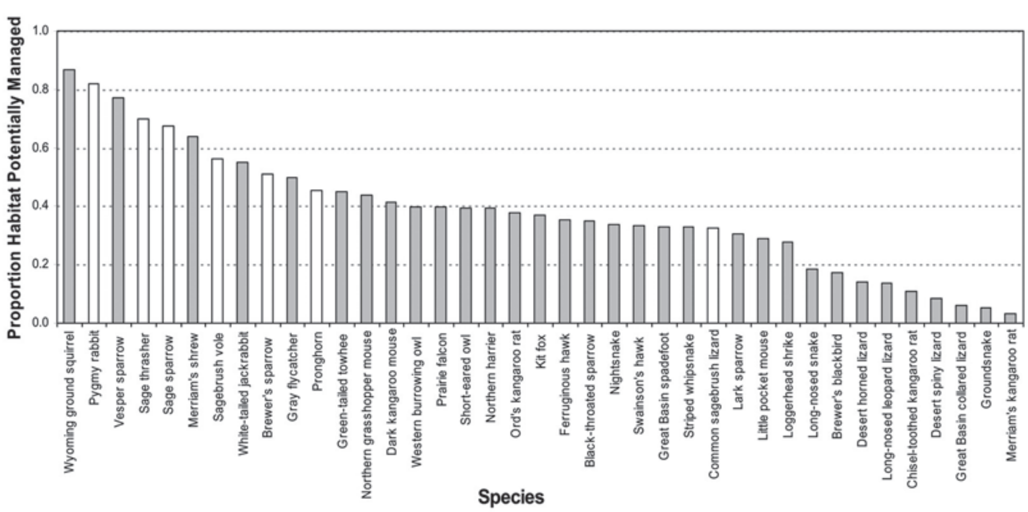

Figure 2—Estimated proportion of habitat for species of conservation concern in the Great Basin that would benefit from management of greater sage-grouse habitat within the historical range of sage-grouse in the Great Basin. Sagebrush-obligate species are indicated by white bars (from Rowland et al. 2006).

a holistic management approach that addresses large-scale persistent threats to sage-grouse habitat may be expected to benefit sagebrush ecosystems and most sagebrush-obligate species (e.g., Chambers et al. 2014c). Davies et al. (2011) conclude that "the sagebrush (*Artemisia*) ecosystem is a prime example of an area where many conservation objectives could be simultaneously achieved by developing a comprehensive ecosystem conservation plan." Multiple conservation objectives can be simultaneously met in sagebrush ecosystems by integrating scientific knowledge on factors such as ecosystem resilience and resistance and species habitat requirements into comprehensive ecosystem conservation plans (Chambers et al. 2014c,d). However, specific conservation actions for individual species including sage-grouse must necessarily recognize landscape-scale heterogeneity and differences in individual species' habitat requirements (Hanser and Knick 2011; Rowland et al. 2006).

The Forest Service, with a rich history of research and collective expertise in studying sagebrush ecosystems, has contributed substantially to sagebrush conservation, threat mitigation, and restoration efforts. FS scientists' capacity to explore novel areas of sage-grouse and sagebrush biome science is facilitated by research station facilities in strategic locations. In particular, FS scientists continue to contribute unique science, services, and management tools to partners needing information in the following research areas pertinent to sagebrush ecosystem restoration and sage-grouse conservation:

- Application of landscape analyses to planning
- Genomics for conserving plant and animal populations
- Effects, prevention, and control of fire and invasive species
- Restoration science and applications
- Seed and plant materials development sciences
- Application of resilience and resistance concepts
- Climate change adaptation science and models
- Effectiveness monitoring and adaptive management.

Since the mid-1980s, the FS Research & Development (R&D) Mission Area has addressed key science and management questions about sagebrush ecosystems, specifically the role of sagebrush genetics in restoration science, the impacts and control of pinyon–juniper (*Pinus*-*Juniperus* spp.) expansion, and effects of annual grass invasions, especially in the Great Basin. As threats to GRSG became a dominant consideration for managing sagebrush habitats, FS R&D began integrating findings from earlier research into assessments, models, and new research for understanding and managing sage-grouse populations and habitats. This new research focused on controlling cheatgrass (*Bromus tectorum*) invasions in sagebrush ecosystems, treating and managing fire and postfire landscapes, restoring ecosystems affected by multiple disturbances, and linking sage-grouse biology and habitat requirements to management of plant communities and landscapes. Research expanded after 2000 to evaluate and control the spread of other invasive species; examine stressors such as energy development, drought, and climate change; assess effectiveness of sagebrush restoration actions; assess habitat and bird vulnerabilities; and evaluate sage-grouse and sagebrush genetics for improving restoration strategies and landscape design.

Yet concerns about the conservation of the sagebrush ecosystem and sage-grouse continue to mount, creating expectations for natural resource agencies to demonstrate an ability to effectively manage sagebrush habitat and conserve GRSG across 11 western States (up to 35 national forests or grasslands in the National Forest System), as well as to conserve the threatened Gunnison sage-grouse (*Centrocercus minimus*). The latter species is a Federally listed species (U.S. Fish and Wildlife Service 2014) whose small population occurs in Utah and Colorado, including the GrandMesa/Uncompahgre/Gunnison National Forest. Although the focus of this assessment is on GRSG, we recognize that key points are most likely applicable to Gunnison sage-grouse.

To be successful, land managers largely depend on integrating relevant and applicable scientific information. FS R&D has demonstrated strong leadership in identifying threats to natural resources, developing methods and models to address those threats, and providing managers science-based tools and options. FS R&D is committed to ensuring that its relevant and applicable science findings are available and delivered into the hands of practitioners through partnerships, publications, conferences, webinars, and consultations. Where FS R&D has unique research capabilities, it is committed to effectively responding to requests for additional information and to the need for more research and testing of hypotheses.

We have four objectives with this assessment. First, we intend to promote understanding and recognition of FS R&D strengths, science leadership, and collaborative opportunities in key areas of sagebrush and sage-grouse science, identify research emphasis areas within FS R&D based on a review of existing knowledge and future needs, stimulate increased development and delivery of knowledge about sagebrush ecosystems and sage-grouse conservation, and serve as a communication tool. This assessment aims to improve awareness of the FS's collective expertise, partnerships, and existing facility resources by summarizing the sagebrush ecosystem and sage-grouse conservation science we conduct. It is intended to identify, for the benefit of other agencies and stakeholders, the FS's current research niches of expertise that can be expanded in the future.

Second, we intend for this assessment to serve as a planning guide for managers, staff, and scientists working on, or concerned about, sagebrush ecosystems and sage-grouse related issues. To this end, information from this assessment was integrated into the *USDA Forest Service Sage-Grouse Conservation Science Strategy* (Finch et al. 2015).

Third, we hope that this assessment, coordinated through scientists using a team approach, serves to foster synergistic collaborations among FS R&D scientists, their partners, and the management community. We invited sagebrush and sage-grouse scientists to share what they do across locations and disciplines and to succinctly synthesize their efforts into this single document.

Fourth, our intention is to support our colleagues in the National Forest System in achieving sagebrush ecosystem and sage-grouse conservation objectives. Much of our science is developed to aid management decisions on NFS and other Federal lands. For GRSG, NFS manages 8 percent of the GRSG range; most of the remainder is on BLM-managed lands. BLM and FS are the leads for developing Federal management action plans for GRSG. Importantly, the FS-managed GRSG habitat occurs mostly at higher elevation and may be disproportionately important to the future of GRSG because of the greater resilience of higher elevation habitat to invasive species and climate change.

Our assessment presents areas of research emphasis where FS scientists have demonstrated significant leadership and strengths, as reflected by a review of FS R&D publications, science delivery, applications by stakeholders, and future research needs. Four research emphasis areas of FS R&D, identified based on existing knowledge and future needs and priorities, and outlined in the Sage-Grouse Conservation Science Strategy (Finch et al. 2015) are:

- Evaluating links between sage-grouse population ecology, monitoring, and habitat
- Understanding disturbances and stressors in sagebrush ecosystems
- Analyzing and designing landscapes to improve habitat connectivity
- Developing methods, models, and plant materials to restore sagebrush habitats.

This assessment is divided into five sections. The first section is an overview. The second section assesses existing knowledge developed by FS R&D scientists who exemplify strengths and science leadership, clarifies and emphasizes how these scientists are experts in these research emphasis areas, and frames the science within the context of each of the four research emphasis areas. The third section discusses research needs identified through the assessment process. The fourth section identifies NFS needs for future science and identifies science delivery methods to meet those needs. Finally, the fifth section reviews key facilities and locations having relevant science expertise and capacity.

2.0—Forest Service Research and Development Strengths and Leadership: A Review of Knowledge

2.1—Sage-grouse Population Ecology, Monitoring, and Habitat Links

Several comprehensive publications describe the basic ecology and habitat requirements of greater sage-grouse (Connelly et al. 2000; Schroeder et al. 1999). A landmark contribution was the book *Greater Sage-grouse: Ecology and Conservation of a Landscape Species and its Habitat* (Knick and Connelly 2011). Forest Service (FS) research contributed to specific chapters in this book (e.g., Wisdom et al. 2011) that deal with management and conservation status, basic sage-grouse ecology, sagebrush ecology, and factors associated with extirpation of GRSG. FS scientists have developed a plethora of sage-grouse models, many of which were subsequently used in broad-scale assessments of the species and its habitat. Other research focuses on links between sage-grouse demographics and habitat status or human disturbance. Below we describe primary lines of FS research on these topics.

2.1.1—Modeling greater sage-grouse and its habitat

Mechanistic models that clearly link animal distributions and performance to habitat variables are useful tools for species conservation and management. Forest Service scientists have developed a variety of models that address greater sage-grouse (GRSG) ecology and habitat requirements. As part of the Interior Columbia Basin Ecosystem Management Project (ICBEMP) in the late 1990s, the science strategy team developed more than 30 Bayesian belief network models for key species of conservation concern, including GRSG. These models combined empirical and hypothesized relations in probability-based projections of conditions. The models were subsequently used to estimate abundance and distribution of habitat and population outcomes under a suite of management alternatives across the

58 million ha of the Great Basin (Marcot et al. 2001; Raphael et al. 2001). Wisdom et al. (2002a) validated two restoration models by using areas of extirpated versus occupied range. One restoration scenario assumed a 50-percent reduction in detrimental grazing effects and a sixfold increase in actively restored areas compared with future management proposed by the FS and the Bureau of Land Management (BLM). The second scenario assumed a 100-percent reduction in detrimental grazing effects and the same increase in active restoration as the first scenario. In an ecoregional assessment in the Wyoming Basin, Hanser et al. (2011a) developed a statistical model relating GRSG occurrence and abundance to environmental covariates.

2.1.2—Assessment and monitoring of sage-grouse habitat

Connelly et al. (2000) offered guidelines to manage sage-grouse populations and habitats and later provided guidance on habitat monitoring (Connelly et al. 2003). More recently, the BLM and FS collaborated to develop a comprehensive monitoring framework with methods to monitor habitat and evaluate effectiveness of FS and BLM land management plans to conserve GRSG and its habitat (DOI, BLM and USDA Forest Service 2014). The technical guide of Rowland and Vojta (2013) describes standardized methods of wildlife habitat monitoring on NFS and other lands that are now widely adopted. The methods are included in State wildlife action plans and land management units that are revising forest plans under the 2012 FS planning rule (USDA Forest Service 2012). One chapter in this technical guide features example habitat monitoring programs for three species, including GRSG (Goldstein et al. 2013). It illustrates conceptual models at landscape and site scales for processes acting as stressors on GRSG and projected impacts on its habitat, and discusses specific monitoring objectives and indicators at each scale, including fragmentation and connectivity.

FS scientists have spearheaded large-scale GRSG habitat assessments. Through the ICBEMP, FS scientists evaluated GRSG habitat conditions across the interior Columbia basin under various management scenarios (Hemstrom et al. 2002; Raphael et al. 2001; Wisdom et al. 2000, 2002). In recognition of that work, the BLM requested that FS researchers lead a broad-scale habitat assessment for GRSG and other sagebrush-associated species in the Great Basin ecoregion; information was shared through a book (Wisdom et al. 2005b) and other publications (Rowland and Wisdom 2009; Rowland et al. 2006, 2010b). Using methods developed in the Great Basin, Wisdom and Rowland subsequently led an ecoregional assessment of GRSG and sagebrush communities in the 350,000 km^2 Wyoming Basins and contributed to several chapters in the resulting book (see Hanser et al. 2011b). These chapters cover selection of sagebrush-associated species of concern (Rowland et al. 2011), a model of GRSG occupancy and abundance (Hanser et al. 2011a), and management considerations (Knick et al. 2011).

2.1.3—Quantification of core and edge habitats across sage-grouse range

Patterns of species occurrence can help in evaluating factors associated with population losses. Wisdom et al. (2011) evaluated environmental conditions in areas of former (extirpated) range and range still occupied by GRSG and Gunnison sage-grouse. They identified the environmental conditions most strongly associated with landscape-scale extirpations based on the strongest environmental differences between areas of extirpation and current occupation. A variety of landscape metrics related to concepts of "core" versus "edge" areas were considered in the evaluation. Mean size of core areas (defined as the mean size of contiguous sagebrush patches) were >12 times larger in occupied range (3,964 ha) than in extirpated range (332 ha). Mean size of core areas were included in the second-best model, which provided >80 percent accuracy in discriminating between occupied and extirpated range. The single-best factor in correctly classifying occupied versus extirpated range was the percent area of sagebrush. Occupied range had nearly twice as much sagebrush area (46 percent) as extirpated range (24 percent); these results served as an additional indicator suggesting that the size of core areas was substantially larger in occupied range, which further corroborated results by Aldridge et al. (2008). Finally, Wisdom et al. (2011) identified "strongholds" of occupied range—these had large core areas and minimal edge, and were far from areas of extirpated range. In contrast, areas associated with a high risk of extirpation had small core areas that were often isolated and disjunct. These results provide a strong management framework for landscape designs to maintain and restore desirable characteristics of suitable habitat across the historical range of both sage-grouse species.

2.1.4—Linking sage-grouse populations and demography to habitat change

Understanding the demographics of life-history stages and linking these to environmental factors can improve management to positively influence sage-grouse populations and conservation planning. FS R&D has extensive experience evaluating demographic parameters and environmental covariates at multiple scales throughout the range of GRSG.

Habitat alteration may affect GRSG populations' site occupancy, size of leks (male courtship assemblage areas) (e.g., Hess and Beck 2012; Smith et al. 2005; Wisdom et al. 2011), or survival during individual life-history stages, such as juvenile or brood-rearing. FS scientist Rumble collaborated with many partners, including State wildlife agencies (in North Dakota, South Dakota, and Wyoming) and two universities to link sage-grouse habitat and demographic parameters in the eastern portion of the sage-grouse range (e.g., fig. 3) (Fremgen et al. 2015; Herman-Brunson et al. 2009; Kaczor et al. 2011a,b; Schreiber 2014; Schreiber et al. 2015a,b; Swanson et al. 2013). Rumble and his colleagues have studied

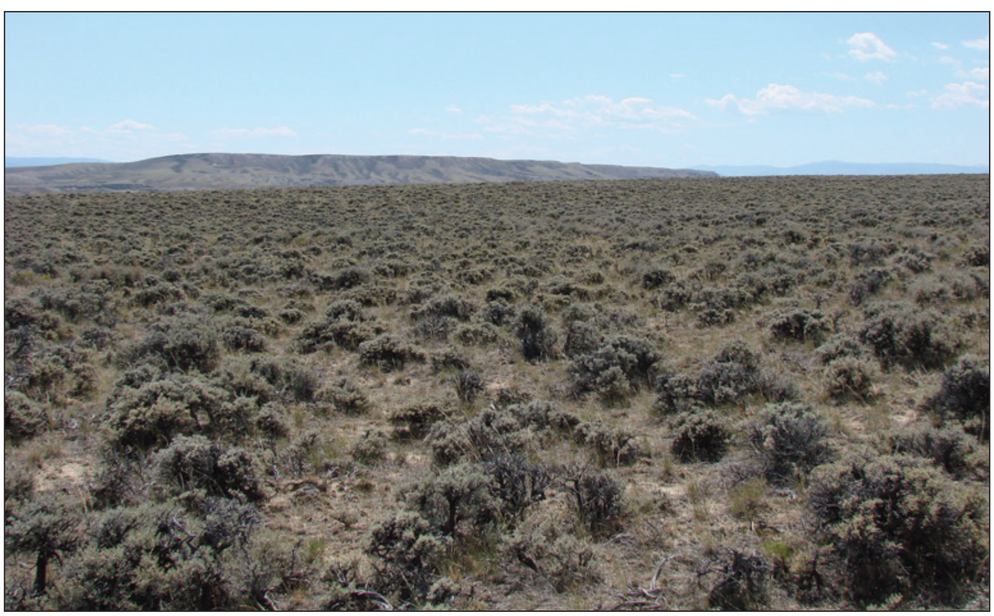

Figure 3—Vegetation sampling site in greater sage-grouse nesting habitat, Carbon County, Wyoming (photo by Brian Dickerson, USDA Forest Service).

movement patterns and habitat selection of telemetered GRSG (fig. 4) in relation to natural disturbances and plan to evaluate effects of wind energy development on GRGS populations (e.g., Hanser et al. 2014; Schreiber et al. 2015a,b).

By using the Bayesian belief network models developed for GRSG as part of the ICBEMP (see *2.1.1—Modeling greater sage-grouse and its habitat*), population outcomes were projected across the range of the species within the Interior Columbia Basin; potential outcomes ranged across a gradient from well-distributed and abundant to scarce, patchy, and at risk of extirpation (Raphael et al. 2001). Managers then applied model results to guide selection of alternatives in the environmental impact statement for this basin.

Figure 4—Greater sage-grouse with solar-powered PTT-100 global positioning system transmitter in a study of movement patterns in Wyoming (photo by Brian Dickerson, USDA Forest Service).

2.2—Disturbances and Stressors in Sagebrush Ecosystems

Sage-grouse are "landscape" species (species that use and may influence large landscapes) and declines in populations can often be attributed to the loss, fragmentation, and degradation of sagebrush ecosystems (Connelly et al. 2011). Primary drivers of change in sagebrush ecosystems are the direct effects of human land use and development and their interactions with more complex factors, such as altered fire regimes, invasive species, expansion of trees to larger areas, drought stress, and livestock grazing (Connelly et al. 2011). Effects of these disturbances and stressors are manifest at temporal scales ranging from years to centuries and spatial scales ranging from sites to large landscapes (Arkle et al. 2014; Doherty et al. 2010). Superimposing rapid climate changes over disturbances makes assessment and management of shrubland ecosystems and their services increasingly difficult (Finch 2012). The influences of a changing climate potentially have profound implications for the distribution of sagebrush ecosystems. Kitchen et al. (in preparation) show the historical environmental settings for the development and establishment of sagebrush communities, their trajectories since the Pleistocene, and the implications for current and future distribution of sagebrush communities. Still and Richardson (2015) and Balzotti et al. (in review) modeled climate envelopes that are useful in identifying areas where sagebrush habitat is most likely to change in a warming climate. Balzotti et al. (in review) also integrated the confounding effects of invasive species. This information is valuable for understanding implications of changes to sage-grouse habitat and for identifying where management effort can best conserve habitat connectively.

A primary strength of FS research is in developing the required understanding of disturbance effects on sagebrush ecosystems across scales necessary to develop effective management strategies. Key areas of FS science leadership in sagebrush ecosystems pertain to disturbances and stressors associated with invasive species, conifer expansion, and fire (fig. 5A,B,C), as described next.

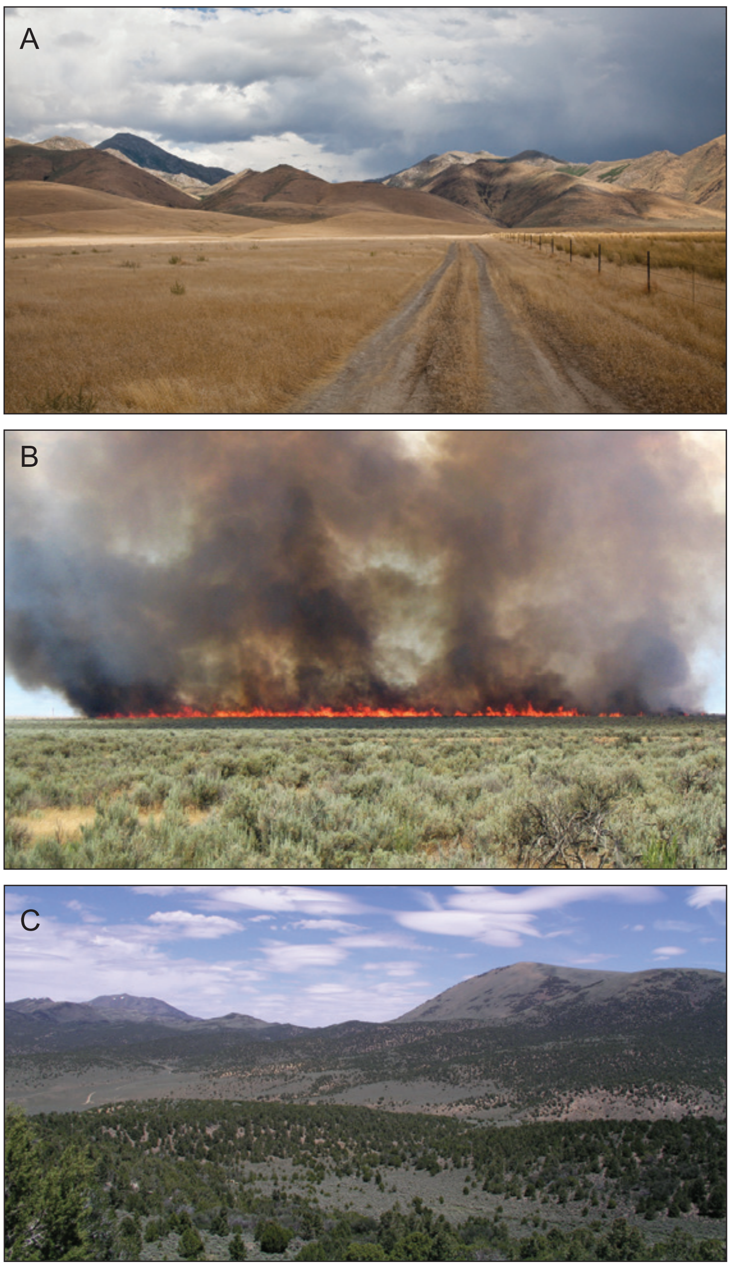

Figure 5—(A) Landscape converted to *B tectorum* in north-central Nevada (photo by Nolan Preece, independent artist, used with permission), (B) sagebrush fire in south-central Idaho (photo by Doug Shinneman, U.S. Geological Survey), and (C) pinyon and juniper expansion in central Nevada (photo by Jeanne Chambers, USDA Forest Service).

2.2.1—Invasion of annual grasses into sagebrush ecosystems

Invasion and expansion of annual grasses is resulting in an annual grass-driven fire cycle and progressive conversion of lower elevation, warmer, and drier sagebrush ecosystems to ecosystems dominated by annual grasses, especially cheatgrass (Kitchen 2014). Successful management strategies require a detailed understanding of attributes of sagebrush ecosystems that determine resistance to invasion. To gain that understanding, FS scientists examined effects of climatic factors (temperature and precipitation) and common disturbances (fire, grazing) on soil water and nutrients (Whittaker et al. 2008), and on establishment, reproduction, and persistence of the most widespread annual invader—cheatgrass (Beckstead and Augsburger 2004; Beckstead et al. 2010, 2011; Blank et al. 2007; Chambers et al. 2009, 2014d; Jones et al. 2015a, 2015b; Roundy et al. 2007). To understand implications for its adaptation, spread, and control, FS scientists examined germination characteristics and genetic structure among cheatgrass populations (Merrill et al. 2012) and interactions of cheatgrass with native plant species (Goergen and Chambers 2009) and sagebrush plant communities (Jones 2014). This research was the basis for creating conceptual and statistical models of factors that influence resistance to annual grass invasion across the environmental gradients that characterize sagebrush ecosystems (e.g., fig. 6B) (Brooks and Chambers 2011; Chambers et al. 2014b). These models are used widely to develop management strategies (Miller et al. 2013, 2014b, 2015). More recent collaborative research has examined how climate change is likely to affect both expansion and contraction of the invasive annual brome grasses, cheatgrass and red brome (*Bromus rubens* L.) (Bradley et al. 2015).

2.2.2—Expansion of pinyon and juniper into sagebrush ecosystems

Conifer expansion, particularly by species of pinyon (and juniper), is a primary threat to sagebrush communities on national forest lands because it typically results in a decrease in understory sagebrush, grasses, and forbs (fine fuels), an increase in woody fuels, and less frequent but more intense fires (Miller et al. 2013). FS researchers and collaborators examined pinyon juniper ecology (Chambers 2001; Chambers et al. 1999), and the changes that occur in soil resources (Rau et al. 2007, 2008) and plant community composition (Chambers 2000, 2005), reductions in sagebrush cover in relation to pinyon-juniper expansion (Rowland et al. 2010a), and the consequences for fuel loads with progressive tree expansion and infilling (Miller et al. 2008, 2014b; Roundy et al. 2014a,b). They also examined resilience of these areas to wildfire and management treatments and resistance to invasive annual grasses across the environmental gradients that characterize these ecosystems (fig. 6A,B) (Chambers et al. 2014b,c). This research was the basis for management guides for prioritizing areas for treatment and selecting the best treatment options (Chambers et al. 2014d; Miller et al. 2014a, 2015; Pyke et al. 2014, 2015).

2.2.3—Altered fire regimes and post-fire recovery

Fire is a dominant disturbance process regulating composition and structure of sagebrush ecosystems. Understanding variability in natural and altered disturbance regimes and their effects on vegetation is critical for developing effective management and restoration strategies. FS scientists and collaborators characterized historical (multi-century) fire regimes for big sagebrush (*Artemisia tridentata*) ecosystems, and evaluated the changes that are occurring in these fire regimes (Heyerdahl et al. 2006; Kitchen and McArthur 2007; Miller and

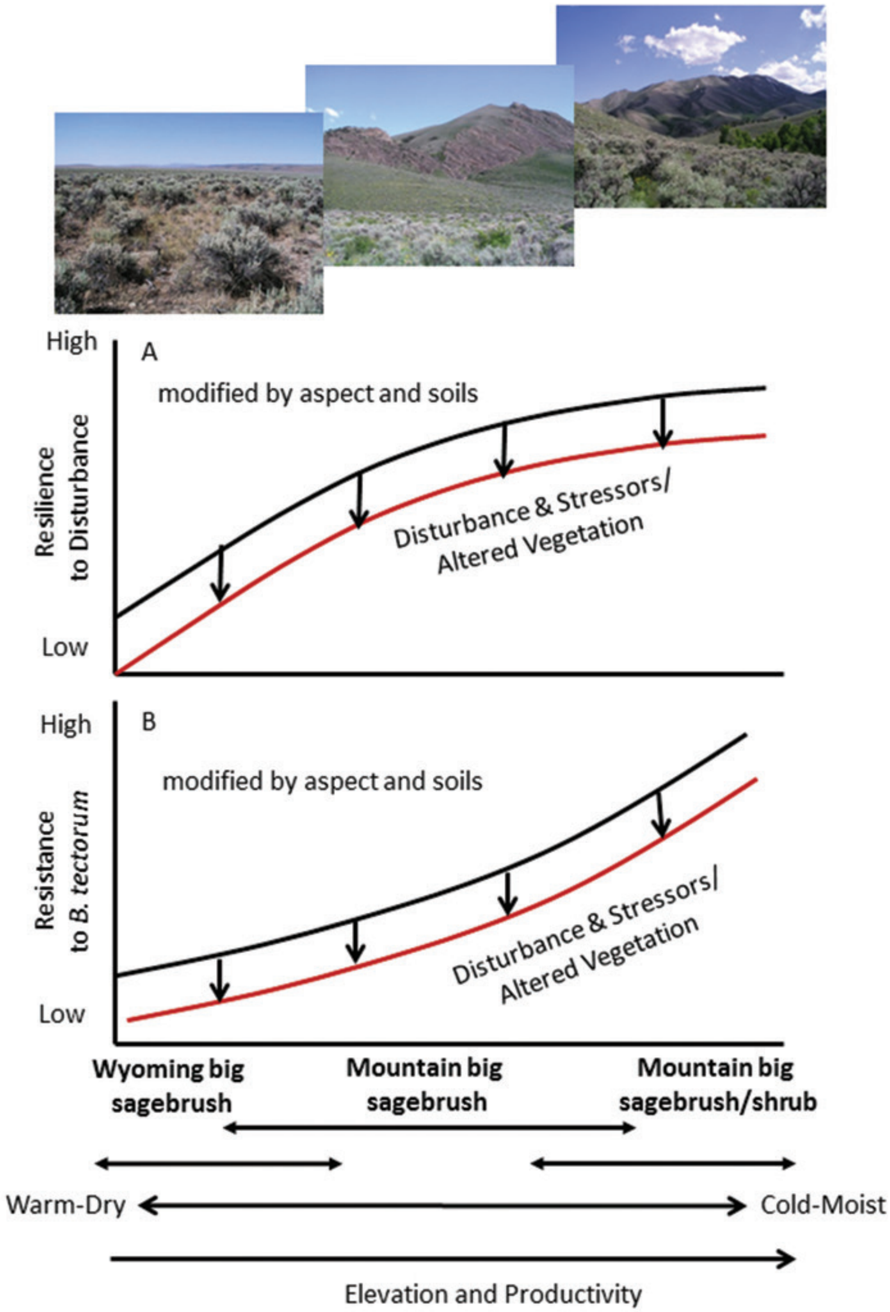

Figure 6—(A) Resilience to disturbance and (B) resistance to cheatgrass (*B. tectorum*) over a typical soil temperature and moisture gradient in sagebrush ecosystems of the western United States (adapted from Chambers et al. 2014b).

Heyerdahl 2008; Miller et al. 2008). Working across a diverse range of big sagebrush sites, they assessed the drivers of, and variability in, sagebrush population recovery (fig. 7) and tree occupation (Goodrich et al. 2008; Nelson et al. 2014), and quantified the effects of post-fire sagebrush seed production on recovery rate (Landeen 2015). On landscapes prone to tree invasion, sagebrush dominance is facilitated by fire-free intervals long enough for sagebrush recovery but short enough to prevent tree invasion and dominance (Miller and Rose 1999; Miller et al. 2013).

Figure 7—Vegetative recovery 5 years after a fire in a mountain big sagebrush community. Scattered sagebrush plants grew from seeds that survived the fire and are now large enough to begin producing the seeds that will give rise to a second postfire generation. Plant density is sufficient for full sagebrush recovery in 25–35 years after the fire (photo by Stanley G. Kitchen, USDA Forest Service).

Landscape-scale vegetation dynamics across a range of fire frequencies and climate scenarios are being modeled in order to assess the resilience of big sagebrush ecosystems at various spatial and temporal scales. Fire frequency is expected to increase with increasing air temperature and drought. If fire frequency is too great, it may stimulate a phase change from sagebrush-dominated vegetation to steppe and will likely become unsuitable for sage-grouse. Even without fire in the system, climate change is likely to reduce current distribution of sagebrush (Friggens et al. 2012; Richardson et al. 2012a). Habitat for sage-grouse may shift to higher latitudes and elevations under warming climates (Finch et al. 2012) and may be needed at higher elevations (e.g., FS lands), where habitat will be less at risk of fire and invasion by annual invasive grasses.

2.2.4—Sage-grouse response to disturbance impacts on habitat

Forest Service researchers have extensive experience in evaluating effects of landscape change and land management actions on wildlife species, including sage-grouse, through direct evaluations of movement patterns, and demographics and resource selection models applied to evaluate various types of disturbance. This expertise is particularly relevant to the evaluation of land disturbance from invasive species, fires, or anthropogenic development (e.g., energy sources, roads, transmission lines), and stems from a long history of research on relationships between wildlife populations and vegetation patterns. A key example is the FS-led evaluation of factors associated with extirpation of sage-grouse by Wisdom et al. (2011), which identified a wide variety of anthropogenic and vegetation factors strongly associated with extirpation (see *2.1.3—Quantification of core and edge habitats across* *sage-grouse range*). Results are being used for conservation planning across the range of the species on public and private lands. Another example of FS expertise deals with wind energy, projected to compose about 20 percent of the U.S. energy demand by 2030 (U.S. Department of Energy 2008). High-quality wind resources overlap the range of sage-grouse, particularly in the eastern portion of the range (Becker et al. 2009). FS scientists have expertise to evaluate effects of wind energy development on populations and habitat, and research on these effects on GRSG habitat use and movements is underway in Wyoming (Mark Rumble, personal communication, USDA Forest Service, Rapid City, SD, 2015; Schreiber et al. 2015a,b). In addition, Rowland (2004) identified and synthesized effects of a large suite of management activities on GRSG habitats and populations across the species range, including prescribed fire, livestock grazing, and land use change.

Degradation of sagebrush habitat during a drought year was evaluated by using MODIS (moderate resolution imaging spectroradiometer) imagery "ForWarn": http://forwarn.forestthreats.org/. Field observations noted a significant loss of leaves and branches from decadent old sagebrush at this south-central Oregon site, which was experiencing a single year of severe drought (25 percent of average precipitation). A dynamic vegetation model (Drapek et al. 2015) will be used to show expected end-of-century sagebrush habitat distribution and sagebrush productivity levels in the region (Grulke et al., in preparation).

FS researchers also have a long history of evaluating gene flow of sensitive species and how gene flow is altered by changes in the landscape (see *2.3.2—Assessment of sage-grouse gene flow and connectivity*). Of particular value is the use of spatially explicit genetic data to test hypotheses of how genes move across landscapes and how this movement will be affected by disturbances (Cushman et al. 2006; Manel et al. 2003; Schwartz et al. 2009; Shirk et al. 2015). Currently, FS researchers are analyzing thousands of feather samples from sage-grouse leks to evaluate gene flow and genetic continuity across the northern portion of the species' range (see 2.3.2—*Assessment of sage-grouse gene flow and connectivity*). This research will also be used to assess how stressors such as land conversion, energy development, and fire may influence movement (e.g., Shirk et al. 2015).

2.2.5—Assessments of sage-grouse vulnerability to stressors

Recent FS efforts have focused on assessing the vulnerability of sage-grouse and their habitat to the effects of climate change and other natural and anthropogenic stressors in the Intermountain Region (Balzotti et al., in review). Contemporary and projected future conditions were evaluated based on past distribution patterns reconstructed from paleoclimatological and historical data. Specific objectives included: (1) describing pre-Euroamerican settlement sagebrush distribution and changes during the last several millennia; (2) developing models of climate and sagebrush ecological niches and assessing their implications for sage-grouse habitat occupancy and use; (3) identifying natural and anthropogenic causes for sagebrush degradation and loss, with emphasis on those associated with wildfire, invasive species, and conifer expansion on NFS lands; (4) identifying habitats at greatest risk for loss and disruption of sage-grouse population connectivity; and (5) providing management options, including identifying and prioritizing those areas where sagebrush restoration efforts could best conserve habitats and connectivity of sage-grouse habitats. Objectives 4 and 5 were also the focus of an FS-led assessment of habitat threats in the Great Basin that provided broad-scale evaluation of the risks of sagebrush loss from pinyon-juniper expansion and cheatgrass invasion (Rowland et al. 2010b; Wisdom et al. 2005b,c).

2.3—Landscape Analysis and Design to Improve Habitat Connectivity

FS R&D has been instrumental in studying changes in sage-grouse and the landscapes they inhabit. Fragmentation of the species' preferred habitat and effects of this fragmentation on sage-grouse population cohesion and dispersal have made these studies of paramount importance. This research spans multiple scales and uses multiple approaches, from experiments to species distribution modeling to landscape-scale genetic approaches. Recent analyses also are addressing the influence of climate change on these systems and the implications for connectivity of sage-grouse habitats.

2.3.1—Landscape connectivity and corridors

A variety of natural and anthropogenic disturbances have fragmented sage-grouse habitats. These disturbances include removal of sagebrush through prescribed fire and mechanical means, natural fire, energy development and mining, exurban development, agricultural development, and road and transmission line corridors. These disturbances must also be viewed in the context of a changing climate.

FS scientists have evaluated broad-scale fragmentation in sagebrush ecosystems through several projects. As part of the ICBEMP (see *2.1.1—Modeling greater sage-grouse and its habitat*), Hann et al. (2003) developed a spatially explicit disturbance departure and fragmentation index across the basin and found high levels of departure and fragmentation in low-elevation rangelands. Other ICBEMP analyses led by FS scientists projected future trajectories and effects of land management on the persistence of sage-grouse habitats and populations (Hemstrom et al. 2002; Wisdom et al. 2002a,b). Landscape configurations related to landscape connectivity, as measured by habitat size, arrangement, and fragmentation, were considered. In the Great Basin ecoregion, Wisdom et al. (2005) evaluated risk of cheatgrass encroachment for habitats of several species groups, including sagebrush-associated species such as GRSG. Their composite risk map can be used to depict habitat connectivity by highlighting watersheds in the Great Basin that have low cheatgrass invasion risk and relatively high habitat abundance. In an additional analysis, Rowland and Wisdom (2009) identified habitat networks in the Great Basin for sagebrush-dependent vertebrate species, including GRSG, based on sagebrush habitat area and configurations.

As discussed earlier (*2.1.1—Modeling greater sage-grouse and its habitat*), Wisdom et al. (2011) evaluated environmental conditions in areas of former (extirpated) range and range still occupied by sage-grouse. They considered a wide variety of landscape metrics, including multiple measures of habitat fragmentation, core size, patch size, edge area, roads, and transmission lines, all of which are part of, or directly influence, measures of landscape connectivity. Moreover, they identified habitat "strongholds" for sage-grouse persistence based on characteristics of landscape connectivity and isolation, which depicted de facto corridors. These FS-led evaluations have been widely used in conservation planning by public and private land managers across the range of sage-grouse.

Modeling potential occupied area of a species and the factors that affect its distribution has become a useful tool in ecological research and management. In particular, bioclimate models are becoming even more important, but, like any model, they require assumptions and appropriate interpretation (Pearson and Dawson 2003; Soberon and Nakamura 2009). Two primary issues with bioclimatic models are that they (1) rarely take into account intraspecific genetic variation (note that common garden genecological and reciprocal transplant studies, used in seed zone construction for example, can be used to understand how intraspecific genetic variation interacts with climate; see Kilkenny 2015) and (2) rarely take into account how biotic interactions might affect species distributions and possibly could be mistaken for climatic interactions. FS R&D has developed many of the analytical tools (Iverson et al. 2008; Rehfeldt et al. 2006) and data (FS, Forest Inventory and Analysis) used to create these models. For sagebrush, three such models have been developed that can be used in connectivity planning. Two models used land cover imagery to assess cheatgrass and disturbance threats (Bradley 2010) and evaluate the effects of ecohydrology on sagebrush occurrence (Schlaepfer et al. 2012). Recently, Still and Richardson (2015) used presence and absence data of Wyoming big sagebrush (*A. tridentata* subsp. *wyomingensis*) to develop a subspecies model.

Currently, FS-managed GRSG habitat tends to occur at higher elevations on more mesic sites than GRSG habitat on non-FS lands, as mentioned earlier. Under a changing climate, the total area of sagebrush communities and high-quality sage-grouse habitat may potentially shrink and move upslope (Friggens et al. 2012), increasing the importance of these FS-managed habitats. To plan for this possibility, Balzotti et al. (in review) modeled and analyzed climate patterns at regional and sub-regional scales and evaluated potential changes in sagebrush and pinyon-juniper communities on national forests in Utah and Nevada. When overlaid with the distribution of sage-grouse habitats, the model allows managers to evaluate areas where conservation may have the greatest benefit for population retention and recovery.

2.3.2—Assessment of sage-grouse gene flow and connectivity

As noted earlier (*2.2.4—Sage-grouse response to disturbance impacts on habitat*), gene flow of sensitive animal species, including gene flow altered by changes in the landscape, has long been a focus of Forest Service research. Using spatially explicit genetic data to test various hypotheses is particularly valuable, especially when considering disturbances to the ecosystem (Manel et al. 2003; Schwartz et al. 2009). This discipline is called landscape genetics and was developed and advanced by FS researchers (Cushman et al. 2006; Manel et al. 2003; Schwartz 2001). It is used in ongoing FS research that is exploring how disturbances, including exurban expansion, agricultural conversion, sagebrush fragmentation, energy development, and invasive species, affect gene flow across multiple scales (Braun 1998; Copeland et al. 2009; Knick et al. 2003; Naugle 2011; Naugle et al. 2004, 2006, 2011; Shirk et al. 2015).

Using genetic data collected from feathers and blood, and observations of bird presence in about 70 different breeding areas in eastern Washington, FS scientists in collaboration with other research institutions, developed a model for predicting how GRSG move across the landscape under different future disturbance scenarios (Shirk et al. 2015). Their findings showed that transmission lines are barriers that limit GRSG movement between patches of habitat, which could interrupt gene flow among subpopulations and reduce genetic diversity. At the smaller scale, research is exploring how potential disturbances influence movement among Core Breeding Areas in Montana (Cross et al., in review). A larger collaboration of scientists with the U.S. Geological Survey, Department of the Interior and the FS is asking a similar question across the entire distribution of GRSG (Cross et al., in review; Hanks et al., in review; Oyler-McCance et al., in preparation).

Cross et al. (in review) analyzed 16-locus microsatellite genotypes from 2,108 GRSG associated with 508 spatially distinct locations across Montana, North Dakota, and South Dakota. Subpopulation structure aligned closely with ecologically distinctive areas of the landscape created by historical biogeographic processes. This finding suggests that contemporary GRSG fine-scale genetic population structure is shaped by the underlying landscape physiography. The ability to match genetically distinct populations with suitable landscapes may be useful when designing corridors for connecting populations, or for reintroducing populations to vacated areas. Finally, new approaches applying graph theory are being used in conjunction with the FS's multiscale sage-grouse genetics work to explore the impacts of degradation or loss of individual leks to the overall connectivity of the system.

2.4—Methods, Models, and Plant Materials to Restore Sagebrush Habitats

FS researchers and collaborators are instrumental in developing effective restoration approaches and treatments for sagebrush ecosystems. FS researchers are developing climatically adapted plant materials with high genetic diversity that confer resistance and resilience to a community, as well as seed transfer guidelines for planting the right seed in the right place. The establishment of partnerships such as the Great Basin Native Plant Project (see 2.4.3—*Native plant development—seed and seedling biology and plant propagation*) has been instrumental in advancing seed science and plant material development for application in restoration of the sagebrush ecosystem. Additional strategies focus on active restoration methods, such as vegetation management to reduce fuels and remove trees, control of exotic annual grasses, and reestablishing native, perennial vegetation.

Timely restoration of degraded sagebrush plant communities at landscape scales is essential for maintaining sage-grouse habitats. An understanding of factors that regulate plant community resilience to disturbance and resistance to invasion by annual grasses is necessary for prioritizing restoration activities, selecting the most effective treatments, and choosing the most appropriate plant materials. Treatments that reduce woody fuel loads, increase herbaceous perennials, and decrease annual invasive abundance promote increases in resilience and resistance while restoring structure and function needed for sagebrush-dependent wildlife (Brooks and Chambers 2011; Chambers et al. 2014b,c,d; Korfmacher et al. 2003; Tausch et al. 2009). Restoration using seed mixes that contain seed adapted to appropriate climate zones and conditions will promote resilience and resistance of sagebrush communities as well (Richardson et al. 2015). Although passive restoration measures, such as changes in land use, can often be effective in improving ecological condition, these measures alone are insufficient to meet the burgeoning restoration needs in the face of multiple threats. Among these threats are altered fire regimes including large high-severity fires, current and projected rates of spread and dominance by trees and exotic annuals, existing poor condition of herbaceous vegetation in many areas, and projected increased stress due to climate change.

2.4.1—Sagebrush genetic and taxonomic complexity

Restoration of sagebrush ecosystems is complicated by the taxonomic and genetic variability of sagebrush. FS common garden research on big sagebrush has shown that three

Figure 8—Indication of the different growth rates among big sagebrush subspecies: *tridentata* (far right), *wyomingensis* (middle), and *vaseyana* (far left) (photo by Bryce Richardson, USDA Forest Service).

widespread subspecies (*tridentata, wyomingensis*, and *vaseyana*) (fig. 8) are genetically distinct (Richardson et al. 2012b) and adapted to different habitats (McArthur and Welch 1982; McArthur et al. 1988; Wang et al. 1997). Correct subspecies identification and use of source plant materials (seed or outplanted seedlings) are critical for successful sagebrush restoration. Past efforts to identify and match seed sources to planting sites have been hampered by a lack of reliable tests of seed-lot identity. Of particular importance to sage-grouse habitat restoration is proper identification of Wyoming big sagebrush (subspecies *wyomingensis*), which is the predominant subspecies seeded following large wildland fires. A recent study demonstrated that seeds of Wyoming big sagebrush can be distinguished from those of basin big sagebrush (subspecies *tridentata*), based on weight; and a retrospective analysis of past BLM seed purchases (years 2012 and 2013) showed that Wyoming big sagebrush seed lots were largely composed of basin big sagebrush (Richardson et al. 2015). This research can be used to develop a certification step to distinguish seeds of these two subspecies of big sagebrush. It also suggests that restoration failure of burned sagebrush sites may be linked to use of seed mixes having seed of the wrong sagebrush subspecies.

2.4.2—Adaptive genetic variation and seed transfer guidelines

Climate is a principal factor affecting adaptation within a plant species. Knowledge of how plants are climatically adapted is fundamentally important to the process of seed collection and proper transfer to restoration sites. Seed collection should be focused on regions that are most likely to be threatened by disturbance so that restoration can proceed with seed that is appropriately adapted to the threatened region. The research approach to elucidate climatic adaptation is long established (Turesson 1925), and the large body of subsequent research primarily focused on tree species. During the last decade, FS has begun to apply this approach to native grasses, forbs, and shrubs (Bower et al. 2014; Johnson et al. 2013; Richardson et al. 2014; St. Clair et al. 2013), a number of which are important species in sage-grouse related plant communities. Genecological research has been used to determine areas where plant species are under threat from climate change and to identify promising seed sources for use in changed climates (Kilkenny 2015). Data from common garden genecological and reciprocal transplant studies, used in seed zone construction, can be used to estimate the effects of intraspecific genetic variation on species distribution under climate change. Currently, FS researchers at the Rocky Mountain Research Station and the Pacific Northwest Research Station are performing a large-scale reciprocal transplant study (using 16 common garden sites) on bluebunch wheatgrass (*Pseudoroegneria spicata*), a keystone structural species in many sagebrush habitats, to determine in unprecedented detail the climatic adaptation of 78 wild seed sources (Kilkenny et al. 2013).

The FS-managed Western Wildland Environmental Threat Assessment Center has a comprehensive seed zone website where seed zones are displayed (http://www.wwetac.net/index_files/seedzone.shtml). Bower et al. (2014) developed generalized provisional seed zones that can be applied to any plant species in the United States to help guide seed movement in the face of climate change. Preliminary work for understanding the adaptive genetic variation in big sagebrush ecosystems is available (fig. 9; Richardson et al. 2013).

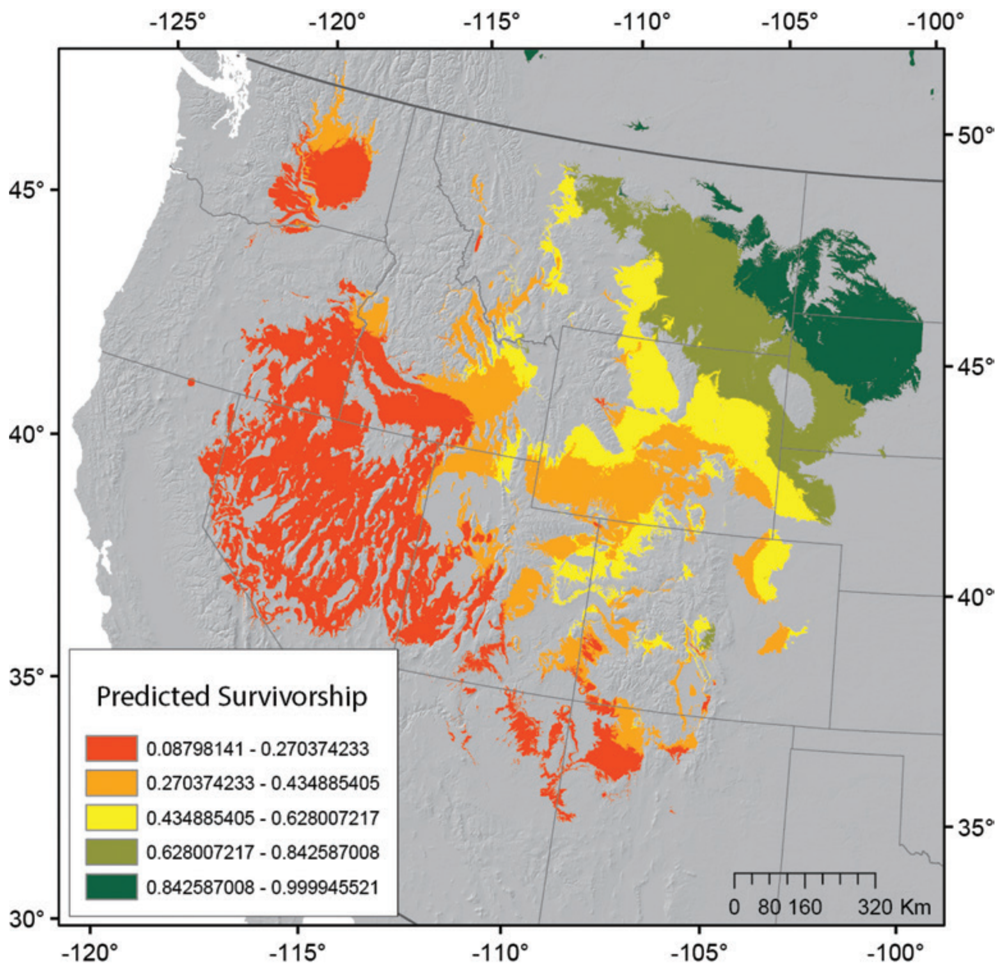

Figure 9—Predicted landscape survivorship of Wyoming big sagebrush based on common garden mortality patterns (Richardson et al. 2013). These patterns are largely explained by climate variables describing cold winter and spring temperatures. This model is projected based on climate surface data and partitioned into groups from low to high survival (red = low survival, green = high survival). Survival is one of several traits that can be combined to develop seed transfer zones.

In addition, FS research has addressed other genetic characteristics of sagebrush species (Meyer 1994; Miglia et al. 2007; Smith et al. 2002; Welch and McArthur 1981).

2.4.3—Native plant development—seed and seedling biology and plant propagation

Active restoration of sagebrush communities generally includes planting seeds and seedlings of native plants. Chambers and MacMahon (1994) developed a conceptual model of seed movement and fate that is helpful in understanding how likely a seed will successfully establish. Availability of adequately adapted seed sources of forbs, shrubs, and many grasses is limited (fig. 10), creating a bottleneck to large-scale restoration (Roundy et al. 1997; Shaw and Jensen 2014). A multi-state partnership initiated by FS and BLM in 2001, known formerly as the Great Basin Native Plant Increase and Selection Project (Shaw et al. 2012) and now as the Great Basin Native Plant Project (GBNPP), is helping to address this problem. More than 20 Federal, State, and private cooperators are involved in the GBNPP. Current research conducted by GBNPP and others focuses on developing seed zones where plant materials can be transferred with little risk of being poorly adapted to their new location, increasing seed availability, understanding native plant response to climate change, and evaluating native plant interactions with invasive species. The GBNPP hosts an active website (http://www.greatbasinnpp.org/) where its publications, presentations, and annual reports are posted.

In 2001, FS also created the Reforestation, Nurseries and Genetic Resources Program (RNGR) (http://rngr.net/), with the mission to supply people who grow seedlings with the latest technical information, and to provide links to other organizations and individuals with similar interests (Haase et al. 2011). Scientists and other professionals on the RNGR team

Figure 10—Although many species of forbs are already in production, reliable methods are needed to economically produce a broader suite of forb species with appropriate genetics to meet restoration objectives (photo by Matt Fisk, USDA Forest Service).

contribute regularly to the literature on native plant propagation and nursery science (e.g., Dumroese et al. 2012). These contributions include papers on the influence of container size and storage on big sagebrush seedling growth, survival, morphology, and cold hardiness (Herriman et al. 2009; Overton et al. 2013), as well as broader reviews about forbs, pollinators, and GRSG (Dumroese et al. 2015, in press), assisted plant migration (Williams and Dumroese 2013), and tribal nursery plants (Dumroese et al. 2009). All of these publications have value for understanding ideas and approaches for restoring sagebrush ecosystems.

Knowledge of life-history traits is necessary to add new species to the restoration menu (Kitchen 1994; Shaw and Jensen 2014). FS scientists and collaborators have developed conceptual approaches for seed movement and fate in any ecosystem (Chambers and MacMahon 1994) and have investigated seed dormancy and germination regulation (Bonner and Karrfalt 2008; Meyer 1994; Meyer and Kitchen 1994a,b; Meyer and Monsen 1991; Meyer et al. 1995; Scholten et al. 2009), seedling emergence and growth (Chambers 2002; Chambers and Linnerooth 2001; Kitchen 1995; Monsen and Kitchen 1994; Shock et al. 2012, 2015), pollination strategies (Cane 2008), and fecundity and plant longevity (Kitchen 1995; Shock et al. 2015; St. Clair et al. 2013) for numerous species native to sagebrush ecosystems. Specialized equipment and cultural practices are being developed by FS scientists and collaborators to improve seed yields for species grown in agronomic settings (Shock et al. 2014, 2015) and managed wildland stands (Armstrong 2007; Ott et al., in preparation) (fig. 11). FS scientists have developed standardized seed testing protocols and storage practices needed to stabilize markets and ensure seed quality for many native species (Karrfalt and Shaw 2013; Kitchen 2001).

Figure 11—A rangeland drill in use at the burned site of the Scooby Fire, in northern Utah, in 2008. This drill was modified for seeding diverse mixtures of native plant species. It is an example of the specialized seeding techniques under development for restoring sagebrush ecosystems following wildfire in the Great Basin (photo by Beth Newingham, USDA Agricultural Research Service).

Novel equipment for collecting seeds has been described (Jensen 2004) and guidelines are available for proper collection and certification of seed from natural stands (Adair et al. 2006; Currans et al. 1997; Young et al. 1995). FS researchers and their collaborators continue to develop cultural practices needed to increase the availability and quality of seed needed for sagebrush ecosystem restoration (Shaw et al. 2012).

2.4.4—Restoration methods—practices and equipment for weed control and seeding

Active restoration of arid and semiarid sagebrush ecosystems that lack the necessary perennial plants for unassisted recovery is particularly challenging because of low, and highly variable, precipitation, episodic plant establishment, and widespread invasion by exotic weeds. FS researchers and their collaborators have a productive history of developing the necessary plant establishment methods and seeding equipment for restoring sagebrush and its communities. They have produced hundreds of publications on the subject (Kiehl et al. 2014; Kitchen and Monsen 1995; Meyer and Warren 2015; Monsen and Meyer 1990; Monsen et al. 1992, 2004a,b). Research by the FS as part of the Shrubland Research Consortium has kept researchers and practitioners up-to-date on current restoration topics and approaches through biennial symposia and publication of 16 symposium proceedings (1983–2011). The GBNPP (see 2.4.3—*Native plant development—seed and seedling biology and plant propagation*) generates research products, annual conferences, and webinars focused on improving the availability of native plant materials and on providing the knowledge and technology required for their use in restoring diverse native plant communities across the Great Basin. Research on restoration methods is broad and includes topics such as testing the use of drilling to establish native species after fire (Thompson et al. 2006), determining the effectiveness of different types of drills for establishing native mixes containing seeds of different sizes (Ott et al., in preparation; Taylor et al. 2014), evaluating species compatibility and invasion resistance within restored communities (Allen and Meyer 2014; Parkinson et al. 2013), developing methods and testing seed mixes for restoring key plants (e.g., forbs) required by GRSG (Dumroese et al., in press), and testing use of carbon addition and repeated burning to decrease soil nitrogen availability and invasive annual grass (cheatgrass) establishment and reproduction (Jones et al. 2015b; Mazzola et al. 2008, 2011). Outplanting of seedlings to reestablish difficult-to-seed species such as sagebrush is increasing (McAdoo et al. 2013) and is supported by FS research that examines (1) native plant nursery cultural practices including seedling storage, (2) the consequences of those practices on seedling physiology and outplanting success, and (3) the biophysical limitations of outplanting sites (Davis et al., in press; Overton et al. 2013; Pinto et al. 2012, 2015) (fig. 12).

2.4.5—Responding to threats: Loss of habitat through invasive plants, fire, and other stressors and disturbances

FS researchers and collaborators developed and tested many of the vegetation management treatments currently used to reduce woody fuels and increase native perennial vegetation in sagebrush ecosystems (Monsen et al. 2004b). The FS's research uses syntheses and regional studies to develop basic information and conceptual models on resilience and resistance of sagebrush systems to better target management actions (Board et al. 2011; Brooks and Chambers 2011; Chambers et al. 2007, 2014b,c,d; D'Antonio and Chambers 2006; McIver et al. 2010; Miller et al. 2013; Monsen and Kitchen 1994). The Sagebrush

Figure 12—Sagebrush being grown as bareroot stock at the USFS Lucky Peak Nursery near Boise, Idaho. Shrub seedlings like these could be outplanted as part of islands to act as microsite engineers to foster establishment of forbs required to support a variety of wildlife species (photo by R. Kasten Dumroese, USDA Forest Service).

Treatment Evaluation Project (SageSTEP; http://www.sagestep.org/) provides regional information on effects of prescribed fire, mowing, and herbicide treatments in sagebrush ecosystems exhibiting cheatgrass invasion (Pyke et al. 2014; Rau et al. 2014) and prescribed fire, cut-and-leave, and mastication (shredding) treatments on those exhibiting pinyon or juniper expansion (Miller et al. 2014a; Roundy et al. 2014a,b). An interdisciplinary framework is used to couple environmental indicators of resilience and resistance with sage-grouse habitat requirements to prioritize management actions on the landscape (Chambers et al. 2014c). Field guides have been developed that use resilience and resistance concepts to select appropriate sites for treatment (fig. 13) and to determine the most effective treatments (fig. 14) (Miller et al. 2014a, 2015; Pyke et al. 2015).

Recent work by Kitchen et al. (in preparation) portrays the influences of climate change in the distribution and abundance of sagebrush communities during the last several millennia, and the implications of climate change on projected distributions. This is intended to provide a valuable backdrop to the environmental envelope of sagebrush communities, and offers insight to areas where restoration may be most beneficial. Richardson et al. (2013) and Balzotti et al. (in review) developed climate envelopes for sagebrush, pinyon-juniper and invasive species, and modeled potential changes in the communities as a result of climate change. When coupled with anthropogenic landscape changes, this work suggests current and future conservation and restoration opportunities relative to these stressors.

For more than two decades, Meyer and her colleagues have evaluated biocontrol approaches for controlling cheatgrass infestations, including examinations of the head smut *Ustilago bullata* (e.g., Meyer et al. 2000, 2001, 2010a), the fungal seed pathogen

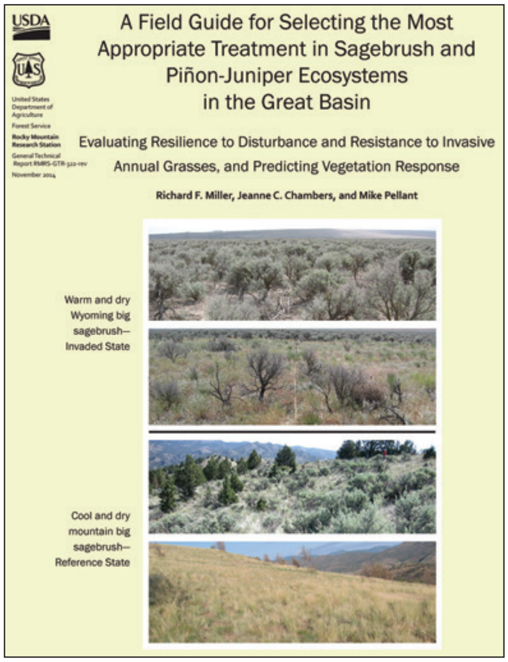

Figure 13—In 2014, the Forest Service published *A field guide to selecting the most appropriate treatments in sagebrush and pinyon-juniper ecosystems in the Great Basin: Evaluating resilience to disturbance and resistance to invasive annual grasses and predicting vegetation response.* Gen. Tech. Rep. RMRS-GTR-322. Fort Collins, CO: USDA Forest Service, Rocky Mountain Research Station.

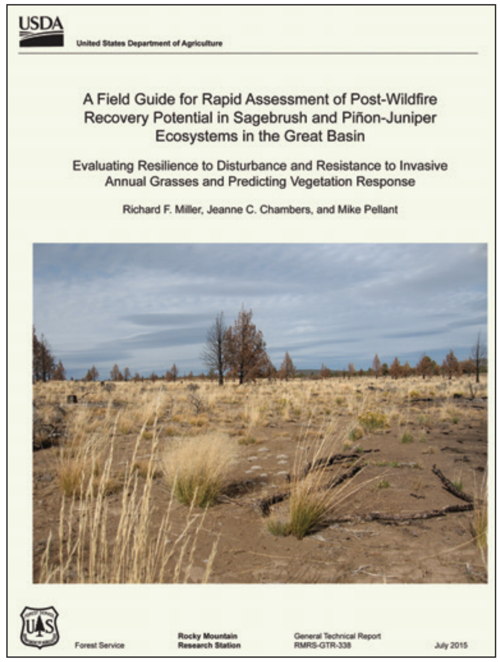

Figure 14—In 2015, the Forest Service published *A field guide for rapid assessment of post-wildfire recovery potential in sagebrush and piñon-juniper ecosystems in the Great Basin: Evaluating resilience to disturbance and resistance to invasive annual grasses and predicting vegetation response.* Gen. Tech. Rep. RMRS-GTR-338. Fort Collins, CO: USDA Forest Service, Rocky Mountain Research Station.

Pyrenophora semeniperda (e.g., Beckstead et al. 2010, 2011; Masi et al. 2014; Meyer et al. 2008, 2010b, 2013, 2015; Soliai et al. 2014), and underlying reasons for cheatgrass die-offs (Baughman et al. 2016; Meyer et al. 2014). Currently the most promising biocontrol organism Meyer's team has evaluated is a fungal seed pathogen that can kill dormant cheatgrass seeds and sometimes a high proportion of germinable seeds as well. This pathogen (*Pyrenophora semeniperda*) has been dubbed "black fingers of death" because of the fingerlike, black fruiting bodies that protrude from killed seeds (fig. 15). Their research has included extensive work on the population and evolutionary genetics of both cheatgrass and its pathogens, as well as biocontrol technology research aimed directly at developing effective field application methods. In some field inoculation treatments with the black fingers of death pathogen, complete control of the dormant carryover seed bank has been achieved. The goal of a practical, safe, and cost-effective commercial product for cheatgrass biocontrol on rangelands is now within reach. This biocontrol product addresses the problem of ungerminated seeds that carry over across years and hamper establishment success in restoration seedings even after successful control of germinated cheatgrass seeds or established stands.

2.4.6—Monitoring effectiveness of restoration treatments

Understanding the effectiveness of restoration treatments is the basis for adjusting methods to increase restoration success. Along with collaborators, FS researchers have evaluated restoration treatment effectiveness across the environmental gradients and ecological types

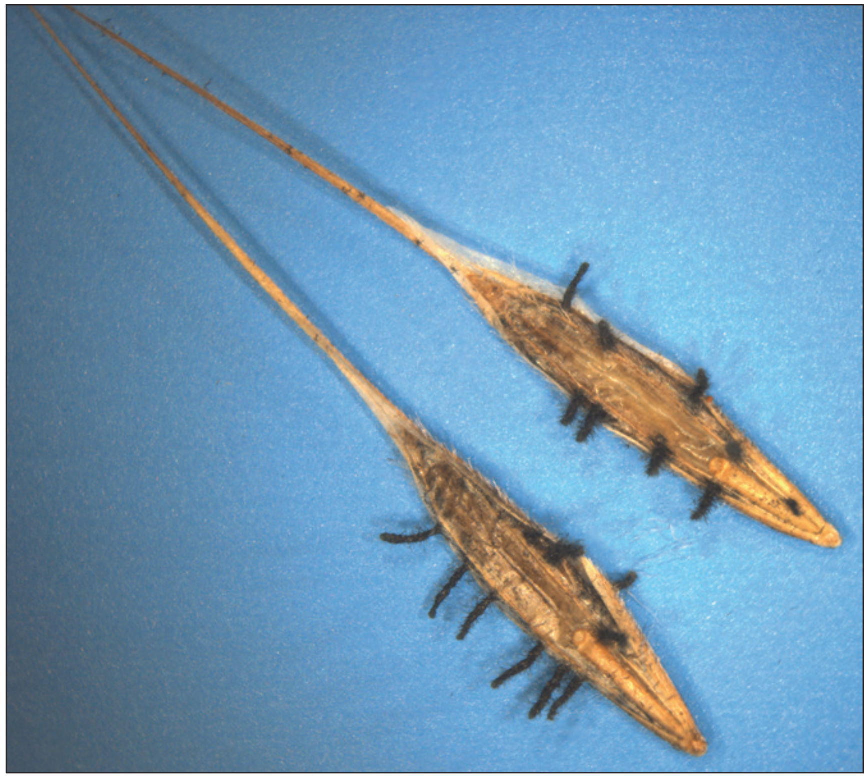

Figure 15—Fruiting bodies of the seed pathogen *Pyrenophora semeniperda*, which illustrate why the pathogen was given its nickname "black fingers of death" (photo by Susan Meyer, USDA Forest Service).

that characterize sagebrush ecosystems. Evaluations include (1) effectiveness of broadcast versus drill seeding or other seeding techniques, (2) success in establishing big sagebrush, (3) tradeoffs between seeding aggressive introduced species and native species recovery, and (4) effects on invasive plant species (Knutson et al. 2014; Ott et al. 2003, in preparation). FS researchers also have participated in modeling the predicted probability of sage-grouse occupancy on treated sites based on sagebrush species and establishment, perennial grass cover, and invasive annual cover (Arkle et al. 2014).

2.4.7—Conceptual models—linking habitat restoration to sage-grouse recovery

FS scientists led the development and implementation of a variety of groundbreaking conceptual models for sage-grouse habitat restoration and recovery as part of ICBEMP, and later in ecoregional assessments in the Great Basin and across the entire range of GRSG (see *2.1.1—Modeling greater sage-grouse and its habitat*). Conceptual models developed by FS scientists for sage-grouse restoration and recovery for application across the 58-million ha ICBEMP area include: (1) novel state-and-transitions models for sagebrush to evaluate future sagebrush habitat trajectories (Hemstrom et al. 2002); (2) innovative Bayesian belief network models developed and applied by Wisdom et al. (2002a) for evaluating current and future sage-grouse habitats; (3) development of a new habitat network approach for sagebrush-dependent species, including sage-grouse, and demonstration of this conceptual model in restoration planning (Wisdom et al. 2002b); and (4) additional integration and synthesis of sage-grouse models for restoration planning (Wisdom et al. 2005a).

In the Great Basin, FS researchers evaluated the use of (1) umbrella species concepts for managing sagebrush-dependent species (Rowland et al. 2005, 2006), and (2) restoration modeling using ecosystem resilience concepts for sagebrush habitats occupied by sage-grouse (Wisdom and Chambers 2009). Rowland and Wisdom (2009) also developed and applied new habitat network approaches for sagebrush-dependent vertebrate species in the Great Basin, including sage-grouse. FS-led conceptual models for sagebrush habitat restoration and sage-grouse recovery across the historical range of the species include those by Wisdom et al. (2005a), which introduced novel modeling paradigms and management approaches for prioritizing landscape conservation and restoration.

Most recently, an interdisciplinary working group of the Western Association of Fish and Wildlife Agencies (WAFWA) developed a strategic, multidisciplinary approach to reduce impacts of invasive annual grasses and altered fire regimes on sagebrush ecosystems and sage-grouse (Chambers et al. 2014d). The approach uses information about factors that influence sagebrush ecosystem resilience to disturbance and invasive annual grasses (Brooks and Chambers 2011; Chambers et al. 2014b,c; Wisdom and Chambers 2009) and distribution, relative abundance, and persistence of sage-grouse populations (Aldridge et al. 2007, 2008; Doherty et al. 2010; Knick et al. 2013; Wisdom et al. 2011) to develop management strategies at landscape and site scales (fig. 16; Chambers et al. 2014d). A sage-grouse habitat matrix links relative resilience and resistance of sagebrush ecosystems with sage-grouse habitat requirements for landscape cover of sagebrush to help decisionmakers assess risks and determine appropriate management strategies at landscape scales. Focal areas for management are assessed by overlaying matrix components with sage-grouse Priority Areas for Conservation (PACs), breeding bird densities, and specific habitat threats. Decision tools are discussed for determining the suitability of focal areas for treatment and the most

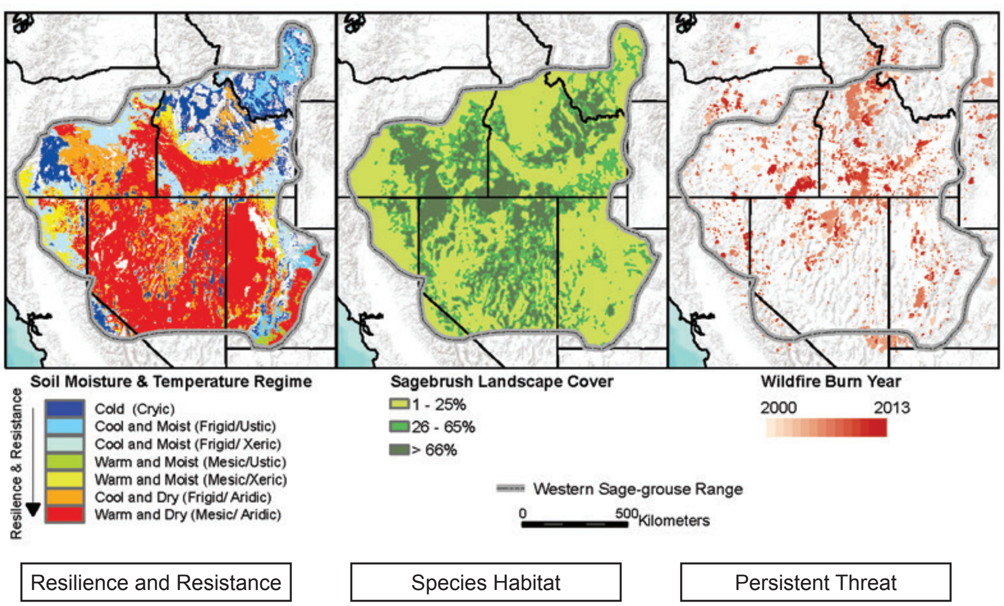

Figure 16—Landscape indicators of resilience and resistance, species habitat, and persistent habitat threats for sagebrush ecosystems and sage-grouse in the western portion of the species' range. Soil temperature and moisture regimes are used to indicate landscape resistance and resilience, and sagebrush landscape cover is used to indicate sage-grouse habitat abundance. Wildfire is a persistent threat. See Chambers et al. (2014d) for a detailed explanation.

appropriate management treatments. Management actions considered include fire operation (preparedness, prevention, and suppression), fuels management, postfire rehabilitation, and restoration/recovery.

Understanding the role of climate change is an important factor in prioritizing restoration opportunities (Richardson 2015; Still and Richardson 2015). Balzotti and colleagues (in review) have evaluated and modeled the implications of climate change on regional and sub-regional scales and the potential shifts in sagebrush and pinyon-juniper communities. They provide recommendations for identifying areas where conservation is most needed to retain connectivity of sage-grouse habitats.

These many and varied conceptual models developed and applied by FS scientists have been widely used in restoration planning for sage-grouse habitat at both landscape and site scales across the species range, and demonstrate a historical area of strength in FS research on sage-grouse and sagebrush ecosystems. This holistic approach has broad applicability for the conservation of threatened ecosystems and species across the western United States.

3.0—Research Needs

This section describes research needs associated with the four high-priority areas identified in the previous section. These research needs were identified based on stakeholder interests in relation to what areas of research Forest Service, Research and Development (FS R&D) scientists can begin to address given their current expertise, cooperators, and existing facilities and locations. Additional capacity such as increased numbers of scientists and resources (e.g., funds, technical support) is needed to address many of these needs.

1. Evaluate Links Between Sage-Grouse Population Ecology, Monitoring, and Habitat
    - Assess and monitor the contribution of NFS lands to sage-grouse population persistence, especially in the context of climate change
    - Evaluate the effects of livestock grazing on vital rates of sage-grouse populations
    - Determine the contributions of life-history stages (e.g., nesting versus brood-rearing) to sage-grouse population growth
    - Evaluate the impacts of disease and predation on sage-grouse survival, nesting success, habitat use, and population persistence
    - Find cost-effective surrogates to help monitor sage-grouse populations
    - Determine how establishment of core areas, as identified by Farm Bill (Conservation Reserve Program) policy and State efforts, and management of them over time, affects sage-grouse population growth rates and nesting success
    - Assess the impacts of restoration efforts (e.g., juniper and pinyon reduction or invasive species removal on sage-grouse growth rates and survival
    - Evaluate sage-grouse habitat use and population movement responses to different restoration treatments of burned or degraded sagebrush sites
    - Determine effects of transmission lines and other linear infrastructure, such as livestock fences, on habitat, dispersal (gene flow), and population dynamics of sage-grouse
    - Evaluate effects of agriculture and suburban developments, within and adjacent to current sage-grouse range, on population persistence
2. Understand Disturbances and Stressors in Sagebrush Ecosystems

- Identify factors that influence resistance of sagebrush ecosystems to medusahead grass (*Taeniatherum caput-medusae*), North African grass (*Ventenata dubia*), and other recent annual invaders
- Identify cover, species composition, and characteristics of perennial grasses and forbs required for sagebrush ecosystems to recover after disturbance and to resist invasive annual grasses
- Determine potential effects of a warming, drying climate on spread and contraction of invasive annual grasses, pinyon and juniper species, sagebrush species, sagebrush communities, and sage-grouse
- Assess effects of multiple fires on persistence and recovery of big sagebrush and its sage-grouse populations in the context of resilience and resistance
- Assess impacts of past fire on the size, severity, and spatial patterns of future wildland fire in sagebrush ecosystems
- Evaluate effects of livestock grazing on postfire sagebrush ecosystem recovery and rates of invasive annual grass and tree expansion
- Evaluate effects of livestock grazing on habitat occupancy, use, and movement by sage-grouse
- Assess effects of tree expansion on shrub species (e.g., bitterbrush, *Purshia tridentata*) known to co-dominate with sagebrush
- Assess effects of energy development (e.g., wind, oil, gas) and associated infrastructure (e.g., roads, pipelines) on sage-grouse habitats and populations and interpopulation movements
- Study effects of communication towers and associated roads on sage-grouse land use patterns
- Project the effects of climate change on vegetation composition and fuels characteristics and how these changes will affect future fire regimes of sagebrush habitats.

3. Analyze and Design Landscapes to Improve Habitat Connectivity

- Evaluate the use of foundational species and core landscape elements as habitat indicators for sage-grouse and sagebrush-obligate species
- Evaluate additional biophysical indicators of ecosystem resilience and resistance that can be used to prioritize management activities and select appropriate management actions
- Determine functional genetic variants that are identified to be under selection and assess how these vary in the different sage-grouse Distinct Population Segments (DPSs; i.e., smallest taxonomic unit protected under the ESA) and among different core areas
- Develop seed zones and seed transfer guidelines for grass, shrub, and forb species to facilitate restoration of spatial links between sagebrush communities and sage-grouse populations
- Evaluate and test restoration approaches and seeding and outplanting practices for improving habitat connectivity between sagebrush habitats and sage-grouse populations

- Understand the relative contributions of environmental, demographic, and genetic effects on the decline of sage-grouse at the periphery of their range where populations are declining
- Assess how fire management and other land management and restoration activities influence the movement of sage-grouse among core breeding areas
- Evaluate potential changes in sage-grouse habitat connectivity and fragmentation under a variety of climate change scenarios
- Conduct a spatial analysis of contributions by landowner to core sage-grouse habitats in order to better understand management limitations and opportunities
- Conduct large-scale analyses of overlaps in sage-grouse populations with those of other sagebrush-dependent wildlife to better understand GRSG's role as an umbrella species
- Evaluate the individual and cumulative effects of all human activities and land uses on resistance and resilience of sagebrush habitats at ecoregional scales.

4. Develop Methods, Models, and Plant Materials to Restore Sagebrush Habitats
    - Develop suitable plant materials, with attention to native grasses, shrubs, and forbs, for restoring sagebrush communities and sage-grouse habitats in sites affected by fires, invasive species, and other stressors and disturbances
    - Develop seed zones and seed transfer guidelines for grass, shrub, and forb species that are important components of sagebrush ecosystems
    - Identify the climate envelopes for sagebrush, pinyon-juniper, and annual invasive communities and model their current and potential future distributions
    - Intersect sage-grouse habitats with those areas that will potentially be most affected by climate change to identify the areas where conservation and restoration will have the greatest benefits
    - Develop protocols for incorporating climate change analyses into landscape assessments
    - Create high-resolution models of resilience to disturbance and resistance to invasive annual grasses that include climate, soils, and vegetation
    - Determine successful restoration approaches for recovering sage-grouse habitat and encouraging colonization by sage-grouse
    - Design and test restoration approaches and alternatives for warmer and drier sagebrush ecosystems with low resilience and resistance
    - Design and test restoration approaches and alternatives for pinyon and juniper communities that pose the greatest threats to sage-grouse habitats
    - Develop knowledge of the effects of livestock grazing (timing, amount, and duration) on restoration outcomes
    - Develop additional information on treatment effectiveness based on regional data and repeated monitoring over time
    - Develop information on treatment effectiveness based on new analytical approaches such as meta-data analyses
    - Understand climatic adaptation and develop seed transfer zones in big and dwarf sagebrushes and other key restoration species of their communities

- Develop knowledge about and determine appropriateness of establishing novel sagebrush habitat in areas where newly emerging climate envelopes may allow it to develop.

4.0—Science and Communication to Aid Management Decisions on National Forest System Lands

Forests and grasslands in the National Forest System (NFS) across the western United States support key habitats for sage-grouse, especially higher elevation brood-rearing habitats in mountain big sagebrush communities (fig. 17). The Forest Service (FS) and Bureau of Land Management have worked to evaluate sage-grouse and sagebrush conservation measures in their land use plans. Due to recently adopted conservation measures, the U.S. Fish and Wildlife Service determined in 2015 that neither the greater sage-grouse nor the bi-state Distinct Population Segment (DPS) warranted listing under the Endangered Species Act, but Gunnison sage-grouse does have protection as a threatened species. Therefore, it is important to understand the kinds of knowledge and tools that FS land managers need to address sage-grouse and sagebrush conservation. This information is necessary to assess the effectiveness of conservation measures for sage-grouse, as well as to ensure that adaptive management and monitoring provide accurate information for future management. It is equally important to identify the knowledge gaps to improve or establish conservation measures that are informed by the best available science. In addition to sage-grouse, numerous species depend on sagebrush communities and are of conservation concern (fig. 2) (Rich et al. 2005; Rowland et al. 2006). Healthy sagebrush plant communities that support wildlife

Figure 17—Female greater sage-grouse observed at a high-elevation mountain big sagebrush site (about 3050 m), Inyo National Forest, California (Photo by Chris Balzotti, Stanford University, used with permission).

such as the GRSG also support healthy pollinator communities, particularly because both GRSG and pollinators thrive on a high biodiversity of native forbs (see Dumroese et al., in press). GRSG populations require large landscapes and specific habitat conditions at broad scales to meet their seasonal life requirements. Rowland et al. (2006) and Hanser and Knick (2011) showed that GRSG serves as an umbrella species at landscape scales because of its widespread distribution and the broad range of sagebrush habitats it uses. Thus, a holistic management approach that addresses large-scale persistent threats to sage-grouse habitat may be expected to benefit sagebrush ecosystems and most sagebrush-obligate species (fig. 2). However, specific conservation actions for individual species or groups of species must recognize landscape-scale heterogeneity and differences.

4.1—Questionnaire to Determine Knowledge Needs and Gaps

In May 2013, a working group tasked with addressing FS issues on NFS-administered lands initiated an internal questionnaire related to sage-grouse and sagebrush management. The purpose was to identify and prioritize the kinds and scopes of science-based information and tools needed by FS land managers to address sage-grouse and sagebrush conservation. The questionnaire went to FS employees in the Washington Office, several regions (1, 2, 4, 5, and 6), three research stations (Pacific Northwest, Rocky Mountain, and Pacific Southwest), and all national forests that might potentially manage sage-grouse and their habitats. The working group targeted an array of resource management disciplines and employees working at all levels within the organization.

The questionnaire asked participants to respond to 37 questions in the following categories: (1) ecosystem dynamics of sagebrush communities on NFS lands, (2) contribution of sagebrush communities on NFS lands in supporting broader species/system conservation, (3) sage-grouse populations, (4) habitat management and restoration, and (5) conservation guidance for sage-grouse. Questionnaire results will inform those involved in developing an environmental impact statement (EIS), help in decisionmaking regarding compliance with the National Forest Management Act (NFMA), and support sage-grouse and sagebrush management. See Appendix for more details about the questionnaire.

4.2—Results of Sage-Grouse/Sagebrush Questionnaire

Respondents agreed that understanding sagebrush community dynamics and ecological relationships, especially for high-elevation mountain big sagebrush, was important, but disagreed about how much is known about effects of management on sagebrush restoration and whether sagebrush will be able to reestablish naturally as climate changes. They agreed that more attention should be given to managing sagebrush plant and animal communities on NFS lands and that knowledge was needed on effects of disturbance processes on sagebrush landscape patterns. Respondents indicated that more knowledge was needed about the contributions of NFS lands and habitats to sage-grouse population health and persistence. Respondents strongly agreed that research and monitoring were needed to assess the effects of disturbances, including those from land management, and the effectiveness of habitat restoration on sage-grouse and sagebrush ecosystems. Syntheses of research findings that provided guidance to managers were viewed positively. Opinions differed about the sufficiency of information to address threats and risks to sage-grouse habitats and whether GRSG is an appropriate surrogate for monitoring other species.

4.3—Identifying New Areas of Forest Service Research and Science Delivery to Meet Management Needs

Results of the questionnaire demonstrate that many new avenues of research can be initiated to meet the needs identified by NFS managers. Several of these needs corroborate those identified in section 3.0, “Research Needs.” Additional needs and gaps in information identified by questionnaire respondents can be addressed by FS R&D and partners through collaborative projects with NFS employees, and via consultations, syntheses, tool development, assessments, and science delivery and communication mechanisms.

4.4—Role of Syntheses, Decision Support Tools, Assessments, and Databases

FS R&D scientists are well-known for developing syntheses of existing literature in order to support management needs, and many examples are listed in the references section of this assessment. These often take the form of FS General Technical Reports and other agency serial publications, but they can also be published by journals and in monograph series of professional societies. Syntheses are usually collaborative efforts involving numerous scientists and experts within the FS as well as from other institutions, such as universities, other State and Federal natural resources agencies, and non-governmental organizations (e.g., Miller et al. 2013). A synthesis on a topic such as sage-grouse habitat restoration or landscape ecology is often requested by, or aimed at, land managers.

The Fire Effects Information System (FEIS; http://www.feis-crs.org/beta/) is an online collection of reviews of scientific literature on fire ecology and fire regimes. FEIS provides scientific information for resource management, restoration, rehabilitation, and fire management through three products: Species Reviews, Fire Studies, and Fire Regime Syntheses. Species Reviews are syntheses of literature that describe relationships of plants and animals with fire. Fire Studies provide detailed results from research and management projects on vegetation, fire characteristics, and fire effects. Fire Regime Syntheses describe historical and contemporary changes in fire regimes in particular ecosystems. Species Reviews are currently available for GRSG, Gunnison sage-grouse, sagebrush taxa, cheatgrass, and many other species important to sagebrush habitat (e.g., McWilliams 2002). FEIS is continually being updated to include new information and to respond to requests from land managers (see *4.5*, *Enhance Science Delivery and Communication—What More Can be Done*).

Decision support tools and assessments can take various forms to help meet needs for management of sage-grouse habitats and landscapes. Tools can include field guides and publications that identify models, methods, geographic information systems (GIS) maps, and approaches to address questions about sage-grouse biology, disturbances, landscapes, and restoration (e.g., Miller et al. 2014a, 2015; Tausch et al. 2009). Tools can also be instruments, devices, models, methods, maps, databases, and approaches that are available directly to practitioners who access them online, by video, or through consultations, lectures, presentations, and training sessions. Tools are typically developed to meet a management or science application need and are designed so that new techniques do not have to be developed for routine management projects. Routine tools are also often used to test hypotheses where the question is not about the tool type but rather about how new findings can be revealed by using the tool. Typical tools are those that solve problems, provide outcomes, generate maps, enable consistency in inventory and monitoring, count populations, and model future projected changes in land cover, climate, and disturbances, such as likelihood of fire or invasions of non-native species. The results of assessments are often considered to be tools.

An assessment is an evaluation or estimation of the nature, quality, quantity, or response of organisms, habitats, landscapes, communities, stressors, and disturbances at any given time or place or during a period of time or across space. Assessments associated with sage-grouse may focus on populations in an area as small as a forest stand or as large as its entire range, the amount of occupied habitat, the availability of habitat with potential for occupancy, or the effects of changes on habitat or sage-grouse populations from stressors such as fire, invasive species, grazing, or climate change.

4.5—Enhance science Delivery and Communication—What More Can be Done

Modern communication tools have enhanced the delivery of science enormously during the last 20 years. In addition to traditional methods for delivering science findings, such as meeting presentations, posters, and lectures, more managers and scientists are using vehicles such as webinars, videoconferences, websites, social media, and interactive online databases to share information. For example, FEIS enables more than a half million people (the public and land managers) each year to search for Species Reviews, Fire Studies, and Fire Regime Syntheses (see *4.4—Role of Syntheses, Decision Support Tools, Assessments, and Databases*) by species' name, geographic location, Federal agency, plant community, life form, invasiveness, and nativity. Online newsletters have replaced many printed versions, journal publications often appear "online early" before they are printed with page numbers, and many journals are "online only." FS partners with numerous State and Federal agencies, universities, and non-governmental organizations to design collaborative research and management projects and publish and deliver science findings about sagebrush and sage-grouse at regional, national, and international levels. FS was instrumental in establishing the Great Basin Research and Management Partnership, a group of 20 organizations that focus on developing science and technology transfer products applicable for managers. FS scientists and managers participate in and contribute to many other key partnerships that generate publications, syntheses, workshops and conferences, webinars, websites, and online newsletters such as:

- SageSTEP, The Sagebrush Treatment Evaluation Project
- Great Basin Consortium
- Great Basin Fire Science Exchange
- Range-wide Interagency Sage-Grouse Conservation Team, led by the Western Association of Fish and Wildlife Agencies
- Landscape Conservation Cooperatives managed by agencies in the Department of the Interior
- U.S. Geological Survey Climate Science Centers
- Climate Hubs managed by USDA agencies
- SO 3336 task and action groups responding to the SO3336 final report, *An Integrated Rangeland Fire Management Strategy*
- Many other partnerships throughout the western United States.

FS scientist Jeanne Chambers began the "Great Basin Fact Sheet" series about fire, invasive species, restoration, and other issues in the Great Basin. This series provides managers with brief, accessible summaries of current science concepts related to conservation and restoration of sagebrush, as well as associated management strategies. Several FS scientists have contributed to the series. Many fact sheets have been produced and are posted on websites and newsletters managed by several interagency partnerships, including the Great Basin Landscape Conservation Cooperative's site http://www.greatbasinlcc.org/update/new-great-basin-fact-sheet-series, the Great Basin Fire Sciences Exchange site (http://www.gbfiresci.org/), and the Sage Grouse Initiative's site http://www.sagegrouseinitiative.com/category/great-basin-factsheet-series/.

Treesearch (http://www.treesearch.fs.fed.us/) is an online database system hosted by FS R&D that shares free, full-text publications written or cowritten by FS scientists and published by the FS or in other outlets, such as journals, conference proceedings, or books. The Treesearch website has been delivering publications since January 2004; more than 40,000 publications are included with thousands added annually. Treesearch is searchable by using keywords, author name, title, and year. A mid-October 2015 search using the single keyword "sagebrush" revealed 258 full-text publications in the database.

Conferences, workshops, special sessions at professional society meetings, and training sessions are excellent interactive modes for communicating new science findings, establishing researcher and manager connections, discovering new techniques, and gaining new knowledge. Libraries now make articles available online and articles are accessed easily with online search tools. Online chat sessions are available on many subjects, and literature resource services can be easily found on the Web.

A productive way for managers to engage scientists is when they are in the early stages of planning management projects, such as a habitat restoration project or during forest plan revisions. Another approach to ensure communication and use of science results is for scientists to involve managers during the proposal and implementation phases of science studies and assessments through collaboration on shared goals and activities.

5.0—Facilities, Centers, and Projects Having Key Locations, Contacts, and Expertise

The Forest Service, Research and Development (FS R&D) has several facilities located in sagebrush ecosystems near sage-grouse populations. These are staffed by scientists and other professionals with the experience and expertise to conduct continuing and new research and science delivery for the benefit of sagebrush and sage-grouse conservation. Scientific capacity and resources are expected to decline in the next few years as well-known scientists in key facilities retire and budget trends continue. Some relevant facilities may close owing to declining availability of resources. Workforce planning efforts, capacity-building, and additional funding targeted at key locations will be needed to renew capacity and resources.

Facilities with past or current studies and expertise on sagebrush and sage-grouse and contacts are:

- Grassland, Shrubland and Desert Ecosystems Science Program, RMRS, Albuquerque, New Mexico; Boise, Idaho; Bozeman, Montana; Moscow, Idaho; Provo, Utah; Rapid City, South Dakota; Reno, Nevada. Dr. Deborah Finch.

- Great Basin Ecology Laboratory, RMRS, Reno, Nevada. Dr. Jeanne Chambers.
- Great Basin Native Plant Project, RMRS, Boise, Idaho. Dr. Francis Kilkenny and Dr. Nancy Shaw, Emeritus.
- LaGrande Forestry and Range Sciences Laboratory, PNW, LaGrande, Oregon. Mary Rowland and Dr. Michael Wisdom.
- Missoula Fire Sciences Laboratory, RMRS, Missoula, Montana. Dr. Colin Hardy.
- National Genomics Center for Wildlife and Fish Conservation, RMRS. Missoula, Montana. Dr. Michael Schwartz.
- National Center for Reforestation, Nurseries, and Genetics Resources (RNGR). Moscow, Idaho. Dr. Kasten Dumroese and Dr. Jeremiah Pinto.
- Rapid City Forest and Grassland Research Laboratory, Rapid City, South Dakota. Dr. Jack Butler and Dr. Mark Rumble, Emeritus.
- RMRS Center for Landscape Science, Flagstaff, Arizona. Dr. Samuel Cushman.
- Shrub Sciences Laboratory, RMRS, Provo, Utah. Dr. Stanley Kitchen, Dr. Susan Meyer, Dr. Bryce Richardson, and Dr. Steven Warren.
- Western Wildland Environmental Threats Assessment Center, PNW, Prineville, Oregon. Dr. Nancy Grulke.
- Wildlife and Terrestrial Ecosystems Program, RMRS, Flagstaff, Arizona; Fort Collins, Colorado; Missoula, Montana. Dr. William Block.

6.0—Summary

Forest Service scientists are contributing to the restoration of sagebrush ecosystems and conservation of sage-grouse by providing science-based information and specific recommendations for future conservation and management efforts. Immediate research efforts are needed to establish a scientific foundation for effective management responses that minimize threats from fire and invasive species, for restoring functioning sagebrush ecosystems in the western portion of the range, for preparing for consequences of climate change, and for minimizing threats from energy development in the eastern portion of the range. For decades FS Research and Development (R&D) has been studying sagebrush ecosystem dynamics, investigating mechanisms to manage for resilient and resistant sagebrush ecosystems, and publishing syntheses on the plants and animals that compose sagebrush communities. With this extensive experience, FS R&D is prepared to play a relevant role in sagebrush and sage-grouse conservation. When this work is combined with FS research on sage-grouse genetics, biology, and ecology, along with that of other agencies and organizations, FS expertise will be valuable to efforts for making progress on sage-grouse habitat management. The Forest Service will continue to collaborate with others, with the goal of serving the needs of managers striving to retain or regain sustainable sagebrush ecosystems and sage-grouse or return them to sustainable conditions.

Here we reported on the unique strengths and areas of FS R&D science leadership for conserving sage-grouse and restoring sagebrush ecosystems, and we evaluated stakeholder interests to identify emphasis areas and priorities for future focus. To meet widespread concerns and increased calls for science-based conservation to prevent further declines of sage-grouse populations and loss of sagebrush ecosystems, we recommend that research capacity and science delivery be continued and expanded. Because of the importance of the National Forest System for sage-grouse breeding and brood-rearing habitats and the FS R&D research capacity, strategic locations of facilities, and germane research already completed, we believe the Forest Service can make important contributions for sage-grouse management on FS and other landscapes throughout the western United States.

7.0—Acknowledgments

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Appendix: Results of Sage-grouse/Sagebrush Questionnaire

Respondents

- 126 Forest Service (FS) employees completed the questionnaire
- Most respondents were from middle management (GS9–GS13)
- Senior managers (GS14–GS15) accounted for 12 percent of respondents
- Respondents represented a wide array of research and management disciplines
- Among disciplines, wildlife biologists were the dominant responders (40 percent)
- About 75 percent of the respondents were from the National Forest System; 25 percent were from FS Research & Development
- Nearly 30 percent of respondents work at the District level, versus 21 percent at the Supervisor's Office level

Selected Key Findings by Subject Area

1. Ecosystem dynamics of sagebrush communities on National Forest System (NFS) lands
    - Strong agreement among respondents about the importance of understanding system dynamics of sagebrush communities, including effects of climate change, conifer encroachment, invasive species, and wildfire
    - Emphasis on the importance of better understanding of ecological relationships in high-elevation mountain big sagebrush communities
    - Disagreement about how much is known about effects of management, including livestock grazing and fire, on sagebrush maintenance and restoration
    - Strong disagreement among respondents that sagebrush will reestablish naturally under changing climate regimes
2. Contribution of sagebrush communities on NFS lands in supporting broader species/system conservation
    - Strong agreement that more attention should be given to managing sagebrush plant and animal communities and identifying species found disproportionately on NFS lands
    - Strong agreement on the importance of understanding the effects of disturbance processes on sagebrush on NFS lands
3. Sage-grouse populations
    - Agreement on the need for knowledge about seasonal habitats of sage-grouse on NFS lands, effects of habitat management and restoration on sage-grouse, habitat connectivity for sage-grouse, and effects of energy development
    - Strong agreement about the need to better understand the contribution of sage-grouse that use NFS lands to larger populations of this species, contributions of seasonal habitats to overall species persistence, and landscape and community characteristics where sage-grouse populations are robust

- Disagreement among respondents about whether sage-grouse are an appropriate indicator of sagebrush community condition, but general agreement that sage-grouse could be useful in assessments of other terrestrial species dependent on sagebrush habitats
- Disagreement that seasonal habitats for sage-grouse are used disproportionately on NFS lands compared to those on other land ownerships
- Strong disagreement among respondents that sage-grouse will adapt to rapid climate change

4. Habitat management and restoration
    - Strong agreement that new research is needed about effects of management on sagebrush systems, such as vegetation composition and structure, on NFS lands
    - Strong agreement that monitoring is important to ascertain effectiveness of management, and that disturbances should be monitored to understand recovery timeframes
    - Agreement on the need to synthesize research findings to provide management guidance
    - Strong agreement on the need for more information on restoration of sagebrush communities, especially at the periphery of current sage-grouse range, and in systems invaded by non-native species
    - Disagreement about our current understanding of effects of livestock grazing on sage-grouse habitats
5. Conservation guidance for sage-grouse
    - General (though not unanimous) agreement that the FS lacks sufficient conservation guidance for sage-grouse and sagebrush systems in current forest plans, and agreement that a synthesis of the literature would be useful in providing that guidance
    - A variety of opinions on the sufficiency of information to address threats and risks to sage-grouse habitats and whether sage-grouse are an appropriate surrogate for monitoring other species

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