Chapter 6: Sagebrush Steppe Case Study

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Background

Sagebrush Steppe Ecosystems

Widespread yet vulnerable, sagebrush (*Artemisia* spp.) steppe ecosystems provide a variety of biological, hydrological, and recreational ecosystem services throughout the Interior West (Homer et al. 2015). One particular service is the provision of essential habitat for the greater sage-grouse (*Centrocercus urophasianus*), which was considered for listing under the Endangered Species Act. That listing was avoided in 2015 by an unprecedented conservation partnership across organizations and state boundaries (Chambers et al. 2017). The once widespread sagebrush steppe ecosystem has been significantly reduced in total area (down to 59 percent of historical extent) and is threatened throughout its range by nonnative invasive plant species (especially cheatgrass [*Bromus tectorum* L.]), altered fire regimes, conifer expansion (i.e., conversion of sagebrush steppe to woodlands or forests), and climate change (Chambers et al. 2014a, 2017). Additional threats to sagebrush include energy development, roads, mining, housing development, recreational activities (e.g., off-highway vehicle use), wild horse (*Equus ferus caballus*) use, and poorly managed livestock grazing (Chambers et al. 2017). These stressors and their interactions have reduced the capacity of sagebrush ecosystems to recover from natural disturbances such as wildfires. The natural fire regime in sagebrush steppe ecosystems is characterized as mixed severity, with low plant survivorship in burned areas interspersed with unburned patches (Baker 2006, Connelly et al. 2000).

Fires in sagebrush steppe ecosystems are spatially complex and strongly influenced by topography and soils, resulting in a wide range of return intervals (Miller and Heyerdahl 2008). Fires promote reproduction and seral-stage diversity among sagebrush species, and inhibit conifer encroachment. However, fires must recur at sufficiently long intervals to allow obligate seeding sagebrush species to mature to reproductive size, because the common sagebrush in our project area (mountain big sagebrush [*A. tridentata* ssp. *vaseyana* Nutt. ssp. vaseyana (Rydb.) Beetle]) does not resprout and often requires 30 to 100 years to recover from fire. Fire return

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intervals in these ecosystems prior to Euro-American colonization may have been between 30 and 80 years (Slaton and Stone 2013).

The most serious threat to the sagebrush steppe throughout its range is the invasion of cheatgrass.

The most serious threat to the sagebrush steppe throughout its range is the invasion of cheatgrass. Owing to its early-season growth, cheatgrass can displace native grasses, forbs, and shrubs by reducing moisture and nutrients in surface soils (Norton et al. 2004). Overgrazing contributes to cheatgrass invasion by reducing the abundance of native perennial grasses, disturbing intact soils and complex biological soil crusts, and dispersing cheatgrass seed. Once established, cheatgrass also dramatically alters fire regimes in sagebrush steppe. This annual grass grows rapidly, particularly following wet years, creating a nonhistorical continuous cover of dry fuels that ignite and spread fire easily (Brooks et al. 2004, Knapp 1998). Fire return intervals in cheatgrass-invaded sagebrush steppe can be as frequent as every 3 to 5 years (Whisenant 1990), effectively eliminating sagebrush and other native species adapted to longer fire return intervals that are characteristic of natural sagebrush steppe ecosystems. After a few cheatgrass-exacerbated fire cycles, the native plant seed bank becomes depleted, greatly reducing reestablishment. The invasion of cheatgrass has contributed to the conversion of millions of hectares of sagebrush steppe to low-diversity, annual grasslands that provide low-quality habitat for native plants, wildlife, and grazing livestock (Balch et al. 2013, Knapp 1996).

Sagebrush recovery after fire is influenced by a variety of factors, including distance to unburned shrubs (to provide a seed source), abundance and viability of seed within the soil seed bank (which may persist up to 3 years), pre- and postfire weather, and postfire disturbances such as grazing (Ziegenhagen and Miller 2009, Newingham and Strand 2018). Other important factors include prefire vegetation composition and structure, fire severity, post-wildfire precipitation, and local soil and hydrology characteristics (Arkle et al. 2014; Chambers et al. 2014a, 2017,; Miller et al. 2015b). Native bunchgrasses are a key determinant in postfire recovery (Chambers et al. 2017), but the arid, coarse volcanic soils of the Crowley Basin typically support limited bunchgrass cover.

Owens River Fire

The Owens River Fire was ignited on September 17, 2016, burning 5,482 ac (2218 ha) on the Mammoth and Mono Lake Ranger Districts of the Inyo National Forest. Approximately two-thirds of the fire burned in sagebrush-dominated vegetation, while the remaining third burned Jeffrey pine (*Pinus jeffreyi* Balf.) forest and other vegetation types (fig. 6.1). The fire burned primarily on national forest lands but included 912 ac (369 ha) of lands under private ownership. The Owens River Fire is bordered by the 1993 Bald Mountain Fire and 2001 McLaughlin Fire to the north

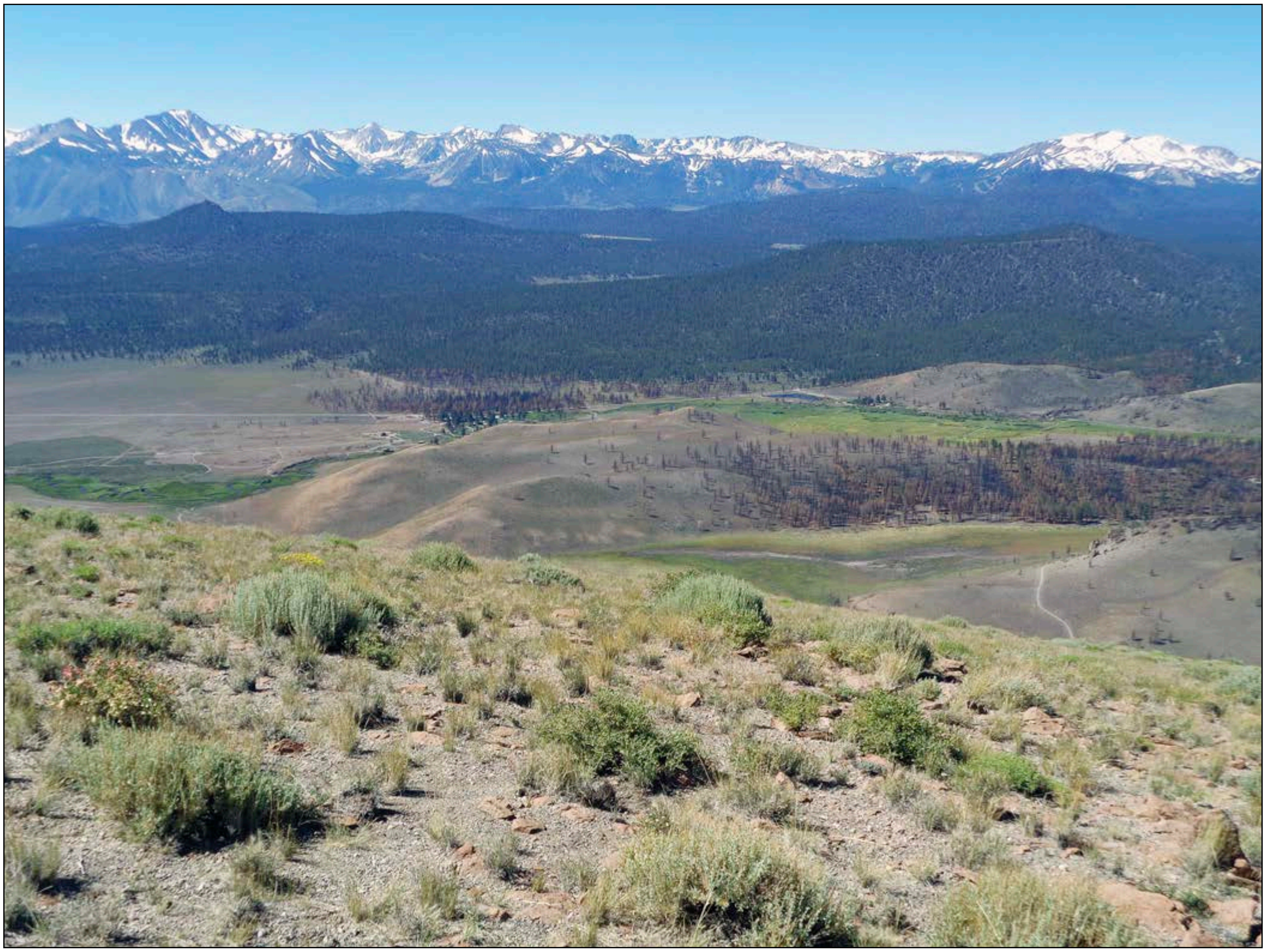

Marc Meyer

Figure 6.1—Postfire conditions in sagebrush steppe and Jeffrey pine forest after the 2016 Owens River Fire (center background). The foreground displays recovering sagebrush steppe outside the 2016 Owens River Fire perimeter that was burned in a 1993 wildfire, about 24 years prior.

and east, respectively. Both of these earlier fires had been followed by cheatgrass invasion, especially on warm south-facing slopes, creating a substantial seed bank for this invasive annual grass adjacent to the Owens River Fire (based on prefire field observations). There were limited historical fires within the Owens River Fire perimeter, largely due to combined effects of fire suppression, livestock grazing, and earlier shrub reduction efforts in the vicinity (e.g., aerial herbicide application and mechanical removal). The prefire plant community was primarily dominated by relatively tall and dense sagebrush with elevated fuel loads (attributed to dense and old shrubs), especially on the bottom of Long Valley. Mountain big sagebrush is the dominant sagebrush species in the analysis area occurring in varying proportions with bitterbrush (*Purshia tridentata* (Pursh) DC. ssp. *tridentata*), yellow rabbitbrush

(*Chrysothamnus viscidiflorus* (Hook.) Nutt.), rubber rabbitbrush (*Ericameria nauseosa* (Pall. ex Pursh) G.L.Nesom & G.I.Baird)), horsebrush (*Tetradymia canescens* DC.), snowberry (*Symphoricarpos rotundifolius* A. Gray), and native perennial and annual forbs and grasses. Limited conifer encroachment of Jeffrey pine had occurred into the shrublands over the past few decades, especially in the western section of the Owens River Fire.

Postfire Restoration Framework

Step 1: Identifying Priority Resources, Desired Conditions, and Restoration Goals

We considered several resources in the Owens River Fire analysis area but focused primarily on sage-grouse habitat and sagebrush vegetation in our assessment (table 6.1). These primary resources were derived from the 2012 Bi-State Action Plan (Bi-State Technical Advisory Committee Nevada and California 2013), the land management plan for the Inyo National Forest, and specialist input. Sage-grouse habitat was considered a primary resource because this species was considered for federal listing under the Endangered Species Act and is currently a U.S. Forest Service species of conservation concern, and is a species of conservation concern under the new draft land management plan for the Inyo National Forest (USDA-FS 2019). The Inyo National Forest manages approximately 20 percent (213,670 ac [86 469 ha]) of priority sage-grouse habitat identified in the Bi-State Action Plan for Conservation of the Greater Sage-Grouse in eastern California and western Nevada (Bi-State Technical Advisory Committee Nevada and California 2013). The BAER team found that approximately 3,550 ac (1437 ha) of suitable sage-grouse habitat were consumed in the fire..

Our primary restoration goals for the assessment area focused on sustaining and restoring sagebrush steppe ecosystems and sage-grouse habitat.

We reviewed desired conditions for sagebrush steppe based on information provided in the bi-state action plan and land and resource management planning documents relevant to our assessment area (USDA FS 2013a, 2013b). Desired conditions, based upon scientific understanding of historical references, include the following:

- Sagebrush occurs mixed within complex and diverse assemblages of other shrubs, perennial grasses, and forbs.
- At the landscape scale, sagebrush is represented by a range of age classes, including mature shrubs and seedlings.
- Invasive annual grasses (e.g., cheatgrass) are absent or rare, and the introduction and spread of invasive species are minimized.
- Within sagebrush steppe, encroachment by conifer trees such as pinyon pine (*Pinus monophylla* Torr. & Frém.), Utah juniper (*Juniperus utahensis* (Torr.) Little), or Jeffrey pine, is generally rare.

Table 6.1—Primary resources and stressors considered in a postfire assessment of the Owens River Fire (2016)

Resources	Spatial data	Explanation
Sage-grouse habitat[a]	Sage-grouse critical habitat (U.S. Fish and Wildlife Service) and suitable habitat	Maintenance and restoration of sage-grouse habitat is a high-priority goal.
Sagebrush vegetation[a]	EVeg or TEUI (see app. 2)	Sagebrush vegetation is critical to support suitable sage-grouse habitat and regional biodiversity.
Soils	Soil survey data, soil burn severity (see app. 2)	Soil productivity is important to maintain; soil type may influence restoration success.
Watersheds	Subwatershed boundaries	Subwatershed boundaries inform where cumulative impacts of wildfire may result in undesirable negative impacts to watershed resources.
Forest vegetation	EVeg or TEUI (see app. 2)	Forest vegetation (e.g., Jeffrey pine) provides numerous ecosystem services including carbon sequestration and wildlife habitat.
Riparian vegetation	EVeg or TEUI (see app. 2)	Aspen stands and other riparian vegetation are important for biodiversity and wildlife habitat.
At-risk plants	Natural Resource Information System	Nearby occurrences of three at-risk plant species (Mono Lake lupine [*Lupinus duranii* Eastw.], Mono milkvetch Barneby [*Astragalus monoensis* Barneby]. Long Valley milk-vetch [*Astragalus johannis-howellii* Barneby]).
Wildlife and fish habitat (excluding sage-grouse)	Migratory bird habitat, mule deer habitat, freshwater fish habitat	Migratory Bird Treaty Act, recreational hunting, and fishing are important for the local economy.
Rangelands	Grazing allotment	Arid rangelands provide forage for livestock.
Stressors or constraints:		
Fire	Vegetation burn severity (RAVG), FRID, Fire management zones	Fire severity affects short-term vulnerability of vegetation; Fire return interval departure influences sagebrush resilience; Fire management zones show potential strategic treatment areas to contain fire spread
Topographically mediated moisture stress[b]	Landscape management units	Topographic position and steepness can inform relative degree of vegetation moisture stress and restoration treatment access
Invasive plants	Cheatgrass distribution data (spatial interpolation) on the INF; FACTS database	Cheatgrass invasion could facilitate undesirable type conversion of native shrublands to nonnative annual grassland
Conifer encroachment	EVeg or TEUI, especially at the intersection of sagebrush and Jeffrey pine vegetation	Jeffrey pine or pinyon pine encroachment into sagebrush may result in sage-grouse habitat loss or reduced ecosystem resilience to stressors
Grazing	Grazing allotments, wild horse territories	Potential livestock and wild horse grazing impacts to postfire vegetation recovery
Climate change	Climatic Water Deficit (CWD) – either current or projected for early 21st century Climate-smart restoration tool (https://climaterestorationtool.org/csrt)	CWD and climate exposure estimates long-term vulnerability of vegetation; restoration tool provides climate-informed seed zone recommendations for sagebrush and other species
Off-highway vehicles (OHV)	Roads and trails	Areas within 50 ft (15 m) of OHV roads and trails generally receive greater impacts and may affect restoration actions

Many spatial data sources (e.g., sagebrush vegetation, soil and vegetation burn severity, invasive plants) would benefit from field validation using site-specific field data and observations.

[a] Primary resources that are the focus of this case study.

[b] Topographically mediated moisture stress may provide an indication of current and future climate exposure in the absence of more reliable and precise climate exposure spatial data.

- Sagebrush ecosystems provide suitable habitat and connectivity for wildlife species such as greater sage-grouse.
- Biological soil crusts frequently occur within the interstitial spaces among shrubs and perennial grasses.

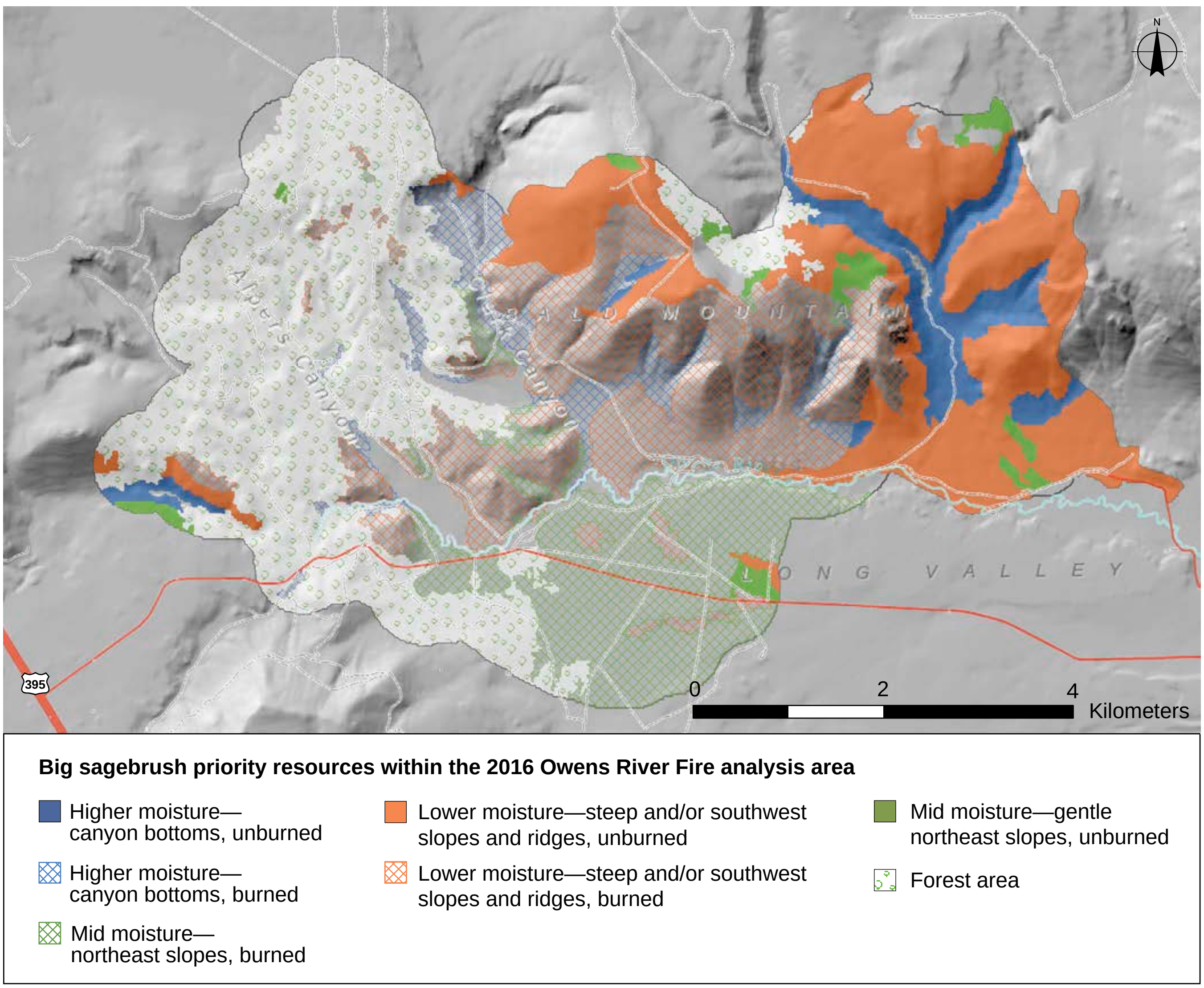
Our primary restoration goals for the assessment area focused on sustaining and restoring sagebrush steppe ecosystems and sage-grouse habitat, based on land management and resource planning sources (table 6.2). The Owens River fire affected several additional resources of concern, including mule deer (*Odocoileus hemionus*) habitat, at-risk plant habitat, active grazing allotments, timber stands, and riparian areas linked to recreational fisheries.

Table 6.2—Postfire flowchart outputs that serve as the foundation of a restoration portfolio

	Output		
Primary restoration goals	• Promote or maintain sagebrush ecosystem integrity and resilience • Maintain and enhance sage-grouse habitat quality and connectivity		
Most relevant guiding principles from the restoration framework	• Restore key ecological processes • Consider landscape context • Support native biodiversity and habitat connectivity • Sustain diverse ecosystem services • Incorporate climate change adaptation		
Analysis area	• Owens River Fire and adjacent recent fire perimeters, including a 500 m (1640 ft) buffer from the Owens River Fire perimeter		
Restoration opportunities	Maintain or promote desired conditions	Take management actions to restore desired conditions	Reevaluate desired conditions considering interacting stressors
Potential restoration actions	• Create fuel breaks where appropriate (Miller et al. 2014b) • Prevent invasion of nonnative plants where feasible • Suppress fires in burned areas for >35 years • Monitor ecological status and trend of passive restoration efforts • Maintain soil biotic crusts where feasible	• Reseed and replant native plants • Remove encroaching conifers • Defer livestock grazing • Install extra signage and barriers to discourage off-highway vehicle use outside of designated roads and routes • Eradicate and contain nonnative plants where feasible • Monitor effectiveness of management actions	• Monitor ecological status and trend • Contain nonnative plants where feasible • Consider adjusting desired conditions to align with current, novel conditions
Additional actions for secondary resources	• At-risk plant species: flag, avoid, and monitor at-risk plant populations • Forest vegetation: consider reforestation using climate-smart approaches • Mule deer habitat: promote forage and hiding cover in suitable habitat		

Step 2: Gather and Review Relevant Spatial Data

Our analysis area included the Owens River Fire, with a 500 -m (0.31-mi) buffer around its perimeter, and the perimeters of the adjacent Bald Mountain and McLaughlin Fires (fig. 6.2). This analysis area captures the influence of previously burned and unburned areas directly surrounding the Owens River Fire, especially because these areas may serve as sources of nonnative plant propagules. The 500-m buffer represented a distance that would capture most neighboring nonnative invasive plant occurrences with the potential to disperse inside the fire perimeter (wind- or animal-facilitated seed dispersal), based on published estimates of dispersal distance in sagebrush ecosystems (Monty et al. 2013, Nielson et al. 2011).



Amarina Wuenschel

Figure 6.2—Spatial assessment identifying mesic sites prioritized for sagebrush restoration in the Owens River Fire on the Inyo National Forest.

We evaluated prefire ecological condition using (1) prefire vegetation type (using pre-Euro-American settlement fire regime classes) and (2) landscape position as an indicator of topographically mediated moisture gradients (based on landscape management units [LMUs]) (app. 1). These topographically mediated moisture gradients are related to sagebrush ecosystem resilience and risk of cheatgrass invasion, with higher resilience and lower invasibility associated with cooler and moister sites on the landscape (Chambers et al. 2014a, Condon et al. 2011). We also reviewed but did not include additional prefire data sources in our initial analysis, including sage-grouse habitat data (suitable habitat, habitat connectivity) and soil survey data that provided moisture gradient information at finer spatial scales (table 6.1).

Next, we evaluated postfire ecological condition using spatially explicit datasets most relevant to sagebrush ecosystems. To do this, we initially examined a combination of vegetation burn severity and fire return interval departure (FRID) data. Although vegetation burn severity and FRID data can be informative for evaluating the general condition of terrestrial ecosystems, these spatial data may have methodological issues when applied to sagebrush ecosystems (i.e., vegetation burn severity) or have received little attention in the published literature focused on sagebrush steppe (i.e., FRID). Consequently, their utility in assessing the ecological condition of sagebrush ecosystems is uncertain. We used Rapid Assessment Of Vegetation Condition after Wildfire (RAVG) data to evaluate vegetation burn severity. Vegetation burn severity is an indicator of aboveground biomass consumption (Keeley 2009) that may be correlated with shrub and perennial grass mortality in arid, shrub-dominated ecosystems (Miller et al. 2013). Vegetation burn severity also may inform ecosystem resilience to disturbance and resistance to invasive plants in sagebrush and other Great Basin ecosystems (Miller et al. 2013, 2015a), with high-severity burned patches often considered a priority for restoration (Chambers et al. 2014b). In sagebrush vegetation, the use of delta Normalized Burn Ratio (dNBR) or relativized delta Normalized Burn Ratio (RdNBR) values may provide more resolved information on vegetation change than the broadly defined fire severity classes (i.e., unchanged, low, moderate, high). Regional Forest Service data based on the RdNBR developed by Miller and Thode (2007) were not available during our initial analysis, and rapid assessment data are more sensitive to postfire resprouting (including species such as rabbitbrush and bitterbrush). However, we found that vegetation burn severity was less informative for the Owens River Fire area because more than 85 percent of sagebrush vegetation burned at high severity), a pattern observed in published studies of burned sagebrush ecosystems (Miller and Thode 2007, Slaton and Stone 2013). Although we found soil burn severity to be slightly more informative than vegetation burn severity in assessing fire effects to sagebrush ecosystems in the Owens River

Fire, we assumed the stratification of topographic position and slope was sufficient for assessing the risk for postfire runoff and erosion in the analysis area. We examined FRID data, but only about 5 percent of the Owens River Fire burned in previously recorded wildfires, suggesting limited impacts of a surplus fire frequency (i.e., too-frequent fire that may favor cheatgrass invasion) in the analysis area. Because neither fire severity nor FRID data were particularly discriminating in our analysis, we predominantly used prefire data (i.e., prefire vegetation type, landscape position) for our final spatial assessment of the Owens River Fire.

We considered sagebrush vegetation situated in more sheltered topographic positions as indicative of relatively lower moisture stress, including valley bottoms and gentle slopes (<30 percent) on northeastern facing aspects (mesic sites). Ridgetops, steeper slopes (>30 percent), and southwestern facing aspects were indicative of areas of higher moisture stress (xeric sites) that ranked as lowest priority in our assessment. We chose to prioritize areas with a higher probability of success to improve restoration achievement in high-value areas, based on several factors such as overall landscape condition (fair), resource availability (low), and specialist input.

Twelve patches totaling 533 ac (216 ha, or 10 percent of the area burned) of sagebrush were located in lower topographic positions with high moisture availability (fig. 6.2). Of this area, 473 ac (191 ha) were also located within suitable sage-grouse habitat, and 41 ac (17 ha) were previously burned in the 1993 Bald Mountain Fire or 2001 McLaughlin Fire. Sage-grouse habitat burned in the Owens River Fire did not include any significant habitat corridors or patches of sagebrush connectivity in the region (Bi-State Technical Advisory Committee Nevada and California 2013).

Step 3. Use the Postfire Flowchart to Identify Restoration Opportunities

Question A: Where did fire improve or maintain ecological conditions and are fire effects within desired conditions or NRV?—

We first examined whether the Owens River Fire burned within the natural range of variation (NRV) for fire severity and frequency. The comparison of fire severity patterns with historical reference conditions suggests that the analysis area is burning at the higher end of the range of severity historically experienced by these ecosystems (i.e., primarily mixed vegetation burn severity); although lack of reference data for historical high-severity patch sizes (e.g., mean, maximum) and their effects of sagebrush recovery suggests that our NRV evaluation of fire severity is inconclusive. Nevertheless, mapping of larger high-severity burned sagebrush patches (patches with interior regions that extend about 200 m from the perimeter can be used to represent areas lacking sufficient propagules for ecosystem recovery) may locate areas where fire effects did not maintain desired conditions for sagebrush ecosystem resilience (box 6A). Although historical fire return interval estimates for big sagebrush are highly variable (decades to centuries) (Slaton and Stone 2013, Van de Water and Safford 2011), FRID data (with estimates on the low end of the range) indicated that nearly all prefire vegetation in the analysis area was burning less frequently than historically prior to the Owens River Fire: 55 percent was in condition class 3 (high departure from NRV; mostly nontargeted Jeffrey pine forest), about 44 percent was in condition class 2 (moderate departure from NRV; mostly sagebrush), 0.4 percent was in condition class 1 (sagebrush burning within NRV). After the Owens River Fire, most of these areas dominated by sagebrush were burning within NRV (condition class 1), suggesting that, in the absence of interacting stressors (e.g., cheatgrass and altered fire regimes) (see question B below), the Owens River Fire could possibly

Box 6A:
Assessing High-Severity Burned Sagebrush Areas for Replanting Needs

Mountain big sagebrush (*Artemisia tridentata* ssp. *vaseyana* Nutt.) can take at least 30 years to recover after fire (see chapter 6 "Background"). Along with receiving adequate precipitation, distance to live sagebrush has been identified as one of the most important factors in determining sagebrush recovery after fire (Ziegenhagen and Miller 2009). Most sagebrush species do not resprout after fire, and there are low densities of viable seeds in the soil (Young and Evans 1989) making seed dissemination from adult plants critical for postfire recruitment. Sagebrush seeds are typically only dispersed within 9 to 12 m of the parent plant (Blaisdell 1953, Johnson and Payne 1968, Mueggler 1956). Biological constraints on sagebrush dispersal imply that interiors of large burned areas will be among the slowest to recover after fire.

We undertook a simple Geographic Information System exercise to delineate the interiors of high-severity burn patches that will be most in need of replanting sagebrush. We (1) chose a vegetation dataset with the best available delineations of sagebrush vegetation types for the project area, (2) intersected the project vegetation dataset with a vegetation burn severity dataset to identify high burn severity areas (75 to 100 percent basal area loss) in sagebrush, and (3) created an interior buffer (200 m inside severely burned sagebrush patches that had a higher probability of natural recovery and may be excluded from restoration actions) and clipped data to create the final selection of high burn severity areas in the interiors of sagebrush patches. We tested the use of a smaller buffer, but ended up with more area in the interior areas than was potentially treatable; likewise, a larger buffer resulted in excluding areas in the interior that were in need of restoration. Our final selection (fig. 6.3) provided a reasonable number of potential candidates for interior areas in need of restoration, which field staff could further refine once they had performed site visits.

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improve ecological conditions by restoring the fire frequency and structural class diversity considered within the NRV for sagebrush ecosystems. However, although we answered a tentative "yes" to the question of whether fire improved ecological conditions and was within NRV, we needed to consider additional interacting stressors in our next step (question B) according to the postfire flowchart.

Question B: Where do other factors threaten long-term ecological resilience and sustainability?—

There are several stressors that might interfere with long-term ecological resilience and sustainability of sagebrush ecosystems in the analysis area, including (1) non-native annual grasses (i.e., cheatgrass, with its subsequent effects on fire frequency and ecological succession), (2) inappropriate past or present livestock grazing, (3) off-highway vehicle (OHV) use, (4) conifer encroachment, and (5) climate change. To address potential impacts of these stressors, we examined spatial data of invasive

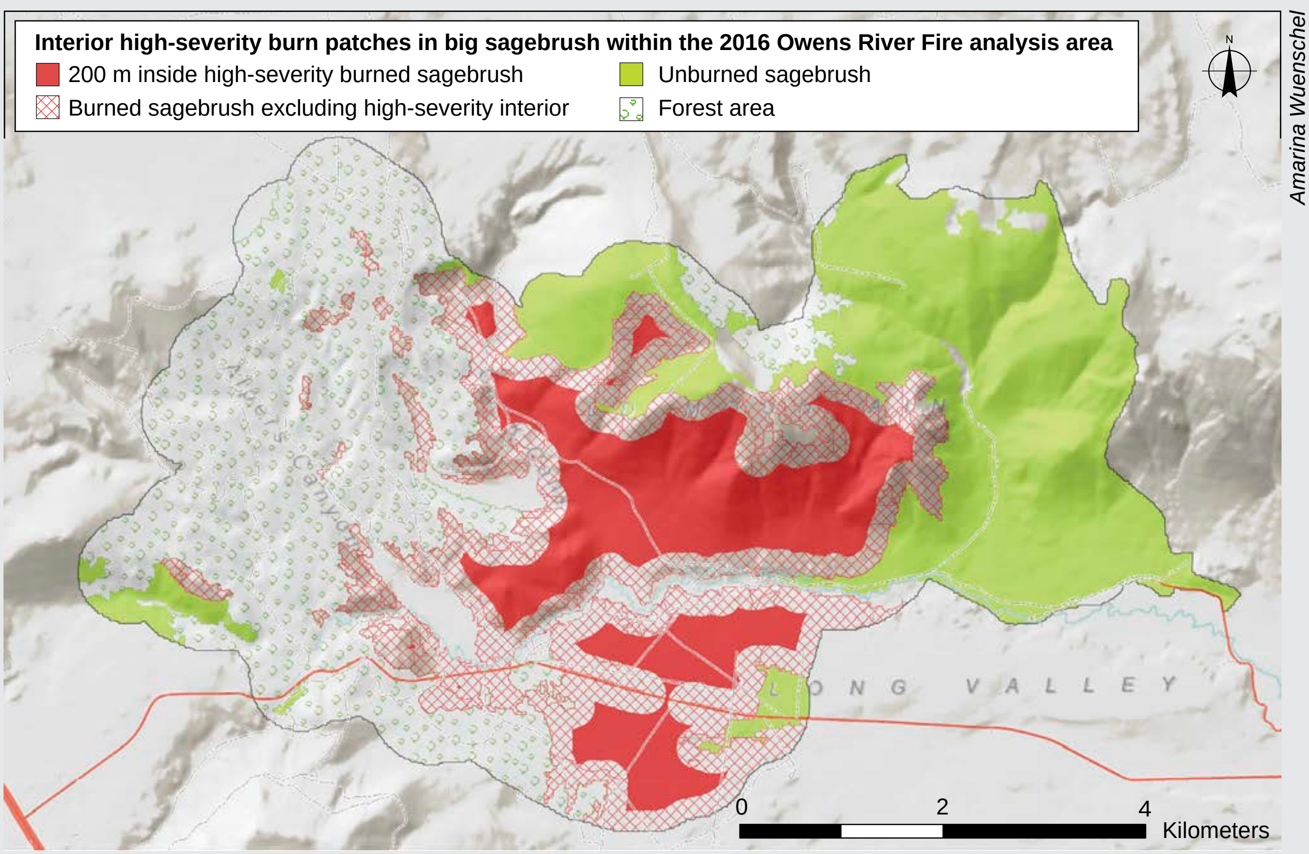

Figure 6.3—Map of burned and unburned sagebrush patches, with areas highlighted in red located 200 m (656 ft) inside the perimeter of severely burned sagebrush. These areas may be in greatest need of sagebrush replanting efforts, given slow sagebrush recovery in burn patch interiors.

plants, livestock grazing allotments, OHV road access, and climate exposure (table 6.1), especially in relation to mesic sagebrush sites identified in step 3. First, we observed several prefire cheatgrass occurrences totaling about 6 ac (2.4 ha) in the Owens River Fire analysis area, with additional occurrences about 750 m from the fire perimeter. Because of limitations in accurate mapping of cheatgrass extent, we assumed the mapped occurrences were most likely an underestimate of true extent (see box 6B). Second, rangeland allotment data showed that the analysis area was covered by four grazing allotments, suggesting potential impacts of livestock grazing in sagebrush ecosystems, but with no clear indication of where inappropriate grazing levels may have occurred. No wild horse territories occurred in or near the analysis area based on spatial data and recent field observation. Third, 3 of 12 (25 percent) mesic sagebrush sites (145 ac [59 ha] total) were bisected by national Forest Service system roads totaling 1.9 mi (3.1 km) in length. The BAER team identified an additional impact as a result of firefighting activities (15.2 mi [24.4 km] of dozer line, 1.4 mi [2.2 km] of hand line, and four drop points within the analysis area) that required invasive plant species response efforts. Fourth, potential for conifer encroachment into sagebrush, primarily by Jeffrey pine, was identified in western Long Valley (especially the southwestern section of Owens River Fire) based on prefire vegetation data and recent prefire field accounts from the area (for conifer encroachment mapping techniques see box 6B). Vegetation burn severity data indicated that most of these encroached areas burned at high severity, suggesting that they had little or no potential for conifer encroachment in the near future. However, unburned and some burned sagebrush located immediately outside the southern edge of the Owens River Fire had also experienced conifer encroachment that warrants management action (restoration opportunity 2). Lastly, climatic water deficit (CWD) data suggested moderate increases (15 to 20 percent) in projected CWD in the analysis area over the next two decades, especially in Clark and Alpers Canyons where recent mapping of shrubland patch mortality confirmed that these areas had undergone loss of sagebrush and bitterbrush cover during several years of drought preceding the fire.

Collectively, this information indicated that potential stressors could interfere with long-term ecological resilience and sustainability in sagebrush ecosystems throughout the analysis area. This was especially apparent in mesic sagebrush sites bisected by roads and adjacent to nonnative invasive plant occurrences. These areas led us to question C in the postfire flowchart. Additionally, despite potential widespread impacts of stressors, we recognized that other mesic sagebrush sites in the Owens River Fire were less affected by nonnative invasive plants and OHV access. We categorized these areas as relatively unaffected by localized stressors, where the management goal would be focused on maintaining or promoting desired conditions (restoration opportunity 1).

Box 6B:
Remote-Sensing Tools for Arid Shrubland and Woodland Burn Restoration Planning and Monitoring

The scale and complexity of spatial patterns within burn perimeters are usually great enough that remote-sensing technologies are required to assess conditions efficiently and adequately. Managers have access to a variety of imagery sources, acquired from sensors on satellites or aircraft, which measure electromagnetic radiation reflected from the vegetation canopy and ground surface (fig. 6.4). Temporal, spatial, and spectral resolution vary across sources, as does cost, though some technologies, such as the Landsat archive and newly emerging synthetic aperture radar are currently available for free. Three examples are given below demonstrating the range of products available, including derived products, such as change-detection algorithms based on imagery. These products are also described in "Appendix 2: Data Sources for Data Gathering and Analysis."

Detecting cheatgrass infestation and native shrub cover change—

F3 is an algorithm that combines ground-based and remote sensing data to create maps of ecosystem metrics (Huang et al. 2018). The U.S. Forest Service Pacific Southwest Region Remote Sensing Lab used this approach in the Owens River Fire, leveraging the distinct phenological signal of invasive annual grass as compared to perennial vegetation. Optical data from the RapidEye satellite constellation plus Synthetic Aperture Radar (SAR) were used to map invasive annual grasses and native shrubs. The optical dataset detects the

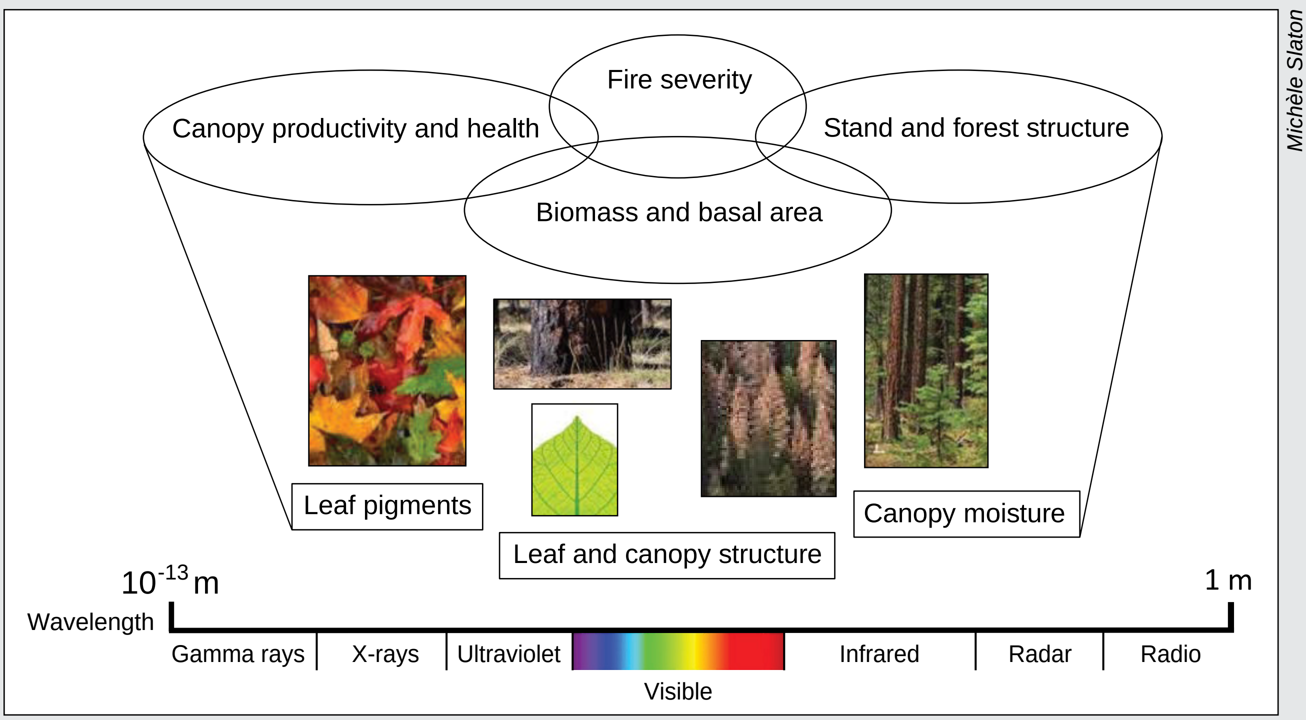

Figure 6.4—A conceptual diagram illustrating the leaf to ecosystem attributes derived from remote-sensing analyses of the electromagnetic spectrum. Mapping tools and applications used in vegetation monitoring are based on these biophysical principles.

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unique phenology, while the addition of radar data discriminates shrub versus grass canopy structure. The resulting map (fig. 6.5) depicts gain and loss of shrub cover in the study area over the decade preceding the Owens River Fire. Gains were due in part to regrowth after previous fires (fig. 6.6), and losses were due largely to drought-induced shrub mortality.

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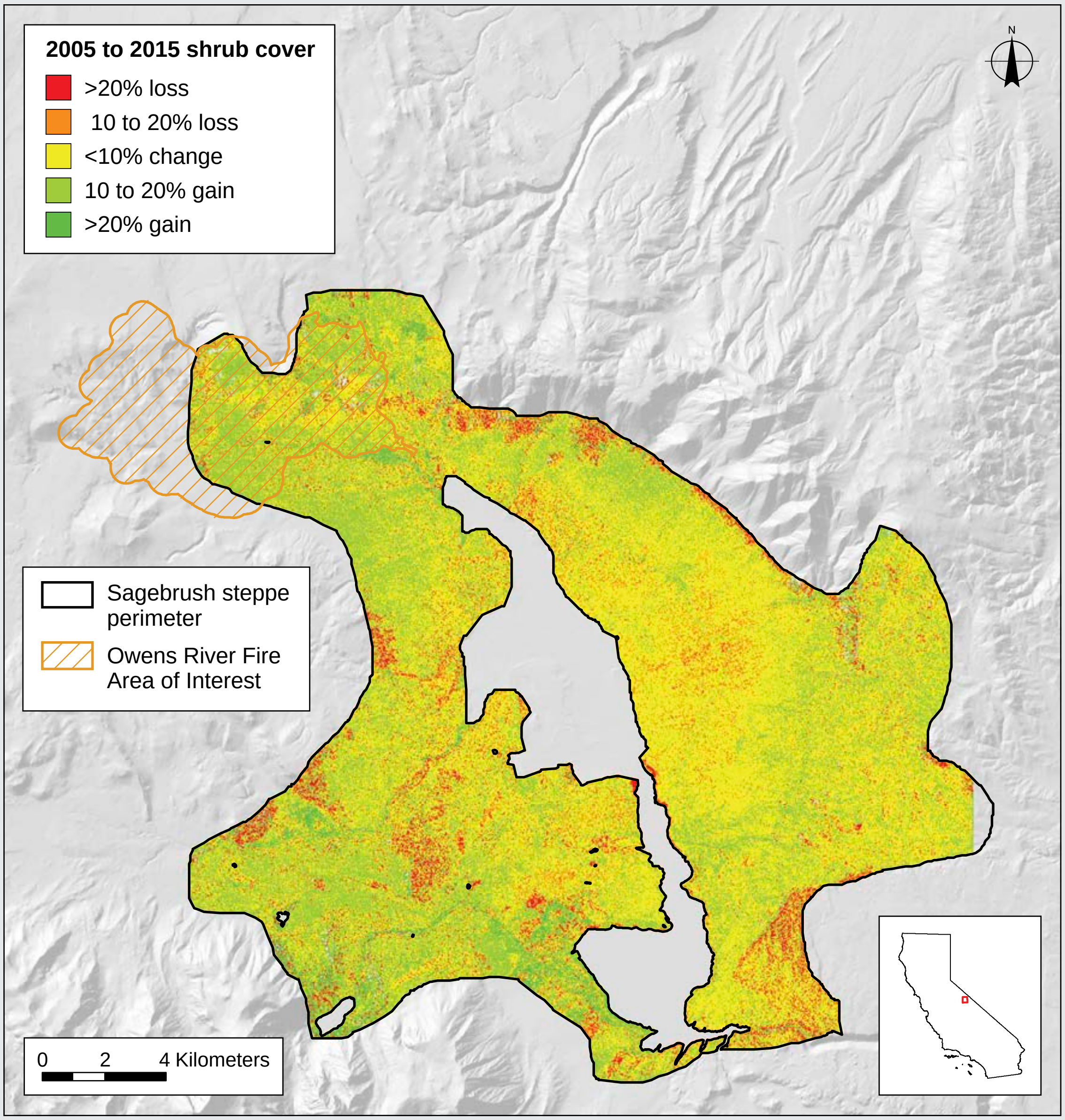

Figure 6.5—Map of changes in native shrub cover 2005–2015, based on remote-sensing and field training data used in F3 model. Changes in cover prior to the Owens River Fire were mostly caused by drought or regrowth after previous fires or rangeland management projects. This prefire trend information can help prioritize areas where restoration may be most successful within the Owens Fire area of interest (AOI), Inyo National Forest.

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Mapping conifer encroachment—

Light detection and ranging (LiDAR) uses laser light to provide an accurate, high-resolution, 3-D image of an area (McGaughey 2014). In the Owens River Fire, prefire LiDAR (fig. 6.7) detected encroaching trees into sagebrush (fig. 6.8), providing both a visual and a quantitative measure for planning efforts for potential management action.

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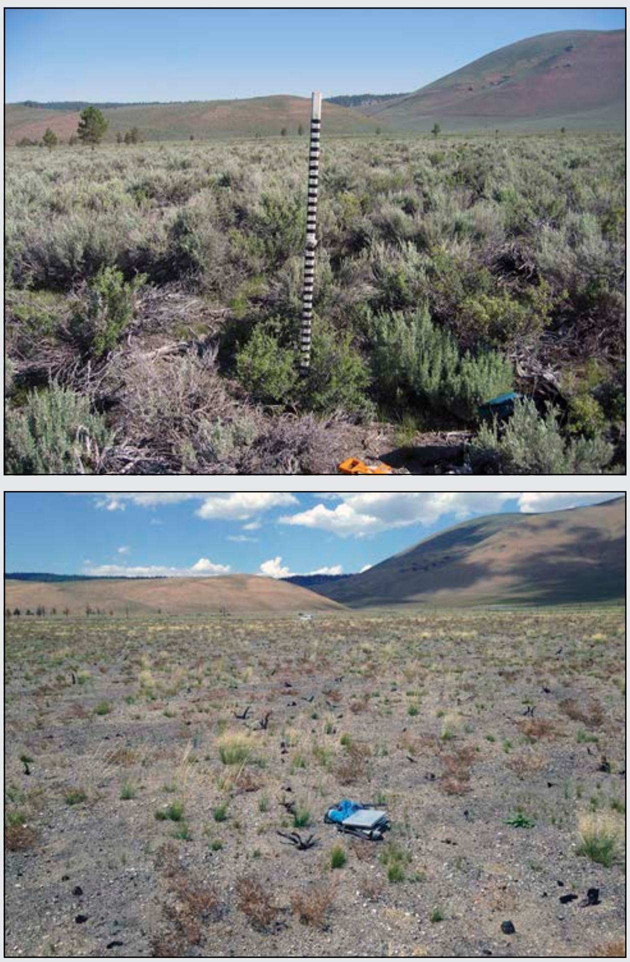

Figure 6.6—Vegetation regrowth 3 years after the 2002 McLaughlin Fire within the footprint of the Owens Fire. Dominant shrubs are resprouting bitterbrush (*Purshia tridentata*), and rabbitbrush (*Chrysothamnus viscidiflorus*), with native perennial grasses and nonnative grass (*Bromus tectorum*) in the interspaces.

Mortality induced by causes other than fire—

The Ecosystem Disturbance and Recovery Tracker (eDaRT) is an automated anomaly detection algorithm that compares vegetation to a recent historical baseline (Koltunov et al. 2020). eDaRT uses all available Landsat imagery (30 m or 100 ft) to map disturbances, including canopy mortality. Outputs for the Owens River Fire area (fig. 6.9) showed that significant prefire shrub mortality had occurred in the 2009–2016 drought (fig. 6.10).

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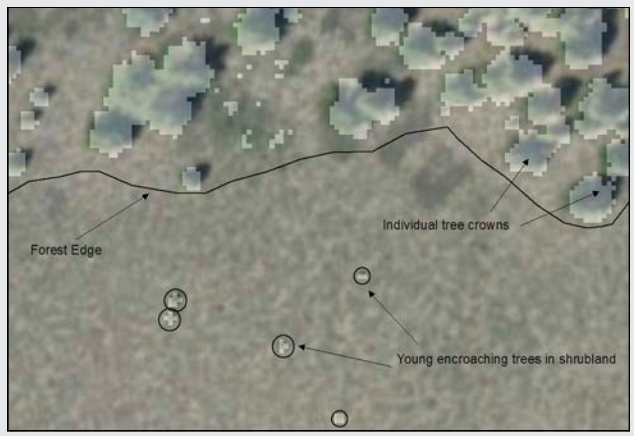

Figure 6.7—LiDAR-derived map of conifer encroachment in the sagebrush-forest ecotone of the Owens River Fire area (Inyo National Forest).

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Figure 6.8—Jeffrey pine (*Pinus jeffreyi*) encroachment in sagebrush steppe within a section of the Owens River Fire area that had no previously recorded burn history.

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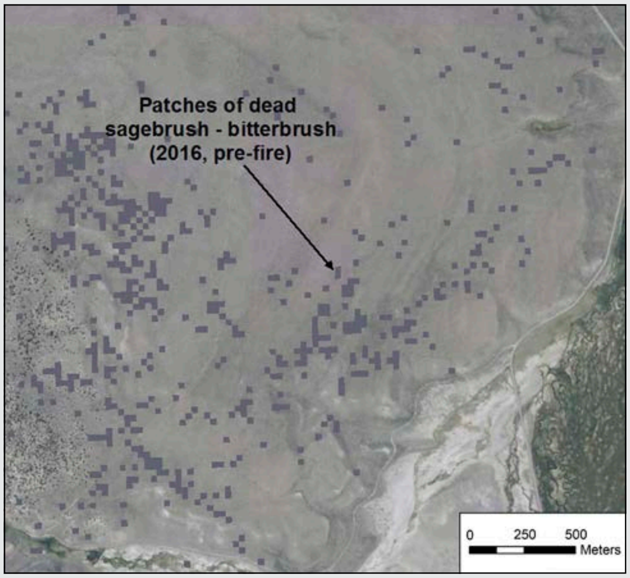

Figure 6.9—Map of shrub mortality patches identified using the Ecosystem Disturbance and Recovery Tracker in the Owens River Fire area.

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Figure 6.10—Localized patch of sagebrush mortality near the Owens River Fire area, likely owing to drought conditions.

Question C: Where are management approaches feasible for the restoration of desired conditions given current and anticipated future conditions?—
We reexamined the spatial data for the mesic sites of sagebrush identified in the sections above (addressing questions A and B) for essential structural features (e.g., shrub cover), indicators of ecosystem integrity, and extent of departure from NRV. As noted above, vegetation burn severity data indicated a loss of shrub cover in all four sagebrush patches and subsequent impacts to sage-grouse habitat. Soil burn severity data reported by the BAER team indicated that two of these larger patches were burned at high soil burn severity, suggesting loss of soil productivity, nutrient availability, biological soil crusts, and hydrologic function (e.g., soil water infiltration and runoff) and greater susceptibility to cheatgrass invasion. Collectively, these patterns suggest that postfire conditions for sagebrush ecosystems in our analysis area have substantially departed from our desired conditions, and restoration activities may be required to achieve landscape desired conditions for sagebrush steppe; field visits to the site would be necessary to confirm these patterns of departure from desired conditions. There are several feasible management actions (e.g., sagebrush restoration) that could be developed to address this departure of current postfire conditions from desired conditions and NRV (outlined below).

Restoration opportunity 1: maintain or promote desired conditions—
In mesic sagebrush sites, management opportunities could include passive restoration, nonnative invasive plant management, and status and trend monitoring. Facilitating postfire succession of native species in the analysis area, combined with small, strategically placed fuel breaks in areas neighboring the Owens River Fire (addressed in restoration opportunity 2), may enhance the long-term resilience of arid shrubland ecosystems to wildfire, particularly through limiting future wildfire spread into the Owens River Fire perimeter during the critical period of postfire recovery. Control of nonnative invasive plant species on the valley bottom would facilitate the growth of native early-seral plant species (e.g., buckwheats [*Eriogonum* spp.], cryptantha [*Cryptantha* spp.], gilia [*Gilia* spp.] skeletonweed [*Stephanomeria* Nutt.], goosefoot [*Chenopodium* spp.]) that provide native ground cover and summer forage for sage-grouse.

Long-term monitoring would greatly complement passive restoration and nonnative plant treatments in the Owens River Fire area (Pyke et al. 2018). For example, five long-term ecological monitoring plots were burned in the Owens River Fire, offering an opportunity to track postfire vegetation trajectories and evaluate the effectiveness of passive restoration approaches. Remote-sensing techniques (box 6B) also greatly contribute to monitoring efforts in the analysis area.

Restoration opportunity 2: take management actions to restore desired conditions—
In four of the burned mesic sites and one unburned site with conifer encroachment into sagebrush (step 3, questions B and C), management actions could be selected to restore desired conditions, diminish the impact of stressors, and reduce departure from NRV. We compiled a potential list of restoration actions for sagebrush and pinyon-juniper ecosystems (e.g., evaluation of ecological site conditions, species selection for revegetation) based on local expert input and published resources (Chambers et al. 2014a; Finch et al. 2016; Miller et al. 2014a, 2015b; Pyke et al. 2014, 2015) (table 6.2).

Restoration opportunity 3: reevaluate desired conditions considering climate change and other stressors—
Restoration of some sites in the Owens River Fire may no longer be feasible owing to the dominance (biomass or cover) of cheatgrass or other nonnative invasive species observed in the field by forest staff in 2018. This may occur in areas of cheatgrass occurrence that burned too frequently (e.g., negative FRID condition class), or areas exposed to additional site-specific stressors (e.g., inappropriate livestock grazing) or widespread stressors (e.g., climate change) that inhibit or preclude

native plant recovery. In these cases, conversion to nonnative annual grassland may be likely, with concomitant losses of ecosystem services. It may be important to monitor these areas for long-term vegetation change and nonnative species containment, or to apply adaptive management approaches for managing these potentially novel or hybrid ecosystems (e.g., by revegetating areas with unique combinations of species that tolerate high disturbance). Finally, emerging evidence elsewhere in the Great Basin indicates that despite the presence of cheatgrass, maximizing the cover of perennial grasses and forbs promotes elements of ecosystem resilience and integrity (Chambers et al. 2017). Although this is not the ideal invasion-free landscape that may be desired, such mixed-vegetation conditions do provide benefits to wildlife, range, and other resources and suggest a reevaluation of desired conditions in light of interacting stressors. Additional native forbs and shrubs, including early-seral species, could be particularly beneficial as perennial grass cover may have been historically limited in the Crowley Basin. In some limited cases, seeding or planting of sagebrush and other native shrub species may be feasible in localized, targeted areas (e.g., high-value habitat corridors, experimental sites) to achieve long-term native vegetation recovery (Ott et al. 2019).

Step 4: Develop and Integrate Restoration Opportunities Into Potential Restoration Actions

Based on our review of the postfire flowchart (i.e., restoration opportunities 1, 2, and 3 described above), we proposed a list of restoration opportunities (table 6.2), including some related to other valued resources not specifically addressed earlier. Based on these opportunities, we generated a list of potential management actions for the Owens River Fire analysis area:

- Reseed and plant greenhouse-stock sagebrush, bitterbrush, and other native species obtained from local seed sources (Gucker and Shaw 2019, Miller et al. 2014a) focusing on creating or expanding sagebrush islands within the fire perimeter or within fire suppression activity areas
- Remove encroaching conifers (e.g., Jeffrey pine) in sagebrush within burned and unburned patches adjacent to the southern fire perimeter
- Defer livestock grazing for at least the first 2 years postfire or longer if desirable forage species have not recovered
- Install signage or barriers to discourage illegal off-road vehicle use in the burned area
- Eradicate or contain the spread of nonnative invasive plants where feasible
- Apply strategic fuel breaks to neighboring unburned areas to limit future wildfire spread (and nonnative plant invasions)

- Implement slope or road rehabilitation measures to stabilize soils and encourage native plant regeneration
- Monitor restoration treatment effectiveness

Most of these management actions (most also listed in table 6.2) can be combined and integrated to maximize treatment effectiveness and efficiency. For example, native plant revegetation efforts could be combined with nonnative plant and grazing management, and off-road vehicle closures to ensure greater success of restoration efforts (i.e., in areas targeted for revegetation efforts, install signage or barriers to discourage off-road vehicle use, eradicate or control nonnative plants, and work with grazing permittees to redirect livestock grazing to other areas). Consolidation of high-priority restoration areas may be enhanced using additional spatial tools and site-specific evaluation and analysis (see box 6B). For example, three of the mesic sagebrush patches in or adjacent to Clark Canyon are characterized by (1) sufficient road access (provides increased accessibility for revegetation activities), (2) close proximity or connectivity with cheatgrass occurrences (i.e., higher potential for invasion), (3) availability of suitable habitat for sage-grouse, (4) relatively lower moisture stress (i.e., topographic positions of higher moisture availability and lower current CWD), and (5) patches of high soil burn severity that would influence recovery (Figs. 6.2 and 6.3); sage-grouse habitat, CWD, and soil burn severity not displayed). These areas of recovering sagebrush could be targeted for a combination of native plant reseeding, deferred grazing, prohibitive off-road vehicle signage, nonnative plant control, road stabilization, and effectiveness monitoring efforts.

Consolidation of high-priority restoration areas may be enhanced by using additional spatial tools and site-specific evaluation and analysis.

Step 5: Build a Restoration Portfolio by Prioritizing Actions

For sagebrush steppe ecosystems, postfire revegetation efforts will be constrained by local greenhouse and seed stock availability (e.g., native plant seeds and seedlings), which requires precise application in the priority mesic sagebrush patches. However, even small patches of recovering sagebrush vegetation may facilitate more rapid and desirable successional transitions (Chambers et al. 2017, Finch et al. 2016), underscoring the importance of identifying priority treatment areas. Another primary constraint for the Owens River Fire area is accessibility, especially road access, which is further limited by private property inholdings and limited river crossings. Mesic sagebrush patches in Clark and Alpers Canyons (fig. 6.2) are accessible and operable for the types of management actions identified in table 6.3. The prioritization of management actions (fig. 6.11) will depend on the integration of these and other factors, such as availability of resources.

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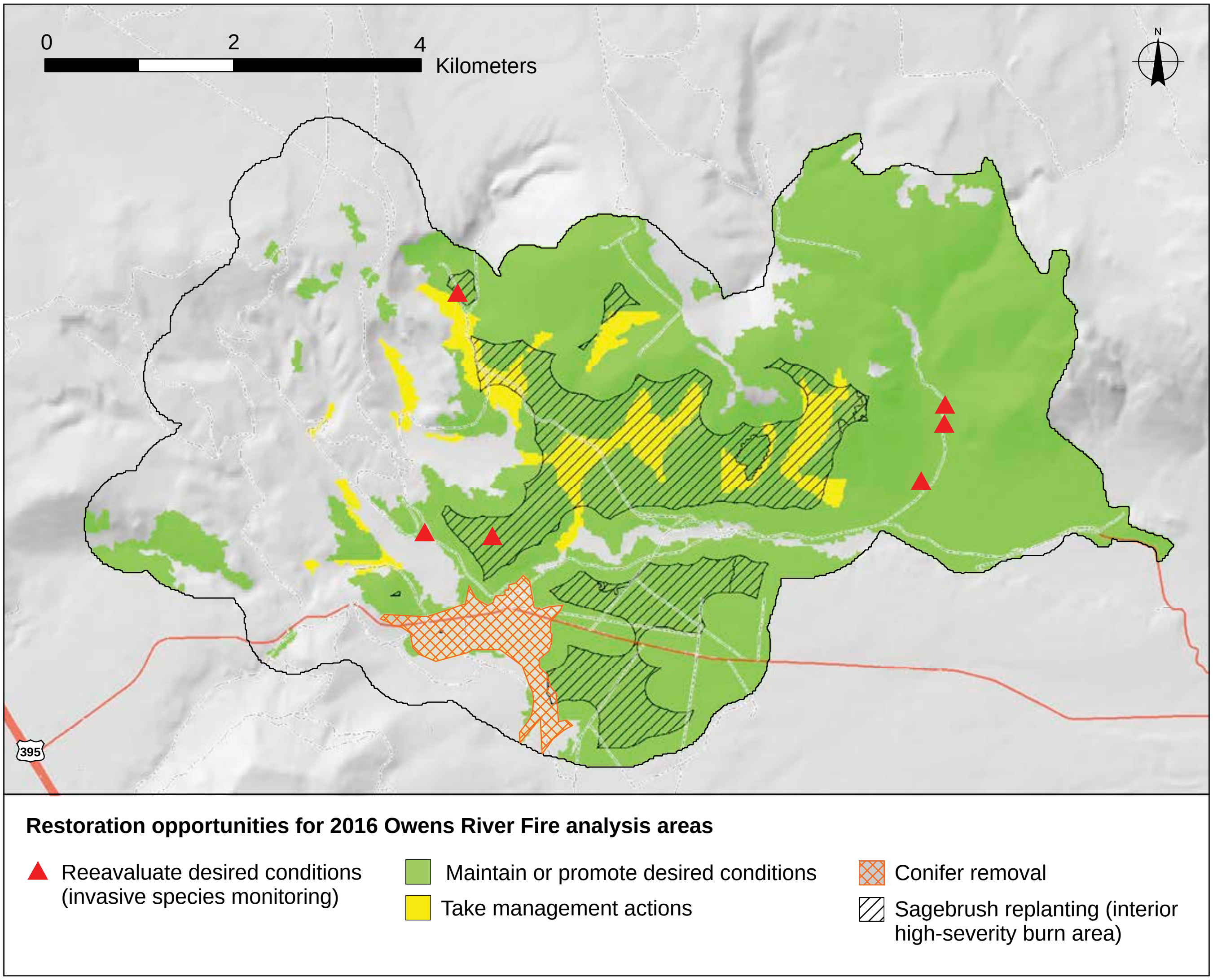

Figure 6.11—Restoration opportunities for sagebrush vegetation in the Owens River Fire analysis area. Areas selected to take management actions and identified for potential sagebrush replanting (i.e., overlap between yellow and cross-hatching polygons) could be prioritized for sagebrush replanting efforts and complementary restoration actions (e.g., redirect grazing outside of priority restoration areas).

Finally, we developed a restoration portfolio based on these integration and prioritization steps (table 6.3). The management actions we identified provide the basis of an ecological restoration portfolio for the Owens River Fire that includes areas where the fire improved ecological conditions, as well as areas where the fire degraded priority resources. By employing a suite of actions designed to address the full range of restoration opportunities created by the fire, this restoration portfolio maximizes the potential for achieving the postfire restoration goals in the Owens River Fire analysis area.

Table 6.3—Restoration portfolio for the Owens River Fire analysis area based on the primary management goals, approaches, and opportunities presented in table 6.2.

Restoration opportunity	Target areas	Management actions	Timing	Feasibility	Cost of inaction
Maintain or promote desired conditions	Burned sagebrush patches, especially in areas of management activities	Contain and, where feasible, eradicate nonnative plants	Short term (1 to 3 years)	Low to Moderate	High
	Burned sagebrush patches, especially in areas of management activities	Create appropriate fuel breaks (Miller et al. 2014b) around burned areas to facilitate fire suppression until sagebrush ecosystem can benefit from subsequent fire (>35 years)	Mid-term (3 to 10 years)	Moderate	Moderate
	Sagebrush vegetation in Clark Canyon and Alpers Canyon	Install long-term vegetation monitoring plots in native plant reseeding and replanting sites and areas of conifer removal to evaluate treatment effectiveness	Mid to long term (>5 to 10 years)	High	Moderate
Take management actions to restore desired conditions	Sagebrush vegetation in Clark Canyon	Reseed native grasses and forbs and replant native shrubs (likely limited to localized patches due to limited availability of seed stock, seedlings, and personnel)	Short term (1 to 3 years)	Moderate	High
	Unburned sagebrush located outside of the north edge of the Owens River Fire	Hand thin Jeffrey pine from unburned sagebrush stands	Short term (1 to 3 years)	High	Moderate
	Burned sagebrush patches	Work with grazing permittees to redirect livestock grazing outside of target burned areas	Short term (1 to 3 years)	Moderate	High
	Burned area especially in Clark Canyon	Install signage or barriers to discourage illegal off-road vehicle use	Short term (1 to 3 years)	Moderate	High
Reevaluate desired conditions considering interacting stressors	Nonnative plant distribution	Conduct long-term monitoring of nonnative plants using remote sensing and field surveys	Mid to long term (>5 to 10 years)	High	Moderate

Note: This restoration portfolio has not yet been applied on a national forest to inform project planning.

Conclusions

We assessed the pre- and postfire ecological condition of the Owens River Fire analysis area based on vegetation type and landscape management unit, but also included vegetation burn severity and FRID condition class. Most of the target ecosystem (i.e., sagebrush) burned at stand-replacing severity in a landscape that is not departed from the historical fire return interval or is burning slightly less frequently than NRV (i.e., low to moderate FRID). These conditions suggested that maintaining or promoting desired conditions (restoration opportunity 1) was appropriate for much of the analysis area. However, some unburned and burned areas located along or immediately outside the southern edge of the Owens River Fire had experienced conifer encroachment that warranted intervention and some areas of severely burned sagebrush in Clark Canyon were targeted for native plant reseeding and replanting efforts (restoration opportunity 2). Finally, some areas that were heavily invaded by nonnative species suggest a reconsideration of desired conditions (restoration opportunity 3) that would reflect a mix of native and nonnative species in the future. The restoration portfolio included seven important restoration management actions for restoration and maintenance of sagebrush steppe in the Owens River Fire analysis area. Most of these actions were considered feasible, integrative, and critical to supporting the primary management goals, especially in target areas located within and adjacent to the Owens River Fire perimeter.

References

Arkle, R.S.; Pilliod, D.S.; Hanser, S.E.; Brooks, M.L.; Chambers, J.C.; Grace, J.B.; Knutson, K.C.; Pyke, D.A.; Welty, J.L.; Wirth, T.A. 2014. Quantifying restoration effectiveness using multi-scale habitat models: implications for sage-grouse in the Great Basin. Ecosphere. 5(3): 1–32.

Baker, W.L. 2006. Fire and restoration of sagebrush ecosystems. Wildlife Society Bulletin. 34(1): 177–185.

Balch, J.K.; Bradley, B.A.; D'Antonio, C.M.; Gómez-Dans, J. 2013. Introduced annual grass increases regional fire activity across the arid western USA (1980–2009). Global Change Biology. 19(1): 173–183.

Bi-State Technical Advisory Committee Nevada and California. 2013. Bi-state action plan—past, present, and future actions for conservation of the greater sage-grouse bi-state distinct population segment. [Place of publication unknown]: Bi-State Executive Oversight Committee for Conservation of Greater Sage-Grouse. 108 p + appendices. http://clearinghouse.nv.gov/public/Notice/2012/E2012-211.pdf.

Blaisdell, J.P. 1953. Ecological effects of planned burning of sagebrush-grass range on the upper Snake River Plains. Tech. Bull. 1075. Washington, DC: U.S. Department of Agriculture. 39 p.

Brooks, M.L.; D'Antonio, C.M.; Richardson, D.M.; Grace, J.B.; Keeley, J.E.; DiTomaso, J.M.; Hobbs, R.J.; Pellant, M.; Pyke, D. 2004. Effects of invasive alien plants on fire regimes. Bioscience. 54(7): 677–688.

Chambers, J.; Maestas, J.; Pyke, D.; Boyd, C.; Pellant, M.; Wuenschel, A. 2017. Using resilience and resistance concepts to manage persistent threats to sagebrush ecosystems and greater sage-grouse. Rangeland Ecology & Management. 70(2): 149–164.

Chambers, J.C.; Pyke, D.A.; Maestas, J.D.; Pellant, M.; Boyd, C.S.; Campbell, S.B.; Espinosa, S.; Havlina, D.W.; Mayer, K.E.; Wuenschel, A. 2014a. Using resistance and resilience concepts to reduce impacts of invasive annual grasses and altered fire regimes on the sagebrush ecosystem and greater sage-grouse: a strategic multi-scale approach. Gen. Tech. Rep. RMRS-GTR-326. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 73 p.

Chambers, J.C.; Miller, R.F.; Board, D.I.; Pyke, D.A.; Roundy, B.A.; Grace, J.B.; Schupp, E.W.; Tausch, R.J. 2014b. Resilience and resistance of sagebrush ecosystems: implications for state and transition models and management treatments. Rangeland Ecology & Management. 67(5): 440–454.

Condon, L.; Weisberg, P.J.; Chambers, J.C. 2011. Abiotic and biotic influences on *Bromus tectorum* invasion and *Artemisia tridentata* recovery after fire. International Journal of Wildland Fire. 20(4): 597–604.

Connelly, J.W.; Reese, K.P.; Fischer, R.A.; Wakkinen, W.L. 2000. Response of a sage grouse breeding population to fire in southeastern Idaho. Wildlife Society Bulletin: 90–96.

Finch, D.M.; Boyce, D.A.; Chambers, J.C.; Colt, C.J.; Dumroese, K.; Kitchen, S.G.; McCarthy, C.; Meyer, S.E.; Richardson, B.A.; Rowland, M.M.; Rumble, M.A.; Schwartz, M.K.; Tomosy; M.S.; Wisdom, M.J. 2016. Conservation and restoration of sagebrush ecosystems and sage-grouse: an assessment of USDA Forest Service Science. Gen. Tech. Rep. RMRS-GTR-348. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 54 p.

Gucker, C.L.; Shaw, N.L. 2019. Western forbs: Biology, ecology, and use in restoration. [Updated]. http://greatbasinfirescience.org/western-forbs-restoration. (16 December 2019).

Homer, C.; Xian, G.; Aldridge, C.; Meyer, D.; Loveland, T.; O'Donnell, M. 2015. Forecasting sagebrush ecosystem components and greater sage-grouse habitat for 2050: learning from past climate patterns and Landsat imagery to predict the future. Ecological Indicators. 55: 131–145.

Huang, S.; Ramirez, C.; McElhaney, M.; Evans, K. 2018. F3: Simulating spatiotemporal forest change from field inventory, remote sensing, growth modeling, and management actions. Forest Ecology and Management. 415: 26–37.

Johnson, J.; Payne, G. 1968. Sagebrush reinvasion as affected by some environmental influences. Journal of Range Management. 21(4): 209–213.

Keeley, J.E. 2009. Fire intensity, fire severity and burn severity: a brief review and suggested usage. International Journal of Wildland Fire. 18(1): 116–126.

Knapp, P.A. 1996. Cheatgrass (*Bromus tectorum* L) dominance in the Great Basin Desert: history, persistence, and influences to human activities. Global Environmental Change. 6(1): 37–52.

Knapp, P.A. 1998. Spatio-temporal patterns of large grassland fires in the Intermountain West, USA. Global Ecology & Biogeography Letters. 7(4): 259–272.

Koltunov, A.; Ramirez, C.M.; Ustin, S.L.; Slaton, M.; Haunreiter, E. 2020. eDaRT: The Ecosystem Disturbance and Recovery Tracker system for monitoring landscape disturbances and their cumulative effects. Remote Sensing of Environment: 111482.

McGaughey, R.J. 2014. FUSION/LDV: software for LiDAR data analysis and visualization. Version 3.42. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

Miller, J.D.; Thode, A.E. 2007. Quantifying burn severity in a heterogeneous landscape with a relative version of the delta Normalized Burn Ratio (dNBR). Remote Sensing of Environment. 107(1): 66–80.

Miller, R.F.; Heyerdahl, E.K. 2008. Fine-scale variation of historical fire regimes in sagebrush-steppe and juniper woodland: an example from California, USA. International Journal of Wildland Fire. 17(2): 245–254.

Miller, R.F.; Chambers, J.C.; Pyke, D.A.; Pierson, F.B.; Williams, C.J. 2013 A review of fire effects on vegetation and soils in the Great Basin Region: response and ecological site characteristics. Gen. Tech. Rep. RMRS-GTR-308. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 126 p.

Miller, R.F.; Chambers, J.C.; Pellant, M. 2014a. A field guide for selecting the most appropriate treatment in sagebrush and pinon-juniper ecosystems in the Great Basin: evaluating resilience to disturbance and resistance to invasive annual grasses, and predicting vegetation response. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 66 p.

Miller, R.F.; Chambers, J.C.; Pellant, M. 2014b. 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-rev. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 76 p.

Miller, R.F.; Chambers, J.C.; Pellant, M. 2015a. A field guide for rapid assessment of post-wildfire recovery potential in sagebrush and piñon-juniper ecosystems in the Great Basin. Gen. Tech. Rep. RMRS-GTR-338. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 70 p.

Miller, R.F.; Chambers, J.C.; Pellant, M. 2015b. A field guide for rapid assessment for post-fire recovery potential in sagebrush and pinon-juniper ecosystems in the Great Basin: evaluating resilience to disturbance and resistance to invasive annual grasses and vegetation response. Gen. Tech. Rep. PNW-GTR-338. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 70 p.

Monty, A.; Brown, C.; Johnston, D. 2013. Fire promotes downy brome (*Bromus tectorum* L.) seed dispersal. Biological Invasions. 15(5): 1113–1123.

Mueggler, W.F. 1956. Is sagebrush seed residual in the soil of burns or is it wind-borne? Res. Note INT-RN-35. Odgen, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 9 p.

Newingham, B.A.; Strand, E.K. 2018. Do post-fire fuel treatments and annual grasses interact to affect fire regimes in the Great Basin? Final report to the Joint Fire Science Program Project 14-1-01-7. Reno, NV: U.S. Department of Agriculture, Agricultural Research Service Great Basin Rangelands Research Unit. 30 p.

Nielson, S.E.; Aldridge, C.L.; Hanser, S.E. 2011. Occurrence of non-native invasive plants: the role of anthropogenic features. In: Hanser, S.E.; Leu, M.; Knick, S.T.; Aldridge, CL., eds. Sagebrush ecosystem conservation and management: ecoregional assessment tools and models for the Wyoming Basins. Lawrence, KS: Allen Press: 357–377. Chapter 10.

Norton, J.B.; Monaco, T.A.; Norton, J.M.; Johnson, D.A.; Jones, T.A. 2004. Soil morphology and organic matter dynamics under cheatgrass and sagebrush-steppe plant communities. Journal of Arid Environments. 57(4): 445–466.

Ott, J.E.; Kilkenny, F.F.; Summers, D.D.; Thompson, T.W. 2019. Long-term vegetation recovery and invasive annual suppression in native and introduced postfire seeding treatments. Rangeland Ecology & Management. 72(4): 640–653.

Pyke, D.A.; Shaff, S.E.; Lindgren, A.I.; Schupp, E.W.; Doescher, P.S.; Chambers, J.C.; Burnham, J.S.; Huso, M.M. 2014. Region-wide ecological responses of arid Wyoming big sagebrush communities to fuel treatments. Rangeland Ecology & Management. 67(5): 455–467.

Pyke, D.A.; Chambers, J.C.; Pellant, M.; Knick, S.T.; Miller, R.F.; Beck, J.L.; Doescher, P.S.; Schupp, E.W.; Roundy, B.A.; Brunson, M.; McIver, J.D. 2015. Restoration handbook for sagebrush steppe ecosystems with emphasis on greater sage-grouse habitat—Part 1. Concepts for understanding and applying restoration. Circular 1416. Reston, VA: U.S. Department of the Interior, Geological Survey. 44 p.

Pyke, D.A.; Chambers, J.C.; Pellant, M.; Knick, S.T.; Miller, R.F.; Beck, J.L.; Doescher, P.S.; Schupp, E.W.; Roundy, B.A.; Brunson, M.; McIver, J.D. 2018. Restoration handbook for sagebrush steppe ecosystems with emphasis on greater sage-grouse habitat— Part 3. Site level restoration decisions. Circular 1426. Reston, VA: U.S. Department of the Interior, U.S. Geological Survey. 62 p.

Slaton, M.R.; Stone, H. 2013. Natural range of variation (NRV) for pinyon-juniper in the bioregional assessment area, including the Sierra Nevada, southern Cascades, and Modoc and Inyo National Forests. Unpublished report. On file with: U.S. Department of Agriculture, Forest Service, Pacific Southwest Region, 1323 Club Drive, Vallejo, CA 94592.

U.S. Department of Agriculture, Forest Service [USDA FS] 2013a. Final Sierra Nevada bio-regional assessment. R5-MB-268. Vallejo, CA. 199 p. https://www.fs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb5444575.pdf

U.S. Department of Agriculture, Forest Service [USDA FS] 2013b. Final Inyo National Forest assessment. R5-MB-266. Vallejo, CA: Pacific Southwest Region. 266 p.

U.S. Department of Agriculture, Forest Service [USDA FS] 2019. Land management plan for the Inyo National Forest: final environmental impact statement and record of decision. Vallejo, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Region.

Van de Water, K.M.; Safford, H.D. 2011. A summary of fire frequency estimates for California vegetation before Euro-American settlement. Fire Ecology. 7(3): 26–58.

Whisenant, S.G. 1990. Changing fire frequencies on Idaho's Snake River Plains: ecological and management implications. In: McArther, E.D.; Romney, E.M., eds. Symposium on cheatgrass invasion, shrub dieoff, and other aspects of shrub biology and management. Gen. Tech. Rep. GTR-INT-276. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station: 4–10.

Young, J.; Evans, R. 1989. Dispersal and germination of big sagebrush (*Artemisia tridentata*) seeds. Weed Science. 37(2): 201–206.

Ziegenhagen, L.; Miller, R. 2009. Postfire recovery of two shrubs in the interiors of large burns in the Intermountain West, USA. Western North American Naturalist. 69(2): 195–205.