



Resilience to fire and resistance to annual grass invasion in sagebrush ecosystems of US National Parks

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ABSTRACT

Western North American sagebrush shrublands and steppe face accelerating risks from fire-driven feedback loops that transition these ecosystems into self-reinforcing states dominated by invasive annual grasses. In response, sagebrush conservation decision-making is increasingly done through the lens of resilience to fire and annual grass invasion resistance. Operationalizing resilience and resistance concepts requires place-based understanding of resilience and resistance variation among landscapes over time. Place-based insights allow for landscape prioritization in targeted areas of significance such as protected-area sagebrush ecosystems that exhibit inherently low resilience and are therefore at high risk of loss. We used a multi-scale approach to evaluate sagebrush resiliency and strategic planning across 1) the US National Park system, 2) a regional suite of five parks, and 3) for two specific park case studies. First, we summarized broad patterns of relative resilience to fire and resistance to annual grass invasion across all parks with sagebrush ecosystems. We found that national parks represented ~11% of US protected-area sagebrush ecosystems and reflected a similar low-resilience bias that occurs across the biome, broadly. Climate change is likely to shift both low- and high-resilience park sagebrush ecosystems towards moderate resiliency, creating new opportunities and constraints for park conservation. Approximately seventy park units include at least some sagebrush shrublands or steppe, but we identified 40 parks with substantial amounts (>20% of park area) that can be included in an agency-wide conservation strategy. Second, we examined detailed patterns of resilience and resistance, fire history and fire risk, cheatgrass (*Bromus tectorum*) invasion, and sagebrush shrub (*Artemisia* spp.) persistence in five national park units in Columbia Basin and Snake River Plain sagebrush steppe, contextualized by the broader summary. In these five parks, fire frequency and size increased in recent decades. Cheatgrass invasion and sagebrush persistence correlated strongly with resilience, burn frequency (0–3 fires since ~1940), and burn probability, but with important variation, in part mediated by local-scale topography. Third, we used these insights to assemble strategic sagebrush ecosystem fire protection mapping scenarios in two additional parks – Lava Beds National Monument and Great Basin National Park. Readily available and periodically updated geospatial data including soil surveys, fire histories, vegetation inventories, and long-term

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monitoring support resiliency-based adaptive management through tactical planning of pre-fire protection, post-fire restoration, and triage. Our assessment establishes the precarious importance of the US national park system to sagebrush ecosystem conservation and an operational strategy for place-based and science-supported conservation.

1. Introduction

Globally, dry rangeland ecosystems face tremendous conservation risks because of inherent limits to system productivity and anthropogenic pressures (Reynolds et al., 2007; Hoover et al., 2020). Low productivity creates high-inertia conditions that make rangeland restoration difficult, if not practically impossible, in many systems following fire, intensive livestock grazing, weed invasion, and other disturbances (Davies et al., 2011; James et al., 2013). Rangelands often exhibit threshold state transition dynamics as a result of cumulative press and pulse disturbances (Ratajczak et al., 2017; Hoover et al., 2020). Hence, proactive protection of remaining intact or quasi-intact rangeland ecosystems is a conservation imperative. However, there are gaps in protected-area coverage within these dry systems, in part a result of low-elevation areas historically being overlooked for conservation value and because of competing demands for livestock grazing, agriculture, and other human uses (Dietz and Czech, 2004; Aycrigg et al., 2013; Hoover et al., 2020). Furthermore, there are gaps in knowledge about the ecological conditions within protected areas that require further investigation in order to strategize effectively and understand conservation efficacy. This is the case in western North America, where a substantial proportion of dry rangelands are represented by sagebrush shrubland and steppe ecosystems that are not well represented within the American protected-area network (Dietz and Czech, 2004; Aycrigg et al., 2013). Sagebrush ecosystems are characterized by the presence of overstory sagebrush shrubs (*Artemisia* spp.) but occur in a variety of ecosystem types ranging from shrub deserts in hotter, drier climates with sparse understory to sagebrush shrub steppe at higher elevations and in northerly latitudes where a substantial herbaceous understory dominated by perennial bunchgrasses and forbs is typical (Miller et al., 2013). Sagebrush ecosystems have experienced the same kinds of conservation losses (Chambers and Wisdom, 2009; Davies et al., 2011) as have other rangelands, globally, triggering conservation attention on sagebrush-obligate ecosystem services, plants, and animals, notably the greater sage-grouse (*Centrocercus urophasianus*; e.g., O'Neill et al., 2020). Substantial losses of sagebrush ecosystems have occurred as a result of encroachment and densification of pinyon-juniper woodlands and fire-driven conversion to annual grasslands (Davies et al., 2011).

To support more effective conservation, practitioners are attempting to better operationalize the concepts of resilience to disturbance, namely fire, and resistance to annual grass invasion (Chambers et al., 2019). Within the context of sagebrush ecosystems, resilience (general resilience *sensu* Chambers et al., 2019) to fire refers to the reassembly of pre-fire structure (e.g., species composition) and function (e.g., soil stability) following fire disturbances, whereas invasion resistance refers to the system attributes and processes that limit annual grass invasion (Chambers et al., 2014, 2019). Resilience and resistance are inter-related and often covary in sagebrush systems such that when resistance is lost, the subsequent establishment of invasive annual grasses reduces resilience to fire, and vice versa, creating positive feedback loops of fire-driven degradation. Recent advances in understanding the biophysical influences on sagebrush ecosystem resilience and resistance (e.g., Chambers et al., 2014) have made it possible to begin predicting and mapping potential resilience and resistance currently (e.g., Maestas et al., 2016) and in the future under scenarios of accelerated

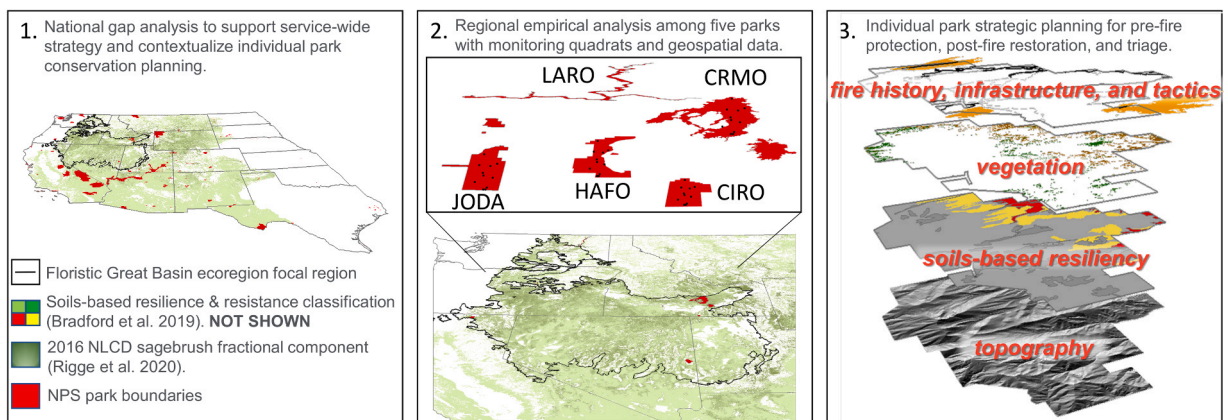


Fig. 1. Study design schematic with three parts: 1) a national-scale gap analysis of sagebrush ecosystems resilience and resistance across the US National Park System; 2) a regional empirical analysis of vegetation cover from 15,144 monitoring quadrats surveyed in five park units (City of Rocks National Reserve [CIRO], Craters of the Moon National Monument and Preserve [CRMO], Hagerman Fossil Beds National Monument [HAFO], John Day Fossil Beds National Monument [JODA], and Lake Roosevelt National Recreation Area [LARO]) in the northern portion of the Floristic Great Basin Region (the Columbia Plateau and Snake River Plain ecoregions) relative to soils-based resilience and resistance classifications, fire history, topographic variation, and fire ignition risk (burn probability); 3) geospatial planning scenarios for two additional parks (Great Basin National Park [shown in panel 3] and Lava Beds National Monument) using soils-based resilience and resistance, fire history, topography, vegetation maps, and tactical considerations (e.g., road access and burn probability).

climate change (Bradford et al., 2019). Variation in site effective soil moisture and site productivity corresponds well to variation in resilience and resistance, which increases predictably with elevation and colder and wetter soil regimes, and on cooler north-facing slopes (Chambers et al., 2014). This predictability makes it possible to prioritize sites for more effective conservation actions (e.g., restoration and protection). For example, low-resilient sites that have not recently burned and still support shrubland and steppe vegetation can be aggressively protected from fire; highly resilient sites that have burned or been invaded can be more successfully restored than degraded low-resilient sites (Chambers et al., 2019).

This new capability for a resilience-based conservation strategy creates opportunities for the US National Park Service (NPS) and other protected-area stewards to increase efficacy and efficiency in sagebrush ecosystem conservation (Chambers et al., 2017). Geospatial datasets such as the resilience and resistance classification by Bradford et al. (2019) can be overlain on protected-area boundaries and combined with terrain maps and vegetation and soil surveys to develop spatially explicit plans (e.g., Maestas et al., 2016; Chambers et al., 2017). There is an urgency to pursue this opportunity because of the increasing risk of catastrophic wildfires across the western US, including in parks with sagebrush shrublands (Westerling, 2016). Furthermore, the role of both unplanned and

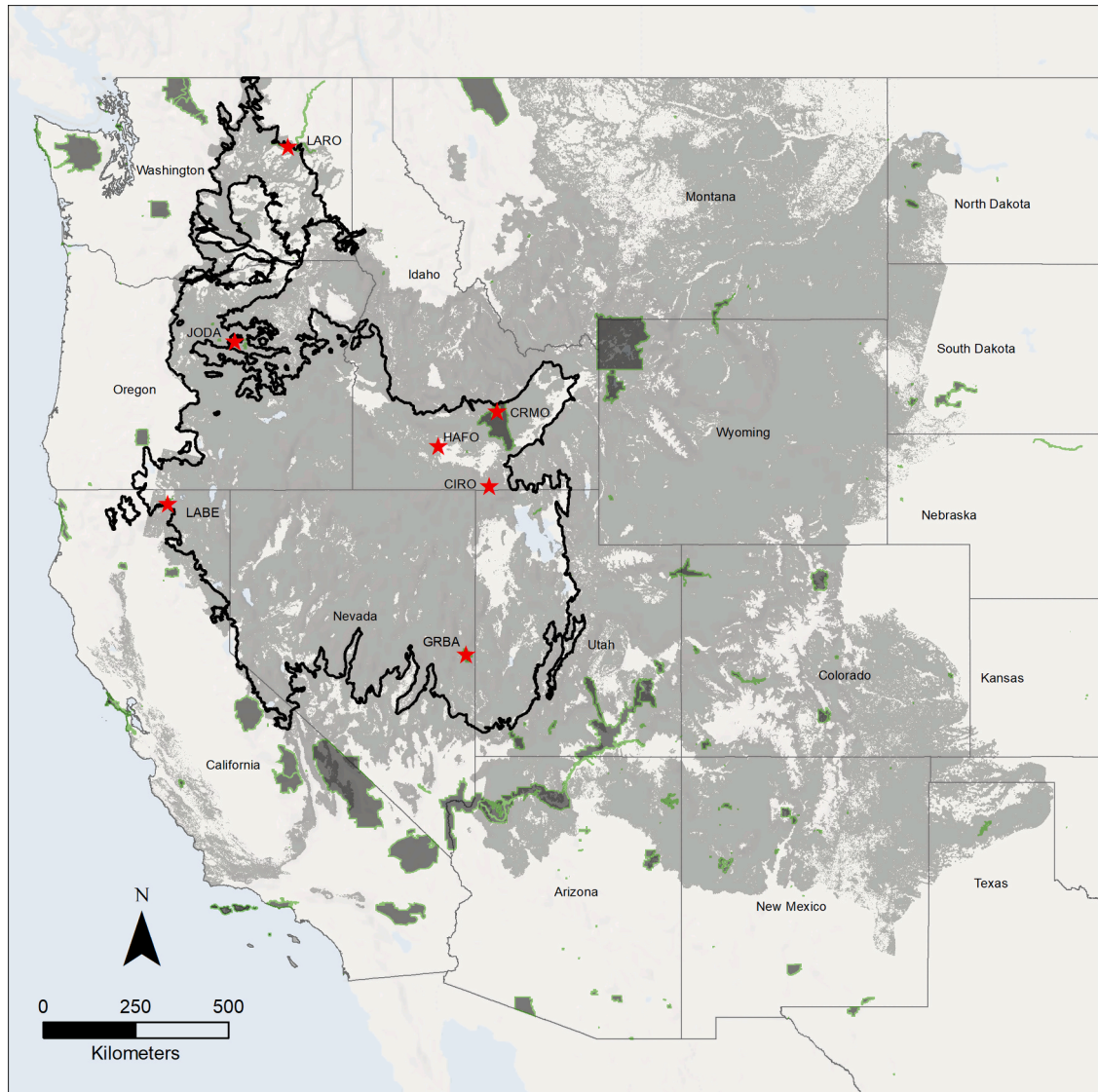


Fig. 2. National parks (dark gray fill with green outline) and sagebrush shrublands and steppe (light gray fill) in the western United States, as mapped by Rigge et al. (2020). The seven closely-examined parks are symbolized by a red star and park acronym (City of Rocks National Reserve [CIRO], Craters of the Moon National Monument and Preserve [CRMO], Great Basin National Park [GRBA], Hagerman Fossil Beds National Monument [HAFO], John Day Fossil Beds National Monument [JODA], and Lake Roosevelt National Recreation Area [LARO]), and Lava Beds National Monument [LABE]). A mapped outline (black line) is also provided for the broader floristic Great Basin Region that forms the core of the range of sagebrush steppe ecosystem types with similar floristic and climatic characteristics that influence resilience and resistance and has very few NPS park units. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

prescribed fires in accelerating losses of sagebrush shrub overstory and steppe bunchgrass cover and increases in annual grass invasion in sagebrush parks is well established (e.g., Bangert and Huntly, 2010; Powell et al., 2013; Reed-Dustin et al., 2016; Mata-Gonzalez et al., 2018; Ellsworth et al., 2020; Rodhouse et al., 2020).

We conducted our study in three parts (Fig. 1). 1) First (see Fig. 1 panel 1), we assessed the overall footprint of the US national park system across sagebrush shrublands and steppe ecosystems, broadly, relative to other protected areas and ownership patterns (Fig. 2). We included an evaluation of the predicted contemporary and potential future resiliency of park sagebrush ecosystems by overlaying across park boundaries the coarse-grain (10 km²) soils-based resiliency map developed for the Western US by Bradford et al. (2019). 2) We then examined detailed quadrat-based patterns of resilience and resistance, fire history and future fire risk, annual grass invasion (specifically cheatgrass [*Bromus tectorum*]), and sagebrush shrub overstory persistence in five national park units in Columbia Plateau and Snake River Plain ecoregions with sagebrush steppe (Fig. 1 panel 2, 3). In a sixth steppe park located on the western edge of the Northern Basin and Range ecoregion we assembled geospatial datasets of resiliency, topography, extant vegetation, and fire risk into a planning scenario and contrast that *post-hoc* with the outcome of a complex of wildfires that burned through the park in 2020. We demonstrate in a seventh park (Fig. 1 panel 3) in the Central Basin and Range ecoregion how these same kinds of geospatial data can be used to develop a proactive strategic prioritization and fire protection plan. Our study provides a comprehensive review of the conservation potential of the system of US parks and protected areas to sagebrush ecosystems and the fire-related risks facing these parks. Our goal is to establish the foundation for proactive prioritization and operational planning by parks to identify, protect, and restore their most important sagebrush shrubland and steppe communities. By explicitly contextualizing this foundation within the framework of resilience and resistance we provide a scientific basis for decision-making at the park-specific (local) scale, the multi-park (regional) scale, and across the entire system of national parks and protected areas.

2. Methods

2.1. National Park System study areas

For the first part of our study (Fig. 1 panel 1), we examined the footprint of the National Park System relative to the sagebrush shrublands across all jurisdictions using the US Geological Survey GAP Analysis Program for its US Protected Area Database (PAD-US version 1.4; USGS, 2017; Fig. 2). For purposes of general comparison, we considered all NPS units, in aggregation, as a protected-area group, acknowledging that there is a relatively wide range of uses and impacts occurring within NPS units and that, formally, some units are classified as GAP status 3 (protected from land cover conversion but subject to extractive uses including recreation and livestock grazing). However, all NPS units are managed within the context of long-term resource preservation, per the 1916 US Organic Act.

For the second part of our study (Fig. 1 panel 2), we examined in detail the conditions within the sagebrush steppe communities of five NPS units in the Columbia Plateau and Snake River Plain ecoregions (Fig. 2). These parks are: City of Rocks National Reserve, Craters of the Moon National Monument and Preserve, Hagerman Fossil Beds National Monument, John Day Fossil Beds National Monument, and Lake Roosevelt National Recreation Area (Fig. 2). These parks were selected for detailed study in part because they are all included within a single monitoring program with a common vegetation survey protocol, facilitating empirical comparisons of park steppe ecological condition.

For the third part of our study, we chose a sixth park with sagebrush steppe, Lava Beds National Monument located on the Modoc Plateau (Eastern Cascades Foothills ecoregion; Miller et al., 2013) adjacent to the Northwestern Great Basin, to develop an assemblage of geospatial data relevant to sagebrush steppe resilience for strategic vegetation protection and restoration planning. This park experienced a large wildfire during our study which provided a *post-hoc* opportunity to consider how *a priori* information might be applied. Finally (Fig. 1 panel 3), we assembled these same kinds of geospatial data to demonstrate a different prioritization strategy for fire management and restoration planning in Great Basin National Park, which is located in the Central Basin and Range ecoregion and where a variety of sagebrush ecosystem types occur across gradients of resilience, topography, fire risk, fire history, and roads accessibility.

Broadly, these 7 parks evaluated in the second and third parts of our study (Fig. 2 panels 2 and 3) share many characteristics of sagebrush steppe within the Great Basin Region, which includes the Columbia Plateau, Snake River Plain, and several other ecoregions adjacent to the Basin and Range ecoregions (Chambers and Wisdom, 2009; Miller et al., 2013). They experience cold semi-desert climates predominated by winter precipitation, and precipitation zones ranging from ~20 to 30 cm (8–12 in) across most areas with sagebrush steppe but reaching ~40 cm in some of the higher elevations. Soil temperature regimes were typically mesic at low elevations and frigid to (rarely) cryic at high elevations whereas soil moisture regimes were aridic or xeric, but notably never ustic (a summer moisture regime as occurs in the Colorado Plateau south and east of the Great Basin), according to soil surveys conducted by the Natural Resource Conservation Service (NRCS) for NPS as part of its system-wide soils inventory (<https://www.nps.gov/subjects/geology/sri.htm>). The herbaceous understory is dominated by cool-season grasses, including both native perennial bunchgrasses and cool-season invasive annual grasses, most notably cheatgrass. They represent the only NPS units within this region (Fig. 1; Miller et al., 2013).

2.2. Classification of resilience and resistance

For the first part of our study (Fig. 1 panel 1), we used the resilience and resistance classification approaches used by Maestas et al. (2016) and Bradford et al. (2019) that relied on soil moisture and temperature regimes provided by NRCS soil surveys. For all NPS units

and to compare resilience of NPS to the background pattern of the broader shrublands biome-wide resilience, we utilized the results from Bradford et al. (2019), which were aggregated from the US General Soils Map [STATSGO2, 1:250,000 scale] and a water balance model (SOILWAT2) generalized to 10 km² grid cells. The purpose of their (Bradford et al., 2019) study was to report on likely shifts in soil temperature and moisture regimes, and hence effective resilience and resistance, as a result of climate change projections in Western North American dryland ecosystems including sagebrush steppe and shrublands. Here, we report on both their current resilience (for “normal” conditions within 1 SD of long-term means) and future scenario of median resilience in ~2100 with temperature and precipitation changes for the 8.5 representative greenhouse gas concentration pathway (see Bradford et al. (2019) for details). For our summaries we aggregated moderate low, moderate, and moderate high into one moderate category. For brevity, we also focus our summary on resilience only because resilience and resistance are generally highly correlated (see Results Section 3.2). Note that Bradford et al. (2019) restricted their analytical coverage to drylands with a ratio of mean annual precipitation to potential evapotranspiration was < 0.6, and therefore excluded some NPS lands with sagebrush ecosystems.

For our detailed park-specific examinations within the seven park units (Fig. 1 panels 2 and 3; City of Rocks National Reserve, Craters of the Moon National Monument and Preserve, Great Basin National Park, Hagerman Fossil Beds National Monument, John Day Fossil Beds National Monument, Lake Roosevelt National Recreation Area, and Lava Beds National Monument) we reclassified NPS soil survey polygons as low, moderate low, moderate, moderate high, and high resilience based on soil temperature and moisture regimes, using the same logic as developed by Bradford et al. (2019). NPS soils surveys were completed by NRCS for each park unit (Appendix A; described generally at <https://www.nps.gov/subjects/geology/sri.htm>; available on-line at <https://irma.nps.gov/DataStore/Reference/Profile/2190427>). These surveys were produced to the same resolution (ranging from 1:12,000 to 1:63,360) and accuracy standards as the NRCS soil survey geographic database for the National Cooperative Soil Survey (SSURGO), providing more granularity than products derived from STATSGO2 (e.g., Bradford et al., 2019). In some cases (notably for Lava Beds National Monument) soils inventories did not designate temperature and moisture regimes in all soil map units, interfering with our ability to designate resilience and resistance. For this reason, we compared the resiliency classifications of Bradford et al. (2019) and those derived from park soil surveys in order to ascertain agreement and the relative utility of the Bradford et al. (2019) classification for park managers when higher resolution products are unavailable. Links to these park soils-based resilience and resistance maps are provided in Appendix A.

2.3. Range-wide evaluation

For part one of our study (Fig. 1 panel 1), we acquired a spatial approximation of sagebrush shrublands and steppe across the western US from the Multi-Resolution Land Characteristics Consortium (<https://www.mrlc.gov/>) 2016 National Land Cover Dataset (NLCD) sagebrush shrubland fractional component 30-m pixel raster dataset (Rigge et al., 2020). Sagebrush shrub overstory species encompassed by this dataset included big sagebrush (*Artemisia tridentata*), low sagebrush (*A. arbuscula*), black sagebrush (*A. nova*), three-tip sagebrush (*A. tripartita*), and silver sagebrush (*A. cana*). For purposes of our analysis, we summed the fractional component of sagebrush over all pixels contained within NPS jurisdictional boundaries and also within each of the four protected-area designations established by the US Geological Survey GAP Analysis Program (PAD-US version 1.4; USGS, 2017). Generally, GAP status 1 and 2 levels designate lands managed to promote biodiversity whereas GAP level 3 represents lands managed for multiple use and level 4 lands have no known management mandate. We used GAP status levels 1 and 2, and all NPS managed lands to represent the protected area network within the US. We took an additional step to approximate the potential current and future resilience of NPS sagebrush shrublands by summarizing the resiliency classifications provided by Bradford et al. (2019) within each NPS unit. We provide a list of parks with their amounts of sagebrush ecosystems land cover as estimated by the NLCD fractional component coverage within park boundaries in Table S1.

2.4. Park-scale evaluations

For parts two and three of our study (Fig. 1 panels 2 and 3), we developed geodatabases (Appendix A) for the seven closely examined parks (see Fig. 2). We included the range-wide datasets described in Section 2.1 and additional high-resolution datasets that described terrain, fire history and risk of ignition (burn probability), soil and vegetation surveys, and the soils-based resilience and resistance classifications. A list of all data sources included in park geodatabases and links to the geodatabases themselves is provided in Appendix A. Risk of ignition was obtained from Short et al. (2020), and we used only their estimated burn probabilities and not also their flame length conditional probabilities since we considered ignition risk irrespective of severity. Short et al. (2020) developed their burn probability model from the FSim wildfire risk simulation system at 270-m resolution.

For the five parks examined in Fig. 1 panel 2, (City of Rocks National Reserve, Craters of the Moon National Monument and Preserve, Hagerman Fossil Beds National Monument, John Day Fossil Beds National Monument, and Lake Roosevelt National Recreation Area) we examined field data from vegetation monitoring; each of these parks have been included in a long-term sagebrush steppe vegetation monitoring program since 2009 (Yeo et al., 2009). Sagebrush steppe monitoring data consisted of above-ground (foliar) plant species ocular cover observations, binned into Daubenmire percent cover classes, from 15,144 1-m² quadrats that were placed randomly within pre-established sampling frames containing sagebrush steppe (approximately 1200 quadrats observed each year; see Yeo et al. (2009)). Data represented the quadrats visited and observed over 11 years (2009–2019) in the five parks, which we pooled for purposes of the present study, but with which we have also examined year effects (e.g., Rodhouse et al., 2020).

We overlaid the quadrat locations on park geodatabases to assign spatial attributes of resilience and resistance, fire histories (times burned), burn probability, and topographic position. The number of times that quadrats burned since ~1940 ranged from 0 to 3,

according to overlay with published wildfire perimeters (National Interagency Fire Center Wildland Fire Open Data and Bureau of Land Management Fire Occurrence and History Perimeter, see [Appendix A](#)) and park prescribed fire perimeters, acknowledging that burn severity within perimeters varies widely. These fire histories were comprised almost entirely of unplanned (wild) ignitions except for a series of prescribed fires in John Day Fossil Beds National Monument circa ~2000.

We binned quantitative attributes (burn probability and topographic position) into categories based on the empirical distributions within our dataset. Topographic position, quantified with the formula $\sin(\text{slope}) \times \cos(\text{aspect})$ that ranged from -1 to 1 ([McCune and Keon, 2002](#)), was binned into 3 approximately equal categories of steep south slope (-1 to -0.02), flat (-0.02 to 0.02), and steep north slope (0.02 – 1). Burn probability was also binned into three approximately equal categories to correspond to low, medium, and high levels. We then used alluvial diagrams to provide visualizations of the relationships, from left to right, of each plot to each of these factors, where each plot was represented by a line and assigned a color based on the first (left) factor ([Rosvall and Bergstrom, 2010](#)). For this study, we focused on above-ground cover of cheatgrass and sagebrush shrubs from the monitoring quadrat data because these taxa have similar growing potential across all of the ecological sites of the five parks and provide a strong indication of the expression (realization) of resilience and resistance within these parks. Furthermore, the cover of cheatgrass and sagebrush are particularly useful for guiding resiliency-based strategic planning ([Chambers et al., 2019](#)).

2.5. Park planning scenarios

In Great Basin National Park and Lava Beds National Monument, we assembled these same geospatial data (see [Appendix A](#)) for proactive scenario planning and protection of sagebrush vegetation from fires ([Fig. 1](#) panel 3). We focused on five data layers for planning consideration, following recommendations from [Chambers et al. \(2019\)](#) and motivated by our own analyses presented in this manuscript: soils-based resilience classification (from both the coarse-grain [Bradford et al. \(2019\)](#) approach and the fine-grain NPS soils inventory), topography derived from 10 m digital elevation models, extant (pre-burn) sagebrush steppe land cover from NPS vegetation inventories ([Cogan et al., 2012](#); [DiPaolo et al., 2015](#)), predicted burn probability from [Short et al. \(2020\)](#), and recent fire histories ([Appendix A](#)). For Lava Beds National Monument, we consider how these data could have been used to prepare for and mitigate the subsequent 2020 July Complex wildfire that originated east of the Monument and burned westward into the Monument, affecting ~70% of the eastern half of the Monument. We created a raster approximation of burn severity for the 2020 July Complex fire using the difference normalized burn ratio (dNBR), generated from the US Geological Survey (USGS) suite of Landsat Surface Reflectance-Derived Spectral Indices products (see [Masek et al. \(2006\)](#); available in [Appendix A](#)). In Great Basin National Park, we overlaid a 2016 fire perimeter that burned through a portion of extant sagebrush steppe and influenced subsequent prioritization.

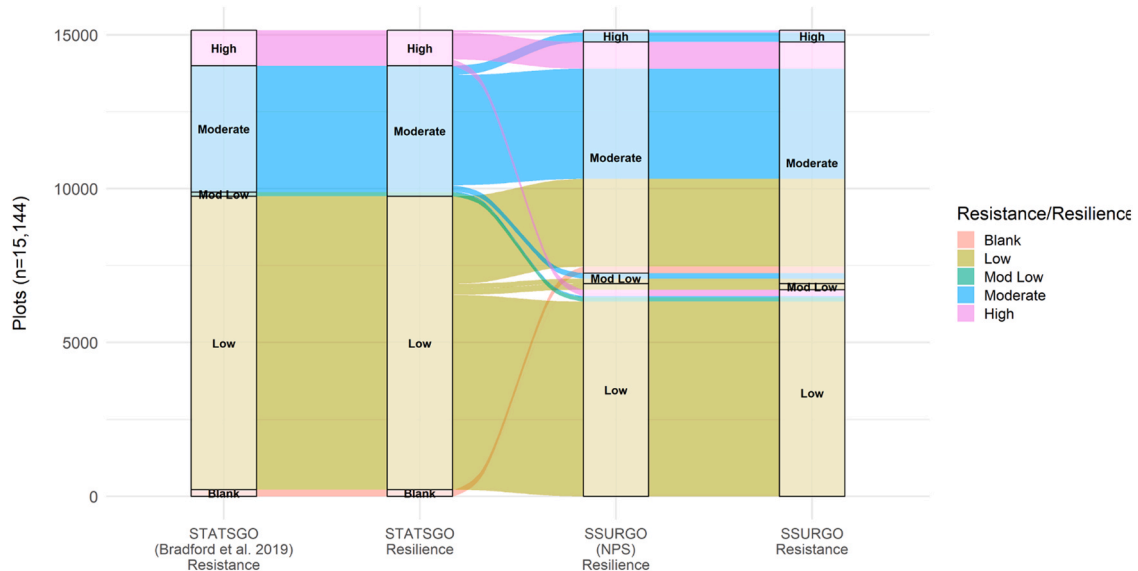


Fig. 3. Alluvial diagram of coarse-grain (study part 1, [Fig. 1](#); derived from the US General Soils Map [STATSGO2]; see [Bradford et al. \(2019\)](#)) versus fine-grain (study part 2, [Fig. 1](#); derived from the National Cooperative Soil Survey [SSURGO, see [Appendix A](#)]) resilience and resistance classifications for $n = 15,144$ 1-m x 1-m vegetation monitoring survey quadrat locations within five US national parks in the Columbia Plateau and Snake River Plain (CIRO, CRMO, HAFO, JODA, LARO). Each line in the diagram represents a quadrat. The alluvial diagram is read from left to right to show cross-factor classifications of each quadrat.

3. Results

3.1. Range-wide evaluation

Ten percent of mapped sagebrush shrublands were included in protected-area status (GAP level 1, 2, and NPS jurisdiction) and 90% of that protected sage shrubland was under federal jurisdiction. National Park Service jurisdiction represented only 1.2% of sagebrush shrublands but 11% of the protected subset of sagebrush shrubland and 12.5% of federal protected shrubland. There were 71 NPS units that overlapped with at least some sagebrush shrublands, although only 40 have substantial amounts (>20%) of sagebrush shrublands and steppe ecosystems cover relative to their overall park areas (Table S1).

NPS sagebrush shrublands overlapped the Bradford et al. (2019) regional classification as 21% low resilience and 31% moderate, with only 4.5% high resilience. This is a similar distribution to the overall background pattern of resiliency across all sagebrush shrublands (37% low, 40% moderate, and 14% high). Eight percent of sagebrush shrublands, overall, and 43% of NPS sagebrush shrublands fell outside of the evaluation area provided by Bradford et al. (2019). Future projections of change in resilience on NPS lands resulting from climate change suggested a shift towards moderate resiliency (3% low, 53% moderate, and 1% high). A similar pattern was seen across the sagebrush shrubland biome, generally (25% low, 64% moderate, 2.5% high), as described previously by Bradford et al. (2019).

3.2. Park-scale evaluations

We overlaid the 15,144 unique monitoring quadrat locations from the five studied parks on both the Bradford et al. (2019) coarse-grain and the park-scale soil inventory-based resilience and resistance classifications and found high correlation between resilience and resistance (Fig. 3). Resilience appears to be effectively synonymous with resistance in our study context. However, we found disagreement (32%) when comparing between the two classification datasets, demonstrating the benefit of more granular data when available, as encouraged by Maestas et al. (2016) and Bradford et al. (2019). Overall, both classifications suggested low to moderate resiliency in these five parks. However, 30% of plots classified as low resilience using the coarse-grain dataset was classified as moderate resilience when using the soils inventories. Also, most high resilience areas were reclassified as moderate resilience (75%), and a small proportion were reclassified as low resilience (18%), when NPS soil survey data were used.

We found consistent patterns among the quadrat location resilience classification, number of times burned, and foliar cheatgrass (Fig. 4A) and sagebrush shrub cover (Fig. 4B). A summary of available (mapped) burn history since ~1940 suggests increasing frequency and magnitude in all parks, but with a notable 20-year gap since 2000 in City of Rocks National Reserve (CIRO; Fig. 5). Interestingly, most low resilience locations have experienced at least one burn, but this was not so for moderate and high resilience locations (Fig. 4).

Notably, almost all (96%) of low resilience quadrats had at least some cheatgrass (Fig. 4A) and 73% also had no sagebrush cover (Fig. 4B). There was no path in the alluvial plots in Fig. 4 for low-resilience locations burned more than once to be free of cheatgrass nor for sagebrush to persist. Moderate resilience locations exhibited more variability, but substantial proportions of locations remained unburned, free of cheatgrass or nearly so (category 1, 1–5% cover), and with persistent sagebrush cover. However, it was rare for moderate resilience locations to burn and remain cheatgrass free and with sagebrush cover. High resilience locations were few but were primarily uninfested by cheatgrass, unburned, and with sagebrush cover (Fig. 4).

Topographic heterogeneity was high among quadrat locations and there was considerable variation in the combinations of topographic position, fire history, cheatgrass, and sagebrush shrub cover (Fig. 6). Flat ground was less frequently burned, less infested

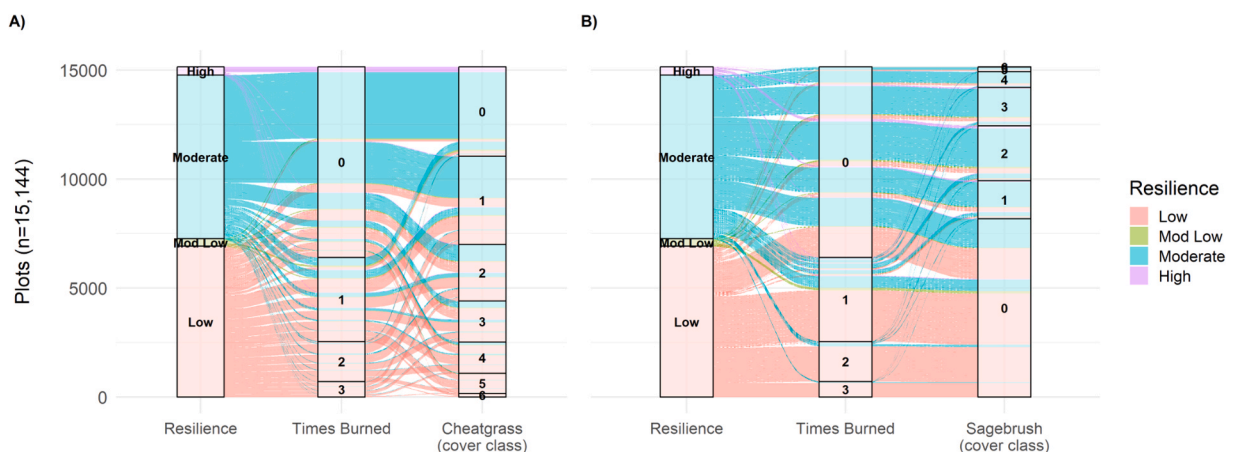


Fig. 4. Alluvial diagram of resilience, fire history (times burned), and A) cheatgrass (*Bromus tectorum*) and B) sagebrush shrub (*Artemisia* spp.) cover in five US national parks in the Columbia Basin and Snake River Plain. Plots in low resilience areas have experienced more fires, are heavily invaded by cheatgrass, and much less likely to have persistent sagebrush cover.

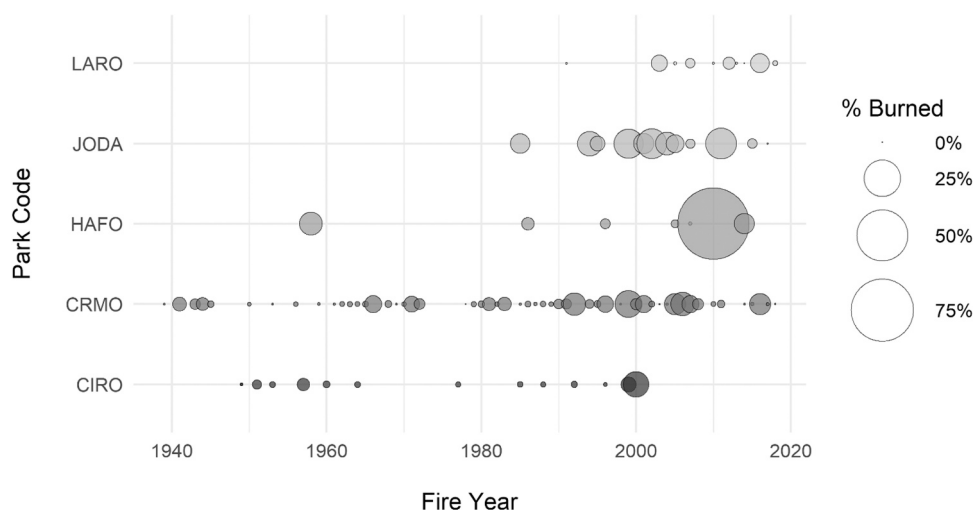


Fig. 5. Fire history of five studied US national parks in the Columbia Basin and Snake River Plain, by year and % of park area burned during each fire. Parks included are: City of Rocks National Reserve (CIRO), Craters of the Moon National Monument and Preserve (CRMO), Hagerman Fossil Beds National Monument (HAFO), John Day Fossil Beds National Monument (JODA), and Lake Roosevelt National Recreation Area (LARO). Fire histories were reconstructed from mapped polygons available from sources listed in [Appendix S1](#). Only fire polygons that intersected established park boundaries were included.

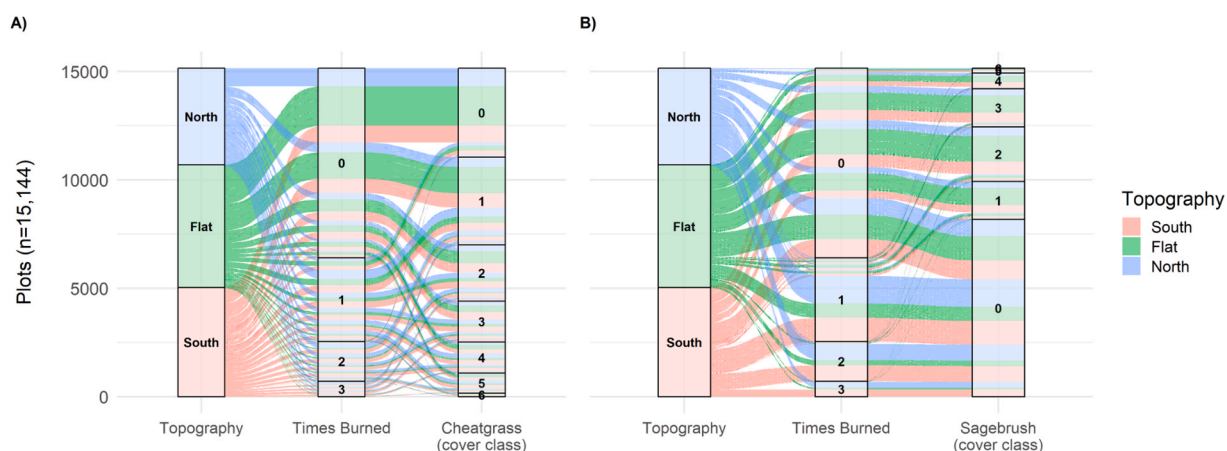


Fig. 6. Alluvial diagram of vegetation quadrats' mapped topographic position, fire history (times burned), and A) cheatgrass (*Bromus tectorum*) and B) sagebrush shrub (*Artemisia* spp.) cover in five US national parks in the Columbia Basin and Snake River Plain. There is high topographically mediated variation in the relationship between fire history and cheatgrass and sagebrush cover, demonstrating the fine-grained place-based processes that influence resilience and resistance within parks and that is requisite knowledge for effective park conservation.

by cheatgrass (Fig. 6A), and more often had high sagebrush cover (Fig. 6B) than steeper slopes of any aspect. Fig. 7 provides additional insights into this topographically mediated variability when resilience and a fourth factor, burn probability, were examined with topography and sagebrush cover. Areas of low resilience across all three slope/aspect categories had higher fire ignition risk, also reflected in burn frequency (Fig. 6), and almost no persistent sagebrush cover. In contrast, large numbers of flat locations with moderate resilience also shared persistent sagebrush cover and low fire risk. Notably, moderate resilience locations on slopes with sagebrush cover tended to map to moderate or high fire risk (Fig. 7). Figs. 6 and 7 reveal the existence of vulnerable areas represented by quadrat locations that pass through low and moderate resiliency, persistent sagebrush cover, and high burn risk factor levels that can be identified for urgent protection.

3.3. Park planning scenarios

We assembled geospatial data describing resiliency (Figs. 8A and 9A), topography (Figs. 8B and 9B), extant sagebrush steppe (Figs. 8C and 9C), burn probability (Figs. 8D and 9D), and roads and burn severity (Fig. 8E) and roads, potential priority areas, and a recent (2016) fire perimeter (Fig. 9E) to guide strategic planning for Lava Beds National Monument (Fig. 8) and Great Basin National

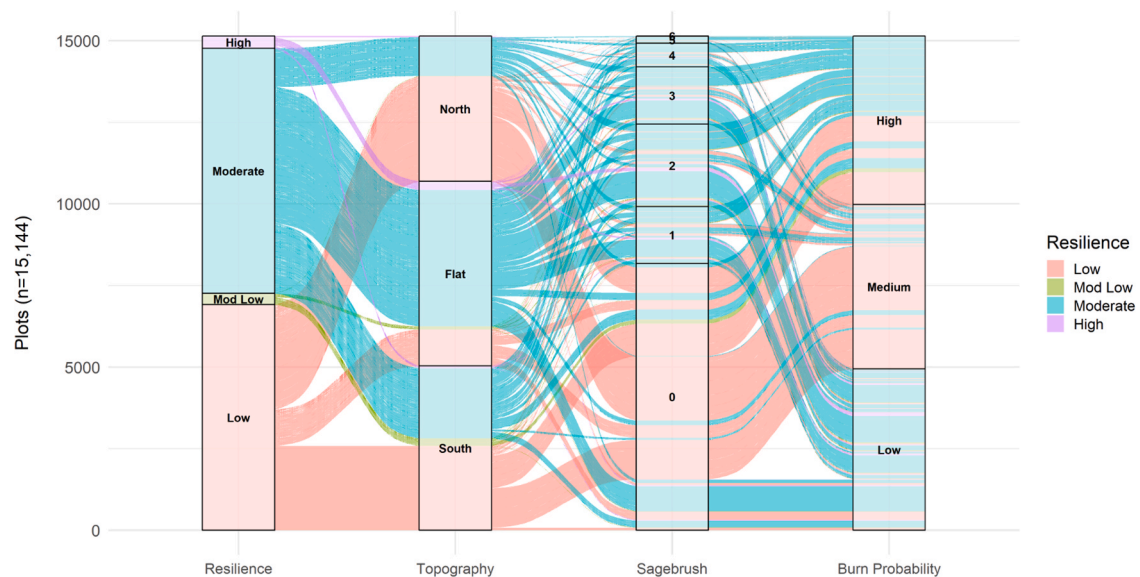


Fig. 7. Alluvial diagram of vegetation quadrats' mapped resilience, topographic position, sagebrush shrub (*Artemisia* spp.) cover, and burn probability. Notably, few plots from low-resilience areas have persisting sagebrush cover, but those that do and that map to moderate or high burn probability are recommended candidates for high-priority protection. Substantially more plots from moderate and (rare) high resilience areas have extant sagebrush cover, and if mapped to moderate and high burn probability are also important areas for high-priority protection.

Park (Fig. 9). In Fig. 8, low resiliency contiguous sagebrush steppe was widespread, bisected (Fig. 8D) by sparsely vegetated lava flows and an eastern half with high burn probability and western half with relatively low burn probability. Notably, topographic heterogeneity was also higher in the western half of the Monument (Fig. 8B). Wildfires in 2020 originating east of the Monument where burn probability was predicted to be highest resulted in patterns of severity estimation mapped in Fig. 8E. Notably, the road network within the Monument was used to contain the fire (Fig. 8E), although we identify a potential alternative containment line that might have utilized the lava flows (Fig. 8D).

In Great Basin National Park, sagebrush shrublands and steppe of different types were scattered widely across the lower slopes of the Park (Fig. 9C), with varying proximities to roads (Fig. 9E). Predicted resiliency was notably lower along the eastern edge of the Park. Topographic heterogeneity was high throughout (Fig. 9B), complicating ground-based fire management operations but also creating variability in sagebrush community types, resiliency, and restoration potential. High predicted burn probabilities occurred at mid-elevations in north-south trending paths bisected by a mountain range. In Fig. 9E, we proposed a prioritization of largest contiguous stands of extant sagebrush ecosystems at lowest resiliency and where road access appears highest (circles 1 and 2 in Fig. 9E). Other contiguous stands of sagebrush (circles 3 and 4 in Fig. 9E) have either recently experienced wildfire and are now targets for restoration or are less accessible for fire protection and restoration efforts.

4. Discussion

4.1. Range-wide evaluation

We found that NPS lands contain a very small fraction of the total extent of US sagebrush ecosystems, but a more substantial (~11%) amount of protected-area sagebrush. More generally, federal agencies own and manage the majority (~90%) of protected-area sagebrush ecosystems, of which NPS manages 12%. However, we also found that the majority of NPS sagebrush ecosystems, and federal protected-area sagebrush systems generally, are ranked as low or moderate resiliency to disturbance and resistance to annual grass invasion based on soil attributes (Bradford et al., 2019). We also found (Section 3.1) that NPS sagebrush vegetation is likely to converge towards moderate resiliency (both from low to moderate and from high to moderate) under current trajectories (RCP 8.5) of climate change, resulting from increases in cool season precipitation and elevation soil moisture as described by Bradford et al. (2019). Such shifts could create some new conservation opportunities for NPS managers in areas that exhibit increasing resiliency, but moderately resilient sagebrush also exhibits considerable vulnerability to invasion, especially after fire (e.g., Fig. 4A).

Our findings have important conservation implications because of the growing risk of droughts (Cartwright et al., 2020; Bradford et al., 2020), unplanned wildfires (e.g., Westerling, 2016), and fire-driven losses of protected-area sagebrush shrublands. Sagebrush ecosystems exhibit threshold-type dynamics that make restoration very difficult (Suding et al., 2004; James et al., 2013), underscoring the importance of protection strategies advocated by Chambers et al. (2019) and others (e.g., Chambers and Wisdom, 2009; Davies et al., 2011). The NPS has a meaningful role in the conservation of sagebrush shrublands and steppe, but one that is precarious given the predominance of low and moderate resiliency and the potential for fire-driven losses. Fire protection of intact and quasi-intact (i.e.,

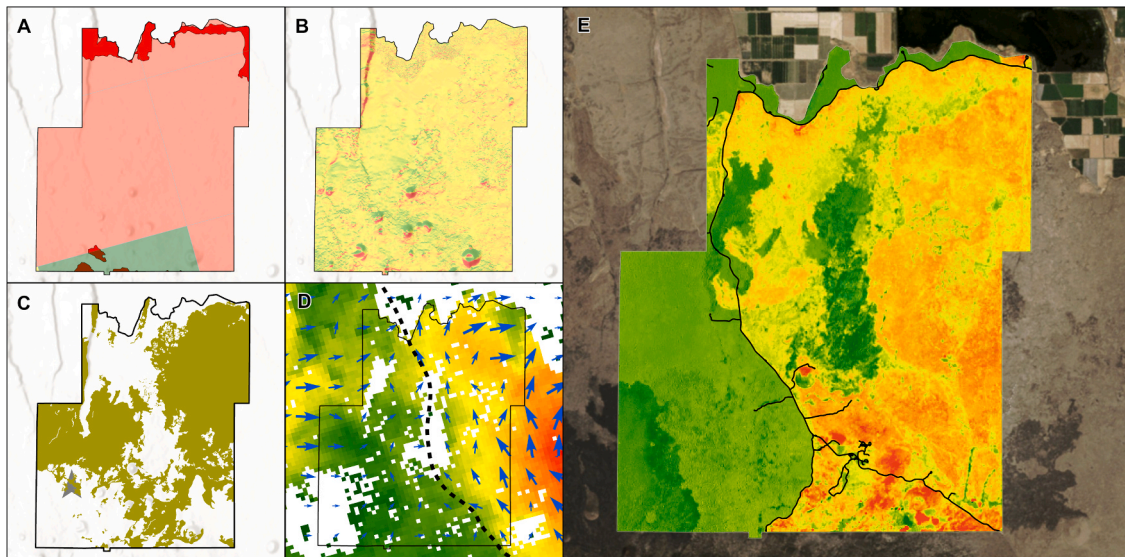


Fig. 8. An assemblage of geospatial data for Lava Beds National Monument, California, that can be used to guide sagebrush steppe landscape prioritization and fire management planning. Panel A shows two resilience classifications across the Monument one by Bradford et al. (2019) for 10 km² grid cells and the other by NPS soils inventory map unit polygons. Low resilience areas are shown in red, high resilience is shown in green. Note the apparent disagreement on the south end of the Monument between the finer-grained soils inventory classification (dark red polygons) and the coarse-grain grid-based approach (green grid cell) which is influenced by cooler and moister high-elevation soil conditions south of the Monument boundary (not shown). However, the majority of the Monument soils inventory map units were not assigned soils temperature and moisture regimes, precluding the ability to complete the fine-grained resilience classification. In panel B, a summary metric of topographic position ($\sin[\text{slope}] \times \cos[\text{aspect}]$) is displayed, revealing greater topographic relief in the southern half of the Monument. North-facing slopes are shown in green, flat ground is shown in yellow, and south-facing slopes are shown in red. In panel C, sagebrush steppe is shown in green, as mapped by DiPaolo et al. (2015). In panel D, the predicted burn probability (wildfire risk), as mapped by Short et al. (2020), with arrows weighted by size and direction towards highest probability which is centered east of the Monument boundary. The black dashed line illustrates a possible line of fire suppression and control, tying into sparsely vegetated lava fields in the center of the Monument, to protect sagebrush steppe in the southwestern portion of the Monument. In panel E, burn severity is displayed for the 2020 July Complex wildfires that swept across the eastern half of the Monument, from low to high severity illustrated by a green to red color gradient, showing how roads (black lines) were used to control fire spread. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

with some weed invasion but intact community structure and function) NPS sagebrush ecosystems, and protected-area sagebrush generally, is a recurring theme central to contemporary sagebrush conservation that can be facilitated in part by our assessment and the rankings of parks by the amounts of sagebrush vegetation within each park (Table S1).

Inferential limits to our range-wide analysis include uncertainties in GAP protected-area status designations. We suspect that some multi-use lands designated as level 2 inflate the amount of actual protected area lands dedicated to biological diversity protection and understate the potential footprint and conservation capacity of NPS sagebrush ecosystems. The 30-m pixel fractional component characteristic of the description of sagebrush ecosystems extent data source (Rigge et al., 2020) we used may also contribute to an overestimate of functional sagebrush ecosystems within NPS and across the matrix of jurisdictions examined within the GAP protected area database, especially in burned areas where sagebrush overstory cover is scarce (Applestein and Germino, 2021). The contiguity of sagebrush is an important consideration, and spatial resiliency (Chambers et al., 2019) arising from the preservation of large intact tracts of sagebrush shrublands and steppe is not necessarily reflected in our assessment of net overlap. We suggest that our list of 71 parks be more closely examined, emphasizing the ~40 parks with substantial amounts of apparent sagebrush ecosystems (Table S1), for consideration as comprising the network of NPS sagebrush ecosystems parks that collaborate and leverage expertise and resources to address common challenges and opportunities. Spatial configuration of mapped sagebrush ecosystems will be an important additional consideration in prioritization.

4.2. Park-scale evaluations

Sagebrush steppe landscapes in the five NPS units that occur in the Columbia Basin and Snake River Plain were approximately split between low and moderate resilience and invasion resistance, with only a small proportion of high resiliency areas. This was consistent with range wide patterns (see 4.1). There was high congruence between resilience and resistance classifications with both the coarse-grained evaluation provided by Bradford et al. (2019) that used STATSGO2 soils maps and the finer-grained NPS soils inventories that met SSURGO standards. The two datasets were often in agreement but with enough differences to warrant caution (e.g., by falsely concluding high resiliency in moderate or low resiliency sites and applying prescribed fire) in park-scale reliance on the coarse data, especially when SSURGO soil maps are available.

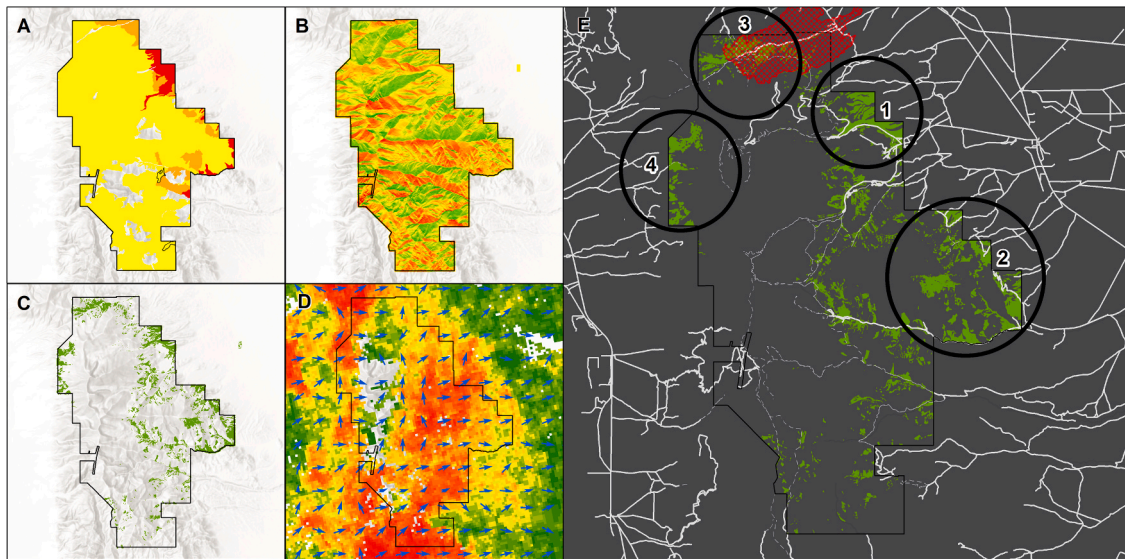


Fig. 9. An assemblage of geospatial data for Great Basin National Park, Nevada, that can be used to guide pro-active sagebrush steppe landscape prioritization and fire management planning. Panel A shows the resilience classification across the Monument by NPS soils inventory map unit polygons. Low resilience areas are shown in red, moderate-low resilience areas are shown in orange, and moderate resilience areas are shown in yellow. In panel B, a summary metric of topographic position ($\sin[\text{slope}] \times \cos[\text{aspect}]$) is displayed, revealing high topographic relief throughout the park. North-facing slopes are shown in green, flat ground is shown in yellow, and south-facing slopes are shown in red. In panel C, sagebrush shrublands are shown in green, as mapped by Cogan et al. (2012) for the park vegetation inventory. A mix of sagebrush ecosystems occur, dominated by relatively more resilient mountain big sagebrush (*A. tridentata* subsp. *vaseyana*) steppe at higher elevations and less resilient basin big sagebrush (*A. tridentata* subsp. *tridentata*) steppe along the eastern edge of the park. In panel D, the predicted burn probability (wildfire risk), as mapped by [Short et al. (2020)], with arrows weighted by size and direction outwards from highest probabilities which occur along mid-elevation slopes on both sides of the Snake Range mountains which traverse the park from north to south. In panel E, an example conservation strategy is displayed in which the lowest-resilient, most vulnerable extant sagebrush communities along the eastern edge of the park are ranked highest for protection (circles 1 and 2), in part because of the available road network for fire management operations and because of the adjacency to high fire risk. A 2016 wildfire (red polygon) burned into the northern edge of the park and damaged sagebrush vegetation (circle 3). North-facing slopes (panel B) could be practical targets for restoration activities there. Mountain big sagebrush communities along the western edge of the park (circle 4) are ranked lower because of relatively higher resiliency and operational complexity (rugged terrain and minimal road access). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

We found that these five parks have been experiencing wildfires at increasingly short intervals and increasingly large extents, consistent with broader trends (e.g., Balch et al., 2013; Westerling, 2016). Monitored areas of sagebrush steppe, as represented by the survey locations visited during 2009–2019 and mapped onto alluvial diagrams (Figs. 3–7) revealed clear correlations between resiliency, fire history, and annual grass invasion. Low resilience park sagebrush steppe has experienced multiple fires, heavy cheatgrass invasion, and substantial losses of sagebrush cover. Moderate and high resilience areas were much less likely to have burned and been invaded, however, moderate resilience areas that have burned were often invaded by cheatgrass. Sagebrush cover loss was less evident among burned moderate resilience areas, whereas sagebrush cover loss was complete in burned low resilience areas. These patterns have been reported in focused park-scale studies (e.g., Rodhouse et al., 2020) but our multi-park synthesis reinforced the generalizability of these patterns and commensurate conservation risks to NPS lands, broadly. Our findings add to those from other recent reports that repeatedly burned sagebrush steppe landscapes transition to self-reinforcing, novel annual grasslands with depauperate native plant diversity (Mahood and Balch, 2019; Ellsworth et al., 2020; Rodhouse et al., 2020), a process of homogenization (*sensu* Olden et al., 2004) that may be irreversible in many settings over ecological time scales. The fire-cheatgrass cycle that has broadly affected sagebrush ecosystems (D’Antonio and Vitousek, 1992), particularly in the Great Basin floristic region (Balch et al., 2013), is well established in sagebrush steppe parks and is likely to expand to other sage parks and refuges (e.g., on US Fish and Wildlife Service lands) rapidly given our range-wide resiliency assessment.

Topographic heterogeneity was highly variable in relation to fire frequency and extant cheatgrass and sagebrush cover. Although topography is well understood to mediate effective soil moisture and site productivity (Chambers et al., 2014), and hence local-scale resiliency and resistance, the amount of variation observed in our alluvial diagrams was somewhat surprising. Rather, we had expected to see, for example, distinct patterns of correlation between south slopes and cheatgrass cover as was reported, for example, in the John Day Fossil Beds National Monument (Rodhouse et al., 2020). However, when considered from our multi-park perspective, south-facing slopes were not more associated with cheatgrass cover and sagebrush loss than flat and north slopes. In fact, flat ground appeared to have burned less frequently and have maintained more sagebrush cover, possibly a result of the association between sagebrush shrubs and deeper soils (Miller et al., 2013), and the phenomenon of fires moving up and across steep slopes. Fire suppression activities along roads and accessible flat ground may also be reflected in these patterns. Such insights underscore the importance of considering

place-based idiosyncrasies (e.g., [Billick and Price, 2010](#)) resulting from historical legacies (e.g., land use prior to park establishment), terrain, and other local influences (e.g., meso- and micro-climates). Our study contextualizes individual parks and outlines general patterns and trends that can inform NPS strategies but also points to the need for park specificity in operational planning. Moreover, additional nuances that have been masked by pooling our data over years need to be explored in relation to water balance and other year effects, for example as was done by [Rodhouse et al. \(2020\)](#) for the John Day Fossil Beds National Monument. We encourage park managers to utilize topographic variation as an operational foothold for protection and restoration in landscapes that are inherently of low resilience and resistance, especially where sagebrush ecosystems are intact.

4.3. Park planning scenarios

In the Lava Beds National Monument scenario ([Fig. 8](#)), burn probability approximated the actual 2020 burn severity and the east-to-west direction of spread into of the park. Such data, if shown repeatedly to be generally predictive, can be widely useful to fire management operational planning scenarios when combined with resilience and resistance assessments, extant vegetation cover, and terrain and accessibility maps. In our demonstration of this for Great Basin National Park ([Fig. 9](#)), we considered where higher ignition risks that occur at mid elevations could threaten extant low-resilience sagebrush steppe at lower elevations along the edge of the park boundary where fire protection may be feasible. Our scenarios resonated with park resource management staff upon their review (D. Hays and M. Horner, National Park Service, personal communication) and the encircled areas in [Fig. 9E](#) have in fact already been targeted for active vegetation manipulations in pursuit of park preservation goals. Effective use of the kinds of mapped prioritizations that we demonstrate does also require detailed companion plans that direct specific activities towards managing fuels loads, suppression of invasive species, and fire management operations such as equipment staging and fire breaks. Broadly, guidance provided by [Chambers et al. \(2017\)](#) established the scientific framework for agency policies that can be more easily implemented when supported by our approach to mapping priorities and scenarios. The decision-support frameworks such as Ecologically-based Invasive Plant Management ([Sheley et al., 2010](#)), which are contextualized within the resilience and resistance framework, provide land managers with a suite of conceptual and practical tools. Finally, park plans such as those written for John Day Fossil Beds National Monument ([Hoh et al., 2015](#)) that are informed by these science decision frameworks but that outline the exact prescriptions on the ground guided by the kinds of mapped scenarios we have demonstrated provide for the actual integration of resilience and resistance concepts directly into park fire and vegetation management operations. The increasing availability of high-resolution and range-wide geospatial datasets that we and others (e.g., [Jones et al., 2020](#)) have assembled facilitate the rapid uptake and implementation of these decision-support frameworks into operational plans.

4.4. Conclusions

We used a hierarchical approach to evaluate and operationalize the apparent resilience and resistance of sagebrush ecosystems in national parks, first by providing a broad range-wide overview to contextualize park-specific patterns and planning scenarios. Our results have conservation implications beyond NPS park borders. The precariousness of NPS sagebrush ecosystems resulting from fire-driven state transitions to annual grasslands applies to non NPS lands as well, albeit with the same caveats previously made about

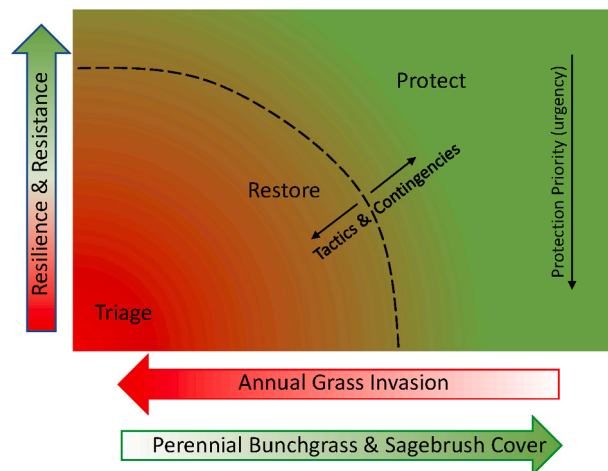


Fig. 10. Conceptual model of bi-variate decision space along the axes of resilience and resistance and vegetation cover (as a proxy for site condition and intactness) that can aid National Park Service sagebrush ecosystem conservation decisions. The relative sizes of the decision space associated with protection, restoration, and triage choices, represented by the dashed curved line, is dynamic and heavily influenced by tactical capacities and other park contingencies. Sites that map on to the bottom right corner of the diagram (i.e., low resilience but relatively intact) emerge as requiring urgent fire protection. We envision that these axes might be quantified so that park management units can be plotted and multiple contingency scenarios explored.

place-based idiosyncrasies and potential exceptions. The evidence is clear that fires, including both prescribed and unplanned, pose an existential threat to most sagebrush ecosystems, despite demonstrated fire resiliency among some foundation species such as the fire re-sprouting shrubs (e.g., *Gutierrezia sarothrae* [Mata-Gonzalez et al., 2018]) and perennial bunchgrasses. The risks of transition to ecologically novel annual grasslands and commensurate losses of sagebrush-associated biodiversity outweigh potential benefits of fire to those species. Alternative management and restoration practices that can increase resiliency and invasion resistance include mechanical thinning and mowing that check woodland encroachment and act as fire breaks, reseeding and transplanting, and in unique circumstances also some creative uses of livestock grazing to reduce fuels (e.g., Davies et al., 2015, but see Pyke et al. (2016)). However, such activities are difficult to do at scale, especially across very large and rugged terrain, and may not be permissible in protected areas (particularly livestock grazing). Many of these practices also can facilitate annual grass invasion, especially in low-resilience sites (e.g., Pyke et al., 2014). Furthermore, expensive restoration investments are themselves also at risk of subsequent loss due to wildfire (Shinneman et al., 2019). Therefore, strategic prioritization and protection of remaining intact sagebrush ecosystems emerges as the conservation imperative, especially for protected areas that are managed for long-term biodiversity preservation goals. This will require difficult decisions to triage some protected areas, at least temporarily and until capacity exists. Our step-wise scientific assessment of 1) the sagebrush ecosystem resiliency across the US national park system, 2) groups of parks with comparable data contextualized by the broader assessment, and 3) highly detailed mapped prioritization and fire protection scenarios of park landscapes will greatly facilitate meeting this conservation strategy. In support of this goal, we contribute a conceptual framework for NPS decision-makers (Fig. 10) that reflects this dynamic interaction between the generalizable findings from our study (e.g., fire-driven invasion and sagebrush loss was highest in low-resilience parks) and the place-based contingencies that influence the actual conservation decisions taken. In Fig. 10, sagebrush conservation choices are broadly categorized as protection, restoration, and triage constrained by inherent resiliency (y-axis) and site conditions (x-axis; inferred by proxy from vegetation cover). Heavily invaded low-resilience sites fall within the triage corner of the diagram, whereas intact sites fall within the protection corner of the diagram. The thresholds for protection, restoration, and triage choices is heavily dependent on park contingencies, including tactical capacities and biophysical factors like topography so that the relative size of the protection decision space will vary for different parks and under different scenarios. Heightened fire protection urgency is notable in those few places that map as low resilience but have not yet been lost to annual grass invasion (the lower right corner of the diagram; Chambers et al., 2019). However, over longer time scales, defense of intact high resilience areas may be more successful. We envision that both axes of this diagram can be quantified such that park management units could be mapped on to this decision diagram, allowing for contingency scenarios to be explored and optimized in a dynamic and structured process.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data for the range-wide evaluation are available on-line from Rigge et al. (2020) and USGS (2017). Data for park-scale evaluations and park planning scenarios are available from Appendix A.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at [doi:10.1016/j.gecco.2021.e01689](https://doi.org/10.1016/j.gecco.2021.e01689).

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