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Will It Burn? Characterizing Wildfire Risk for the Sagebrush Conservation Design☆,☆☆

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ABSTRACT

For millennia, wildfire has helped shape the sagebrush biome of the western United States. Over recent decades, historical fire regimes have been altered by several factors, including contemporary climate and fuel conditions, leading to the loss or degradation of hundreds of thousands of hectares (ha) of sagebrush each year. In response to wildfire threats, extensive fuel treatment investments are proposed across the region. To help inform strategic and cost-effective investments, we conducted a quantitative assessment of wildfire risk for the sagebrush biome. We used a geospatial fire modeling approach, customized for the sagebrush biome, to estimate spatially explicit burn probability and expected average annual area burned within three Sagebrush Ecological Integrity classes under the Sagebrush Conservation Design: Core Sagebrush Areas (CSAs), Growth Opportunity Areas (GOAs), and Other Rangeland Areas. We further used indices of ecological resilience to disturbance and resistance to invasive grasses to characterize fire risk and recovery potential. Our approach indicates that nearly 530,000 ha are likely to burn in a typical contemporary fire year across the highest integrity Sagebrush Ecological Integrity classes (7% in CSAs and 31% in GOAs). Of the CSAs and GOAs likely to burn, nearly 9 000 and 66 000 ha, respectively, are expected to have low resilience or resistance and therefore highest loss potential. Cost-effective conservation investments should include wildfire protection for high-integrity sagebrush with low resilience or resistance. Protection objectives may be met with strategically placed fuel breaks intended to enhance fire prevention and containment efforts. Fuel treatments, including prescribed fire and mechanical activities outside of fuel breaks, are by contrast best suited for high-integrity areas with relatively high resilience and resistance. Those activities should be risk-informed and intended to maintain or improve ecological integrity and resilience to wildfire rather than to exclude fire altogether.

Introduction

Wildfire is one of several environmental processes that have long helped shape the various sagebrush (*Artemisia* spp.) ecosystems across the western United States. Although historical fire regimes and their impacts on landscape-scale composition and distribution of sagebrush ecosystems are not fully understood, they were likely highly variable across the sagebrush biome (Baker 2013; Crist et al. 2023). Ecological gradients such as elevation, seasonal precipitation, and topography vary widely across the biome, strongly influencing fire regimes (Brooks et al. 2015). Generally, sagebrush ecosystems occurring at higher elevations have evolved to be more fire-adapted and can recover relatively quickly after fire. Other sagebrush ecosystems, such as those at lower elevations, have experienced much longer fire return intervals, which has resulted in a lack of fire-adapted species that are inherently slow to recover after disturbance. Many landscapes in the eastern portion of the biome are less fire prone due to summer or monsoonal pre-

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cipitation that tends to extinguish ignitions. In the western part of the biome, most precipitation occurs in the winter, with summers dry and conducive to burning. In general, wildfire likelihood is greater where summers are drier than winters, where ignition frequency is higher, and where fuels are more continuous and less limiting.

Because of a number of drivers, contemporary fire regimes show significant departure from historical conditions across large portions of the sagebrush biome. In recent decades, uncharacteristic fire frequency and behavior caused by the expansion of nonnative annual grasses (e.g., cheatgrass [*Bromus tectorum*]) have become the greatest threat to sagebrush ecosystems, especially in the western portion of the biome. A greatly concerning impact of uncharacteristically frequent fire is the transition from native sagebrush-perennial grass communities to highly flammable invasive, nonnative, annual grasslands (Davies et al. 2012; Pyke et al. 2016; Bradley et al. 2018; Fusco et al. 2019). These community transitions are likely permanent due to the low probability of reestablishing native perennial plants in nonnative annual grass-dominated communities (Mazzola et al. 2011; Germino et al. 2016). Moreover, these grasses can form extensive and continuous fine fuel loads that promote frequent fire and the continued expansion of invasive, nonnative grasses (Davies and Nafus 2013; Fusco et al. 2019; Smith et al. 2023a, 2023b).

Broad-scale invasion of nonnative grasses coupled with human activities and climate change have accelerated wildfire cycles, increased fire size and severity, and lengthened fire seasons in many sagebrush ecosystems (Bradley et al. 2018; Fusco et al. 2022) to the point that current wildfire-management practices and postfire restoration efforts may not keep up with the scale of sagebrush ecosystem loss (Crist, 2023; Crist et al. 2023). From 1984 to 2020 alone, wildfires have burned over 9 million (M) ha (22.3 M ac, or on average 619 000 ac/yr) of sagebrush-dominated lands, primarily in the Great Basin (Crist et al. 2023; Fig. 1). Current wildfire trends reflect more frequent, more severe, and/or larger wildfires than had occurred before EuroAmerican settlement (Balch et al. 2013; Bukowski and Baker 2013; Brooks et al. 2015; Fusco et al. 2019; Shinneman et al. 2021).

More frequent, extensive, and severe wildfires will require greater resources for fire prevention, fire suppression, and postfire restoration activities, while also impacting critical ecosystem services, sagebrush-dependent wildlife habitat and populations, economic and recreational opportunities, and cultural traditions (Crist et al. 2023). Addressing the causes and impacts of altered wildfire regimes on sagebrush landscapes is challenging, but essential to long-term conservation and retention of the high-value resources these landscapes provide.

Quantitative wildfire risk assessments that consider both wildfire likelihood and consequences to highly valued resources (Scott et al. 2013; Chuvieco et al. 2023) have been conducted at a variety of spatial scales in the United States (Hawbaker et al. 2023). The quantification and display of contemporary wildfire risk are valuable for understanding the nature and extent of the fire threat and ensuring that cost-effective risk mitigation investments are made, including restoration and hazardous fuel treatments. In the Great Basin, for example, the Bureau of Land Management is implementing a network of linear fuel breaks extending up to 17 703 km (11 000 miles; BLM 2020), and wildfire risk assessments can help ensure that strategic and cost-effective investments are prioritized therein.

Here, we used a common geospatial wildfire risk modeling approach, customized for the sagebrush biome, to estimate 1) burn probability (BP) and 2) expected average annual area burned for the three Sagebrush Ecological Integrity (SEI) classes that underpin the Sagebrush Conservation Design (hereafter SCD; Doherty et al. 2022a). We leveraged indices of ecological resilience to disturbance and resistance to invasion by nonnative annual grasses to further characterize fire risk and recovery potential. The goal of this assessment is to provide information and context that can help prioritize actions needed for wildfire management and conservation across the sagebrush biome. It is intended to help “defend the core, grow the core, and mitigate impacts” as advocated in the SCD (Doherty et al. 2022a; Doherty et al. this issue). This work expands upon the assessment of Chambers et al. (2023b) by including biome-wide estimates of wildfire probability for SEI classes and estimates of expected average annual area burned under contemporary conditions. This approach should be useful for identifying the relatively high-integrity sagebrush lands with the greatest potential for degradation or loss from burning.

Methods

Study area

Our analysis area spanned the full geographic extent of the US sagebrush biome (~176 M ha/435 M ac), as delineated for the Sagebrush Conservation Strategy of the Western Association of Fish and Wildlife Agency (Jeffries and Finn 2019; Fig. 1). The sagebrush biome is an expansive dryland region covering portions of 13 western/midwestern US states and comprising three broad regions: the Southern Great Basin, Great Plains, and Intermountain West (Doherty et al. 2022a). Although the full extent of the study area covers ~176 M ha (~435 M ac), only ~99 M ha (~245 M ac) are sagebrush dominated lands; the remainder (44%) comprises nonsagebrush areas (e.g., forests, croplands, water bodies, urban areas) (Fig. 1).

Data sources

BP

We acquired the BP data from Short et al. (2023) in 270-m resolution raster format (Fig. 2A). The BP data were generated using a geospatial Large Fire Simulation (FSim) system (Finney et al. 2011) that has been used for several national and regional risk assessments (Hawbaker et al. 2023). The FSim system includes modules for weather generation, wildfire occurrence, fire growth, and fire suppression. FSim is designed to simulate the occurrence and growth of large wildfires under tens of thousands of hypothetical contemporary fire seasons in order to estimate the probability of a given area burning under current landscape conditions and management practices. The Short et al. (2023) BP data were generated using a landscape (i.e., vegetation, fuel) dataset covering ~181 M ha (447 M ac). The modeling landscape was derived from ca. 2016 vintage (version 2.0.0) LANDFIRE data (www.landfire.gov) that were updated to ca. 2020 fuel conditions after accounting for recent disturbances, including wildfires. The surface and canopy fuel data were further modified by subject matter experts to better reflect expected fire behavior in the sagebrush biome, including influences from exotic annual grass invasion and conifer expansion (Short et al. 2024). FSim was run for the sagebrush biome using 31 pyromes, which represent areas of relatively homogeneous contemporary fire regimes (Short et al. 2020; Fig. S1; available online at doi:10.1016/j.rama.2024.08.014), as separate simulation units. Model results were objectively evaluated via comparison with historical wildfire patterns and statistics within each pyrome. This evaluation is part of the FSim calibration process, whereby simulation inputs are adjusted until the validation statistics fall within an acceptable range (70% confidence interval) of historical reference values. Statistics used as validation targets were: 1) mean annual area burned, 2) mean large fire size, and 3) mean number of large fires per M burnable ha (Short et al. 2023; Table S1;

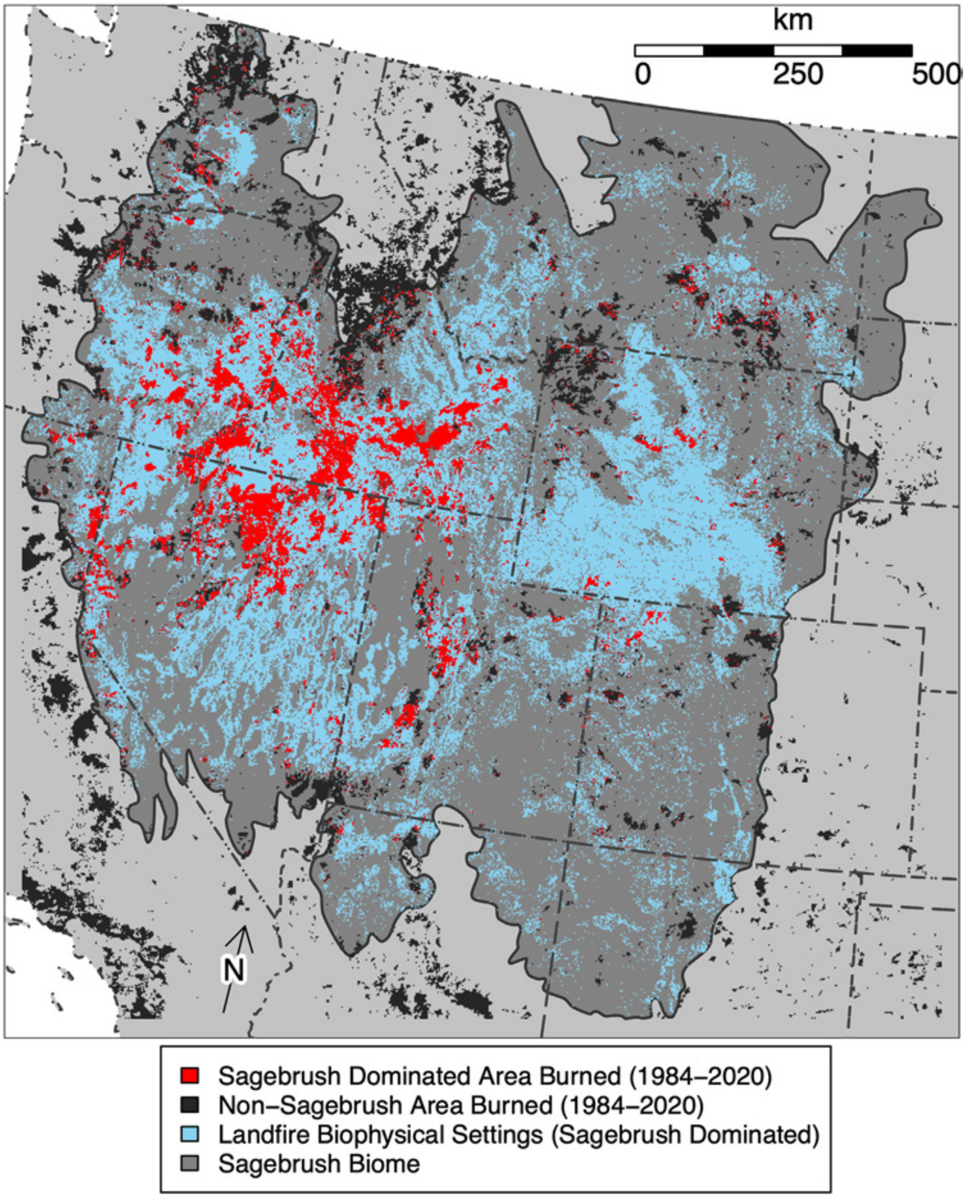

Figure 1. Map of the sagebrush biome (Jeffries and Finn, 2019; dark gray fill) and wildfire area burned during 1984–2020 in the western United States (adapted from Crist et al. 2023). Sagebrush-dominated landscapes are shown in blue per Crist et al. (2023). Area burned is indicated with red fill if in sagebrush dominated areas, and with black fill otherwise (i.e., in forests, woodlands, and nonsagebrush lands).

available online at doi:10.1016/j.rama.2024.08.014; Fig. S2; available online at doi:10.1016/j.rama.2024.08.014). The reference period for validation targets was the most recent 15 yr (2006–2020) included in the Fire Program Analysis Fire-Occurrence Database (Short 2022). This period best represents current conditions given ongoing changes/trends (nonstationarity) in wildfire activity across the sagebrush biome over recent decades (Short et al. 2023). Pixel values in the BP raster indicate the number of times that cell was burned by an FSim modeled fire, divided by the total number of hypothetical annual weather scenarios simulated. The BP data indicate the contemporary annual probability of a given pixel burning.

SEI

The SEI dataset (Doherty et al. 2022) was compiled as part of a landscape conservation design effort for the sagebrush biome and is the result of a spatially explicit analysis that characterized ecological integrity using a suite of thresholded factors for percentage cover of sagebrush, perennial grasses, annual grasses, and conifers, plus an index of human modification (Doherty et al. 2022). These factors were combined to produce one value representing SEI for each 30 m grid cell, then thresholded to categorically delineate three spatially distinct classes of ecological integrity across the sagebrush biome (as defined by Jeffries and Finn 2019). The SEI classes, in order of decreasing ecological integrity, are 1) Core Sagebrush Areas (CSAs), 2) Growth Opportunity Areas (GOAs), and 3) Other Rangeland Areas (ORAs). Higher integrity areas are characterized by abundant sagebrush, well-developed native understories, and minimal presence of invasive grasses and human modification. CSAs represent places where high-integrity patches converge to create large, intact, functioning sagebrush landscapes. GOAs are moderately high ecological integrity areas and represent relatively functioning sagebrush ecosystems impacted by one or more evaluated landscape threats. ORAs have low integrity val-

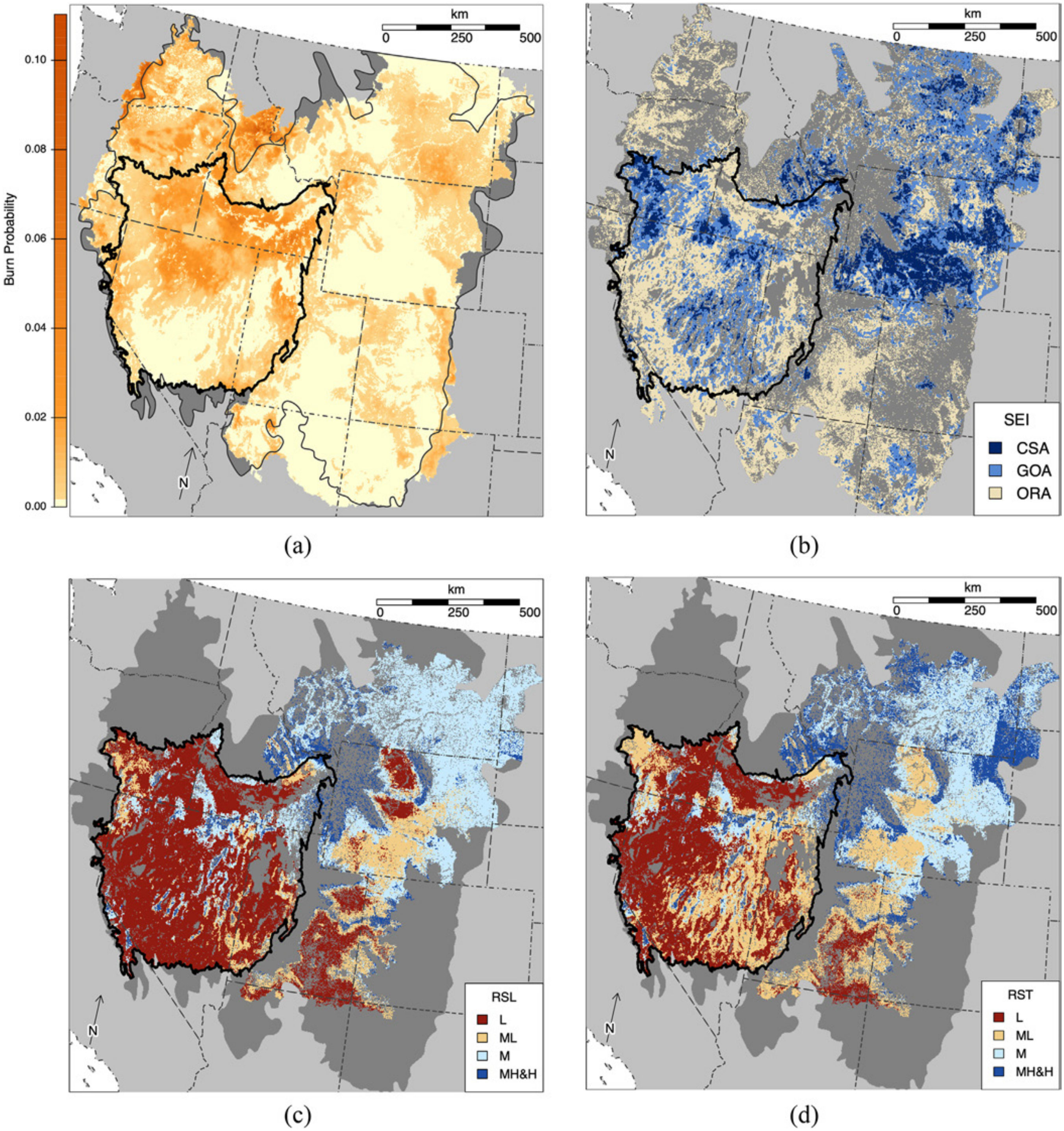

Figure 2. Maps of continuous burn probability (**A**; Short et al. 2023) and classed Sagebrush Ecological Integrity (SEI; **B**; Doherty et al. 2022b), resilience to disturbance (RSL; **C**; Chambers et al. 2023a), and resistance to invasion (RST; **D**; Chambers et al. 2023a) data used in this analysis. Areas in lower resilience and resistance classes (warmer colors in **C** and **D**), which predominate in the Great Basin (solid black line in **C** and **D**), have relatively poor potential for recovery following disturbances like wildfire and are likely to be invaded by nonnative annual grasses, like cheatgrass. The SEI data (**B**) cover the entire extent of the sagebrush biome as delineated by Jeffries and Finn (2019). The BP (**A**) raster was clipped to the Jeffries and Finn (2019) extent (black outline and dark gray fill in A, dark gray fill elsewhere) for analysis, with data available for 94% of the biome. Assessments of burning rates in low resilience or resistance areas were restricted to the 37M ha (91M ac) within which those conditions were mapped by Chambers et al. (2023a, 2023b; panels **C** and **D**). CSA indicates Core Sagebrush Area; GOA, Growth Opportunity Area; L, low; M, moderate; MH&H, moderately high to high; ML, moderately low; and ORA, Other Rangeland Area.

ues due to a higher degree of threats impacting a large portion of the area. Doherty et al. (2022a) produced SEI maps for historical time periods from 1998 to 2020, and for one future time period (2030–2060). We used the dataset representing the most contemporary period, 2020, for our analyses (Fig. 2B). The full extent of the SEI dataset covers ∼176 M ha (435 M ac) of which ∼99 M ha (245 M ac) are sagebrush dominated lands; the remainder (44%) comprises nonsagebrush vegetation types (e.g., forests, croplands, water bodies, urban areas) within the biome extent.

Table 1
Estimates of 1) area (ha) of the sagebrush biome within annualized burn probability and Sagebrush Ecological Integrity classes and (2) expected average annual area burned by SEI class.

		CSA[1,2] [Low R|R]	GOA [Low R|R]	ORA [Low R|R]	Overall [Low R|R]
Burn Probability Class	Low 0–0.0001	628 257 [36 485]	1 535 828 [319 729]	6 316 125 [2 845 208]	20 708 563 [3 589 213]
	Moderately low >0.0001–0.001	5 780 392 [576 349]	8 674 192 [2 700 856]	11 454 557 [4 720 907]	37 884 170 [8 838 267]
	Moderate >0.001–0.01	6 458 027 [1 379 199]	17 123 624 [4 403 460]	20 649 379 [6 222 725]	79 335 597 [14 102 807]
	Moderately high and high >0.01–1.0	669 215 [181 562]	5 476 424 [2 633 988]	11 655 178 [7 088 199]	27 241 293 [10 550 241]
	All	13 535 891 [2 173 595]	32 810 068 [10 049 032]	50 075 238 [20 877 039]	165 169 623 [37 080 527]
Expected average annual area burned (ha)		34 820 [8 721]	164 763 [65 164]	325 881 [182 214]	837 886 [274 854]

[1] Data are model (FSim) outputs per Short et al. (2023). Values in brackets indicate the area mapped as either low resilience or resistance (R|R) and therefore most susceptible to degradation or loss from burning.
[2] CSA indicates Core Sagebrush Area; GOA, Growth Opportunity Area; and ORA, Other Rangeland Area.

Resilience and resistance

To aid in assessing risks and prioritizing areas for conservation and restoration, Chambers et al. (2023a) categorized landscape ecological resilience to disturbance and resistance to invasion by nonnative annual grasses across seven level III environmental protection agency (EPA) ecoregions of the sagebrush biome (i.e., ~83 M ha [205 M ac]; Figs. 2C and 2D). Their models were built on spatial measures of static soil moisture and temperature, employing new indicators based on climate and soil water availability variables derived from process-based ecohydrological simulations. The top indicator variables (mean temperature, coldest month temperature, climatic water deficit, and summer and driest month precipitation) were used to generate paired spatial data layers for resilience and resistance at 30-m resolution. The resilience and resistance datasets are classified into four categories of increasing resilience and resistance: 1) low, 2) moderately low, 3) moderate, and 4) moderately high to high. Higher resilience and resistance areas are typified by relatively cool and moist conditions with low climatic water deficits, which enhance potential for native recovery after disturbance and inhibit annual grass invasion (Chambers et al. 2023a). In contrast, postfire recovery potential of sagebrush and perennial grasses is lowest and cheatgrass cover is generally highest in low resilience or resistance areas (Chambers et al. 2023b). The resilience and resistance data have shown promise for use in combination with the assessments of current sagebrush ecosystem conditions, including SEI, to develop management prioritization schemes (Chambers et al. 2017, 2023a, 2023b).

Data preparation and analysis

We took several steps to align the three input datasets and prepare them for analysis. The Jeffries and Finn (2019) biome map was rasterized (30-m resolution), and the BP in its native 270-m resolution was downscaled to match the 30-m resolution of the other rasters. All datasets were reprojected as necessary to align with the SEI raster (Doherty et al. 2022b; Projection = NAD83 / Conus Albers [EPSG:5070]). The BP, SEI, resilience, and resistance datasets were then clipped to the Jeffries and Finn (2019) extent, excluding any areas outside the sagebrush biome perimeter from further analysis. Areas of low resilience or resistance are most susceptible to degradation or loss after fire, so we created a single binary raster identifying areas where either resilience or resistance (hereafter R|R) was low. The resulting low R|R raster encompassed 37 M ha (91 M ac). For this and all other spatial and statistical analyses performed herein, we used the terra package (Hijmans 2023) in R v. 4.3.1 (R Foundation for Statistical Computing, Vienna, Austria; R Core Team 2023).

For ease of interpretation, we created a classed version of the continuous BP dataset using breaks that produced four categories similar to the R|R data: 1) low, 2) moderately low (mod-low), 3) moderate, and 4) moderately high to high (mod-high) (Fig. 3A). The low probability class included values up to 0.0001, which represents a 1-in-10 000 annualized probability of burning under contemporary conditions for its maximum pixel value. The maximum pixel values in the mod-low, moderate, mod-high, and high categories were 0.001, 0.01, 0.1, and 1, respectively, such that each represented a ten-fold increase in BP. However, the maximum BP value for the entire analysis area was 0.112, and there were very few pixels in the highest (>0.1) category—hence the reason that the moderately high and high classes were combined to form the mod-high class.

For each BP class, we calculated the area within each of the three rangeland SEI categories (CSAs, GOAs, and ORAs) first in their entirety and then only considering areas with low R|R. The extent of the R|R dataset is more restricted than either the BP or SEI products (Fig. 2), and low R|R assessments were accordingly constrained.

We also used the continuous BP values (Fig. 2A) to calculate the expected average annual area burned in each SEI class and SEI-low R|R combination, by first multiplying the BP value of each raster cell by the area of the cell (0.09 ha [0.22 ac] at 30-m resolution), and then calculating the sum of all cells in each analysis unit (Scott 2014).

Results

Because of some mismatch in the BP and SEI extents (Figs. 2A and 2B), wildfire probability could only be summarized across ~165 M ha (94%, 408 M ac) of the sagebrush biome as delineated by Jeffries and Finn (2019). CSAs, GOAs, and ORAs represented 8%, 20%, and 30% of the overall analysis area, respectively (Table 1). Of the ~99 M ha (245 M ac) of sagebrush lands analyzed, 9%, 27%, 46%, and 18% were characterized as low, mod-low, moderate, and mod-high BP, respectively. Across the SEI classes, only 5% of the area in CSAs were classified as mod-high BP, with 48% in moderate, 43% in mod-low BP, and only 5% in low BP. Seventeen percent of the area in GOAs were classified as mod-high BP, 52% as moderate BP, 26% in mod-low BP, and 5% in low BP. Of all SEI classes, ORAs were composed of the greatest percent of mod-high (23%) and low (13%) BP classes, with 41% and 23% in moderate and mod-

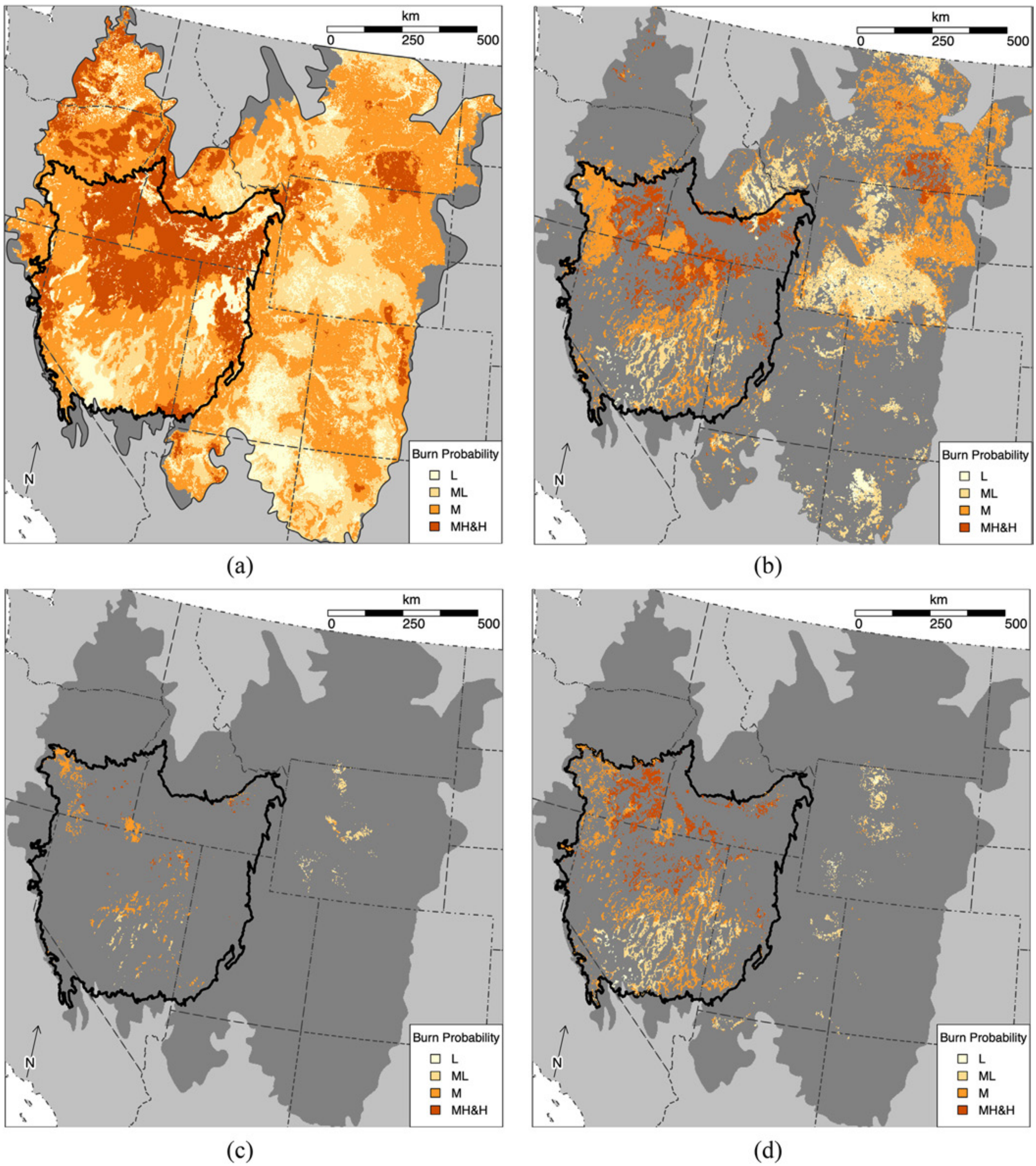

Figure 3. Maps of classified annualized burn probability showing the full extent within the sagebrush biome as delineated by Jeffries and Finn (**A**; 2019; black outline and dark gray fill in A; dark gray fill elsewhere), extent within Sagebrush Ecological Integrity Core Sagebrush Areas and Growth Opportunity Areas (**B**), extent within low resilience or resistance (R|R) Core Sagebrush Areas (**C**), and extent within low R|R Growth Opportunity Areas (**D**). Modeled burning rates of high-integrity Sagebrush Ecological Integrity classes with low R|R are not uniform across the landscape, with some of the highest fire risk apparent in the Great Basin (black outline). L indicates low; M, moderate; MH&H, moderately high to high; and ML, moderately low.

low classes, respectively. Mean BP in CSAs, GOAs, and ORAs was 0.0026, 0.005, and 0.0065, respectively.

Of the 37 M ha mapped as Low R|R, 6%, 27%, and 56% occurred in CSAs, GOAs, and ORAs, respectively (Table 1). Within the highest BP class (≥0.01, or greater than 1/100 annualized probability of a 30-m pixel burning), 27%, 31%, and 42% of CSAs, GOAs, and ORAs, respectively, were classed as low R|R. However, those may be conservative estimates because the resilience and resistance data do not extend across the entire domain for which the BP and SEI products are available (Fig. 2).

Our analysis suggests a contemporary average annual probability of ∼526 000 ha (1.3 M ac) burning under current landscape conditions across the three SEI classes, and ∼838 000 ha (2.1 M ac) burning across the entire 165 M ha (408 M ac) analysis area (Table 1). CSAs are expected to burn at a rate of ∼35 000 ha/y (87 000 ac/y) under average contemporary fire weather conditions. Another ∼165 000 ha (408 000 ac) is likely to burn in GOAs, with the remainder, ∼326 000 ha (806 000 ac), in ORAs. Approximately 37% of that impact is to CSAs (∼9 000 ha [22 000 ac]) and GOAs (∼66 000 ha [163 000 ac]) in low resilience or resistance categories. Expected annual area burned is not uniform across the landscape, with some of the greatest threats to low R|R CSAs and GOAs occurring within the Great Basin (Fig. 3).

Discussion

A sagebrush biome-wide assessment of wildfire risk for the SCD (Doherty et al. 2022a) offers a consistent means of understanding and comparing the likelihood of wildfire affecting valued resources. Here, the probability of burning is summarized for SEI classes, including high-integrity CSAs and GOAs, with focus on low resilience and resistance areas within these classes in order to account for likely degradation or loss where they exist. This assessment can be used by land managers and collaborators to identify the need for and to prioritize management activities aimed at reducing wildfire potential and/or the impacts resulting from wildfire. Combined with other research and analytical tools (e.g., Shinneman et al. 2022, 2023; Buchholtz et al. 2023a, 2023b; Boyd et al. this issue; Holdrege et al. this issue; Theobald et al. this issue; Wollstein et al. this issue; O'Connor et al, this issue) this assessment can help identify where fire may be a threat due to uncharacteristic fire frequency or extent due to the connectivity of invasive grass fuels, where wildfire can be a benefit by naturally maintaining sagebrush ecosystem processes, and where postfire recovery intervention may or may not be needed.

Geographically, BP varies widely across the entire sagebrush biome and across the three SEI classes with regional concentrations of higher, moderate, and lower probability (Figs. 2 and 3). This pattern aligns well with other research that quantified wildfire trends by ecoregion. Crist et al. (2023) highlighted trends toward increased wildfire area burned within some ecoregions of the sagebrush biome, even if an increase was not detected as significant or across all ecoregions. There is also agreement in ecoregional trends of increasing area burned, especially for the Great Basin, the Columbia Basin, and the Great Plains (Brooks et al. 2015; Chambers et al. 2017) due to expansion of invasive nonnative grasses (Fusco et al. 2019; Chambers et al. 2023c). Furthermore, these studies document that a disproportionately larger area has burned in the western portion (21%) of the sagebrush biome compared to the eastern portion (5%) (Crist et al. 2023). Our findings show a similar pattern, where higher BP is evident in the western part of the biome relative to the eastern portion (Figs. 2A and 3A).

Although we expect to see wildfire in a substantial portion of the western sagebrush biome, the consequences of wildfire depend not just on SEI classification, but also on the area's resilience to disturbance and resistance to nonnative invasive annual grasses (R|R; Chambers et al. 2023a). We found that a majority of the CSAs and GOAs characterized as low R|R and relatively high fire risk are located in the Great Basin (Figs. 3C and 3D). Much research has documented a substantial increase in wildfire frequency and extent due to the large expansion of nonnative invasive grasses in this ecoregion (D'Antonio and Vitousek 1992; Brooks et al. 2015; Fusco et al. 2019; Crist 2023). Risk is exacerbated given that these sagebrush communities historically experienced wildfire infrequently, are composed of plant species that are not fire adapted, and are at a higher risk of invasion by nonnative grasses shortly after fire (Brooks et al. 2015; Chambers et al. 2017). In addition, these CSAs and GOAs are smaller patches surrounded by larger areas of degraded sagebrush dominated by invasive nonnative grasses. Buchholtz et al. (2023a, 2023b) found a similar landscape pattern of intact sagebrush patches surrounded by connected fuel beds of invasive nonnative grasses, and the authors provide a landscape-scale prioritization model for fragmenting this fuel connectivity. Building upon Buchholtz et al. (2023a, 2023b) and Chambers et al. (2023b), which focused on resilience and resistance, we recommend placing fuel treatments in the surrounding or adjacent ORAs to protect the higher integrity CSAs and GOAs with low R|R from uncharacteristic fire.

Our results indicate that across all SEI classes, a relatively low percentage of area in the CSAs (5%) and GOAs (17%) fall within the highest BP class (mod-high). These results are not surprising given the spatial factors used to delineate these areas for the SCD. The CSAs and GOAs delineations are based on “intactness,” measured as a higher presence of sagebrush and perennial grasses, a very low presence of invasive annual grasses, and “lack of disturbance,” measured as a low presence of human modification. Wildfire occurrence is used to adjust ecological integrity values lower so that the effects of fire are incorporated in the delineations of the SEI classes (Doherty et al. 2022a). In comparison, the ∼12 M ha (30 M ac) of ORAs (Table 1) with high wildfire likelihood are closer to developed areas and are highly fragmented with roads, increasing their susceptibility to human ignitions. In addition, some areas tend to have a higher presence of nonnative grasses that promote uncharacteristically frequent fire, and some of the areas have burned in the recent past. Research has shown that increased ignition frequency and presence of invasive-annual-grass-dominated areas occur in proximity to developed areas (Fusco et al. 2016; Balch et al. 2017; Fusco et al. 2022), thereby contributing to overall BP in these areas.

This SEI-based assessment can help identify areas where certain low R|R CSAs and GOAs may be at a greater wildfire risk due to their adjacency with the more fire-prone ORAs class, which may increase the likelihood of fire transmission (i.e., wildfire igniting in one class and burning into an adjacent class). Where investments are made in CSAs and GOAs to achieve the goal of creating larger patches of intact sagebrush areas and increasing sagebrush connectivity (see Theobald et al. this issue), investments should also be made within adjacent ORAs with relatively high BP or fire transmission probability to reduce the chance of fire spread into adjacent low R|R CSAs or GOAs and further protect these areas.

The expected average annual burned area of ∼526 000 ha (1.3 M ac) in the SEI classes and ∼838 000 ha (2.1 M ac) for the near full extent of the sagebrush biome helps provide insight into how much sagebrush may burn in the future and where future burns may be concentrated. Our results indicate that 37% of the expected area burned in CSAs and GOAs is likely to occur in the low R|R condition. These measures can be used to inform wildland fire preplanning and positioning of firefighting resources, especially in concert with more real-time seasonal outlooks of fire likelihood (e.g., Smith et al. 2023a). The FSim BP model calibration is based on historical fire activity patterns over a recent 15-yr period across the sagebrush biome (Short et al. 2023). Caution is advised in the interpretation and use of expected area burned estimates because there is much variability around the mean (as with nearly all historical data), and the landscape used in simulation is static, reflecting ca. 2020 conditions. Our estimates of "annual" area burned do not predict future conditions with regard to landscape/fuels or climate. However, the recent 15-yr historical window (2006–2020) used for model calibration and validation (Table S1; Figs S1 and S2) corresponds to a period of relatively high fire activity in terms of area burned in the sagebrush biome, including a few years with exceptionally large fires (Crist et al. 2023). Studies of temporal patterns of large wildfires within bioclimatic regions suggest the strong influence of interannual climate variability on area burned (Littell et al. 2009; Balch et al. 2013; Pilliod et al. 2017). Other research works, such as Fusco et al. (2019), Bradley et al. (2018), and Brooks et al. (2015), quantify increasing wildfire trends compared with historical activity due to the extent of the invasive grass-fire cycle expanding across the sagebrush biome and should provide additional context within which to consider our findings. In addition, Holdrege et al. (this issue) show how the interaction between projected climate change, which creates conditions conducive to more wildfire, combined with invasive annual grass expansion will likely increase BP in the future.

Our analysis is based on BP, SEI, and resilience/resistance datasets that represent ca. 2020 landscape conditions. Our assessment has potential synergy with Smith et al. (2023a) wherein a dynamic fire risk model for the Great Basin was developed based on wildfire trend correlation with historical annual weather patterns conducive to invasive grass productivity. In addition, our analysis aligns well with BLM's National Fire Risk Assessment (2019), for which we found similar but slightly lower estimates of total area with higher, moderate, and lower wildfire risk within SEI classes when we applied the same analyses used here. The BLM assessment used different methodology and included other geospatial factors (e.g., national-scale BP, wildland urban interface, altered fire regimes, invasive cover, and conifer expansion) in quantifying wildfire risk. Lastly, an overlay of the SEI classes with the United States Department of Agriculture, Forest Service, Wildfire Crisis Strategy (2022) "firesheds" revealed relatively high fire probability CSAs, GOAs, and ORAs primarily in the Snake River Plain and northern Great Basin regions. There are a number of wildfire risk assessments with different methodologies and factors available for use in wildland fire management (Hawbaker et al. 2023), and each assessment will have different spatial and tabular results of fire risk. A comparison among them should be made to ensure that management decisions are based on a holistic perspective of fire risk.

Implications

The National Cohesive Wildland Fire Management Strategy (2023) specifies three goals for wildland fire management programs: 1) resilient landscapes, 2) fire adapted communities, and 3) a safe, effective, risk-based wildland fire response. Our wildfire risk analysis can be used to help achieve these goals at a landscape level by promoting fire resilient sagebrush ecosystems across the biome. Applying landscape level approaches to reduce fire risk where necessary will require stronger integration and coordination across state, tribal, private, and federal lands, as well as more integration between invasive management and wildland fire management programs (Maestas et al. 2023). This assessment can be used to prioritize SEI classes and resilience/resistance areas for wildfire management and help determine the most appropriate types of actions for wildfire prefire planning and fire prevention strategies, fire response and suppression strategies, and vegetation management and postfire recovery efforts that will be the most effective at reducing fuel loads and restoring landscape resilience prefire and postfire across the entire biome.

Wildland fire management strategies combined with other management actions (e.g. see Boyd et al. this issue; Holdrege et al. this issue; O'Connor et al, this issue; Reinhardt et al. this issue; Theobald et al. this issue; Wollstein et al. this issue) to reduce invasive nonnative grass expansion, conifer expansion, and human modification offer new concepts for managers to achieve the conservation and restoration tenets outlined in the SCD (Doherty et al. 2022; Doherty et al. this issue) and is complementary to Crist et al. (2019). For example, Boyd et al. (this issue) developed a framework for where GOAs should be prioritized for restoration and reducing invasive annual grasses. These concepts can be applied in or coordinated with fuels management programs. In addition, Shinneman et al. (2023) provides innovative ideas for fuels management in sagebrush ecosystems through the use of the resist, accept, direct framework for landscape-level management. Below, we provide examples of holistic wildland fire strategies that can be applied to each of the SEI classes with higher fire probability.

CSAs:

- Use Early Detection and Rapid Response strategies for removing invasive nonnative plants that have a strong influence on fire regimes to maintain SEI.
- Implement or modify monitoring programs to collect data on vegetation conditions through field surveys, drones, and/or Landsat imagery (Pastick et al. 2021) to evaluate landscape conditions and identify when restoration may be warranted.
- Prioritize wildfire suppression resources for multiple fires that may occur outside of the wildland fire urban interface where appropriate and possible.
- Allow for natural recovery after wildfire where SEI classes have high to moderate levels of R|R and monitor for nonnative plant invasions.

GOAs:

- Prioritize where GOAs should be targeted for coordinated strategic prevention, control, and eradication of invasive grass fuels (e.g., Boyd et al, this issue).
- Implement restoration treatments needed to restore these areas, especially where GOAs are located next to CSAs to create larger continuous intact sagebrush patches.
- Increase firefighting capacity in rural areas through rural fire fighting partnerships.
- Focus postfire recovery efforts on invasive resistant strategies.
- Implement or modify monitoring programs (see above in CSAs) to continue to evaluate landscape conditions and identify when intervention (e.g., restoration investments) may be needed.

ORAs:

- Conduct needed vegetation treatments (e.g., fragment invasive grass fuel connectivity or reduce expansion) to reduce transmission of wildfire to CSAs and GOAs.
- Prioritize ORAs for siting of fuel treatments and fuel breaks that are adjacent to CSAs and GOAs to reduce potential fire spread to these areas, especially where ORAs are located near low R|R CSA and GOA.
- Implement wildfire prevention and mitigation efforts including public campaigns oriented at reducing human-caused ignitions.

In response to potential wildfire threats, extensive fuel reduction treatments that include thousands of km of linear fuel breaks are already proposed throughout the Great Basin and elsewhere in the sagebrush biome. The quantification and display of wildfire risk are critical for ensuring strategic placement and cost-effective investments of fuel reduction treatments and fuel breaks, as well as continually maintaining fuel break networks (Shinneman et al. 2019, 2023; Weise et al. 2023). Low R|R CSAs and GOAs are expected to need some moderate-to-high level of management intervention to minimize risk of invasion and maintain or enhance ecosystem function (Chambers et al. 2023b). Those higher integrity but low R|R areas should be prioritized for management intended to protect them from burning; linear fuel breaks outside of intact stands may be most appropriate given their unsuitability for prescribed fire or mechanical treatments (due to low R|R). Recent research indicates that fuel treatments are best suited for higher ecological integrity areas with high resilience and resistance (Chambers et al. 2023c). Such investments should be informed by fire probability but intended to maintain or enhance ecological integrity and resilience to wildfire disturbance rather than for fire exclusion purposes only.

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.

CRediT authorship contribution statement

Michele R. Crist: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Resources, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Karen C. Short:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Resources, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Todd B. Cross:** Formal analysis, Investigation, Methodology, Project administration, Resources, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Kevin E. Doherty:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Writing – original draft, Writing – review & editing. **Julia H. Olszewski:** Data curation, Formal analysis, Investigation, Methodology, Resources, Software, Validation, Visualization, Writing – review & editing.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.rama.2024.08.014.

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