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Fuel treatment response groups for fire-prone sagebrush landscapes

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Abstract

Background Sagebrush shrublands in the Great Basin, USA, are experiencing widespread increases in wildfire size and area burned resulting in new policies and funding to implement fuel treatments. However, we lack the spatial data needed to optimize the types and locations of fuel treatments across large landscapes and mitigate fire risk. To address this, we developed treatment response groups (TRGs)—sagebrush and pinyon-juniper vegetation associations that differ in resilience to fire and resistance to annual grass invasion (R&R) and thus responses to fuel treatments.

Results We developed spatial layers of the dominant sagebrush associations by overlaying LANDFIRE Existing Vegetation Type, Biophysical Setting, and Mapping Zone, extracting vegetation plot data from the LANDFIRE 2016 LF Reference Database for each combination, and identifying associated sagebrush, grass, shrub, and tree species. We derived spatial layers of pinyon-juniper (PJ) cover and expansion phase within the sagebrush associations from the Rangeland Analysis Platform and identified persistent PJ woodlands from the LANDFIRE Biophysical Setting. TRGs were created by overlaying dominant sagebrush associations, with and without PJ expansion, and new indicators of resilience and resistance. We assigned appropriate woody fuel treatments to the TRGs based on prior research on treatment responses. The potential area to receive woody fuel treatments was constrained to 52,940 km^2 (18.4%) of the dominant sagebrush associations (272,501 km^2) largely because of extensive areas of low R&R (68.9%), which respond poorly and were not assigned treatments. Prescribed fire was assigned to big sagebrush associations with moderate or higher resilience and moderately low or higher resistance (14.2%) due to higher productivity, fuels, and recovery potential. Mechanical treatments were assigned to big sagebrush associations with moderately low resilience and to low, black, and mixed low sagebrush associations with moderately low or higher R&R (4.2%) due to lower productivity, fuels, and recovery potential. Persistent PJ woodlands represent high value resources and were not assigned treatments (9%).

Conclusions Mapped TRGs can help identify the dominant sagebrush associations and determine appropriate fuel treatments at intermediate scales and provide the basis for quantitative wildfire risk assessments and outcome-based scenario planning to prioritize fuel treatment investments at large landscape scales.

Keywords Great Basin, Sagebrush, Fuel treatments, Ecological resilience, Resistance to invasion, Treatment durability, Fire behavior, Pinyon-juniper expansion, Persistent woodlands, Fuel treatment response groups

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Resumen

Antecedentes Los arbustales de Atemisia spp. (Sagebrush) en la gran cuenca (Great Basin) de los EEUU, están experimentando incrementos generalizados en tamaño y área quemada, lo que resulta en nuevas políticas y apoyo económico para implementar tratamientos de combustibles. Sin embargo, carecemos de datos espaciales para optimizar tipos y ubicaciones de tratamientos de combustibles, a través de grandes paisajes, para mitigar el riesgo de incendios. Para afrontar este desafío, desarrollamos Tratamientos por Grupos de Respuesta (TRGs), que son asociaciones de artemisia y pino-junípero (PJ) que difieren en resiliencia al fuego y resistencia a las invasiones anuales (R&R) y por lo tanto a los tratamientos de combustible.

Resultados Desarrollamos estratos espaciales de las asociaciones dominantes de artemisia mediante el solapamiento de la base de datos de tipos de vegetación (LANDFIRE), con conjuntos de datos biofísicos (Biophysical Settings) y Mapeo de Zona (Mapping Zone), extrayendo datos de parcelas de la base de datos de LANDFIRE 2016 LF para cada combinación, e identificando las asociaciones de artemisia, pastos, arbustos, y especies de árboles. Derivamos estratos espaciales de cobertura y fase de expansión de pino-junípero (PJ) dentro de las asociaciones de artemisia desde la Plataforma de Análisis de Rangeland e identificamos bosquecillos persistentes de PJ desde la plataforma LANDFIRE de datos biofísicos. Los TRGs fueron creados mediante el solapamiento de asociaciones dominantes de artemisia, con y sin expansión de PJ, y de nuevos indicadores de resiliencia y resistencia. Asignamos los tratamientos apropiados de combustibles leñosos al TRGs basados en investigaciones anteriores sobre respuestas a los tratamientos. El área potencial para recibir los tratamientos en combustibles leñosos fue restringida a unos 52.940 km2 (18,4%) de la superficie de las asociaciones de artemisia (de 272.501 km2), mayoritariamente debido a que áreas extensas con baja R&R (68,9%) respondieron pobremente y por eso no se le asignaron tratamientos. Las quemas prescriptas fueron entonces asignadas a las asociaciones de artemisia con moderada a alta resiliencia y baja a moderada resistencia (14.2%) debido a la más alta productividad, sus combustibles, y potencial de recuperación. Los tratamientos mecánicos fueron asignados a las asociaciones de artemisia con moderadamente baja resiliencia y a asociaciones de artemisia bajas, negras y mixtas con R&R moderadamente baja o más alta (4,2%) debido fundamentalmente a su baja productividad, sus combustibles y potencial de recuperación. Los bosquecillos persistentes de PJ representaron recursos valiosos y no les fueron asignados ningún tratamiento (9%).

Conclusiones El mapeo con los TRGs puede identificar las asociaciones dominantes de artemisia y determinar tratamientos apropiados a escalas de paisaje intermedias, y proveen la base para la determinación del riesgo de incendio y el escenario de los resultados esperados del planeamiento, para priorizar las inversiones en los tratamientos de los combustibles a grandes escalas de paisajes.

Introduction

There is a critical need to understand the effects of fuel treatments across large sagebrush landscapes. More area burned in shrubland and herbaceous ecosystems (56%) than in forested, tree-dominated ecosystems (44%) from 2000 to 2020 across the western USA (Crist 2023). During this time period, shrubland and herbaceous ecosystems experienced increasing trends in area burned, number of burned patches, and fire sizes (Crist 2023). Major anthropogenic drivers include fire suppression policies (Bates and Davies 2020), an increase in the human footprint (Leu et al. 2008), and greater numbers of human fire starts (Fusco et al. 2016). The primary ecosystem drivers include (1) the invasion of exotic annual grasses, which increase continuous fine fuels that cure earlier in the growing season and result in large increases in fire frequency and extent (Bradley et al. 2018; Chambers et al. 2019), and (2) the expansion of pinyon and juniper tree species into the shrublands, where stand infilling results in a new strata of crown fuel and increased risk of high severity fire (Strand et al. 2013; Miller et al. 2019). In addition, climate warming is exacerbating invasion by the exotic annual grasses (Bradley et al. 2016) and resulting in longer fire seasons and more severe fire weather (Abatzoglou and Kolden 2013, Abatzoglou et al. 2018). The consequences of these altered fire regimes are increased risks to human life and property, high fire management costs, loss of cultural and economic resources, risk of type-conversions to annual grasses, and diminished habitat for a wide variety of sagebrush dependent species (Coates et al. 2016).

The increase in wildfire extent and severity across the western USA has resulted in agency strategies, such as the US Department of the Interior's Integrated Rangeland Fire Management Strategy (USDOI 2015) and the US Forest Service's Wildfire Crisis Strategy (USDA Forest Service 2022), to increase capacity to prevent and suppress wildfires or otherwise reduce wildfire risk. The increase in wildfire activity also has resulted in significant new funding for the management agencies and their

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collaborators to implement fuel treatments through the Infrastructure Investment and Jobs Act (IIJA 2021) and Inflation Reduction Act (IRA 2022). The purpose of these fuel treatments is to reduce or redistribute burnable material with the goal of decreasing fire intensity or burn severity (Reinhardt et al. 2008). Ideally, fuel treatments are implemented in a manner that has reliable and durable effects on fire behavior (Ellsworth et al. 2022, Williams et al. 2023) and that improves ecological resilience to future wildfires and resistance to invasive annual plants (Chambers et al. 2014a, b; 2019). Although the knowledge base needed to effectively implement the number of fuel treatments at the scales proposed is growing, important information gaps remain.

Recent reviews of fuel treatment effectiveness indicate that the adverse effects of wildfires can be mitigated within fuel treatments to varying degrees (e.g., Kalies et al. 2016; Urza et al. 2023), but that we lack the information needed to optimize the types and locations of fuel treatments and mitigate fire risk across large landscapes (McKinney et al. 2022). Outcome-based scenario planning in conjunction with quantitative wildfire risk assessment is an effective tool for prioritizing fuel treatment investments at landscape scales (e.g., Ager et al. 2017). In sagebrush landscapes, generalized spatial data for assessing fuels and fire risk is available across the western USA at 30 m spatial resolution through platforms such as LANDFIRE (LANDFIRE 2023) and the Rangeland Analysis Platform (RAP) (Allred et al. 2021, USDA ARS 2023). However, we lack the necessary spatial data to predict woody fuel treatment outcomes at these scales.

In sagebrush ecosystems, the responses to woody fuel treatments are highly dependent on the predominant vegetation types as well as their resilience to wildfire and fuel treatments (resilience) and resistance to invasive annual grasses (resistance) (Miller et al. 2013, 2019; Chambers et al. 2014a, b; 2019). New ecologically relevant and climate sensitive indicators of resilience and resistance based on climate and water availability have been developed recently (Chambers et al. 2023a). However, information is also needed on the locations and extents of the dominant sagebrush associations, persistent woodlands (PJ; pinyon and/or juniper), and the different phases (successional stages) of PJ expansion into the shrublands (Miller et al. 2019). For example, prescribed fire may be effective for reducing woody fuels and fire risk while maintaining ecological function in mountain big sagebrush (*Artemisia tridentata* ssp. *vaseyana*) associations with high productivity, historically frequent fire return intervals, and relatively high resilience and resistance (Chambers et al. 2014b; 2019, Ellsworth and Kaufman 2017). However, use of prescribed fire could lead to conversion to invasive annual grasses and

development of annual grass—fire cycles in Wyoming big sagebrush (*A. tridentata* ssp. *wyomingensis*) associations with low productivity, historically long fire return intervals, and relatively low resilience and resistance (Chambers et al. 2014b; Ellsworth et al. 2022; Pyke et al. 2022).

In sagebrush associations experiencing PJ expansion, information is needed on the phase of expansion as resilience and resistance often decrease as the phase of expansion and thus tree cover increases and it becomes more difficult to implement woody fuel treatments successfully (Miller et al. 2019; Freund et al. 2021). In addition, the various sagebrush associations are characterized by different levels of site productivity and support different amounts of tree cover, both of which influence the types of fuel treatments that are feasible (Miller et al. 2019). Finally, it is important to recognize that persistent woodlands, which are historical, tree-dominated communities where site conditions (soils and climate) and disturbance regimes are inherently favorable for pinyon and/or juniper and the trees were an important landscape component prior to twentieth century expansion (Miller et al. 2019).

Here, we developed fuel treatment response groups to describe the potential for fuel treatments to reduce fire risk while maintaining or improving resilience and resistance across large sagebrush landscapes. Spatial information on the locations and extents of fuel treatment response groups can be combined with that on burn probabilities (Dillon et al. 2023), current cover of annual forbs and grasses (e.g., Rangeland Analysis Platform; USDA ARS 2023), and high value resources (e.g., the sagebrush ecological index, Doherty et al. 2022, Chambers et al. 2023c) to optimize fuel treatment types and locations and to mitigate fire risk across these large landscapes. We focused on the Great Basin because of the magnitude of annual grass invasion (Bradley et al. 2018; Chambers et al. 2019) and the large area of high fire risk (Dillon et al. 2023). We defined treatment response groups (TRGs) as sagebrush and PJ vegetation associations that differ in their relative resilience and resistance and have specific responses to woody fuel treatments. The TRGs were based on five spatial data layers: (1) the dominant sagebrush associations; (2) persistent PJ woodlands (pinyon and/or juniper); (3) the different phases (successional stages) of PJ expansion; and (4 and 5) new, climate-sensitive indicators of resilience and resistance for sagebrush ecosystems based on climate and water availability (Chambers et al. 2023a). We assigned woody fuel treatments (prescribed fire, mechanical thinning, and none) to each of the TRGs based on the dominant sagebrush association, the presence and phases of PJ expansion, environmental characteristics, and relative resilience and resistance. We asked: (1) What is the

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extent of the dominant sagebrush associations with and without PJ expansion and how are they distributed within the ecoregions in the Great Basin? (2) What are the resilience and resistance categories of the dominant sagebrush associations with and without PJ expansion? (3) What are the extents of the different TRGs and how do they differ among sagebrush associations and ecoregions? We discuss the implications of the results for locating and implementing woody and other fuel treatments across Great Basin landscapes.

Methods

Study area
We focused on the three ecoregions that comprise the Great Basin of the western United States: Central Basin and Range, Northern Basin and Range, and Snake River Plain (US EPA, 2022). These ecoregions are part of the western Cold Deserts and have mid-latitude climates with warm to hot summers and cold winters (Wiken et al. 2011). Most precipitation arrives during the winter months and the ecosystems are characterized largely by shrubland and woodland vegetation. Fire risk varies across the study area but is generally high across much of the Northern Basin and Range and Snake River Plain (Dillon et al. 2023).

Spatial data layers
To identify the dominant sagebrush associations for the three focal ecoregions, we first overlaid the Existing Vegetation Type (EVT), Biophysical Setting (BPS), and LANDFIRE map zone (Rollins 2009; LANDFIRE 2020a, b). We extracted and compiled the values of the EVT, BPS, and map zone found at each vegetation plot within the LANDFIRE 2016 Reference Database (LFRDB; LANDFIRE 2016) to account for all unique combinations of these three layers. We selected all LFRDB vegetation plot records from the resulting database with sagebrush species, extracted the species information for each plot, and summed and ranked the number of instances of the individual sagebrush species for each unique combination of EVT, BPS, and map zone. We also summed and ranked the number of instances of the top five shrub and top three tree and grass species present within the LFRDB vegetation plots. We used this ranking process to characterize and assign the dominant sagebrush associations based on the dominant sagebrush species present as well as the associated grasses, shrubs, and trees. We derived seven sagebrush associations: basin big sagebrush (*Artemisia tridentata* ssp. *tridentata*), Wyoming big sagebrush (*A. tridentata* ssp. *wyomingensis*), Wyoming/Basin big sagebrush (*A. tridentata* ssp. *wyomingensis* and *A. tridentata* ssp. *tridentata* combined), mountain big sagebrush (*A.*

tridentata ssp. *vaseyana*), black sagebrush (*A. nova*), low sage (*A. arbuscula* and *A. rigida*), and mixed low sagebrush (*A. arbuscula* and *A. nova* with minor amounts of *A. tridentata* ssp. *vaseyana* and *A. tridentata* ssp. *wyomingensis*). For the BPSs characterized by sagebrush species that were not included in the original analyses, we determined the dominant sagebrush association based on the BPS descriptions of the dominant species and included them in our data layer.

The tabular dominant sagebrush associations were joined to the spatial data layer describing EVT, BPS, and map zone. This enabled the sagebrush associations to be shown in a spatially explicit manner. We assigned "NA" to the agriculture, developed, barren, open water, snow, and ice categories in the EVT data layer. Those areas that were not associated with a BPS assigned to a dominant sagebrush association were designated the category "Not Sage."

To evaluate PJ (*Pinus monophylla*, *Juniperus occidentalis and/or J. osteosperma*) cover within the dominant sagebrush associations, we used Rangeland Analysis Platform (RAP v. 3.0; Allred et al. 2021) data from 2020, the year that best matched the temporal period of the other data sources. Fuel treatments are conducted primarily in the early phases (Phase I and II successional stages) of tree expansion (Miller et al. 2015; 2019), and it is important to designate these phases on the landscape. In addition, the various sagebrush associations are characterized by different levels of site productivity and thus support different amounts of tree cover (Miller et al. 2019). Therefore, we mapped sagebrush associations with relatively low site productivity, including low, black or mixed low sagebrush, as PJ Phase I where tree cover was 1–10% tree cover, Phase II where tree cover was 10–20%, or Phase III where tree cover was > 20%. We mapped sagebrush associations with higher site productivity, including basin big, basin/Wyoming big, mountain big, or Wyoming big sagebrush as PJ Phase I where tree cover was 1–10% tree cover, Phase II where tree cover was 10–30%, or Phase III where tree cover was > 30%. The RAP does not identify persistent woodlands so to characterize and map them, we identified the LANDFIRE BPS categories that represented persistent pinyon and juniper woodlands within the study area (Table S1). The BPS classifications are based on the current biophysical environment and estimated historical disturbance regimes and are intended to not include areas experiencing recent expansion of PJ. To develop the final map layer, we overlaid the dominant sagebrush associations with the three phases of PJ expansion and the persistent woodlands. We refined the map layer by removing those areas in LANDFIRE EVT dominated by tree species other than pinyon or juniper, including quaking aspen (*Populus tremuloides*) and

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curl-leaf mountain mahogany (*Cercocarpus ledifolius*) (Table S2).

To characterize the relative resilience and resistance of the dominant sagebrush associations and PJ expansion areas, we used ecologically relevant and climate-sensitive indicators based on climate and soil water availability variables derived from ecohydrological simulations (Chambers et al. 2023a, c) (Figs. S1 and S2).

Data compilation and mapping

To develop the TRGs, all five spatial data layers (dominant sagebrush associations, persistent PJ woodlands, expansion PJ, resilience, and resistance) were overlaid to create a single layer representing the different treatment response groups. Each spatial layer, including that for the TRGs, was comprised of 30-m rasters in the Albers CONUS projection.

The initial base TRG layer contained many complex patch shapes and single 30×30-m TRG patches, so we refined the layer by smoothing with two sequential 9-cell moving window majority filters. The resilience and resistance data layers contained some spatial gaps because of missing data within some of the soil polygons that were used to map the resilience and resistance layers (Chambers et al. 2023b), but visual inspection of satellite imagery showed that some of the gaps appeared to contain contiguous sagebrush stands. We therefore filled the resulting TRG spatial gaps by expanding (nibbling) neighboring valid TRG values outward into the regions lacking TRG data. Because some of the resilience and resistance data gaps included types of land cover other than sagebrush, we removed any nibbled data that covered areas not expected to contain sagebrush according to its BPS. We masked out areas with land covers designated as barren, agriculture, developed, or forest being sure not to exclude PJ areas (Reeves and Mitchell 2011). All analyses were performed in R and ArcGIS (Hijmans 2023, R Core Development Team 2022).

Assignment of fuel treatments to treatment response groups

The information used to develop the resilience and resistance categories (Chambers et al. 2023a) was also used to assign treatments to the TRGs. We first developed generalized ecological types for each of the focal ecoregions based on USDA Natural Resources Conservation Service Soil Survey Information (USDA NRCS, 2020) and Ecological Site Descriptions (USDA NRCS, 2022) (see Chambers et al. 2023a for details). Ecological types are a category of land with a distinctive (i.e., mappable) combination of environmental components, specifically, climate, geology, geomorphology, soils, and potential natural vegetation (Winthers et al. 2005). The ecological

sites within each ecoregion were grouped into ecological types based on similarities in climate, soils, and vegetation as well as the concept for the site as indicated by the ecological site description. Five USDA Natural Resources Conservation Service specialists who had helped develop the individual ecological sites for the ecoregions worked together with J. Chambers to obtain consensus on both the ecological site groupings and the relative resilience and resistance categories of the dominant ecological types within each ecoregion. To facilitate comparison across ecoregions, the resilience categorization was based largely on the abiotic characteristics (i.e., climate and soils) that determined the potential response of the ecological types to disturbance (Chambers et al. 2014a). To obtain consistent ratings among ecological types for resistance to annual grass invasion, categorization focused on *Bromus tectorum*. Climate suitability and soils were considered the primary determinants of resistance, but resource availability and competition from perennial herbaceous species were also considered (Chambers et al. 2014a).

To assign treatments to the TRGs, we compiled the ecological types into groups that reflected the dominant sagebrush associations and PJ expansion areas. The groups had similar vegetation associations, environmental conditions, and resilience and resistance categories (Table S3). We used information on the long-term effects of fuel treatments from recent literature reviews (e.g., Miller et al. 2013, 2019) and analyses of the 10-yr regional Sagebrush Steppe Treatment Evaluation Project data (SageSTEP.org; McIver et al. 2010, McIver and Brunson 2014) to assign fuel treatments to each group. Fuel treatments were assigned to the TRGs based on three criteria: (1) treatments were durable in that they resulted in a longer-term (10+years post-treatment) decrease in fire risk, (2) treatments resulted in maintaining or increasing resilience as measured by an increase in perennial herbs and sagebrush establishment, and (3) treatments did not decrease resistance to invasion and resulted in little to no increase in invasive annual grasses and forbs. Thus, prescribed fire treatments were assigned to TRGs characterized by big sagebrush associations with and without PJ expansion that had moderate or higher resilience and moderately low or higher resistance (e.g., Chambers et al. 2014b, Bates et al. 2019, Freund et al. 2021, Ellsworth et al. 2022, Pyke et al. 2022, Williams et al. 2023). Mechanical tree removal treatments that leave understory shrubs in place, such as cut and remove and mastication, were assigned to big sagebrush associations experiencing PJ expansion that had moderately low resilience or resistance, and to low sagebrush, black sagebrush, and mixed low sagebrush associations with PJ expansion that had moderately low or higher resilience or

resistance (e.g., Chambers et al. 2014b; Freund et al. 2021; Roundy et al. 2020; Williams et al. 2023). Treatments were not assigned to low, black, and mixed low sagebrush associations without tree expansion due to generally low productivity and fuels as well as lower recovery potential (Miller et al. 2019) nor to Phase III woodlands due to reduced recovery potential and difficulty in implementing treatments (Bates et al. 2013, Miller et al. 2019). Persistent woodlands were considered high-value resources and were not assigned treatments. TRGs with low resilience or resistance were not assigned treatments, regardless of sagebrush association, due to generally low recovery potential. The resilience and resistance categories used to assign treatments resulted in cheatgrass covers below a treatment threshold of < 15% cover (e.g., Doherty et al. 2022, Chambers et al. 2023c) for the majority of the area within the TRGs (Table S4).

We aggregated the base TRG layer to represent various combinations of the assigned fuel treatments. For example, we combined the dominant sagebrush associations with moderate or higher resilience and moderately low or higher resistance that were assigned the prescribed fire treatment into a common TRG. And we pooled low sagebrush with moderately low or higher resilience and resistance assigned a potential mechanical treatment. We mapped and evaluated the relative extents of these different combinations.

Results

Dominant sagebrush associations
The dominant sagebrush associations within the study area covered 272,502 km^2 (Fig. 1, Table S5). These associations were characterized largely by Wyoming sagebrush (31.7%), followed closely by Wyoming/basin big sagebrush (29.1%), then mountain big sagebrush (14.7%) and black sagebrush (11.7%). Lesser amounts of low sagebrush (5.5%), mixed low sagebrush (4.6%), and basin big sagebrush (2.8%) occurred within the study area. The distribution of dominant sagebrush associations differed across ecoregions, with relatively more black sagebrush and Wyoming/basin big sagebrush in the Central Basin and Range, more low sagebrush and basin big sagebrush in the Northern Basin and Range, and more Wyoming sagebrush in the Snake River Plain (Fig. 1, Table S6).

Pinyon and juniper expansion areas and persistent woodlands
The area of the dominant sagebrush associations without PJ expansion covered 145,731 km^2 or 53.5%, while the area with PJ expansion encompassed 126,771 km^2 or 46.5% (Fig. 2, Table S5). Over a third of the area characterized by sagebrush associations had Phase I expansion (36.9%). Phase II and III expansion areas were much

less extensive (6.0 and 0.05%, respectively). Persistent PJ woodlands, which were their own category, covered 22,636 km^2 and were much smaller in area than the expansion woodlands. As with the dominant sagebrush associations, PJ woodlands and expansion areas were not equally distributed across the ecoregions (Fig. 2, Table S5). The Central Basin and Range contained a higher overall amount of expansion woodland (82,592 km^2) than the Northern Basin and Range (42,702 km^2) and Snake River Plain (12,629 km^2) and had more PJ expansion in Phases II and III than the other ecoregions. In addition, almost 90% of the persistent woodlands were in the Central Basin and Range. The Northern Basin and Range contained the greatest proportion of sagebrush dominated associations without PJ expansion (69,787 km^2). The least amount of sagebrush with or without PJ was found in the Snake River Plain (27,174 km^2).

Resilience and resistance categories
The dominant sagebrush associations were characterized by higher amounts of low and moderately low resilience (218,734 km^2 or 80.2%) and resistance (225,939 km^2 or 82.9%) than moderate to high resilience (53,766 km^2 or 19.7%) and resistance (46,564 km^2 or 17.1%) when evaluated as a whole (Fig. 3, Tables S6 and S7). However, large differences in resilience and resistance existed both among the dominant sagebrush associations and ecoregions (Fig. 3, Tables S6 and S7). The highest levels of resilience and resistance generally occurred within sagebrush associations characterized by cooler and/or wetter environment conditions: mountain big sagebrush > low sagebrush > basin big sagebrush. In contrast, those associations with generally warmer and drier conditions had the lowest resilience and resistance: Wyoming big sagebrush and the combination of Wyoming and basin big sagebrush > black sagebrush > mixed low sagebrush. The resilience and resistance of the different sagebrush associations were generally higher in the Northern Basin and Range or Snake River Plain than the Central Basin and Range, except for Wyoming big sagebrush and the combination of Wyoming and basin big sagebrush which were low consistently.

In the dominant sagebrush associations experiencing pinyon and juniper expansion Phase I was generally categorized by low resilience (66,577 km^2 or 67.5%) and resistance (42,686 km^2 or 43.3%) (Fig. 4, Tables S8 and S9). Phase II also was typically categorized by low resilience (8817 km^2 or 58.2%) as was Phase III (5903 km^2 or 45.3%). However, resistance tended to be moderately low within Phase II (9013 km^2 or 59.5%) and Phase III (9689 km^2 or 74.4%). Values for persistent woodlands were generally like those for Phase II and Phase III. As for the sagebrush associations, resilience and resistance
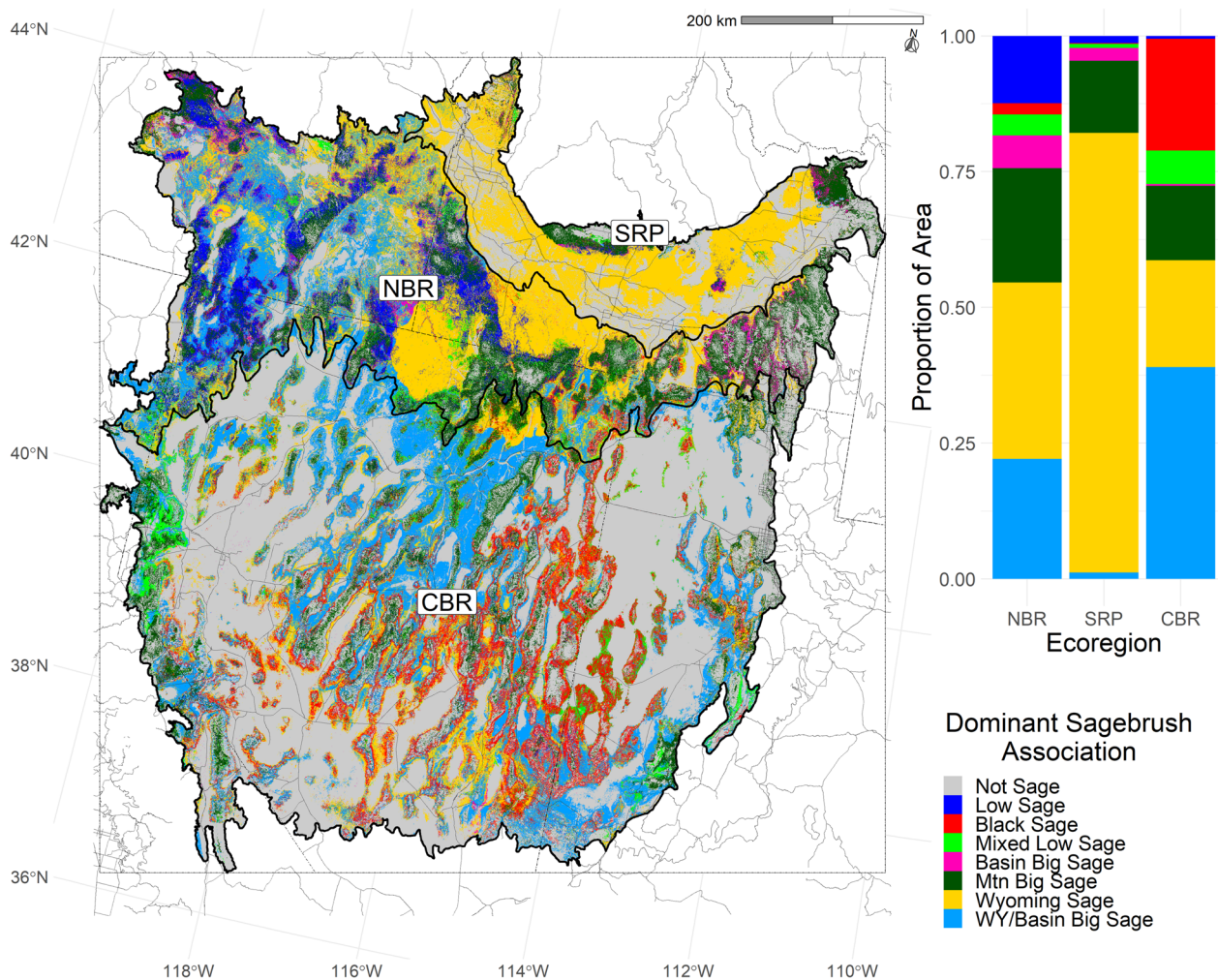
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Fig. 1 Cover of dominant sagebrush associations in the Northern Basin and Range (NBR), Snake River Plain (SRP), and Central Basin and Range (CBR). Bar graph at upper right shows the proportion of the area of each dominant sagebrush association within each ecoregion. Dominant sagebrush associations include low sagebrush (sage) (*Artemisia arbuscula* and *A. rigida*); black sagebrush (*A. nova*); mixed low sagebrush (low sagebrush with minor amounts of mountain big sagebrush (*A. tridentata* ssp. *vaseyana*) and Wyoming big sagebrush (*A. tridentata* ssp. *wyomingensis*); basin big sagebrush (*A. tridentata* ssp. *tridentata*), mountain big sagebrush, Wyoming big sagebrush, and mixed Wyoming and basin big sagebrush

were generally higher in the Northern Basin and Range or Snake River Plain. The persistent woodlands also had higher resilience and resistance in these northern ecoregions, but the persistent woodlands comprised much smaller percentages of the landscape in these ecoregions.

Treatment response groups

The TRGs assigned the prescribed fire treatment comprised 40,905 km^2 or 15.1% of the landscape dominated by big sagebrush associations (Tables 1 and S10; Figs. 5 and S3). More of the prescribed fire area was characterized by sagebrush associations with PJ expansion (23,962 km^2 or 8.8%) than sagebrush associations with no expansion (16,979 km^2 or 6.3%) and by mountain

big sagebrush (27,078 km^2 or 66.2%) than Wyoming big sagebrush and the combination of Wyoming big sagebrush and basin big sagebrush (13,827 km^2 or 33.8%). The TRGs assigned the mechanical tree removal treatment in PJ expansion areas comprised a much smaller amount of the landscape dominated by big sagebrush associations—12,035 km^2 or 4.5% (Table 1, Fig. 5). Mechanical treatment areas assigned to big sagebrush associations with ML resilience or resistance were larger (6917 km^2 or 2.6%) than those assigned to low, black, and mixed low sagebrush associations with ML resilience and resistance or higher (5118 km^2 or 1.9%).

Large areas of the big sagebrush associations were not assigned treatments (163,662 km^2 or 60.6%) because

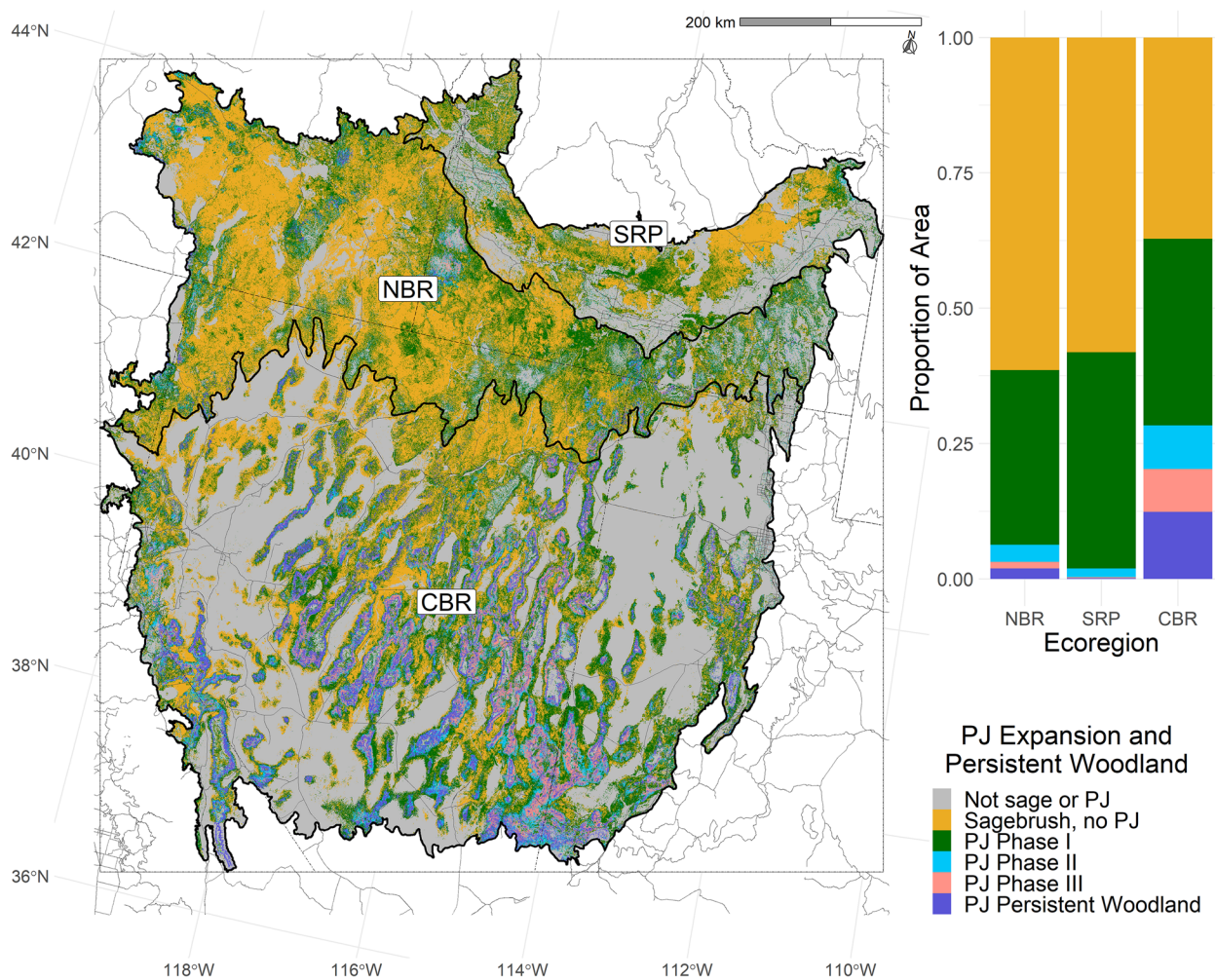Chambers *et al. Fire Ecology*   (2023) 19:70

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Fig. 2 Areal extent of pinyon-juniper (PJ) expansion areas by phase of expansion, PJ persistent woodlands, and sagebrush associations with no PJ cover in the Northern Basin and Range (NBR), Snake River Plain (SRP), and Central Basin and Range (CBR). Bar graph at the upper right shows the proportion of the area of each category within each ecoregion. PJ areas are comprised of singleleaf pinyon (*Pinus monophyla*), western juniper (*Juniperus occidentalis*), and/or Utah juniper (*J. osteosperma*)

they had either low resilience or low resistance (Table 1, Fig. 5). In addition, large areas of the low, black, and mixed low sagebrush associations that lacked PJ expansion (40,706 km^2 or 13.7%) were not assigned fuel treatments due to generally low fuels. Areas designated as Phase III were not assigned treatments (12,848 km^2 or 4.3%) due to low durability and recovery potential. And because of the ecological importance of persistent woodlands, they were not assigned treatments (26,444 km^2).

Discussion

The treatment response groups (TRGs) provide the information needed to optimize the types and locations of fuel treatments to mitigate fire risk across Great Basin landscapes. In this region, the response to fuel treatments

depends on the vegetation association, its response to disturbance, and its susceptibility to invasion by invasive annual grasses (Chambers et al. 2014a, b, 2019; Roundy et al. 2018; Freund et al. 2021). We identified and mapped TRGs based on the dominant sagebrush associations, the expansion woodlands and phase of expansion, the persistent woodlands, and the relative resilience and resistance of each of these vegetation associations. Potential fuel treatments were assigned to the TRGs based on their durability, or likelihood of decreasing longer-term fire risk, and their likelihood of maintaining or increasing ecological resilience and resistance to invaders. The extent of potential fuel treatments was constrained by the extensive area of low resilience and resistance with low recovery potential and high susceptibility to invasive
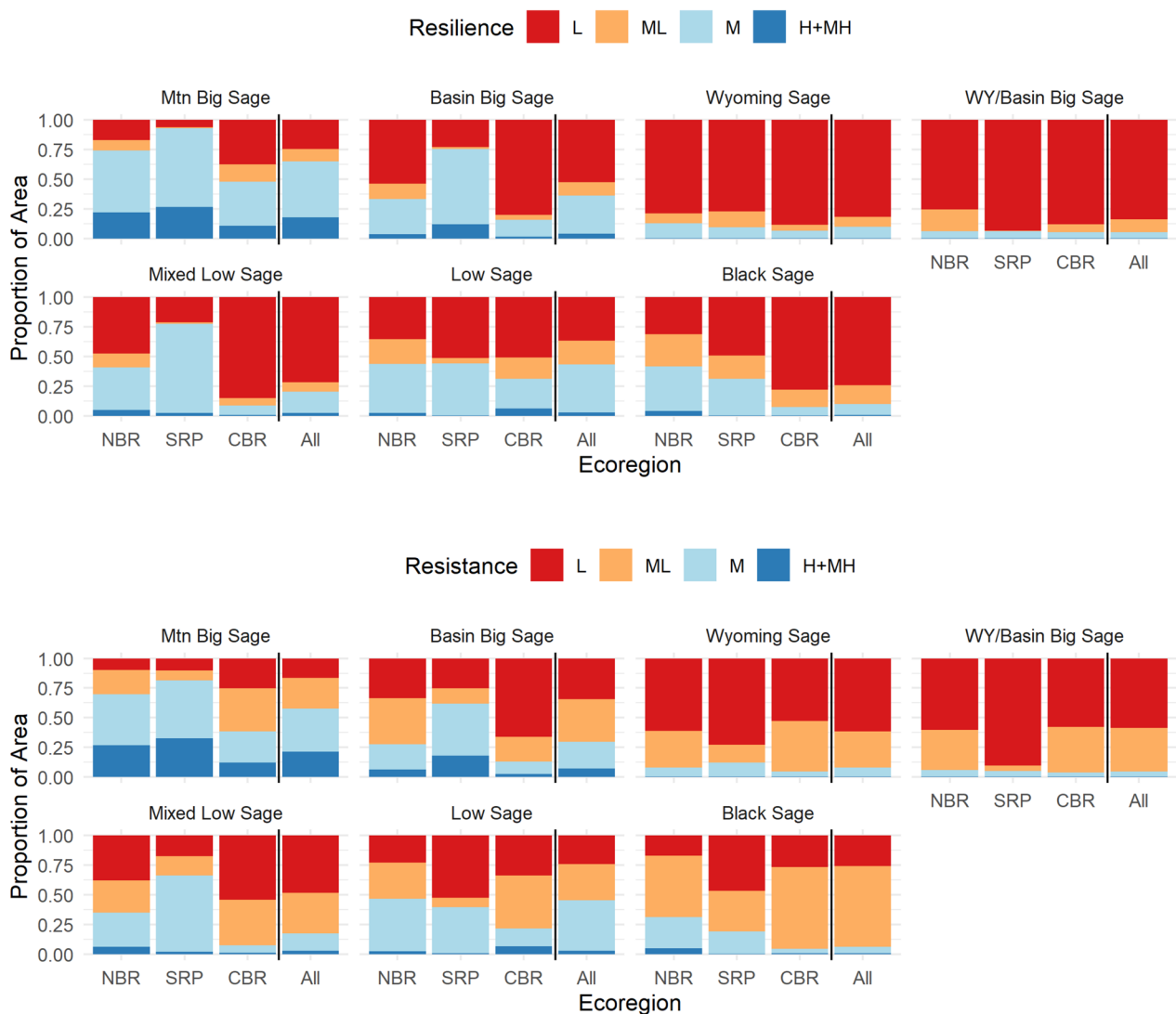
Fig. 3 The relative proportion of the area of the dominant sagebrush (sage) associations within the four resilience (top) and resistance (bottom) categories for the Northern Basin and Range (NBR), Snake River Plain (SRP), Central Basin and Range (CBR). The resilience and resistance categories for the three ecoregions combined are indicated by "All"

annual grasses. Restricting treatments to higher resilience and resistance areas helped ensure that potential treatments were assigned to areas where they could increase durability and help maintain or increase resilience and resistance over time. These assignments also helped identify areas where treatments are not appropriate because the likelihood of recovery is poor. At intermediate scales, such as USDA Forest Service Districts and USDOI Bureau of Land Management Districts, the spatial layers that comprise the TRGs can be used to help identify project areas and determine appropriate treatments. At large landscape scales, such as the Great Basin, the TRGs can be used in outcome-based scenario

planning in conjunction with quantitative wildfire risk assessment to prioritize fuel treatment investments (e.g., Ager et al. 2017).

Relationship of TRGs to treatment areas and types

The area with potential for fuel treatments was relatively small (52,940 km^2 or 19.3%) in comparison to the overall extent of the dominant sagebrush associations in the Great Basin (272,502 km^2). Suitable areas for potential treatments were constrained primarily by the large extents of the sagebrush associations characterized by low resilience and/or resistance (68.9%). Fuel treatments in low resilience and resistance areas typically
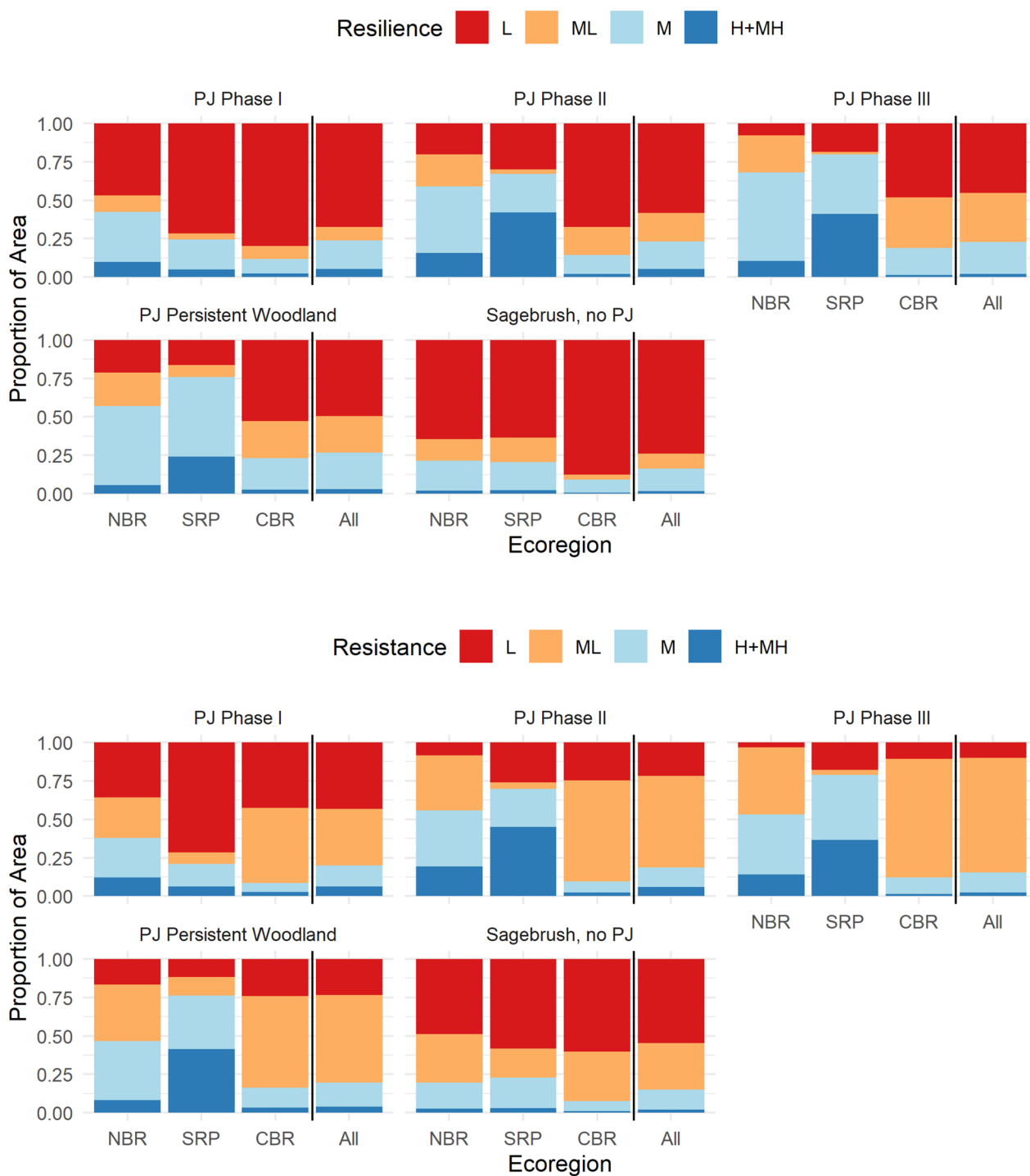
Fig. 4 The relative proportion of the pinyon-juniper (PJ) expansion areas by phase of expansion, PJ persistent woodlands, and dominant sagebrush associations within the four resilience (top) and resistance (bottom) categories for the Northern Basin and Range (NBR), Snake River Plain (SRP), Central Basin and Range (CBR). The resilience and resistance categories for the three ecoregions combined are indicated by "All"

show little to no increase in perennial grasses and forbs, low recruitment of sagebrush, and increases in invasive annual grasses in big sagebrush associations without PJ expansion (Davies et al. 2012; Swanson et al. 2016; Chambers et al. 2021; Pyke et al. 2022) and with PJ expansion (Roundy et al. 2018; Chambers et al. 2021; Freund et al.

Table 1 Areal extents of the condensed list of treatment response groups (TRGs) within the Northern Basin and Range, Snake River Plain, and Central Basin and Range. The area of each TRG is reported in km^2 and percentage (%) of the individual ecoregions and of all ecoregions combined. Figure 5 is the map of these TRGs

Treatment	Treatment response group (TRG)	Central Basin and Range Area		Northern Basin and Range Area		Snake River Plain Area		All Ecoregions Area	
		km^2	%	km^2	%	km^2	%	km^2	%
Prescribed fire	Mtn big sage, no PJ, H-M&H-ML R&R	2743	1.8%	4584	4.1%	1,826	6.3%	9,153	3.1%
Prescribed fire	Mtn big sage, PJ Phase I&II, H-M&H-ML R&R	4890	3.1%	11,555	10.3%	1,480	5.1%	17,925	6.0%
Prescribed fire	WY or basin big sage, no PJ, H-M&H-ML R&R	2036	1.3%	4476	4.0%	1,314	4.6%	7826	2.6%
Prescribed fire	WY or basin big sage, PJ Phase I&II, H-M&H-ML R&R	1774	1.1%	3285	2.9%	941	3.3%	6001	2.0%
Mechanical	Mtn big sage, PJ Phase I&II, ML&H-ML R&R	1350	0.9%	896	0.8%	13	0.0%	2259	0.8%
Mechanical	WY or basin big sage, PJ Phase I&II, H-M&H-ML R&R	1774	1.1%	3285	2.9%	941	3.3%	6001	2.0%
Mechanical	WY or basin big sage, PJ Phase I&II, ML&H-ML R&R	2941	1.9%	1413	1.3%	304	1.1%	4658	1.6%
Mechanical	Mixed low sage, PJ Phase I&II, ML&H-ML R&R	370	0.2%	384	0.3%	19	0.1%	773	0.3%
Mechanical	Low sage, PJ Phase I&II, ML&H-ML R&R,	66	0.0%	2046	1.8%	5	0.0%	2116	0.7%
Mechanical	Black sage, PJ Phase I&II, ML&H-ML R&R	1868	1.2%	361	0.3%	1	0.0%	2229	0.8%
No treatment	All big sage, low R&R	76,555	49.1%	64,742	57.8%	22,364	77.6%	163,662	55.2%
No treatment	Mixed low, low, & black sage, no PJ, low fuels	25,202	16.2%	15,000	13.4%	504	1.8%	40,706	13.7%
No treatment	All sage, PJ Phase III	12,069	7.7%	770	0.7%	8	0.0%	12,848	4.3%
No treatment	PJ persistent woodland	23,979	15.4%	2431	2.2%	34	0.1%	26,444	8.9%

2021). Increases in invasive annual grasses following fuel treatments in big sagebrush associations with relatively low resilience and resistance can result in longer-term (10-year) increases in herbaceous fuel and changes in fire behavior. In sagebrush associations without PJ expansion, both prescribed fire and mechanical shrub removal (mowing) resulted in reduced modeled flame lengths and rates of spread, but in no change in reaction intensity (Ellsworth et al. 2022). Except in those rare cases where the understory is characterized by ~20% cover of perennial native grasses and forbs and minimal invasive annual grasses (Davies 2008; Chambers et al. 2014b), the potential decrease in fire behavior is not worth the risk of conducting fuel treatments that may result in conversion to annual grass dominance and the development of invasive grass—fire cycles (Miller et al. 2013, 2019).

The TRG area assigned to prescribed fire was larger than that assigned to mechanical treatments. Prescribed fire was assigned to big sagebrush TRGs with moderate or higher resilience and was found primarily at higher elevations with the largest area in the Northern Basin and Range (Fig. 5). The prescribed fire area assigned to big sagebrush TRGs without PJ expansion 6.3%) was less than that with PJ expansion (8.8%) and the majority of the area with PJ expansion was characterized by Phase I expansion. The big sagebrush TRGs with higher resilience and resistance that were assigned prescribed fire have generally higher productivity, fuel, and burn probabilities

(Dillon et al. 2023), and burned more frequently historically, regardless of the occurrence of PJ expansion (Miller and Rose 1999; Miller and Heyerdahl 2008; Miller et al. 2013). Fire return intervals in these big sagebrush TRGs have been lengthened due to a combination of fire suppression and removal of fine fuels by domestic livestock grazing (Burkhardt and Tisdale 1976; Miller et al. 2013, 2019). Increases in woody shrub fuels due to longer intervals without fire and decreased competition from grasses and forbs have increased the likelihood of higher fire intensities during wildfires, longer recovery times, and reduced resilience to subsequent wildfires (Miller et al. 2013). Progressive expansion and infilling of PJ further increases woody fuels in these TRGs and can result in wildfires having even more severe effects (Strand et al. 2013, Williams et al. 2023). Thus, prescribed fire is appropriate for big sagebrush TRGs with moderate or higher resilience with and without PJ expansion, although TRGs experiencing PJ expansion may have the greatest longer-term risk of decreased resilience following wildfires and thus may be a more immediate priority.

Prescribed fire treatments in moderate or higher resilience areas typically result in increases in perennial grasses and forbs, moderately high recruitment of sagebrush, and little to no increase in invasive annual grasses in big sagebrush associations without PJ expansion (Ellsworth and Kaufman 2017, Chambers et al. 2017) and with PJ expansion (Roundy et al 2018;
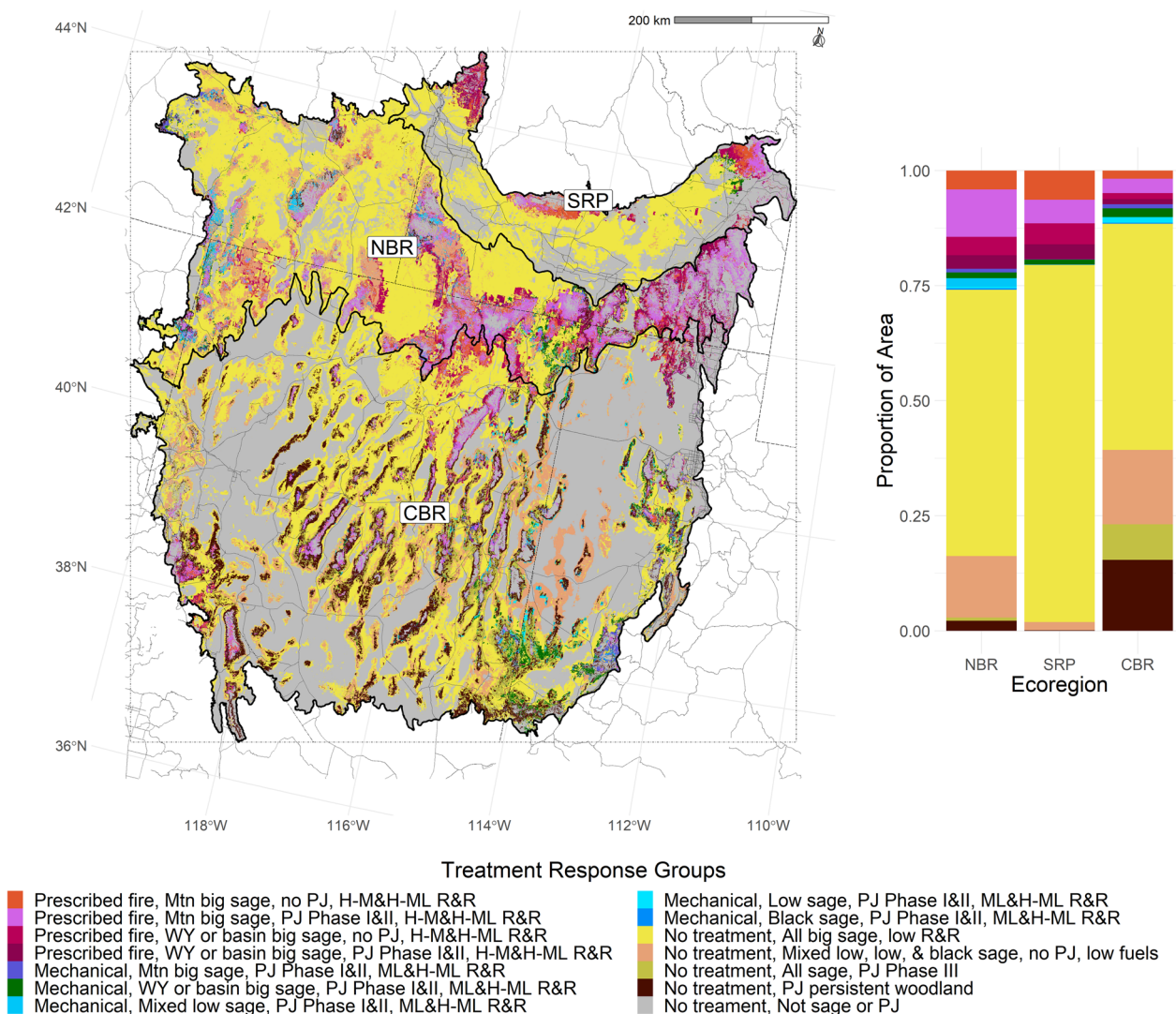
Fig. 5 The primary treatment response groups (TRGs) with assigned fuel treatments, including prescribed fire, mechanical tree removal, and no treatment, for the Northern Basin and Range (NBR), Snake River Plain (SRP), and Central Basin and Range (CBR). Treatment response groups were based on the dominant sagebrush (sage) association, the presence of pinyon-juniper (PJ) expansion and the phase of expansion, and the resilience and resistance category. The map also includes areas of persistent woodland and areas that are not sagebrush associations. The bar graph at upper right shows the proportional area of the TRGs within each ecoregion. The "Big sage, low R&R, no treatment" combines all mountain big sagebrush (*Artemisia tridentata* ssp. *vaseyana*), basin big sagebrush (*A. tridentata* ssp. *tridentata*), Wyoming big sagebrush (*A. tridentata* ssp. *wyomingensis*), and Wyoming/basin big sagebrush associations with low resilience and resistance categories

Freund et al. 2021). Cooler climatic conditions coupled with competition from perennial herbs typically limits establishment and growth of invasive annual grasses (Chambers et al. 2007; Roundy and Chambers 2021) and recruitment of PJ is restricted until reestablishment of sagebrush nurse plants (Chambers et al. 1999, 2001; Urza et al. 2019). Longer-term (10-year) increases in herbaceous fuel and decreases in shrub and tree fuel following prescribed fire are common (Williams et al. 2023). Modeled fire behavior of Phase I

and II PJ expansion areas after prescribed fire resulted in increased rate of spread and higher flame lengths, but reductions in reaction intensity in Phase I and in the initial years after treatment in Phase II (Williams et al. 2023). These changes in plant community composition and fire behavior likely reflect those observed historically when fires burned more frequently. Prescribed fire treatments that mimic the historic, heterogeneous burns that occurred in big sagebrush associations with and without PJ expansion (e.g., Miller and Heyerdahl

2008) will likely be most successful in maintaining or increasing their resilience and resistance.

Mechanical tree removal treatments covered a smaller extent than prescribed fire because they were assigned only to big sage TRGs with moderately low resilience and moderately low or higher resistance (2.4%), and to low, black, and mixed low sagebrush (1.8%) with moderately low or higher resilience and resistance. These sagebrush TRGs with these resilience and resistance categories typically have relatively low productivity, fuel, and burn probabilities and burned infrequently in the past (Miller et al. 2013, 2019). Under these conditions, prescribed fire can be difficult to implement and can result in significant increases in invasive annual grasses over time (Freund et al. 2021). However, mechanical treatments that remove the trees but leave the shrubs in place can result in increases in cover of perennial grasses and forbs and shrubs with smaller increases in invasive annual grass cover, particularly on cooler and wetter sites (Freund et al. 2021). Mechanical treatments to remove trees also may be appropriate in cooler and moister big sagebrush TRGs where treatment objectives include protecting communities or maintaining and improving sagebrush habitat (Coates et al. 2016).

The type of mechanical treatment influences both ecological outcomes and longer-term fire behavior. Cut and leave treatments increase woody surface fuels and to a lesser degree herbaceous fuels, which elevate modeled surface fire intensity, flame length, and especially rate of spread but remove the risk of canopy fire (Williams et al. 2003). Cut and remove treatments may be a better option than cut and leave due to less remaining woody surface fuels, except in Phase I expansion where cut and leave treatments have less effect on fuels and fire behavior (Williams et al. 2023). However, cut and remove treatments increase both shrub and herbaceous fuels over time and are associated with potential increases in surface fire intensity, flame length, and rate of spread. In addition, these treatments may promote localized increases in invasive annuals as a result of broadcast burning of slash (O'Connor et al 2013) or pile burning (Redmond et al. 2014). Mastication treatments result in a high abundance of compacted 1- and 10-h woody surface fuels that likely burn at lower intensity and at a slower rate (Kreye et al. 2014). However, prolonged smoldering may result in increased duff consumption, soil heating, and root injury (Busse et al. 2005). Furthermore, mastication may result in smothering residual plants and reducing seedling establishment in shredded piles, and like the other treatments, increase the potential for invasive plants due to competitive release (Young et al. 2015).

Low resilience and resistance big sagebrush associations with high ecological integrity represent high value resource areas that merit protective management to prevent the development of uncharacteristic fire regimes (Chambers et al. 2023c). Although fuel treatments are not appropriate in these areas, fuel breaks in areas of high fire risk may help facilitate wildfire suppression by reducing fire behavior through fuel modification and allowing safe access points for containment by firefighters (Shinneman et al. 2018, 2019). A recent retrospective analysis indicated that fuel breaks were least effective in low resilience and resistance sagebrush associations composed primarily of woody fuels, particularly under high temperature and low precipitation conditions (Weise et al. 2023). However, fuel breaks were more effective in areas that were readily accessible and dominated by fine fuels (Weise et al. 2023). This indicates that routinely maintained fuel breaks in areas of invasive annual grass and forb dominance adjacent to high value sagebrush associations may provide necessary access points for firefighters and help prevent transmission of wildfires into these high value resource areas.

TRG map layers and spatial data needs

The spatial data layers currently available through the LANDFIRE and RAP platforms allowed us to develop the dominant sagebrush associations, areas of PJ expansion delineated by woodland development phase, and areas of persistent PJ woodlands. Both data sources have known spatial and aspatial uncertainties. The LANDFIRE BPS layer included uncertainty in model assignments, due to greater data availability in economically valuable or otherwise well studied biophysical settings versus those that are less well known (e.g., many of the non-forested drylands; Blankenship et al 2021, Helmbrecht and Blankenship 2016, Provencher et al. 2009). Additionally, LANDFIRE vegetation products are produced at the LANDFIRE map zone scale, so map zone boundary effects can be present when mosaiced data are used. The quantitative assessment of the RAP tree cover layer showed mean absolute error (MAE) and root mean squared error (RMSE) of 2.8 and 6.8% respectively for the modeling validation dataset, whereas the MAE and RMSE of an independent validation dataset were 5.3 and 9.6% (Allred et al. 2021). Thus, we carefully examined aerial photos and cross-checked aerial extents of the different data layers to ensure acceptable accuracy of our derived data layers. Our assessment of the dominant sagebrush associations confirmed the general patterns discussed by other authors (West 1983) and quantified for the first time the areas of the different associations. The dominant sagebrush associations in the Great Basin were characterized largely by Wyoming big sagebrush and Wyoming/basin big sagebrush (61%) followed by mountain big sagebrush (15%), black sagebrush (12%),

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and then low sagebrush, mixed low sagebrush, and basin big sagebrush (3 to 5% each). Developing the spatial data of the dominant sagebrush associations from Landsat imagery at 30 m spatial scales and monitoring their changes over time would facilitate larger-scale analyses not only of fire risk, but also sagebrush habitat.

The RAP layer provided continuous cover of sagebrush associations with PJ cover and this allowed designation of the three woodland development phases. Similar to other research we found that PJ expansion was widespread in the Great Basin (Miller et al. 2008, 2019; Morford et al. 2022) with almost half of the area covered by the dominant sagebrush associations experiencing expansion. Most of the area of expansion was in Phase I (77%) reflecting recent increases in tree cover over the past 30 years due to factors such as fire suppression, livestock overgrazing, and increasing atmospheric CO_2 (Miller et al. 2008; Morford et al. 2022). A high percentage of the expansion area was characterized by warmer and drier conditions with low resilience and resistance (59%), which may result in lower productivity, decreased rates of infilling, and lower cover values typical of Phase I (Johnson and Miller 2006; Miller et al. 2019).

A limitation of the RAP layer is that it did not identify the areas of persistent PJ woodland. Although the LANDFIRE BPS identified persistent woodlands, most of the area was in the Central Basin and Range and undoubtedly underestimated those in the remainder of the Great Basin. Given the ecological importance of the persistent woodlands (Miller et al. 2019), a spatial data layer is needed that more accurately identifies these woodlands across the region. In addition, more research is needed to understand the potential for fuel treatments to reduce fire risk and increase resilience while maintaining woodland ecological values in persistent and high-cover woodland areas (Redmond et al. 2023).

The new resilience and resistance layers that we used are based on climate and soil water availability metrics (Chambers et al. 2023a) and represent a refinement over the original combined resilience and resistance layer based on soil temperature and moisture regimes (Maestas et al. 2016). Recent applications of these new layers are validating their utility for landscape scale spatial analyses and treatment prioritization (Chambers et al. 2023c).

Conclusions

The new spatial layers that we developed can be used in risk assessments to help identify areas where woody fuel treatments have the potential to decrease fire risk and increase or maintain resilience to wildfire and resistance to cheatgrass, and where they are unlikely to meet these objectives. The spatial layers of the dominant sagebrush associations, the area of these associations experiencing PJ expansion, and the persistent PJ woodlands can be used to aid assessments requiring information on the locations and extents of the dominant vegetation types in the Great Basin. The treatment response groups (TRGs) can help identify the likely responses of the different sagebrush associations to woody fuel treatments as well as the most appropriate treatments. At intermediate landscape scales, these TRGs can be combined with geospatial information on the predominant threats, such as wildfire risk and invasive annual grasses, and on high value resources, such as at risk communities and wildlife habitat, to help prioritize areas for woody fuel treatments and to determine the types of fuel treatments that will best meet management objectives. At larger landscape scale, the TRGs can provide the basis for quantitative wildfire risk assessments and outcome-based scenario planning designed to prioritize regional fuel treatment investments.

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Authors' contributions

JCC led the writing of the manuscript and JLB, MCR, and EKS created the maps. CMT, AKU, and KCS contributed to writing the manuscript. All authors participated in the working group that developed the approach and read and approved the final manuscript.

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Availability of data and materials

The metadata and maps have been submitted for publication in the USDA Research Data Archive.

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