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Spatiotemporal patterns of unburned areas within fire perimeters in the northwestern United States from 1984 to 2014

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Abstract. A warming climate, fire exclusion, and land cover changes are altering the conditions that produced historical fire regimes and facilitating increased recent wildfire activity in the northwestern United States. Understanding the impacts of changing fire regimes on forest recruitment and succession, species distributions, carbon cycling, and ecosystem services is critical, but challenging across broad spatial scales. One important and understudied aspect of fire regimes is the unburned area within fire perimeters; these areas can function as fire refugia across the landscape during and after wildfire by providing habitat and seed sources. With increasing fire activity, there is speculation that fire intensity and combustion completeness are also increasing, which we hypothesized would yield smaller unburned proportions and changes in fire refugia patterns. We sought to determine (1) whether the unburned proportion of wildfires decreased across the northwestern United States from 1984 to 2014 and (2) whether patterns of unburned patches were significantly different across ecoregions, land cover type, and land ownership. We utilized a Landsat-derived geospatial database of unburned islands within 2298 fires across the inland northwestern USA (including eastern Washington, eastern Oregon, and Idaho) from 1984 to 2014. We evaluated patterns of the total unburned proportion and spatial patterns of unburned patches of the fires across different ecoregions, land cover types, and land ownership. We found that unburned area proportion exhibited no change over the three decades, suggesting that recent trends in area burned and overall severity have not affected fire refugia, important to post-fire ecosystem recovery. There were ecoregional differences in mean unburned proportion, patch area, and patch density, suggesting influences of vegetation and topography on the formation of unburned area. These foundation findings suggest that complex drivers control unburned island formation, and yield insights to locate potential important fire refugia across the inland northwest.

Key words: fire atlas; fire refugia; fire severity; Landsat; unburned islands; wildfire.

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INTRODUCTION

There is considerable evidence that wildfire activity is increasing across the western United States due to both increased fuel aridity associated with anthropogenic climate change (Abatzoglou and Williams 2016, Abatzoglou et al. 2017) and the increased flammability of vegetative fuels associated with fire exclusion (Marlon et al. 2012) and changes in land cover (Abatzoglou and Kolden 2011, Balch et al. 2013, Lutz et al. 2017). The subsequent potential impacts from changing fire

regimes to dynamic ecosystems are considerable, including changes in tree recruitment and forest succession (Johnstone and Chapin 2006), altered species distributions (Westerling et al. 2011), positive feedbacks to invasive species (Abatzoglou and Kolden 2011), and conversion of carbon sinks to sources (Rogers et al. 2011). However, these large-scale impacts are as yet poorly quantified and modeled, in part due to key uncertainties about the heterogeneity of fire effects. While there is widespread agreement that large fires are burning more frequently over greater extents across the western United States (Dennison et al. 2014, Barbero et al. 2015), the rate and pattern of heterogeneous consumption within fire perimeters at regional scales and over time is still relatively understudied (Morgan et al. 2014), while in other parts of the globe fire activity is decreasing (Moreno et al. 2014, Doerr and Santín 2016, Turco et al. 2016). Until these patterns within fire perimeters are better defined, accurately modeling and predicting the impacts of localized fire mitigation and adaptation actions (such as forest management practices and ecological restoration efforts) on dynamic ecosystem services is not feasible (Smith et al. 2016*a*, Vaillant et al. 2016).

Patterns of heterogeneous fire effects are described in numerous ways and with multiple metrics, but the most commonly used term is burn severity. Despite its wide use, burn severity is rather loosely defined as a measure of fire-induced ecological change (Key 2006, Lentile et al. 2006, Kolden et al. 2015*b*, Smith et al. 2016*b*), albeit the relative, subjective nature of burn severity and lack of physical measurement units make a precise or consistent definition difficult (Morgan et al. 2014). There has been much recent effort focused on determining whether burn severity is also increasing in parallel with the observed increase in area burned (Miller and Safford 2012, Miller et al. 2012, Picotte et al. 2016, Abatzoglou et al. 2017); these efforts have diverged in both scope and scale. Miller and Safford (2012) focused only on whether the proportion of high-severity fire increased over time in California, while Picotte et al. (2016) and Abatzoglou et al. (2017) undertook broader assessments utilizing a comprehensive Severity Metric (Lutz et al. 2011). These studies all rely on datasets wherein burn severity is defined from spectral reflectance acquired by remote sensing, specifically the Landsat sensor series at 30 m spatial resolution. The most common transformation of these spectral data for burn severity analysis was adopted by the Monitoring Trends in Burn Severity (MTBS) program, which creates the differenced normalized burn ratio (dNBR) and its relativized version (RdNBR) for every fire larger than a regionally specified size threshold in the United States (Eidenshink et al. 2007). While this approach is widely used and accepted as a proxy for holistic fire effects, the empirical links between spectral indices and biometric measures of fire intensity and effects are still quite limited and lacking robust ecological connections and applications (Lentile et al. 2006, Morgan et al. 2014, Kolden et al. 2015*b*), particularly because there is rarely pre-fire biometric or field data from which to assess relative change. Recent efforts to quantify relationships between fire energy released and physiological tree responses have demonstrated the utility of an alternative framework (Smith et al. 2016*b*, 2017, Sparks et al. 2016, 2017).

One ecological metric of wildfire severity that has been assessed on a limited basis but has enormous potential to provide insights into changing fire regimes is the pattern of fire refugia within wildfire perimeters. Previously, fire refugia have been defined variably, including both as the unburned islands or inclusions within a fire perimeter (Kolden et al. 2012, 2015*a*) and as remnants of habitat that maintain ecological function following relatively low-severity fire (Krawchuk et al. 2016). Refugia are important for ecosystem recovery following fire, as they often include remnant flora that function as seed sources for neighboring burned areas (Kemp et al. 2016) and provide functional habitat to surviving faunal populations. Unburned inclusions also contribute to the range and complexity of three-dimensional vegetation structure and potentially increase the biodiversity of an ecosystem in a post-fire landscape (Kane et al. 2013, 2014; A. Meddens et al., *unpublished manuscript*). Fire refugia are regularly overlooked in large-scale fire studies because they are rarely mapped or acknowledged in fire perimeter datasets (Kolden and Weisberg 2007), but they have been estimated to comprise 20–25% of the area within mapped fire perimeters (Kolden et al. 2012, Abatzoglou and Kolden 2013).

Kolden et al. (2012, 2015*a*) hypothesized that if wildfires were burning more severely and

completely due to climate change and increased fuel flammability, they would find declining proportions of unburned areas and fire refugia within fire perimeters and strong relationships between climate metrics and refugial patches. These trends were not evident in studies that were limited to three national parks (Yosemite, Glacier, and North Cascades National parks; Kolden et al. 2015*a*) and the Selway-Bitterroot Wilderness Area (Morgan et al. 2017). However, Kolden et al. (2012, 2015*a*) acknowledged that their analyses were limited by two key factors: (1) a relatively small number of ecosystems and fires assessed due to the limited scope of those studies and (2) a definition and classification of unburned islands from remotely sensed data that were not defined from field data (rather, being arbitrary based on gray literature) and therefore not as robust (Kolden et al. 2012, 2015*a*).

Meddens et al. (2016) developed a field-based classification of unburned islands for the entire U.S. Pacific Northwest region (Washington, Oregon, and Idaho) that addresses both of the key limitations of Kolden et al. (2012, 2015*a*). The objective of this study was to analyze an unburned islands database developed following Meddens et al. (2016) to examine spatial and temporal trends in fire refugia for the period 1984–2014 in order to determine (1) whether the unburned proportion of wildfires decreased over the study period for the inland northwest, (2) whether patterns of unburned patches differed by ecoregions, and (3) what the relative influences of land cover type and land ownership were on unburned proportion and patch metrics. These questions are critical to understanding how patterns of fire refugia may be impacted by global change dynamics, through establishing the historical patterns and range of variability of these key landscape components.

Methods

Study area

The study area (499,200 km^2) covers the inland northwest, which includes the eastern Cascades, the Columbia Basin, and the middle section of the Rocky Mountains (or Middle Rockies), USA (Fig. 1). Fire is one of the dominant ecosystem processes shaping the type and distribution of vegetation (Agee 1993). Within the study area, vegetation varies from frequently burned lowland grass and shrublands in the Columbia (WA) and Harney (OR) basins to less frequently burned Engelmann spruce (*Picea engelmannii* Parry ex Engelm.) and subalpine fir (*Abies bifolia* (Hook.) Nutt.) forests on the highest elevations of the Cascades and Rocky Mountains (Franklin and Dyrness 1988). At intermediate elevations, ponderosa pine (*Pinus ponderosa* Lawson & C. Lawson), mixed conifer, and lodgepole pine (*Pinus contorta* Douglas ex Loudon) forests are common, as well as other less extensive forest and vegetation types. Nomenclature follows Flora of North America (1993+). The climate ranges from semi-arid steppe across the Columbia Plateau to more mesic and cooler conditions in the Cascade and Rocky Mountains along the western and eastern boundaries of the study area, respectively.

Unburned area database creation

Within fire perimeters, we separated unburned from burned areas following the methods of Meddens et al. (2016). Here, we summarize the delineation of fire perimeters, initial image processing, and application of classification trees for identification of the unburned areas. See Meddens et al. (2016) for detailed descriptions of processing and accuracy assessments using field observations.

Fire perimeters

The MTBS program processes all fires ≥405 ha (1000 acres) in the western United States. To establish the unburned island database, we extracted all MTBS fires from 1984 to 2014 within the study area, for a total of 2317 fires. The total area within the fire polygons, including burned and unburned areas within the delineated fire perimeters, was 107,000 km^2 (21% of the total study area; average of 3500 km^2 burned/year). After image processing, we found that 19 fires did not have adequate pre- or post-Landsat imagery (mainly because of clouds or timing of the image acquisition) and those fires were removed from the database, leaving a remaining database of 2298 fire perimeters.

Landsat imagery

We obtained surface reflectance climate data record Landsat imagery for each of the fire perimeter locations (http://earthexplorer.usgs.gov/, accessed 29 September 2015). We followed best practices outlined by Key (2006) for paired scene

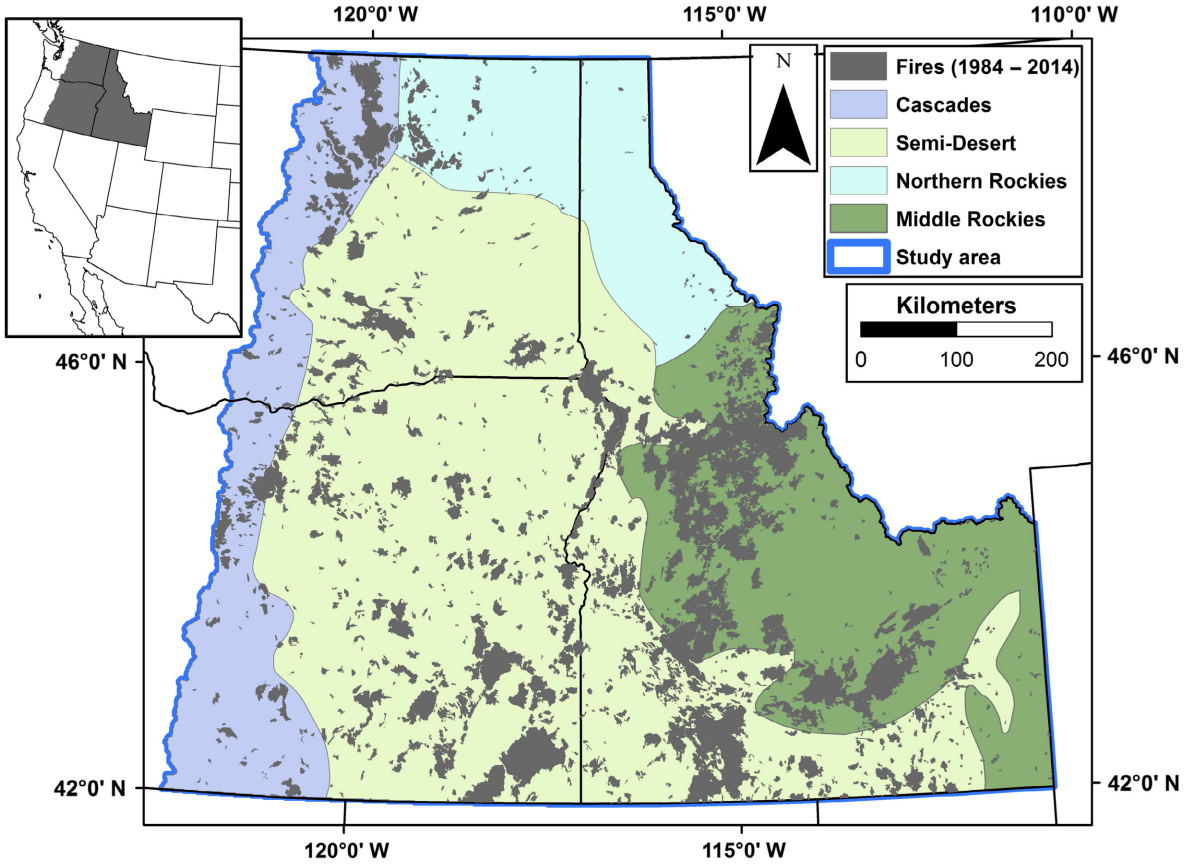

Fig. 1. The inland northwest study area, with the Monitoring Trends in Burn Severity fire extents from 1984 to 2014 shown in gray and the merged Bailey's ecoregions (Bailey 1980) in the background. The inset map shows the location of the study area in the western United States.

selection, including using cloud-free scenes, matched sun angles, and anniversary dates or matched phenology. Two scene pairs were selected per fire, consisting of the immediate post-fire and the one-year post-fire scenes, each paired with a pre-fire scene. The immediate post-fire scene pair consisted of a Landsat scene acquired one year prior to the fire and a paired scene acquired after the fire but within the same fire season. The one-year post-fire scene pair consisted of a scene acquired prior to the fire but within the same fire season and a scene acquired one year following the fire. Because some fires (mostly in the higher-elevation forests) burn into the late autumn, in some cases no immediate post-fire scene was available. In those cases, we used only the one-year post-fire scene pair and used a different classification tree as described below.

Classification approach

To separate the burned from the unburned areas within the fire perimeters, we used the classification tree approach outlined in Meddens et al. (2016). This approach generated an overall classification accuracy of 89% by an independent evaluation using field observations and a 10-fold cross-validation. However, we found that the lowest split sometimes resulted in large areas being incorrectly classified as unburned (especially in non-forested areas). Therefore, we pruned one node of the classification tree presented in Meddens et al. (2016; Appendix S1: Fig. S1), which led to more accurate classification results. No immediate post-fire images were available for 239 (10%) out of the 2298 fires, and for these fires, we used the classification tree that only used one-year post-fire imagery (Appendix S1: Fig. S2; Meddens et al. 2016).

Because the classification tree using only the one-year post-fire imagery did not seem to capture green-up areas in the rangelands (i.e., areas that show anomalous increases in dNBR related to vigorous post-fire grassland recovery following a fire), we separated these burned areas from unburned areas by using the <100 dNBR threshold recommended by Key and Benson (2006). The areas classified in this final split only accounted for 0.34% of the total fire perimeter area.

We applied a phenological correction to address differences within the image collection dates as outlined in Meddens et al. (2016). Finally, to account for spectral mixing and the effects of backscatter, we only classified unburned patches that contained at least two adjacent pixels (rook's case), thus removing single pixels from the database.

Ancillary data

We obtained several ancillary datasets to extract unburned area metrics for different land cover types, land ownerships, and vegetation types. These data included Bailey ecoregions (Bailey 1980), LANDFIRE Biophysical setting (Bps) vegetation data (Version: lf 1.3.0, www.LANDFIRE.gov, accessed: 30 September 2015, Rollins 2009), and land ownership from the U.S. Protected Areas database (version 2.1; Gergely and McKerrow 2013). Bailey ecoregions were used for the fire-level analysis, whereas LANDFIRE Bps and land ownership data were used for the patch-level analysis.

We aggregated similar Bailey ecoregion provinces (seven in total) in our study area into four broader ecoregions and clipped them to our study area extent. The four broader ecoregions we created were as follows: (1) the Semi-Desert ecoregion, which aggregated the Great Plains-Palouse dry steppe province (code: -331) and intermountain Semi-Desert province (-342); (2) the Cascades ecoregion, which aggregated the Cascade mixed forest–coniferous forest–alpine meadow province (M242) and the Sierran steppe–mixed forest–coniferous forest–alpine meadow province (M261); (3) the Northern Rockies ecoregion, which included the northern Rocky Mountain forest–steppe–coniferous forest–alpine meadow province (M333); and (4) the Middle Rockies ecoregion, which aggregated the southern Rocky Mountain steppe–open woodland–coniferous forest–alpine meadow province (M331) and the middle Rocky Mountain steppe–coniferous forest–alpine meadow province (M332; Fig. 1).

Analysis

Unburned proportion, mean patch area and variance (standard error, SE), and mean patch density (number of patches per ha) and variance (SE) were calculated for each fire. To determine whether unburned proportion decreased over the study period, mean annual unburned proportion (i.e., the unburned proportion over all fires in each year), mean annual patch area, and mean annual patch density were calculated for each year from 1984 to 2014. We also evaluated the relationship between unburned proportion and fire size. For the unburned proportion vs. fire size, we used every fire as a single data point. For the unburned proportion across time, we calculated the mean for each year, while eliminating years with less than three fires. The linear least-squares regression was calculated as follows:

$$\%\text{Unburned} = \beta_0 + \beta_1 \times X \quad (1)$$

where %Unburned represents the proportion unburned (%) and X either the individual years or fire sizes (in km^2), β_0 the intercept, and β_1 the slope (or trend). All calculations were made with the R function *lm* in the *stats* package (R Core Team 2017).

At the ecoregion level, we assessed significant differences in patch pattern metrics. We tested for significant differences between ecoregions using the non-parametric Kruskal–Wallis one-way ANOVA test (Kruskal and Wallis 1952), because the data were not normally distributed. The Nemenyi pairwise post hoc test (Nemenyi 1963) was then used to assess whether there were differences among groups. We used a significance level of $\alpha = 0.001$ because of our large sample sizes.

To assess the relative influence of land cover and land management type, we stratified unburned proportions and patch metrics across LANDFIRE Bps settings and land ownership classes. We first merged the LANDFIRE Bps classes to five primary land cover types, namely barren, grassland, shrubland, forest, and riparian. The U.S. Protected Areas database provided six land management types, namely the Department of Energy and Department of Defense (DOE/DOD), State agencies (STATE), Bureau of Land Management (BLM), U.S. Forest Service (USFS), Fish and Wildlife Service (FWS), and the National Park Service (NPS). Private and land management types (e.g., non-governmental organizations) that included <1000 patches were

excluded from the analyses. Individual patch area was calculated across the entire study area and grouped according to the highest overlapping fraction of each given land cover or ownership type. Similar to the ecoprovince-level differences, we tested for patch size differences within the land cover and land ownership types using the nonparametric Kruskal–Wallis one-way ANOVA test and the Nemenyi pairwise post hoc test (significance level; $\alpha = 0.001$).

Results

Temporal trends

The mean unburned area within fire perimeters over all 2298 fires was 9.6% (standard deviation: 10.6%). There were 701,188 patches within the database with a minimum patch size of two adjacent Landsat pixels (0.18 ha) and with a mean of 1.2 ha (standard deviation: 25.4 ha). We found a slightly increasing trend of fire extent (β_1 = +149.9 ha/year, SE = 66.1, $R^2 = 0.15$, $P = 0.03$) across the region, as described in other studies (e.g., Abatzoglou and Williams 2016), resulting in an increasing trend of the total unburned area within fire perimeters within the study area (β_1 = +14.1 ha/year, SE = 5.7, $R^2 = 0.17$, $P = 0.02$). However, the unburned proportion did not significantly change (β_1 = +0.04%/year, SE = 0.60, R^2 = 0.02, $P = 0.44$; Fig. 2 and Appendix S1: Fig. S3). Thus, we found no proof that the mean unburned proportion on a per-fire basis shows a negative trend, which would be associated with a loss of unburned areas within fire perimeters across the western United States. We found that low fire years (years with <10 km^2 fire extent, $n = 5$) had a significantly greater unburned proportion compared to fire years with fire extent >10 km^2 ($n = 26$) (two-sample t-test, $t = -3.03$ (df = 29), $P = 0.005$). Similar to unburned proportion, we did not find a trend of mean patch area between 1984 and 2014 (β_1 = −0.003 ha/year, SE = 0.008, $R^2 = 0.004$, $P = 0.72$) nor a trend of mean patch density between 1984 and 2014 (β_1 = −0.0003, SE = 0.0003, $R^2 = 0.023$, $P = 0.41$).

The lack of a regional trend in unburned proportion was also evident in the ecoregion comparison. We found no robust temporal trends of mean unburned, patch area, or patch density across the time period (1984–2014) across individual ecoregions (Fig. 3). The only significant ($P < 0.05$) trend observed on a per-fire basis (i.e., not area weighted) was for the mean unburned proportion (β_1 = +0.46%/year, SE = 0.181, $P < 0.05$, $R^2 = 0.27$) and patch density (β_1 = +0.002, SE = 0.001, $P < 0.05$, $R^2 = 0.24$) in the Northern Rockies; however, the small sample size for this ecoregion yielded large error bars (Fig. 3A, C).

Ecoregion differences

The mean unburned proportion was significantly lower in the Cascades as compared to the other ecoregions (Kruskal–Wallis $\chi^2 = 43.11$, df = 3, $P < 0.001$ using the Nemenyi pairwise

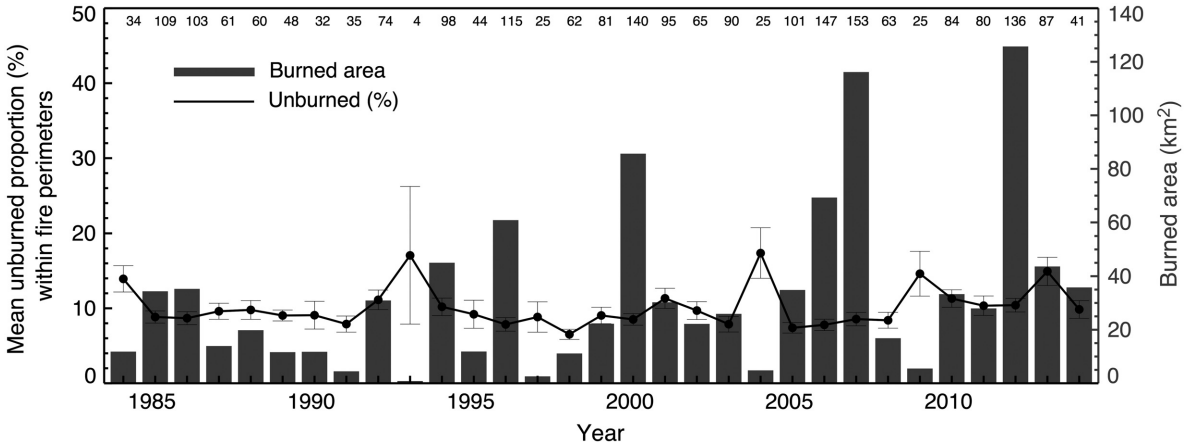

Fig. 2. Total fire extent (km^2, bars) and mean proportion unburned within fire perimeters (%, line) across the inland northwest from 1984 to 2014. The error bars represent the standard error, and the number of fires is shown across the top.

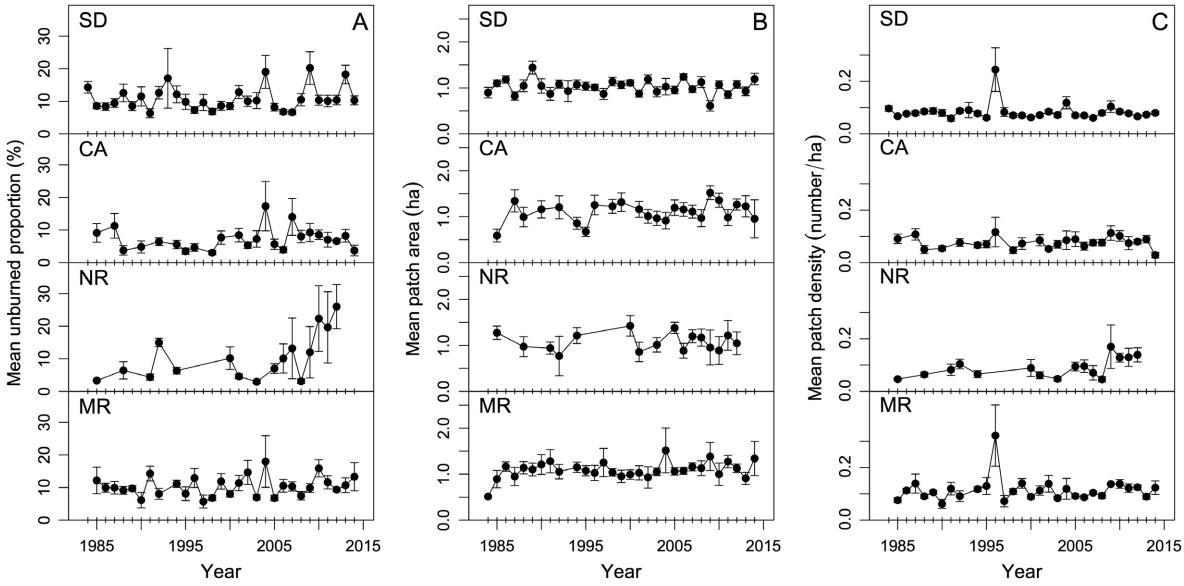

Fig. 3. Mean unburned proportion (%) (a), mean patch area (ha) (b), and mean patch density (number/ha) by fire and by year across the inland northwest from 1984 to 2014 for each of the four ecoregions (derived from the Bailey's ecoregion provinces; Bailey 1980). The error bars represent the standard error. SD, Semi-Desert; CA, Cascades; NR, Northern Rockies; MR, Middle Rockies.

test for multiple comparisons; Fig. 4A). The mean patch area was significantly higher in the Semi-Desert compared to the other ecoregions (Kruskal–Wallis $\chi^2 = 43.06$, df = 3, $P < 0.001$; Fig. 4B), whereas the mean patch density was significantly higher in the Middle Rockies as compared to the other ecoregions (Kruskal–Wallis $\chi^2 = 136.12$, df = 3, $P < 0.001$, Fig. 4C). There was no apparent relationship between fire size and unburned proportion for any of the ecoregions (Fig. 5). The only ecoregion with a significant relationship between fire size and unburned patch area was the Middle Rockies ecoregion ($\beta_1 = +4.1$, SE = 1.7, $P < 0.05$, $R^2 = 0.01$, Fig. 5). Fire sizes in the Cascades ($\beta_1 = -9.8 \times 10^{-5}$, SE = 3.8×10^{-5}, $P < 0.05$, $R^2 = 0.02$) and Middle Rockies ($\beta_1 = -6.8 \times 10^{-5}$, SE = 3.2×10, $P < 0.05$, $R^2 = 0.01$) showed very slight negative relationships with patch density. In addition, smaller fires showed larger variability as compared to the larger fires (Fig. 5).

Environmental contributors

The mean patch area was higher for land cover types with sparse vegetation (i.e., barren, shrubland, and grassland; 1.54, 1.48, and 1.39 ha, respectively) vs. land cover types with denser vegetation (forest and riparian; 0.86 and 0.53 ha, respectively; Table 1). The Kruskal–Wallis test ($\chi^2 = 1917.83$, df = 4, $P < 0.001$) in combination with the Nemenyi pairwise test for multiple comparisons indicated that all group means were significantly different from each other except for grassland and shrubland. The mean patch area across different land management types showed more variability than the mean patch area across land cover types with DOD/DOE and FWS land management having the highest mean patch area (2.99 and 2.60 ha, respectively), whereas the STATE, Bureau of Indian Affairs, and NPS had the lowest mean patch area (1.21, 1.10, and 0.90 ha, respectively; Table 2). The Kruskal–Wallis test ($\chi^2 = 34750.66$, df = 6, $P < 0.001$) indicated that significant differences among the group means existed.

Discussion

Trends in unburned area

Despite the well-documented increase in individual fire size and overall area burned (also observed in our data), unburned areas within fire perimeters across the entire inland northwest demonstrated no trends over the three-decade period of study. This was true of both unburned

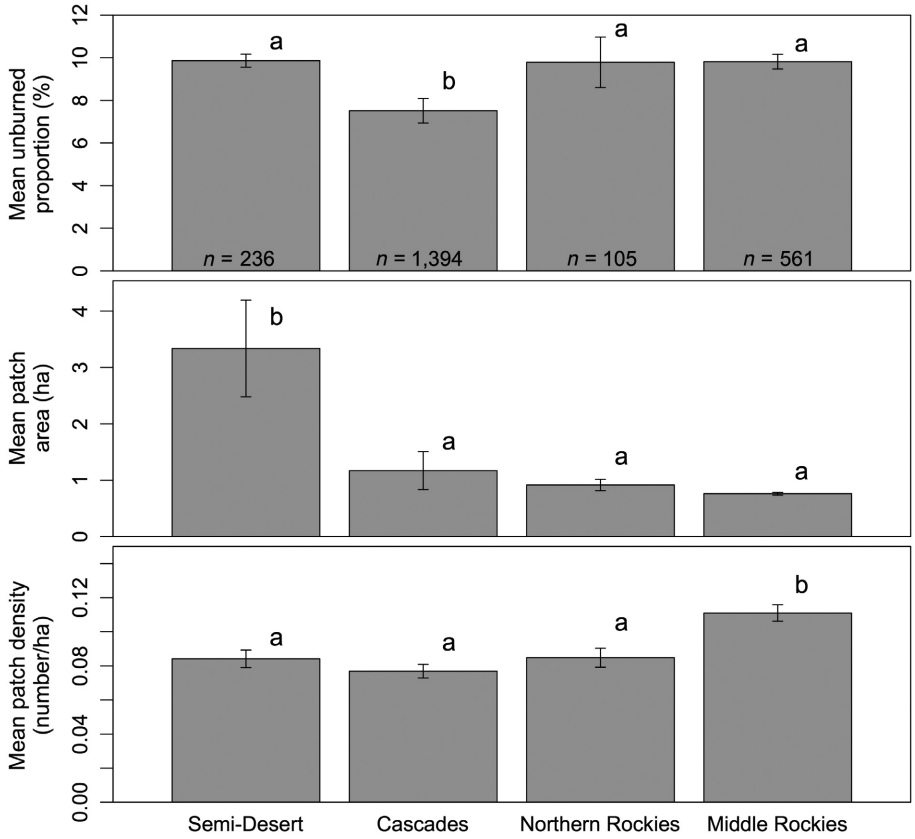

Fig. 4. Mean unburned proportion (%; top), mean patch area (ha; middle), and mean patch density (number/ha; bottom) across the inland northwest from 1984 to 2014 for each of the four ecoregions (derived from the Bailey's ecoregion provinces; Bailey 1980). The error bars represent the standard error. Letters indicate significant differences between the ecoregions using the non-parametric Kruskal–Wallis test with the Nemenyi post hoc test for multiple comparisons ($P < 0.001$), where the ecoregions indicated with (a) are significantly different from ecoregions indicated with (b) for each metric. The number of fires is indicated in the top panel and is identical for the middle and bottom panels.

proportion and the patch size and density metrics. It is consistent with findings from prior, more localized studies (Kolden et al. 2012, 2015*a*), and it is also consistent with recent, national-scale studies showing no trends in burn severity over the entire fire (i.e., not the unburned proportions) for most regions of the country (Picotte et al. 2016, Abatzoglou et al. 2017). A recent, multi-decadal (1880–2012) study of burn area and severity trends in the Selway-Bitterroot Wilderness Area based on fire atlas data, historical aerial photography, and Landsat imagery also found no evidence for increasing burn severity (Morgan et al. 2017). While three decades may not be enough to show strong trends, particularly in long-interval, stand-replacing fire regimes, these analyses suggest that fires are not becoming more uniformly severe and that the local patterns and processes scale to the regional and national extents.

Fire size and unburned area relationships

The lack of a clear relationship between fire size and unburned area metrics is also consistent with prior studies for some ecoregions (Kolden et al. 2012, 2015*a*). This result is particularly interesting because Cansler and McKenzie (2014) found a significant positive relationship between fire size and larger, more homogenous high-severity patches in North Cascades National Park. Cansler and McKenzie (2014) suggested that larger fires

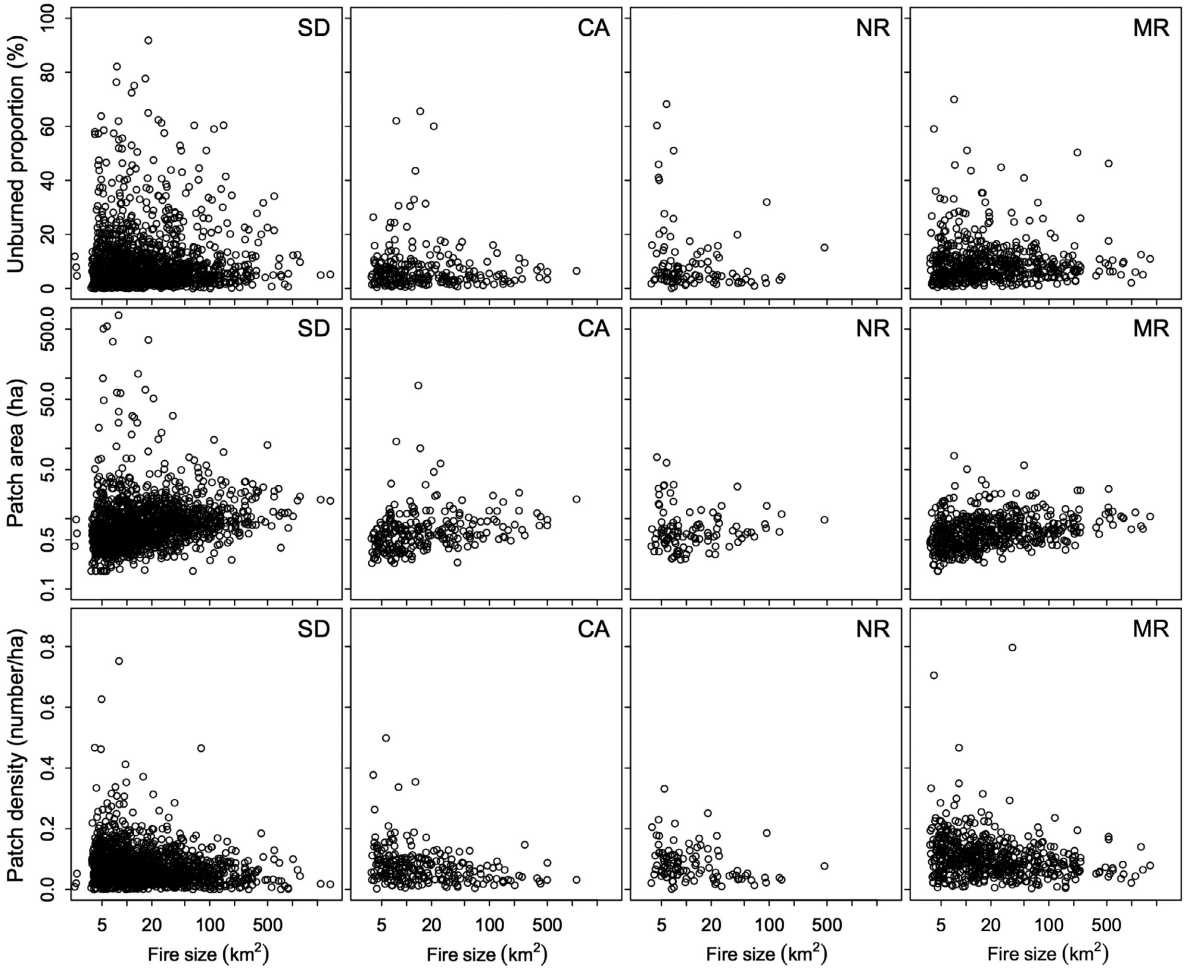

Fig. 5. Scatterplots of average unburned proportion (%, top row), patch area (ha, middle row), and patch density (no/ha, bottom row) vs. total fire extent (or fire area, km^2) by fire for each of the four ecoregions (derived from the Bailey's ecoregion province; Bailey 1980), showing no significant relationship between fire size and unburned proportion, mean patch area, or patch density. SD, Semi-Desert; CA, Cascades; NR, Northern Rockies; MR, Middle Rockies. Note that some fires are smaller than the 405-ha minimum fire size because they were clipped at the study area boundary.

burn more homogenously across their study area, reducing the proportion of low-to-mixed-severity fire effects. Similarly, Lutz et al. (2009) found that larger fires in Yosemite National Park had higher proportions of high-severity and larger high-severity patches. Our analysis suggests that unburned proportion is not reduced within the perimeters of larger fires, suggesting that unburned areas may be tied to static landscape characteristics, such as topography or microclimate-driven vegetation; Krawchuk et al. (2016) found that topography plays a considerable role in this. It is notable, however, that our definition of unburned area was considerably more conservative than prior studies based on our classification tree approach described in Meddens et al. (2016); this is evident in the range of values for unburned proportion by ecoregion. Our study found that mean unburned proportion ranged from 7% to 10% across the four ecoregions, which is considerably lower than the 20–30% found in prior studies of unburned areas (Kolden et al. 2012, 2015*a*, Abatzoglou and Kolden 2013, Cansler and McKenzie 2014).

Table 1. Landscape metrics of the unburned database by land cover (total number of patches is 701,188).

Metric	Land cover				
	Barren	Grassland	Shrubland	Forest	Riparian
Proportion (and area) within fire perimeters†	0.8% (1521 km^2)	12.0% (12,714 km^2)	52.7% (55,984 km^2)	31.5% (33,477 km^2)	2.9% (3108 km^2)
Proportion (and area) of unburned areas‡	2.0% (170 km^2)	16.2% (1394 km^2)	53.0% (4454 km^2)	27.3% (2350 km^2)	1.6% (139 km^2)
Total number of patches	10,770	97,594	301,182	266,259	25,383
Mean patch area (ha; standard deviation)	1.54 (35.2)	1.39 (26.5)	1.48 (34.0)	0.86 (9.22)	0.53 (3.2)
Median patch area	0.36 (4 pixels)	0.27 (3 pixels)	0.27 (3 pixels)	0.27 (3 pixels)	0.27 (3 pixels)
Class patch density (number/land cover type ha)	0.071	0.077	0.054	0.080	0.082

† Proportion of the area within fire perimeters that was classified as a given land cover type; apparent differences in totals due to rounding.
‡ Proportion of the area within unburned areas that was classified as a given land cover type; apparent differences in totals due to rounding.

As the study period includes several regional large fire years and some record individual large fires, these results make clear that while fires may be increasing in size, fires are burning with enough heterogeneity on the landscape to maintain relatively consistent patterns of unburned patches. This is critical for several reasons, as changes in proportion, patch size, or patch density can have significant ecological effects (Fig. 6). Changes in either proportions or patterns of unburned patches could have considerable impacts to species that are sensitive to minimum habitat patch size requirements or distance between patches of fragmented habitat. For example, in a non-fire landscape, Sears et al. (2016) found that shade patch sizes and distance between patches of shade were critical to temperature regulation in ectotherms in hot deserts. Similarly, it is likely that thermal contrasts, differential cover from predators, differential timing of snowmelt, and differential availability of food and water in recently burned areas incite differential levels of stress on faunal species dependent upon patch size and separation distance. It is therefore critical to monitor trends in these patch patterns over time, particularly for species conservation needs. We also note that our analysis did not delineate between unburned patches that actually function as habitat fire refugia vs. unburned patches that do not function as species

Table 2. Landscape metrics of the unburned database by land manager type (total number of patches is 701,188 and because some land manager types were omitted—that is, private, and landowners having <1000 patches—a total of 599,289 patches are presented here).

Metric	Land management agency†						
	DOD/DOE	STATE	BLM	BIA	USFS	FWS	NPS
Proportion within fire perimeters‡	2.7% (1834 km^2)	5.5% (3697 km^2)	39.2% (26,558 km^2)	4.9% (3295 km^2)	46.4% (31,469 km^2)	1.2% (783 km^2)	0.2% (149 km^2)
Proportion of unburned areas§	5.5% (573 km^2)	3.0% (310 km^2)	38.7% (4011 km^2)	2.7% (276 km^2)	48.1% (4983 km^2)	1.9% (197 km^2)	0.1% (15 km^2)
Total number of patches	19,182	25,549	218,937	25,055	301,104	7571	1891
Mean patch area (ha; standard deviation)	2.99 (70.1)	1.2 (15.4)	1.83 (35.6)	1.10 (9.8)	1.66 (20.7)	2.60 (37.5)	0.81 (2.0)
Median patch area	0.27 (3 pixels)	0.27 (3 pixels)	0.36 (4 pixels)	0.27 (3 pixels)	0.54 (6 pixels)	0.45 (5 pixels)	0.36 (4 pixels)
Patch density (number/ha)	0.105	0.069	0.082	0.076	0.096	0.097	0.127

† DOD/DOE, Department of Defense/Department of Energy; STATE, State Land Management Agencies; BLM, Bureau of Land Management; BIA, Bureau of Indian Affairs; USFS, United States Forest Service; FWS, Fish and Wildlife Service; NPS, National Park Service.
‡ Proportion of the area within fire perimeters managed by a given agency; apparent differences in totals due to rounding.
§ Proportion of the area within unburned areas managed by a given agency; apparent differences in totals due to rounding.

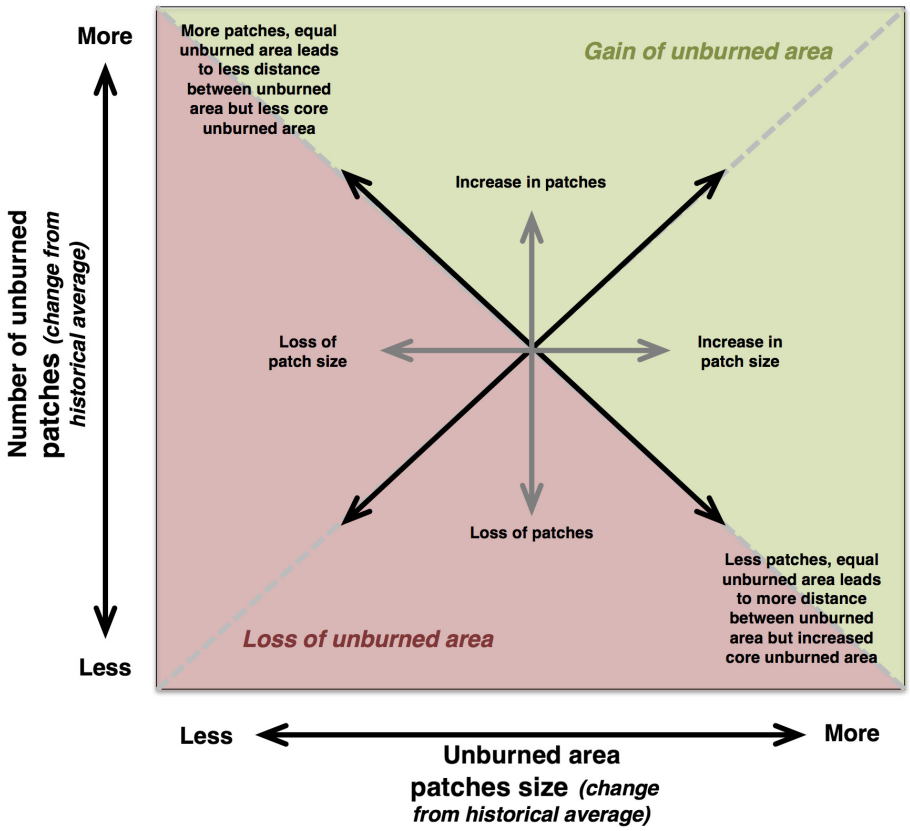

Fig. 6. Conceptual framework for analyzing trends in unburned area and spatial configuration of patches.

refugia (e.g., bare rock), and a key next step is to develop a method for such delineation at landscape scales and assess trends in patches that are considered habitat. Further, these patches would also ideally be graded for quality, since habitat is not binary from a conservation perspective.

Ecoregion, land cover, and land management differences

While no single ecoregion stood out as significantly different from the other ecoregions for any metric of unburned area considered, the differences found between ecoregions for each metric demonstrate the variability in factors determining patch formation during fires. Fire behavior is predicated on three contributing factors: topography, weather, and fuels/vegetation, and Krawchuk et al. (2016) demonstrated the critical role of topography specifically in the formation of fire refugia. That the Semi-Desert ecoregion had the largest unburned patch sizes is likely a function of flatter topography and wind-driven fires in relatively sparse vegetation. This is further evidenced by the land cover and land management stratification, where the barren, grassland, and shrubland land cover types that are primarily managed by DOD/DOE, FWS, and BLM yielded larger mean unburned patches than the more topographically complex forests and riparian systems with denser vegetation managed by FWS and NPS. Finally, differences in patch area could be related to differences in the ability to detect unburned areas within different land cover types (i.e., overstory canopy obscuring low-severity fires (Kane et al. 2014)), although Meddens et al. (2016) showed little to no accuracy differences between forest and non-forest in detecting unburned areas.

Further complicating the ecoregion analysis is the significantly higher density of unburned patches in the Middle Rockies regions. Because the Northern Rockies region is comprised primarily of fires in the eastern Cascades of north-central Washington, the fires that burn in the Middle Rockies occur in areas that are climatically more

variable than the other regions; in addition, the Middle Rockies have a fundamentally different underlying geology. As such, vegetation communities or rocky areas may be driving the higher density of unburned patches. But there is another factor not evident in our analysis, which is the presence of extensive wilderness within the Middle Rockies region that is absent elsewhere. Both the Frank Church-River of No Return and Selway-Bitterroot wilderness areas within central Idaho are part of the Middle Rockies, and these two areas have run natural fire programs in the United States for the last 50 yr. As research indicates that naturally burning fires in these wilderness areas become self-limiting (Teske et al. 2012, Parks et al. 2014, 2015, Morgan et al. 2017), we suggest that these natural fire regimes may be more conducive to smaller, higher-density unburned patches. This is supported by the land management comparison, where NPS, which has the most widespread and longest running natural fire program of the land management agencies, has significantly higher density of patches and smaller unburned patches (Table 2).

Ecological and management implications

One of the chief concerns of conservation biology in regard to climate change has been the need to identify climate refugia for species most sensitive to potential loss of habitat (Morelli et al. 2016). In the inland northwest, the primary natural ecological disturbance is wildfire; thus, the chief mode of acute habitat loss is wildfire-induced land cover change. As fires have grown in extent, and anthropogenic climate change leading to increased fuel aridity has been identified as a primary driver of greater area burned (Abatzoglou and Williams 2016), it is logical to hypothesize that one of the potential negative ecological impacts of these changes would be more complete burning leading to a reduction in refugia within fires. Our results indicate that this is not the case and that fire refugia continue to form with consistent heterogeneity and pattern even as fires have grown larger over recent decades; this remains true even when stratifying by ecoregion within the northwest. This consistency of heterogeneous pattern regardless of size is congruent with Birch et al. (2014), who examined burn severity patterns for individual days of fire progression and found no relationship between days with large fire growth and more homogeneous and higher-severity fire patterns.

Further research in fire effects of the formation of unburned areas is needed. For instance, fire spread modeling that allows the spatial allocation of landscape fuel management strategies could be used to assess the formation of fire refugia. For instance, models such as the Forest Vegetation Simulator in combination with the Fire and Fuels Extension (Ager et al. 2010) and FlamMap (Alcasena et al. 2016) have been used for fire spread modeling to assess the fire risk of valuable resources under different management strategies. Another effect that needs additional research is the development of unburned islands from spot fires that are often linked fire growth and final fire size (Cruz et al. 2012). These aspects could lead to a better understanding of the formation of fire refugia and lead to predictive models on where fire refugia are likely to form following wildfires, which can then be verified by observations and used for informed management decisions.

While this is initially reassuring for conservation efforts, our interpretation of these results is limited by not having a clearer picture of the types of refugia that are forming. Our land cover analysis is based on LANDFIRE, which has never been systematically assessed for accuracy, and the quality of the refugia is unknown and also somewhat dependent upon the specific species requiring it for habitat. For conservation efforts, we suggest that this historic database of refugia is a starting point for further classifying fire refugia by persistence and function, and it provides information that can be utilized at the local level as a baseline for understanding change in patterns of refugia over time. It can also provide critical information for future assessment of areas that re-burn, to understand how refugia from a prior fire function in subsequent fires (Camp et al. 1997, Kolden et al. 2017). One of the key knowledge gaps concerning fire refugia is the extent to and mechanisms by which they persist through multiple successive fires vs. occur ephemerally for a given fire. Krawchuk et al. (2016) found that topography, which we did not assess here, is a prominent determining factor in refugia formation, and previous studies have suggested that topography is generally a key determinant of spatial patterns of burn severity (Dillon et al. 2011, Birch et al. 2015). However, topography is often a proxy for microclimate and

vegetation patterns, further complicating our ability to attribute the underlying mechanisms.

For land managers who seek to facilitate the formation of unburned areas and fire refugia generally, or wish to protect specific critical habitat areas from future negative fire impacts, a key next step for future work is to identify management actions that can achieve these objectives. The multi-decadal database explored in this study can be utilized in existing conservation frameworks built upon spatial datasets to prioritize protecting the most critical or vulnerable fire refugia (e.g., the GAP analysis program; Jennings 2000, Groves et al. 2002); this will allow for the development of adaptive management scenarios that translate general conservation principle to specific actions for conserving critical refugia in regions where wildfire is a primary threat for habitat loss (Heller and Zavaleta 2009). For example, the primary driver of much recent habitat loss for the sage grouse (*Centrocercus urophasianus*) in the Intermountain West is the invasion of the European annual cheatgrass (*Bromus tectorum*) and the subsequent introduction of a high-frequency fire return interval that eradicates the native sagebrush (*Artemisia tridentata*) required for high-quality grouse habitat (Connelly et al. 2000, Balch et al. 2013). There has been some disagreement in the literature on how to use fire as a tool to restore and maintain sage grouse habitat in the face of this change (Baker 2006, Beck et al. 2009); utilizing information gleaned from a long-term refugia database may yield insights as to what topographic features and environmental conditions could be exploited in conjunction with prescribed fire to successfully conserve leks, brood-rearing areas, and other critical habitat components. Similarly, relationships between persistent unburned areas and topographic features could be exploited to select building sites and shape landscaping for homes and communities as the wildland–urban interface expands, thus reducing the fire vulnerability of infrastructure built in fire-prone regions by incorporating natural fire resistance characteristics to the design.

Conclusion

With a changing climate and an ever-expanding human footprint on the landscape, resource managers face many challenges to conserving critical habitat, and these challenges are compounded in regions like the northwestern United States, where wildfires are both a primary agent of acute ecological change and are spatiotemporally expanding due to the warming climate. While there has been much focus on identifying and protecting potential climate refugia, this should be contextualized in understanding fire refugia as well, since fire will be the primary short-term disturbance that can threaten refugia. To address this gap, it is important to characterize fire refugia across the landscape, monitor trends, and understand baseline conditions. Using a database of unburned areas within fire perimeters, which are arguably the most conservative definition of fire refugia, we found no significant trends of unburned proportion, patch size, and patch density over the recent multi-decadal period. In addition, we characterized unburned patches across ecoregions, land management, and land cover. This exploratory analysis lays the foundation for future assessments that can further explore the formation and persistence of unburned areas, and begin prioritizing both high-value refugia and adaptive management strategies to conserve them.

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Supporting Information

Additional Supporting Information may be found online at: http://onlinelibrary.wiley.com/doi/10.1002/ecs2.2029/full