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To cite this article: Rutherford Vance Platt *et al* 2024 *Environ. Res. Lett.* **19** 014044

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OPEN ACCESS

RECEIVED
24 July 2023

REVISED
10 November 2023

ACCEPTED FOR PUBLICATION
1 December 2023

PUBLISHED
13 December 2023

LETTER

Fire refugia are robust across Western US forested ecoregions, 1986–2021

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Keywords: wildfire, refugia, Landsat, composite burn index, ecoregion, Western US, forests

Supplementary material for this article is available online

Abstract

In the Western US, area burned and fire size have increased due to the influences of climate change, long-term fire suppression leading to higher fuel loads, and increased ignitions. However, evidence is less conclusive about increases in fire severity within these growing wildfire extents. Fires burn unevenly across landscapes, leaving islands of unburned or less impacted areas, known as fire refugia. Fire refugia may enhance post-fire ecosystem function and biodiversity by providing refuge to species and functioning as seed sources after fires. In this study, we evaluated whether the proportion and pattern of fire refugia within fire events have changed over time and across ecoregions. To do so, we processed all available Landsat 4–9 satellite imagery to identify fire refugia within the boundaries of large wildfires (405 ha+) in 16 forested ecoregions of the Western US. We found a significant change in % refugia from 1986–2021 only in one ecoregion—% refugia increased within fires in the Arizona/New Mexico Mountain ecoregion (AZ/NM). Excluding AZ/NM, we found no significant change in % refugia across the study area. Furthermore, we found no significant change in mean refugia patch size, patch density, or mean distance to refugia. As fire size increased, the amount of refugia increased proportionally. Evidence suggests that fires in AZ/NM had a higher proportion of reburns and, unlike the 15 other ecoregions, fires did not occur at higher elevation or within greener areas. We suggest several possibilities for why, with the exception of AZ/NM, ecoregions did not experience a significant change in the proportion and pattern of refugia. In summary, while area burned has increased over the past four decades, there are substantial and consistent patterns of refugia that could support post-fire recovery dependent on their spatial patterns and ability to function as seeds sources for neighboring burned patches.

1. Introduction

Extreme weather, rising temperatures, severe drought, and increased ignitions (Westerling 2016) are creating conditions conducive to fires, leading to a global increase in burned area (Abatzoglou *et al* 2021) and forest loss (Tyukavina *et al* 2022). These expanding burned areas are not uniform in severity; fire interacts with landscapes to form a complex mosaic of burned and less affected areas. The islands of unburned or minimally burned areas within fire perimeters are commonly referred to as fire refugia (Krawchuk *et al* 2020). Fire refugia play an important role in enhancing post-fire ecosystem function and biodiversity, offering refuge to species during a fire event and serving as a vital seed source in the aftermath (Kolden *et al* 2017). As the world continues to warm, refugia could help promote forest persistence and disturbance recovery by maintaining legacy species from previous climate conditions (Dobrowski 2011, Stevens-Rumann *et al* 2018, Coop *et al* 2020). Fire behavior can shape the formation of refugia. If climatic or fuel conditions favor higher fire severity and a continuous supply of fuel, fires may burn more completely, resulting in fewer refugia (Whitman *et al* 2022). Conversely, under moderate fire weather the spatial heterogeneity of factors like fuel moisture, temperature, wind, topography may support the formation of refugia (Collins *et al* 2019). Fire suppression efforts like backburning may also play a role by reducing fire severity and generating more patchiness (Stephens *et al* 2009).

Studies have hypothesized that climate change and growing wildfire activity are leading to increases in fire severity and distance to seed sources (Harvey *et al* 2016) and a decrease in the proportion of refugia within fire perimeters (Kolden *et al* 2017, Collins *et al* 2019). There is some evidence of this. For example, studies in the United States have documented increased fire severity in specific regions (e.g. sites in the Northern Rockies, Parks *et al* 2018), specific vegetation types (e.g. the southern Rocky Mountain lower montane, Rocky Mountain subalpine, and California chaparral vegetation types, Picotte *et al* 2016), and within patch interiors (Cansler and McKenzie 2014, Stevens *et al* 2017). In Alberta, Canada unburned areas within fire perimeters significantly have declined since 1985 (Whitman *et al* 2022). However, other studies have not found any consistent temporal trend in fire severity or proportion of fire refugia (e.g. Meddens *et al* 2018b, Chapman *et al* 2020). Thus, there is no scientific consensus regarding whether the proportion of refugia are changing across a wide swath of ecoregions (Meddens *et al* 2018b, Parks *et al* 2020, Buonanduci *et al* 2023).

One possible reason for the lack of scientific consensus is that refugia studies typically focus on narrow time frames and localized regions. For example, previous studies in the United States have focused on the Colorado Front Range (Chapman *et al* 2020), the central Sierra Nevada (Blomdahl *et al* 2019), the Pacific Northwest (Krawchuk *et al* 2016, Meddens *et al* 2018b, Meigs *et al* 2020) and elsewhere. Furthermore, most refugia studies use individual pixels or patches as units of analysis (e.g. Krawchuk *et al* 2016, Meddens *et al* 2016, Meigs and Krawchuk 2018, Blomdahl *et al* 2019, Collins *et al* 2019, Chapman *et al* 2020, Downing *et al* 2021, Meigs *et al* 2020, Mackey *et al* 2021, Talucci *et al* 2022). While the characteristics of pixels and patches are important for refugia formation, so are event level factors like fire-driven weather, fuel moisture conditions, and fire suppression activities (such as backburning and slurry drops). Analyzing event-level patterns of fire refugia is important for understanding the spatial and temporal characteristics of fire regimes (Chuvieco *et al* 2016, Balch *et al* 2020) and provide valuable insights to guide land managers in planning for post-fire recovery and pre-fire mitigation. Yet, with a few notable exceptions (e.g. Kolden *et al* 2012, Meddens *et al* 2018b), few studies analyze refugia at the fire event level across ecoregions.

This study explores how fire refugia within forested areas have changed over time and across ecoregions between 1986 and 2021 across the Western US. We focus the study on fire event-level refugia metrics that reveal the area and patchiness (% refugia, total refugia area, median and maximum refugia patch size, number of refugia patches, refugia patch density, median and maximum distance to refugia). Our hypothesis is that in a preponderance of fires within western US ecoregions, % refugia has decreased over time while the distance to refugia patches within the fire perimeter has increased. This study has several distinctive characteristics that advance our understanding beyond previous work. First, it has the largest spatial and temporal extent of any refugia study (16 ecoregions in the Western US from 1986–2021). Secondly, it classifies fire refugia using a fire severity measure that is spatially consistent across ecoregions (bias corrected composite burn index (CBI), Parks *et al* 2019) and derived from image composites rather than single imagery. Third, this study focuses on fires that took place in relatively dense forest cover (>50% pre-fire forest), not in lower density savannas or woodlands where management is more prevalent (Chapman *et al* 2020). If refugia are becoming smaller and more fragmented, it may forecast a different successional pathway for forest vegetation as the planet warms (Blomdahl *et al* 2019).

2. Methods

To answer the research questions, we summarized refugia characteristics of 2968 fires that met criteria for inclusion in the study. We used the following workflow to answer the research questions (figure 1). The following sections follow each step of the workflow.

2.1. Step 1: Select wildfires within the 16 forested ecoregions in the Western US

This study focuses on wildfires that occurred in forested ecoregions in the Western US (figure 2). The dataset we used to identify wildfires is the Monitoring Trends in Burn Severity (MTBS) fire boundaries, which comprise all large wildfires (405+ ha in the Western US) starting in 1984 (Eidenshink *et al* 2007). MTBS fire boundaries are manually digitized based on standardized analysis of Landsat 4–9 imagery and incident perimeters where available. While the MTBS dataset omits smaller fires, it does not show a temporal bias (Picotte *et al* 2020, Iglesias *et al* 2022).

We selected fires included in the MTBS database (accessed November 2022) using the following criteria:

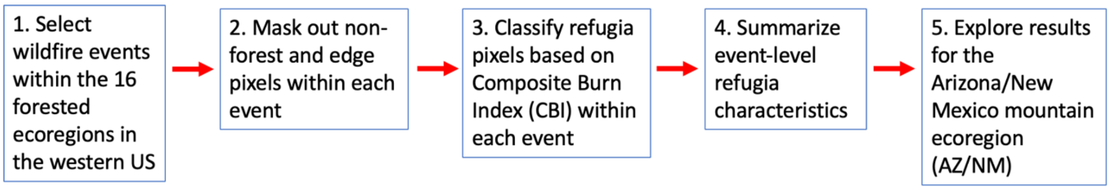

Figure 1. Methods workflow, corresponding to headings below.

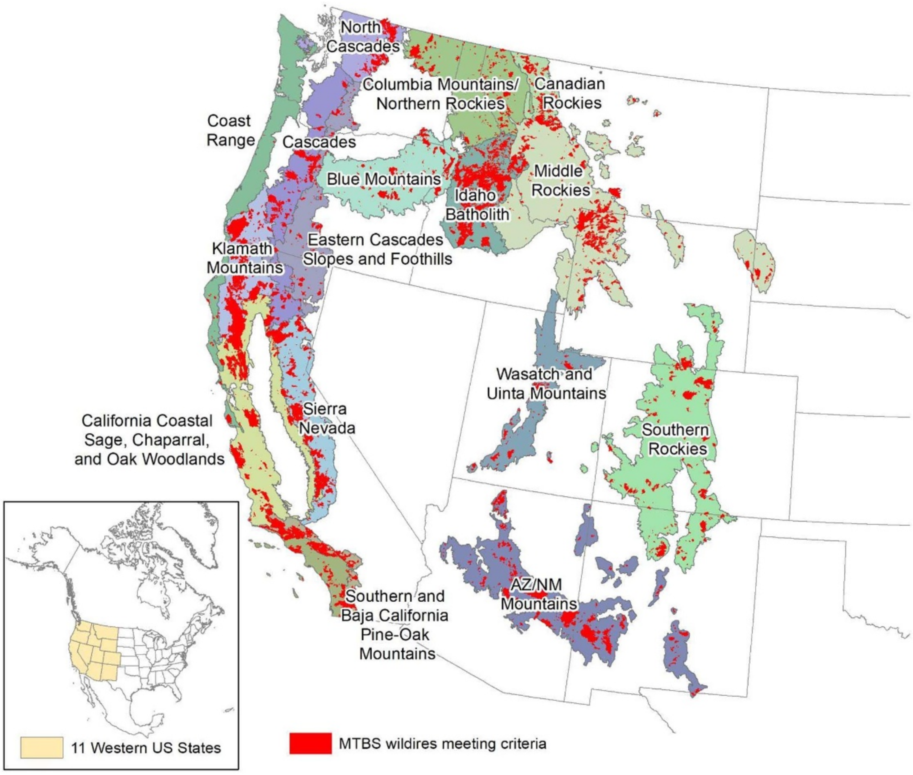

Figure 2. MTBS fires within study area: 16 forested ecoregions in western US.

(1) Fires must be from the years 1986–2021 so that all fires have adequate before and after imagery.
(2) The fire incident type must be MTBS type 'wildfire' (excluding the MTBS types 'prescribed', 'wildland fire use', and 'unknown').
(3) Fire boundaries must overlap forested level 3 ecoregions in the Western US (Omernick and Griffith 2014).
(4) Fire boundaries must have 50%+ of the area classified as forest cover in the year before the fire (Harvey *et al* 2016, Meigs *et al* 2018). To identify forest cover we used the USGS landscape change monitoring system (LCMS) data (Healey *et al* 2018), which classifies pixels as trees if most of the pixel's area comprises trees and no other land cover covers more than 10%.

2.2. Step 2: Mask out non-forest and edge pixels within each event

For each of the selected wildfires, we masked out pixels that were classified as non-forest one year before the fire (LCMS land cover product, Housman 2021). This step removes savannas and open woodlands from the analysis. We also masked out all pixels that were less than 100 m from the edge of the fire perimeter. This excluded the approximate areas where conifer seeds could readily spread from outside the fire boundary (Steel *et al* 2018) and reduced edge effects and digitizing errors (Parks *et al* 2018, Stevens–Rumann *et al* 2018). Finally, pixels were masked out if there were no valid pre- or post-fire pixels (rare, but evident in a few of the earliest fires).

2.3. Step 3: Classify refugia pixels based on CBI within each event

Next, we classified all non-masked pixels as 'forested refugia' or 'forested non-refugia' based on CBI, a widely used and easily interpreted field-based measure of fire severity. CBI was calculated using the Parks *et al* (2019) method, which uses random forests regression to predict CBI based primarily on

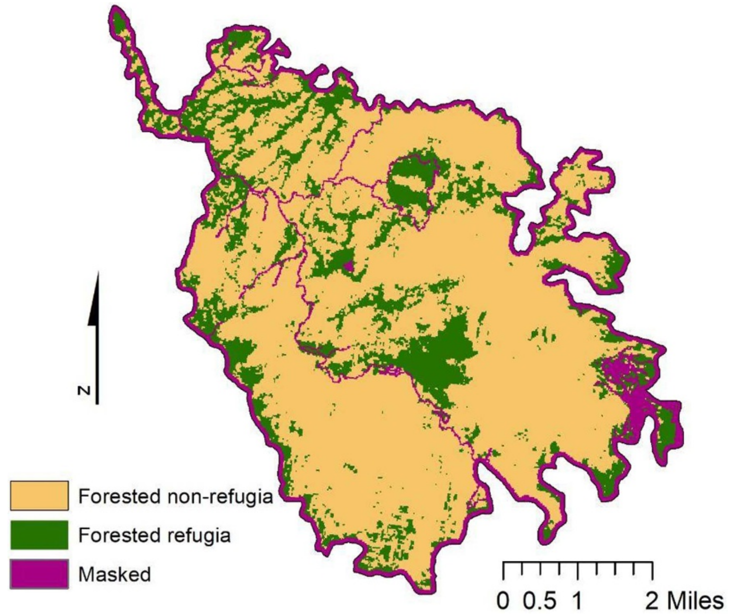

Figure 3. Example refugia classification: the Waldo Canyon Fire near Colorado Springs, CO, USA in 2012.

relativized burn ratio (RBR) and secondarily on latitude, climatic water deficit, and other factors. RBR was calculated from pre- and post-fire image composites, which comprise the mean of all valid pixel values (i.e. no clouds, shadows, water, snow, or scan line corrector gaps) in all available imagery (Landsat 4–9 collection 2) during a specified season (June–September for most ecoregions) for one year prior to and following the fire (see additional details, Parks *et al* 2018, 2019). The number of images available to create the composites was typically 10–20 images for each pre- and post- fire composite. A bias correction was applied to the CBI calculation to prevent overprediction at low values (Parks *et al* 2019). Unlike the MTBS burn severity rasters, this CBI calculation is adjusted for pre-fire vegetation, validated across many ecoregions, and based on image composites rather than single images.

Pixels with a CBI of less than 1.25 were classified as 'forested refugia', and remaining pixels were classified as 'forested non-refugia' (figure 3). The 1.25 CBI threshold indicates little tree mortality (Miller and Thode 2007), and is consistent with other studies that include unburned forests and low severity burn forests as refugia (Krawchuk *et al* 2016, 2020, Meigs and Krawchuk 2018, Walker *et al* 2019, Chapman *et al* 2020, Meigs *et al* 2020, Downing *et al* 2021).

2.4. Step 4: Summarize event level refugia characteristics

After classifying refugia, we summarized the refugia characteristics within each fire in two ways. First we classified the composition of each fire (e.g. the area of each fire that was classified as forest refugia, forest non-refugia, non-forest vegetation, unvegetated, and no data). Secondly, we calculated fire refugia metrics for each fire event:

- % refugia (proportion of pre-fire forest within fire boundary that is classified as refugia (i.e. CBI < 1.25)
- total refugia area
- median and maximum refugia patch size (patches are groupings of adjacent refugia pixels, connected by edge or diagonally).
- number of refugia patches
- refugia patch density
- median and maximum distance to refugia (Euclidean distance from non-refugia pixel to refugia pixel, up to a maximum of 1.5 km).

For each of the metrics, we then used two estimators of the slope of change: OLS and Theil–Sen. The OLS estimator is based on the weighted *mean* of slopes between data pairs, while the Theil–Sen Slope is based on the *median* slope between data pairs (Sen 1968). Thus OLS slope is sensitive to extreme values while Theil–Sen is robust, making it well suited for identifying trends in climate and weather data (Fernandes and Leblanc 2005). We calculate slope using both estimators since we are interested in the trends in refugia metrics both with and without extreme values. For % refugia and slope of % refugia, we also summarized the result within ecoregions.

2.5. Step 5: Explore results for the Arizona/New Mexico mountain ecoregion

We assessed two possible reasons for why AZ/NM experienced a significant increase in % refugia, while the other 15 ecoregions did not. One possible explanation is that re-burns and other forms of forest loss (e.g. thinning and harvesting) could have increased in AZ/NM, thus promoting refugia. Forests with lower stand density that burn frequently tend to experience lower severity fires (Covington *et al* 1994), and are associated with higher % refugia (Meddens *et al* 2018a). To evaluate this possibility, we calculated the slope of change in the following: % of the fire boundary that had experienced a fire in the previous 10 years (henceforth: % reburn) and % of the fire boundary that had experienced forest loss caused by a disturbance other than fire in the previous 10 years (henceforth: % non-fire forest loss). We used the MTBS database to calculate % reburn and the LCMS database 'fast forest loss' layer (Housman 2021) to calculate % non-fire forest loss (i.e. from harvesting, thinning, windthrow, and other drivers). The slopes were calculated for the AZ/NM ecoregion and for the 15 other ecoregions.

A second possible explanation is that fires in AZ/NM could be increasingly occurring in forests with characteristics that are conducive to refugia formation (e.g. lower elevation, less green, or sparser forests). Lower elevation forests tend to have fire regimes with frequent, low severity fires associated with refugia (Covington and Moore 1994). To evaluate this, we calculated slope of change in the following within fire events: mean elevation, mean NDVI in pre-fire forest, and % of fire boundary that comprised forest prior to the fire (henceforth: % pre-fire forest). Note that % pre-fire forest ranges from 50% to 100%, since fires with <50% pre-fire forest cover were excluded from the analysis.

3. Results

3.1. Number, size, and composition of fire events

The MTBS database containd 2968 fires that meet criteria for inclusion in the study. Over the full time series, the median fire size was 1398 ha, mean size was 5721 ha, and interquartile range was 3368 ha. The number of fires have increased over time (figure 4(a)) and so has the mean size of fires (figure 4(b)), though size continues to be highly variable. As the total area of MTBS perimeters increased, so did the area of both refugia and non-refugia (figure 4(c)). Over the full time series, the MTBS fire boundaries contained 27% forested refugia, 66% forested non-refugia, and 7% other (non-forest, non-vegetated, or no data). These percentages remained fairly stable over time (figure 4(d)). In summary, both fire perimeters and the refugia within increased over time, but there has been no obvious trend in % refugia.

3.2. Slope of change of fire refugia metrics

The slope of % refugia is significantly positive for both OLS and Theil–Sen estimators, indicating that % refugia has increased during the time period (table 1). However, this change was driven entirely by the increase in % refugia in the AZ/NM. When excluding AZ/NM, the slope of % refugia was not significantly different from zero. For some refugia metrics (total refugia area, maximum refugia patch size, number of refugia patches, and maximum distance to refugia), results were equivocal. The OLS slope of change was positive and significant but the Theil-Sen slope was not significantly different from zero. The interpretation is that the median slope shows 'no change' while the mean slope shows 'positive increase' driven by fires with unusually high values. For the remaining refugia metrics (refugia patch size, refugia patch density, or mean distance to refugia), slope of change was not significantly different from zero regardless of the estimator (table 1).

3.3. Ecoregion-level results

Within the forested areas of each fire boundary, % refugia varied considerably by ecoregion. Fires in the Rockies, Cascades, and Sierra Nevada ecoregions were characterized by median refugia of 30% or less, while fires in AZ/NM and the Coast Range ecoregions had much higher median refugia (figure 5(a)). While there were big differences in % refugia between ecoregions, there was no significant change over time in most ecoregions (figure 5(b)). The Coast Range ecoregion had a decrease (negative slope) in % refugia, and the Cascades and Blue Mountain ecoregions had an increase (positive slope) in % refugia. However, these changes were not significant with the number of fires in the dataset. In AZ/NM, however, the change in % refugia was positive and significant (figure 5(b)). In the following section, we explore reasons why the trajectory of refugia was different in AZ/NM.

3.4. Exploring the increase in refugia in the AZ/NM ecoregion

To help understand why AZ/NM experienced a significant increase in % refugia, we evaluated two possible explanations. The first explanation is that re-burns and other forms of forest loss (e.g. thinning and harvesting) could have increased in AZ/NM more than elsewhere, thus promoting refugia. The data offers some support to the idea that AZ/NM is experiencing a greater increase in reburning than the other 15 ecoregions. For both AZ/NM and the 15 other ecoregions, % reburn increased significantly with the OLS estimator (mean slope) but not the Theil–Sen estimator (median slope) (table 2). The AZ/NM ecoregion had a much higher OLS slope than the 15 other ecoregions, suggesting that the increase in % reburn was higher there, driven by extreme values (table 2). The change in % non-fire forest loss was not significant with either estimator.

The second possible explanation is that fires in AZ/NM could be increasingly occurring in forests with characteristics that are conducive to refugia

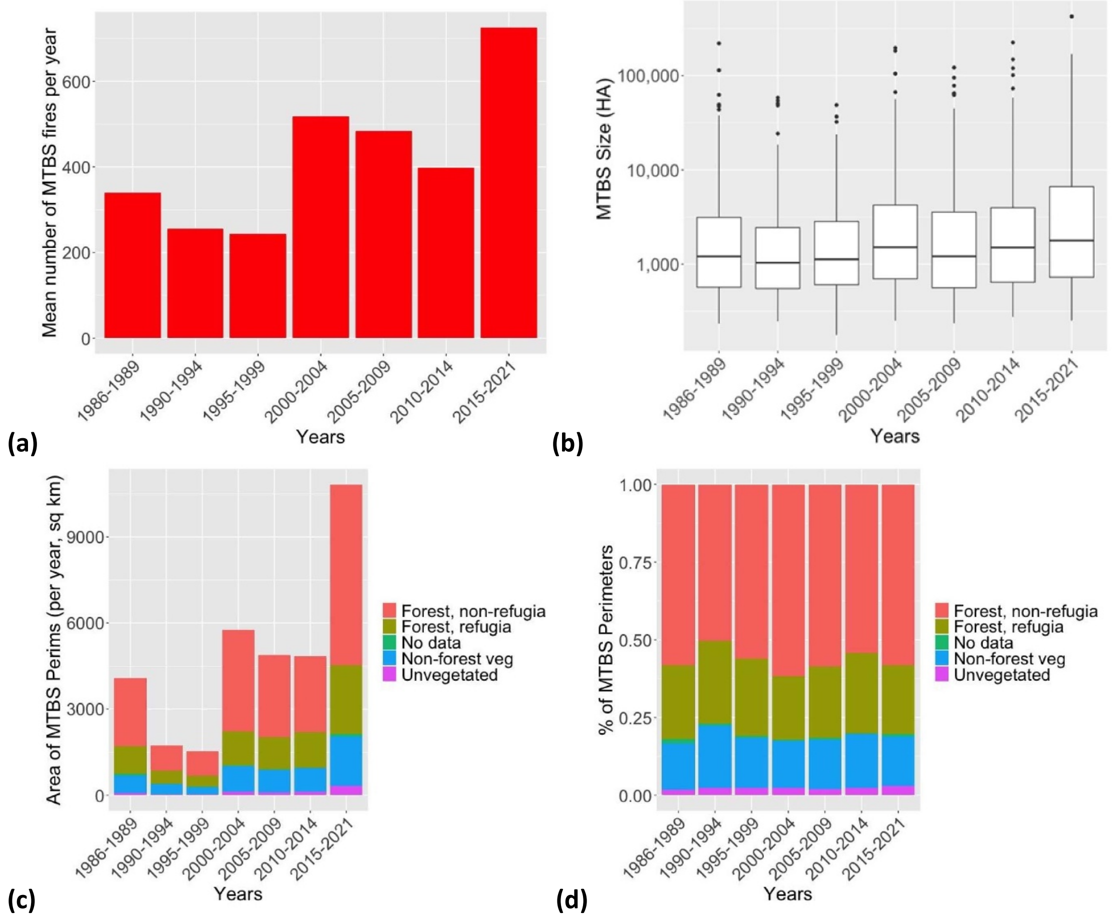

Figure 4. Change over time of (a) number of fires, (b) fire size, (c) area of fire perimeters in 5 classes, and (d) percent of perimeters in 5 classes.

Table 1. Slope of change in event-level fire refugia characteristics 1986–2021 (full results in supplementary materials).

Variable	OLS Slope (std err)	Theil–Sen Slope (std err)
% Refugia[b]	0.188 (0.046)[a]	0.149 (0.048)[a]
% Refugia ex AZ/NM	−0.007 (0.040)	0.040 (0.041)
Refugia total area (ha)	78.170 (15.950)[a]	13.150 (16.520)
Mean refugia patch size (m2)[c]	901 (551)	110 (563)
Maximum refugia patch size (m2)[c]	96 743 (27 666)[a]	12 600 (28 500)
Number of refugia patches[c]	14.6 (2.8)[a]	1.2 (2.9)
Refugia patch density (patches per ha)[c]	-1.169×10^{-04} (7.436×10^{-05})	-1.027×10^{-04} (7.612×10^{-05})
Mean distance to refugia (m)[d]	−0.075 (0.148)	−0.186 (0.151)
Maximum distance to refugia (m)[d]	2.160 (0.772)[a]	0.310 (0.795)

[a] Significant at $p < .01$.

[b] % refugia is defined as the proportion of pre-fire forest within fire boundary that is classified as refugia (i.e. CBI < 1.25).

[c] Patches are groupings of adjacent refugia pixels, connected by edge or diagonally.

[d] Euclidean distance from non-refugia pixel to refugia pixel, up to a maximum of 1.5 km.

formation (e.g. lower elevation, less green, or sparser forests). For fires in AZ/NM, elevation and pre-fire NDVI did not change significantly (table 2). In contrast, for fires in the other 15 ecoregions elevation and pre-fire NDVI increased significantly.

4. Discussion

We expected to observe a decrease in % refugia in a preponderance of Western US forested ecoregions, but instead found a significant increase in 1

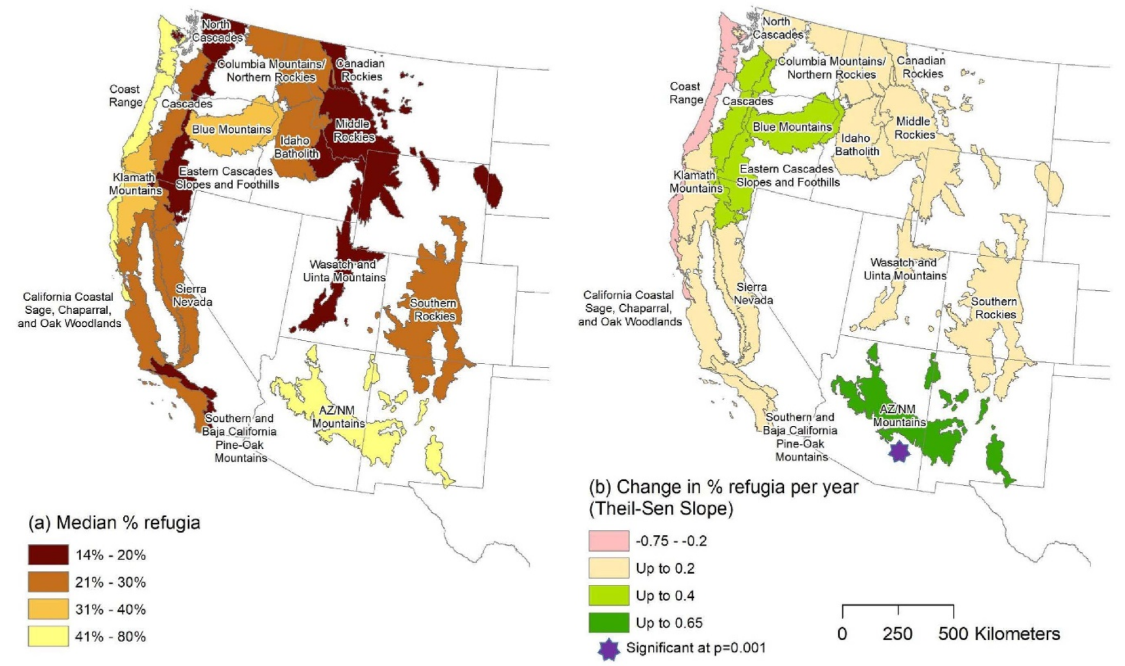

Figure 5. (a) Median % refugia 1986–2021, and (b) slope of annual change for % refugia (full results in supplemental materials).

Table 2. Mean environmental characteristics of fire perimeters in AZ/NM versus 15 other ecoregions. (full results in supplementary materials).

	AZ/NM ecoregion		15 other ecoregions	
	OLS slope (std err)	Theil–Sen Slope (std err)	OLS slope (std err)	Theil–Sen slope (std err)
Elevation (m)	−1.907 (1.518)	−2.551 (1.524)	6.366 (1.302)[b]	6.141 (1.302)[b]
Pre-fire forest NDVI	0.000 (0.000)	0.000 (0.000)	0.002 (0.000)[b]	0.002 (0.000)[b]
% pre-fire forest	−0.201 (0.001)[a]	−0.129 (0.070)	0.012 (0.026)	−0.003 (0.027)
% reburn[c]	0.779 (0.186)[b]	0 (0.209)	0.105 (0.036)[a]	0 (0.038)
% non-fire forest loss[c,d]	0.015 (0.023)	0.000 (0.024)	0.004 (0.016)	0.004 (0.017)

[a] Significant at $p < .05$.

[b] Significant at $p < .001$.

[c] % of the fire boundary that had experienced a fire in the previous 10 years. Date range is 1995–2021.

[d] % of the fire boundary that had experienced forest loss caused by a disturbance other than fire in the previous 10 years. Non-fire forest loss definition: pixels from the LCMS that were classified as 'forest' 10 years prior to the fire and then classified as 'fast loss' in subsequent years up to the year before fire. 'Fast loss' can be caused by harvest, mechanical, debris (e.g. landslides), and fire. Pixels within previous MTBS fire boundaries were excluded, so the forest loss excludes all but the smallest fires (Housman *et al* 2021). To evaluate characteristics within the last 10 years of fire, date range is 1995–2021.

of 16 ecoregions. One possibility is that, contrary to expectations, the expanded area of burning in recent years has similar severity and refugia characteristics to previous burning. Studies have documented an increase in area burning at night (Balch *et al* 2022), a lengthening of the fire season (Balch *et al* 2017), and increased ignitions (Nagy *et al* 2018), but there is little evidence that these fires are burning more severely or homogeneously (Buoanduci *et al* 2023). This suggests that fire behavior for the majority of wildfires has not fundamentally changed over time, resulting in fairly consistent proportions of refugia and non-rugia within fire perimeters. A second possibility is that advances in fire suppression and backburning acted as a counterbalance to rising temperatures and extreme weather, resulting in a net no change in % refugia. While there are data on whether fires since 1992 received a suppression response (Short 2022), those do not include the spatial and temporal characteristics of how a fire was treated. A third possibility is that there is a decline in the smallest of refugia (i.e. individual trees), which we cannot observe using Landsat data, or in woodlands and savannas which do not have a majority of forest cover within a pixel. Small, isolated patches of surviving trees are disproportionately important for tree regeneration (Coop *et al* 2019) so missing such refugia could potentially be important. Regardless of the reason, the assumption that refugia are becoming rarer is not borne out by this analysis. Fires continue to create heterogeneous landscapes that include refugia that can act as seed sources. State changes (e.g. forest to grassland) may be more likely caused by climate-driven recruitment failure (Davis *et al* 2023) than seed availability from lack of refugia. An notable exception is that there was an increase in the maximum distance to refugia, driven by extreme values (i.e. significant with OLS slope, not Theil–Sen slope). This suggests that very large fires may pose a risk for recovery.

While our results show no evidence of widespread changes in % refugia across the West, AZ/NM was an exception. That AZ/NM had a high % refugia is not surprising, as the ecoregion's fire regime is historically characterized by frequent low severity fires that produce little mortality in the structurally dominant forest vegetation (Covington and Moore 1994). Fires in AZ/NM experienced a greater increase in reburning than elsewhere, and did not experience a change in non-fire forest loss (i.e. caused by thinning, harvesting, windthrow, or other non-fire disturbances). This raises the possibility that the increase in fire refugia could be related to increased reburning and consequent reduction in fire severity. Unlike the other 15 ecoregions, fires in AZ/NM did not experience a shift to higher elevations or a decrease in pre-fire NDVI. A shift to higher or greener forests, had it occurred in AZ/NM, might have muted the increase in % refugia. Additional research would be needed to determine whether there is a causal link between these factors.

One limitation to the exploration of the AZ/NM ecoregion investigation is that we do not have spatially explicit data on forest treatments during the 1980s–1990s, so we cannot distinguish natural disturbances from those that were part of a management plan. Another limitation to the exploration of AZ/NM is that we did not investigate changes within the forest land cover type. For example, Gambel oak (*Quercus gambelii)* resprouting and replacing conifer forest (Coop *et al* 2016) could look like refugia on imagery. Finally, in both the main analysis and AZ/NM exploration, we did not control for the increase in familywise error rate in statistical tests. Due to the relatively large sample size and modest number of tests, we believe this to be a reasonable decision but would encourage replication by other studies.

The study shows that dense forest (pixels $>50\%$ cover) show a consistent survivorship in wildfires, with the exception of very large fires where 'maximum distance to refugia' has increased. Overall, the results of this study imply that there are substantial refugia areas that could be used in planning for recovery or restoration efforts. Because post-fire climate conditions may restrict regeneration (Davis *et al* 2019), it is important to place remaining refugia in areas with better microclimates and lower fire severity, facilitating enhanced regeneration (Davis *et al* 2023). Future efforts should explore the persistence of refugia, whether finer-scale resolution data (e.g., at the tree level) reveal different trends in refugia, and whether changes within the forest land cover class can explain some of the patterns. For example, Gambel oak resprouting and replacing conifer forest could be associated with the observed changes in refugia in AZ/NM, but this hypothesis remains to be tested at the resolution of species. As the trends in area burned have been concerning, the prevalence of refugia offers some hope that ecosystems continue to have some of the raw material to begin the process of recovery.

5. Conclusion

We did not find evidence that supports the proposition that refugia are becoming rarer in Western US forests. The total area of refugia and number of refugia have increased proportionally to the total fire boundary area. While % refugia has not changed significantly overall, it has changed in specific ecoregions most notably a significant increase in AZ/NM. Future studies, over a longer time period, may reveal stronger trends. There is also a need to compare fire severity and % refugia in 'newly expanded burns' (e.g. shoulder seasons, or at night) with 'traditional burns', which may display diverging trends in refugia. This study provides compelling evidence that refugia continue to make a considerable contribution to post-fire landscapes, even in the face of an overall increase in burned area across the Western US. In other words, refugia are not disappearing despite the growing extent of wildfires. Refugia studies like this, which characterize broad event-level trends, are important for identifying wide trends, understanding the ecological contexts and landscape mosaics in which refugia exist.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors. Data will be available from 01 January 2024.

Acknowledgments

Gettysburg College Research & Professional Development Fund

Earth Lab at the Cooperative Institute for Research in Environmental Sciences (CIRES) at the University of Colorado (CU), Boulder. JKB was additionally supported by NSF Macrosystems (#2017889) and CAREER (#1846384) awards.

Thanks to Michael Koontz, research scientist at the Earth Lab at the University of Colorado Boulder, for providing his valuable perspectives in the early stages of the project. Also thanks to Andy Wilson, Associate Professor of Environmental Studies at Gettysburg College, for giving feedback on the penultimate draft.

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