FINAL REPORT

Title: Identifying and protecting wildfire refugia in a warmer, drier Pacific Northwest

JFSP PROJECT ID: 16-1-01-1

November 2020

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Abbreviations/Acronyms

dNBR	Differenced Normalized Burn Ratio
FRG	Fire Regime Group
TPI	Topographic position index
TWI	Topographic Wetness Index
TRI	Terrain ruggedness index
CosAsp	Cosine aspect
TRASP	Transformed aspect

Keywords
Fire refugia, unburned areas, unburned islands, burn severity, fire effects, remote sensing, vegetation recovery, wildlife, climate refugia.

Acknowledgements
We thank James Lutz, Lee Foster, Eva Strand, Daniel Kissling, Meg Krawchuk, Nicholas Giannettino, Gavin Jones, and Aaron Ramirez for valuable comments and scientific advise, Tyler Bleeker, Alina Cansler, and Susan Prichard for sharing valuable field data, our field crew (Brian Moe, Emily Noyd, Jamie Peeler, and Martin Holdrege) for their hard work in the field, and finally the workshop participants, students, technicians, and volunteers who helped with this project.

Executive summary

Wildfires are common across the Pacific Northwest, however climate change is projected to cause increases in wildfire activity and severity. Wildfires create a heterogeneous pattern across the landscape from severely burned areas to unburned patches. Unburned areas that are associated with critical habitat where biota can persist (e.g., old growth forest) and/or can recolonize neighboring burned areas are defined as fire refugia. They provide shelter for a range of fauna post-fire and can reduce detrimental impacts on hydrology and erosion. Therefore, management actions focused on maintaining or promoting these ecologically important areas on the landscape will be critical in the future, particularly under rapid climate change.

This report details the finding of a Joint Fire Science Program project funded in 2016 entitled: "*Identifying and Protecting Wildfire Refugia in a Warmer, Drier Pacific Northwest*" funded under L16AC00202. Here we report on creating an unburned area data set for the Inland Northwest from 1984 – 2014 and subsequent analyses using this dataset. Some of our key findings for this JFSP project include:

- Unburned area occurrence is consistent or stabilized to-date, with no evidence of increasing or decreasing trends under current climate conditions
- Unburned areas are utilized by sage grouse and help maintain viable populations when these fire refugia are present
- Persistent unburned islands are ecologically important areas and are related to specific topography and fuel type characteristics
- Persistent unburned area attributes differ between forests and rangelands

From our participatory GIS survey and workshops, we conclude that managers are increasingly interested in managing for fire refugia but that a single one-size-fits-all approach is not feasible for multiple species over large management areas. We also conclude that natural resource managers should place fire refugia in a landscape context to improve monitoring across regional scales.

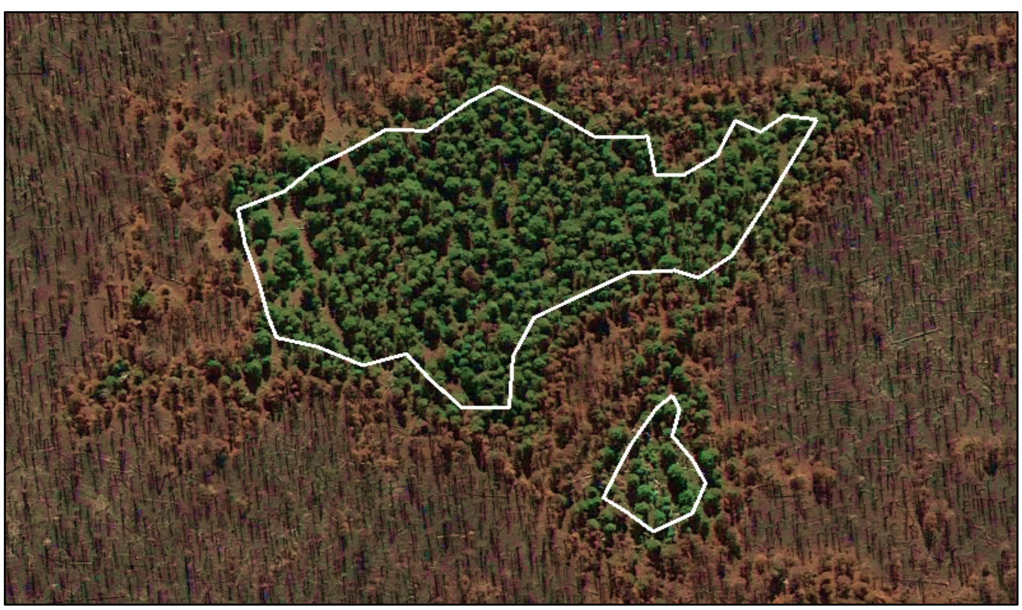

Figure 0. An illustration of delineated fire refugia after the Table Mountain Fire in Washington (2012); Imagery source: NAIP/Google Earth.

1. Introduction

Wildfires are common across the Pacific Northwest and an integral part of many ecological systems (Agee 1993). However, climate change is projected to continue to increase wildfire activity and severity (Littell et al. 2016; Halofsky et al. 2020; Holden et al. 2018; Littell et al. 2009; Miller et al. 2009), thereby affecting ecosystem services and postfire recovery. Wildfires create a heterogeneous pattern in vegetation across the landscape from severely burned areas to unburned patches. Unburned areas that are associated with critical habitat where biota can persist (e.g., old growth forest) and/or unburned areas containing biota that can recolonize neighboring burned areas are defined as wildfire refugia (Camp et al. 1997; Swengel and Swengel 2007). Unburned areas can also reduce detrimental impacts on hydrology and erosion. Increased fire severity due to anomalously hot and dry weather can lead to a decrease in unburned areas within the fire perimeter (Kolden et al. 2015). Therefore, management actions focused on maintaining or promoting these ecologically important areas on the landscape will be critical in the future, particularly under rapid climate change.

Management can influence the formation of unburned islands across the landscape through activities such as mechanical thinning and prescribed burning (R. Harrod, personal communication). During wildfires, critical habitat (in the form of unburned areas) can be protected by focusing suppression in certain areas (e.g., around old growth) or reducing the use of back burning and burnouts. Post-fire management activities help preserve wildfire refugia through monitoring, erosion control, and treating areas around important unburned areas that are at risk of invasion by invasive species. However, no operational detection of unburned areas and assessment of their ecological value exists to help managers prioritize areas for conservation. Furthermore, understanding the types of management actions that produce desired patterns of unburned area occurrence, such as high-quality habitat for an at-risk species, are needed in the context of shifting fire regimes.

In a past project, we established a classification system for detecting unburned areas using satellite (Landsat) and ancillary geospatial data (e.g., topographic data) across the northwestern United States (Meddens et al. 2016). We proposed to leverage this work to first generate new science by validating and applying our model in a year with exceptional hot and dry conditions leading to an extreme fire year (i.e., 2015). Second, we translated our science findings to meet management needs by developing a method that assesses the quality of the unburned areas, based on species' habitat preferences, for resource management. Third, we sought to link unburned areas to surrounding landscape features and management activities, and develop decision-support scenarios for preserving or promoting unburned areas on existing fires or future wildfires, respectively.

This project contributed to improve understanding of where and how unburned areas were giving changing climate conditions. We delivered a spatial database of unburned areas that can be used for assessments of ecosystem functioning within three fires that burned from 1984 to 2014 in the Inland Northwest. The second deliverable of this project was a science-based ranking system (using geospatial data and expert knowledge) for ranking the ecological importance of various unburned areas. Finally, we sought to deliver specific management scenarios that can be implemented to preserve important unburned areas within future wildfires. These findings support improved management decisions in a time of changing fire regimes and support a science-based prioritization scheme of fuel treatments for ecosystem resilience in the future.

1.1 Proposed objectives

Our project consisted of five objectives (Figure 1). The first two objectives relate to new science generation, the third and fourth objectives translates our science findings to inform management decisions, and the fifth objective is the decision-support objective of our project. Proposed objectives were (note that we slightly adapted our objectives/hypotheses from our original proposal):

O1. Evaluate/validate model performance in detecting unburned areas within fires across the inland pacific northwest, including fires in Washington, Oregon, and Idaho. → *This Objective was successfully completed*

O2. Quantify the number, spatial distribution, and sizes of unburned islands across the identified fires in Objective 1. → *This Objective was successfully completed*

O3. Develop a method that assesses the quality of unburned areas to potentially function as wildfire refugia (for at-risk biota) within wildfire perimeters. → *This Objective was successfully completed*

O4. Assess topographical features and management activities that are related to the creation and existence of unburned areas in a post-fire landscape. → *This Objective was successfully completed*

O5. Develop management scenarios that preserve important unburned areas within future wildfires. → *This Objective was successfully completed*

Our Hypotheses related to the objectives above were:

H1. Our unburned area detection model will perform with comparable accuracy in a high area burned year as compared to other years.

H2. The characteristics of unburned patches within fire perimeters of the fires do not differ among fires with different locations, ecosystem type, management agency.

H3. Unburned areas within important mapped habitat area, within the middle of the fire perimeter, and within largely severely burned areas have higher importance (or ranking) than unburned areas not occurring in these locations.

H4. Management actions as well as (surrounding) topographical features are correlated to the spatial distribution of unburned areas within the landscape.

H5. Development of detailed management scenarios involving strategic placement of fuel treatments (such as prescribed burning and mechanical fuel breaks) to facilitate formation of unburned areas will improve landscape resiliency to extreme fires under climate change.

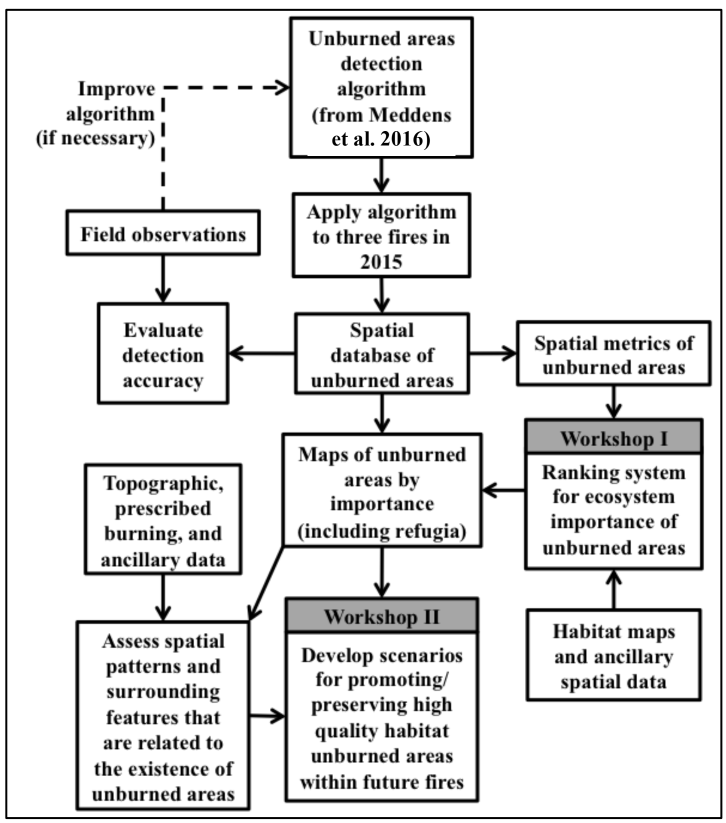

Figure 1. Workflow of the proposed study.

1.2 Relation to 2016 JFSP Task Statement

Our project relates to Task 1 (*Implications for changing ecosystems – selected regions*) in the following ways. First, we generated new science by developing the existence, size, and location of unburned areas within fires that burned in Washington, Oregon and Idaho from 1984 to 2014. Second, once these unburned areas were located, we used this as a platform to inform and actively engage forest managers, wildlife ecologists, botanists, and spatial ecologists to establish a ranking and prioritization scheme for monitoring and maintaining these unburned areas. Third, we assessed the locations and sizes of these unburned areas and developed scenarios with our agency partners for forest managers to maintain or promote these unburned areas on the landscape. These scenarios entailed details of placement, size, and type of fuel treatments near high quality habitat, and promoting preservation of unburned areas during an actively burning wildfire. For instance, fire managers could rethink and scale back questionable suppression actions, such as burning out a high quality refugial patch in critical habitat. To ensure close collaboration with agency partners and technology transfer, we organized two successful workshops; one in year 1 (Portland, OR) and one in year 3 (Moscow, ID) of our project.

2. Background

2.1 Unburned areas

Wildfires shape the distribution and structure of vegetation across the inland northwestern United States. A fire impact that has been less widely addressed is the development of unburned areas (or unburned islands). Unburned areas are areas that do not burn but are located within the fire perimeter. These areas can function as critical ecological refugia for biota during or following wildfires (i.e., fire refugia). However not all unburned areas are fire refugia, only those that are associated with critical habitat where biota can persist (e.g., old growth forest patches, sage grouse lek sites) and/or recolonize neighboring burned areas (Camp et al. 1997; Meddens et al. 2018b; Swengel and Swengel 2007). Until recently unburned areas have been largely ignored in studies using remote sensing, because they are not reliably detected by algorithms for delineating fire perimeters (Kolden and Weisberg 2007). Accurate detection and delineation of unburned areas is increasingly critical, as some of these unburned areas contain habitat that are crucial for maintaining biodiversity and ecosystem functioning. Methods for developing criteria and assessing the habitat quality of unburned islands for management purposes are largely absent (but see section 3.4) and more research is needed to assess the value of unburned areas in an ecosystem conservation framework.

2.2 Fire refugia

Refugia are components of ecosystems where biodiversity can retreat to, persist in, and potentially expand from as environmental conditions change (Keppel, et al. 2015). These conditions can occur across a spectrum of timescales, from changes in climate over eons (e.g., glaciation and deglaciation) to multidecadal variability (drought) to event-driven disturbances (floods and fire); each can result in refugia creation from regional to local scales (Mackey, et al. 2002). While refugia were originally defined in the context of long-term and broad-scale processes related to continental glaciation (e.g., Petit, et al. 2003), refugia created by ecological phenomena that operate on much shorter timeframes across local to regional scales have been the subject of more recent study (Keppel et al. 2012), reflecting concerns about loss of habitat from anthropogenic drivers such as land use and climate change. One such ecological process is wildfire, which is both naturally occurring but also responsive to these anthropogenic drivers. Refugia created by wildfires are prevalent in fire-adapted ecosystems (Agee 1993; Kolden et al. 2012) but have been poorly studied relative to other types of ecological refugia.

Fire refugia were initially defined as locations having a longer fire return interval than the surrounding landscape and locations in which a given species can maintain a viable habitat (Gill 1975). However, there is no universally accepted definition of fire refugia within the fields of ecology or conservation biology (Mackey et al. 2012). Such a characterization is critically needed in order to contextualize, identify, and quantify fire refugia as a component of ecosystem vulnerability and resilience, particularly across landscapes where anthropogenic change is most pronounced (Smith et al. 2014). To date, fire refugia are slowly gaining traction within fire ecology research, although many more studies are focused on the highest burn severities.

Although fire refugia are not well defined, there are suggestions that fire refugia are critical to maintain biodiversity and ecosystem resilience under global change. Projected increases in fire season duration and fuel aridity in response to anthropogenic climate change are expected to increase future fire frequency and extent (Barbero et al. 2015), which may alter the distribution of fire refugia (Kolden et al. 2015). Forest managers could potentially improve landscape resiliency more broadly by identifying, maintaining, and promoting fire refugia (Millar et al. 2007), but a better understanding of fire refugia is needed to identify knowledge gaps and future research directions.

2.3 Remote sensing

In a previous study (Meddens et al. 2016), we developed a classification methodology to separate burned from unburned areas across the Inland Northwest in multiple vegetation types, including grasslands, shrublands, and forested areas. We utilized Landsat, topographical, and field data from 868 plots from 19 wildfires to separate unburned from burned areas within fire perimeters. We achieved high overall classification accuracy of unburned areas within all vegetation types with Random Forest (91.7%) and classification trees (89.2%). Average unburned proportion of the 19 wildfires was ~20% (standard deviation: 16.4%) with high variability among fires. The area of unburned islands was significantly higher in non-forested areas as compared to the area of unburned islands in forested areas. There is a need for accurate detection of unburned areas to identify potential fire refugia across fire prone regions.

2.4 Management applications

Future management actions focusing on identifying, maintaining, or promoting fire refugia within landscapes will become increasingly important. Understanding the persistence of various categories of refugia can help managers maintain resilient ecosystems and allow species being displaced by warming climate to persist. For example, the location of ephemeral fire refugia may be unimportant as long as managers can verify that they exist in the aggregate landscape and the spatial configuration post-fire can be quantified on a per-fire basis using geospatial technologies. On the other hand, understanding the location and environmental characteristics of persistent and semi-persistent fire refugia will become more important for managers to make decisions that increase landscape resilience.

Management actions specifically to support the formation of fire refugia are not yet well documented, but since refugia fundamentally result from modified fire behavior, practices that specifically target cessation or minimization of fire spread, combustion and consumption could produce desired outcomes. Vegetation management activities such as thinning and prescribed burning that generate landscape heterogeneity as opposed to actions that create uniform conditions across a landscape can potentially achieve increase number and size of unburned areas. In this way, managers can seek to exclude fire from portions of the landscape where efforts are likely to be successful, particularly along topographic features or near forest stands that have persisted through many fires. Some studies suggest that prescribed fires on the order of hundreds of hectares can provide fuel breaks that decrease the severity of future fires (e.g., Miller and Safford 2012), potentially increasing refugia. Furthermore, incorporating knowledge of likely refugia can help human communities develop resilient firescapes prior to any fire (Smith et al. 2016).

Probably even more critical than pre-fire activities to facilitate refugia are the tactical decisions and strategies employed both during and following fire events. As fires have become larger and more difficult to control, fire managers in the US and elsewhere have increased the use of suppression strategies that can be detrimental to refugia. Many backfiring operations attempt to completely consume all available fuel ahead of an advancing fire front, including areas that may be potential refugia. Similarly, burnout tactics specifically target remnant islands of vegetation, with firefighters intentionally eliminating the naturally occurring refugia to prevent potential flare-ups that might throw embers across an established fire perimeter. Conversely, targeted suppression efforts can also be utilized strategically to protect sensitive refugia (e.g., high value trees).

In the post-fire environment, remnants and refugial sites are often exposed to a host of additional disturbances that may diminish their longevity and efficacy. They may be left more susceptible to subsequent natural hazards such as the landslides, floods, windstorms, and avalanches that can increase following wildfire (Wondzell and King 2003), or they may be negatively impacted by post-fire rehabilitation work, such as salvage logging or aerial re-seeding efforts, that can destroy or degrade habitat or introduce non-native species (Donato et al. 2006; Kruse et al. 2004). One strategy for addressing these potential negative impacts may be to integrate an inventory and assessment of refugia into the Burned Area Emergency Rehabilitation and long-term post-fire planning processes, as refugia are currently not comprehensively considered (Parsons et al. 2010).

3. Results and Discussion

3.1 Objective 1: Evaluate/validate model performance in detecting unburned areas

We established methods using classification trees for unburned areas in a prior study (Meddens et al. 2016). In this study we showed that we could map unburned areas with an overall accuracy of 91.7% and 89.2%, using randomForest and classification tree methods, respectively, using 868 plots across 19 wildfires. We showed that by utilizing two pairs of pre- and post-fire Landsat imagery, we could improve unburned area detection accuracy (Fig. 2). There was also no clear pattern of increased or decreased detection accuracy of unburned areas within forest versus non-forest areas (Meddens et al. 2016).

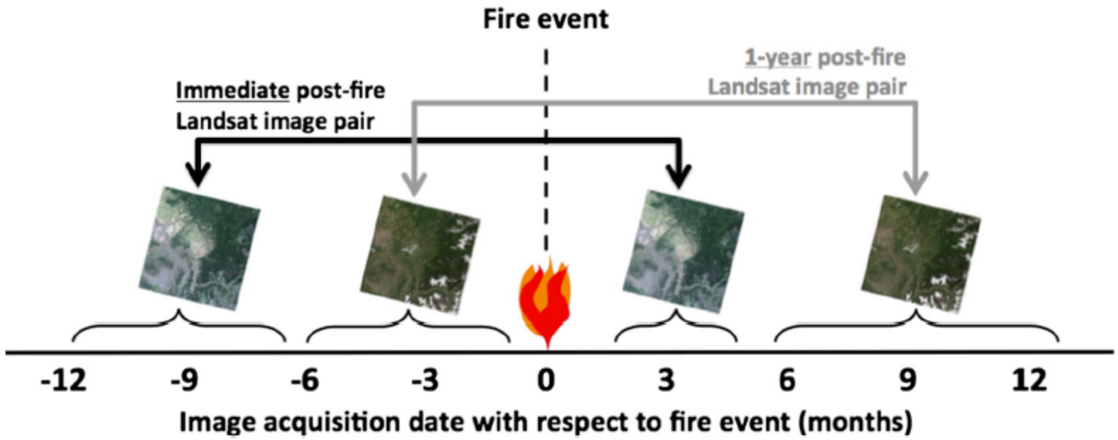

Figure 2. Illustration of the timing of image acquisition date with respect to the fire event, modified from Key and Benson (2006). Both the immediate and 1-year post-fire Landsat image pairs were used (Meddens et al. 2016, Remote Sensing of Environment).

Instead of applying this method to three fires (as was originally proposed in Objective 1), we applied the classification tree method of Meddens et al. (2016) to 2,298 fires across the inland northwestern USA to establish an unburned island data base (Fig. 3; Meddens et al. 2018a). We applied a phenological correction to address differences within the image collection dates as outlined in Meddens et al. (2016). Finally, to account for the salt and pepper effect (caused by spectral mixing and backscatter), we only classified unburned patches that contained at least two adjacent pixels, thus removing single pixels from the database.

After applying the Meddens et al. (2016) classification tree method to the 2,298 fires in the study area, we performed a visual and quantitative accuracy assessment and found no apparent differences in detection capabilities for drier or wetter years. Therefore, we accept our first

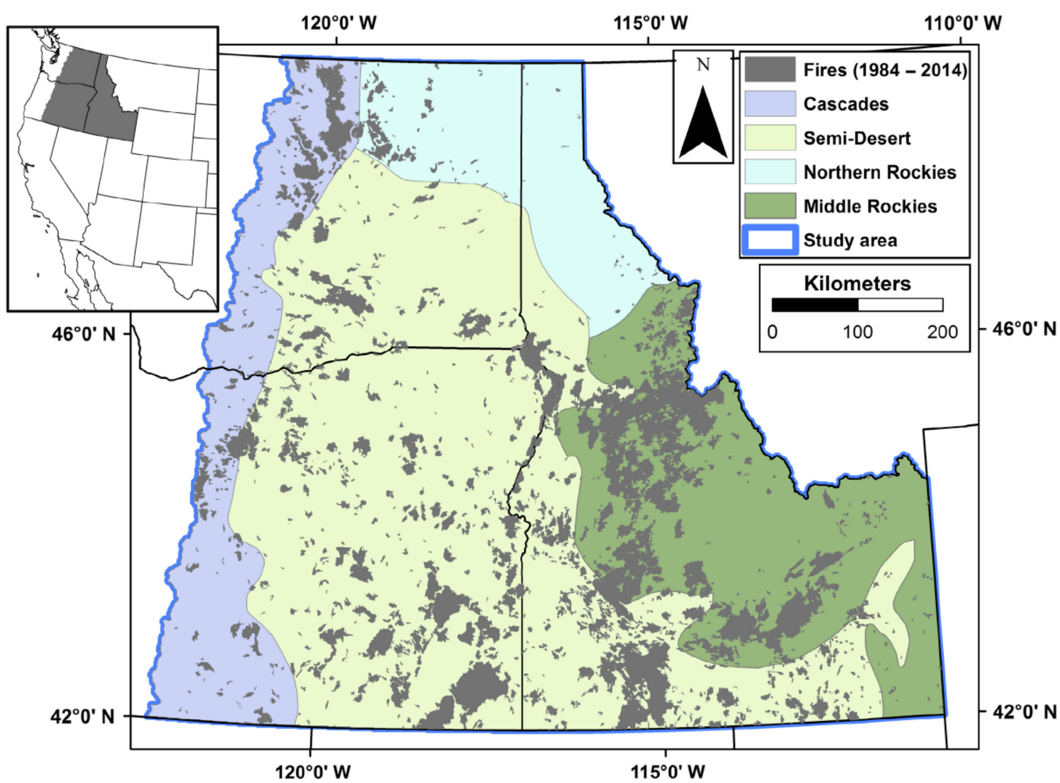

Figure 3. The inland northwest study area, with the Monitoring Trends in Burn Severity fire extents from 1984 to 2014 shown in gray and the merged Bailey's ecoregions (Bailey 1980) in the background (Meddens et al. 2018, Ecosphere).

Hypothesis (H1) that our unburned area detection model performs with comparable accuracy throughout the time series (1984 – 2014). However, we found that low fire years (years with <10 km^2 fire extents, n = 5), normally associated with wet and cool conditions, had a significantly greater unburned proportion compared to fire years with fire extents >10 km^2 (n = 26) (two-sample t-test, t = -3.03 (df = 29), P = 0.005) (Meddens et al. 2018a). As future conditions are trending towards conditions associated with large fire years (Barbero et al. 2015), low fire years will occur less frequently, and therefore fires with higher proportion of unburned areas will decrease as well.

The development of the unburned area database in the inland northwestern US was the basis for multiple subsequent analyses. First, we quantified the number, area, and spatial distributions of the unburned areas within the wildfires (Objective 2). Second, we used the unburned area database in two studies for wildlife: a) an assessment system quantify the relative quality of unburned areas for a focal wildlife species and b) a comparison of Sage Grouse count data on lek sites in unburned areas and burned areas within the fire perimeters (Objective 3). Third, we quantified the degree of persistence of unburned areas and evaluated the topographical and land cover influences on the likelihood of an area being unburned more than once in multiple fires by overlaying the fire perimeters and unburned areas (Objective 4). Fourth, we presented outcomes of the spatial and temporal patterns at two workshops and webinars to solicit management activities that could be associated with these unburned areas (Objective 4 and 5). Finally, we have archived the unburned area dataset and this geospatial data is available for public download through the USGS ScienceBase Catalog system, website: https://www.sciencebase.gov/catalog/item/59a7452ce4b0fd9b77cf6ca0 (accessed September 1, 2020).

3.2 Objective 2: Quantify the number, spatial distribution, and sizes of unburned areas

Following establishment of the unburned area database (Meddens et al. 2018a), we quantified the number, spatial distribution and sizes of unburned areas across the entire Inland Northwest (Fig. 3 and 4). 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 (Fig. 4, Meddens et al. 2018a), suggesting that recent trends in increases of area burned and overall

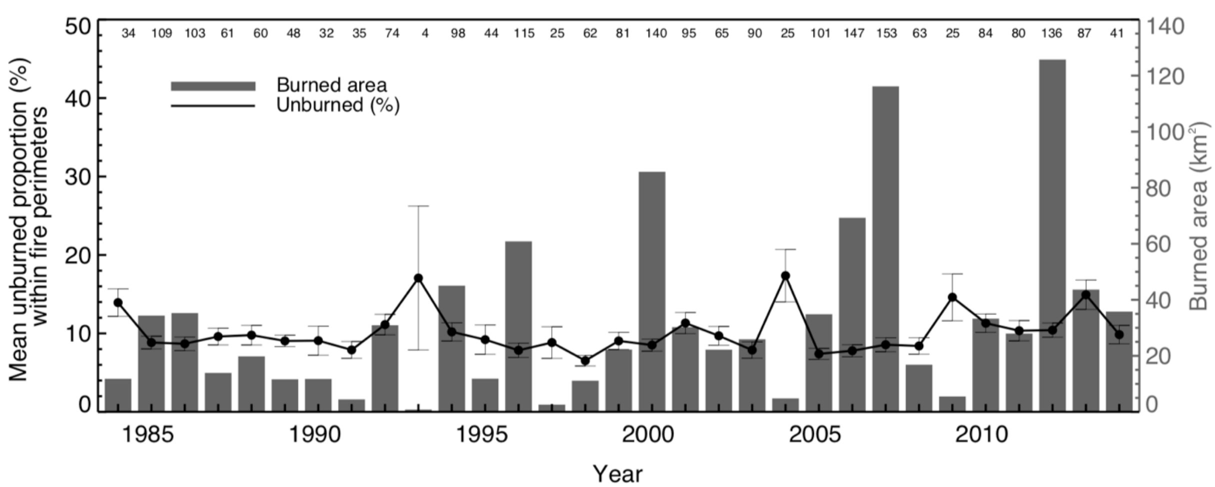

Figure 4. Total fire extent (km^2, bars) and mean proportion unburned within fire perimeters (%, line) across the inland northwest from 1984 to 2014. The error bars represent the standard error, and the number of fires is shown across the top (Meddens et al. 2018, Ecosphere).

severity have not affected the proportion of unburned area. However, we note that due to the short time period of the Landsat record used in our study (~30 years) relative to longer fire return intervals across the Inland Northwest, detecting trends in unburned area characteristics in association with the trend toward warmer/drier conditions may not be feasible and longer-term records might be needed to elucidate effects of shifting climate patterns.

We analyzed the spatial and temporal characteristics of unburned areas across the Bailey's ecoregions. There were some ecoregional differences in the number of unburned areas and mean patch sizes (Fig. 5), suggesting influences of vegetation and topography on the formation of unburned areas. The Cascade region had by far the most unburned areas (1,394) compared to the Middle Rockies (561), Semi-desert (236), and Northern Rockies (105) ecoregions. However, as a proportion of the total burned area the Cascades showed a substantial lower amount of unburned area ~8% versus ~10% in the other three ecoregions. Patches of unburned areas were significant larger in the drier and fuel-limited Semi-Desert ecoregion as opposed to the other three regions. Patch density was highest in the Middle Rockies and significantly different from the other three regions. Therefore, we accept are second hypothesis (H2) that some ecoregions exhibit significantly different unburned areas patterns as compared to other regions with different climate characteristics. For example, areas with lower fuel loading and a higher proportion of rangeland vegetation types exhibit larger unburned areas, and the drier forests of the eastern Cascades exhibit a lower proportion of unburned areas as compared to the more moist forests of the Rockies (Fig. 5).

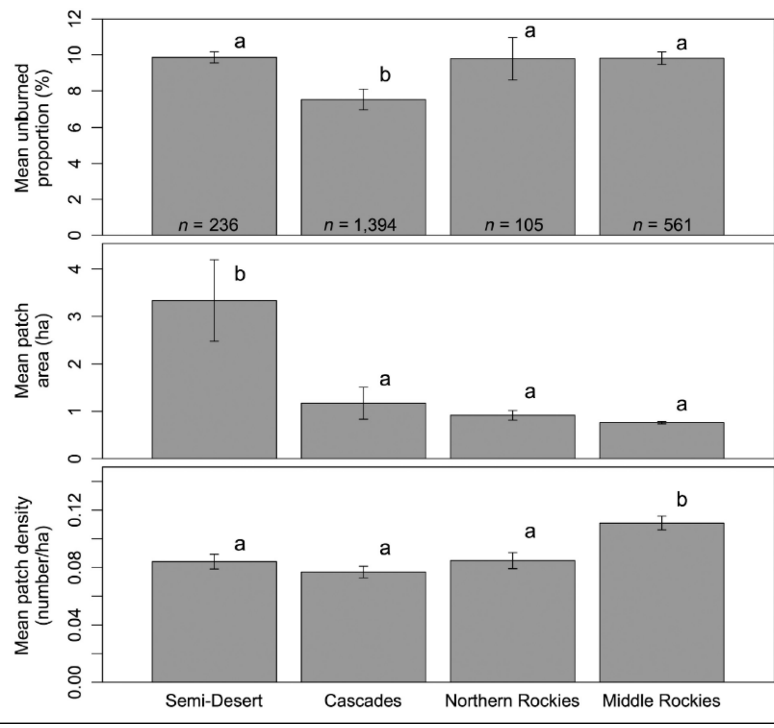

Figure 5. Mean unburned proportion (%; top), mean patch area (ha; middle), and mean patch density (number/ha; bottom) across the inland northwest from 1984 to 2014 for each of the four ecoregions (derived from the Bailey's ecoregion provinces; Bailey 1980). The error bars represent the standard error. 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 (Meddens et al. 2018, Ecosphere).

3.3 Objective 3: Establish a system to assess the importance of unburned areas for wildlife

After organizing two workshops (see also sections 3.4 and 3.5), it became clear that it was not feasible to establish a regional ranking system to assess the quality of unburned areas for multiple wildlife species simultaneously. Based on the advice of stakeholders (e.g., local natural resource managers) during our workshops, we revised our goal and produced two studies that focused on examining the importance of unburned areas for individual animal species. The first study developed an assessment tool that examined the relative quality of unburned areas to function as fire refugia for a focal species, which in this case was the northern spotted owl (*Strix occidentalis caurina*) on the eastern side of the Cascades in Washington and Oregon. The second study quantified the importance of unburned islands for the persistence of the greater sage grouse (*Centrocercus urophasianus*) in rangeland systems in southeast Oregon. Though we modified our research objective, our findings generally supported H3, because unburned areas with suitable habitat were higher quality refugia for our focal species than unburned areas without suitable habitat or surrounding burned areas. Below the key results and findings are discussed.

3.3.1 Assessing quality of unburned areas for focal species

To better understand whether unburned areas may function as fire refugia, we developed the refugia index, a method for land managers to objectively assess the quality of unburned areas for wildlife habitat for a focal species. We assessed the overall quality of individual unburned areas for wildlife species based on characteristics of habitat within and surrounding unburned areas and the refugia index was the output of this model (Fig. 6). Model inputs were developed by merging the unburned areas dataset (Meddens et al. 2018) with wildlife species habitat spatial data modified with burn severity spatial data in a series of geoprocessing steps.

We conducted a case study of the northern spotted owl, an at-risk species with habitat increasingly affected by fire, especially on the eastern side of the Cascade Mountains.

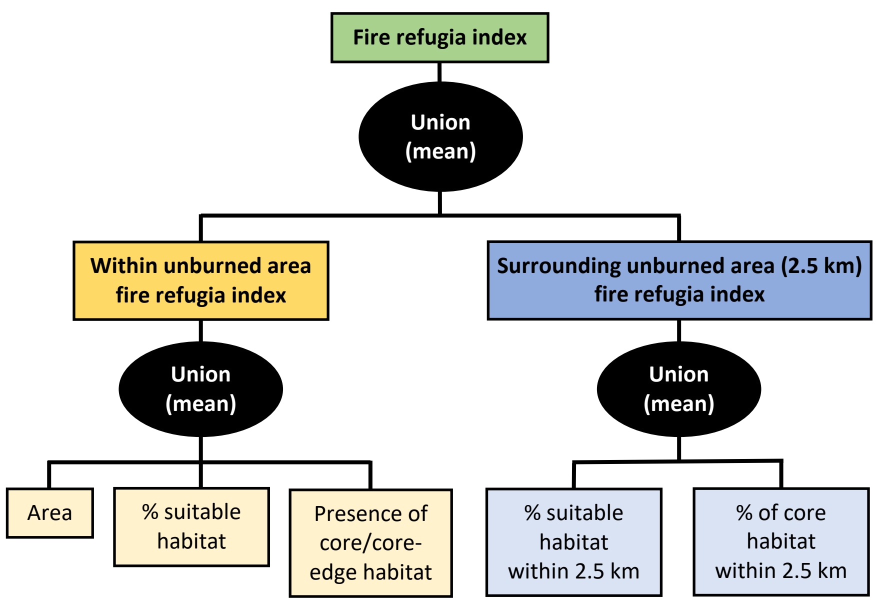

Figure 6: Fuzzy logic tree for ranking unburned island habitat suitability. The final proposition (green) is a union of the two intermediate propositions (yellow and blue). The terminal nodes are the input criteria, which were divided into characteristics within the unburned island (light yellow) and characteristics of the habitat surrounding the unburned island (light blue) (Andrus et al. in review, Forest Ecology and Management).

Specifically, we applied our method (geoprocessing steps and fuzzy logic model) to 4,278 unburned areas in 15 fires that burned in spotted owl nesting/roosting habitat in the eastern Cascade Mountains of Washington and Oregon. Spatial overlay analysis indicated that spotted owl nesting/roosting habitat most commonly burned at high severity (44%; see example Fig. 7A-C), which is negatively associated with site suitability for nesting/roosting habitat (Dugger et al. 2016). Our method successfully identified lower to higher quality unburned areas for spotted owl nesting/roosting habitat (Fig. 7D), which are known to function as fire refugia (Gaines et al. 1997). Tools, such as the method presented here, offer a transparent, repeatable, and effective process for evaluating fire effects on habitat (e. g., habitat losses) and prioritizing areas for post-fire conservation (Fig. 7D).

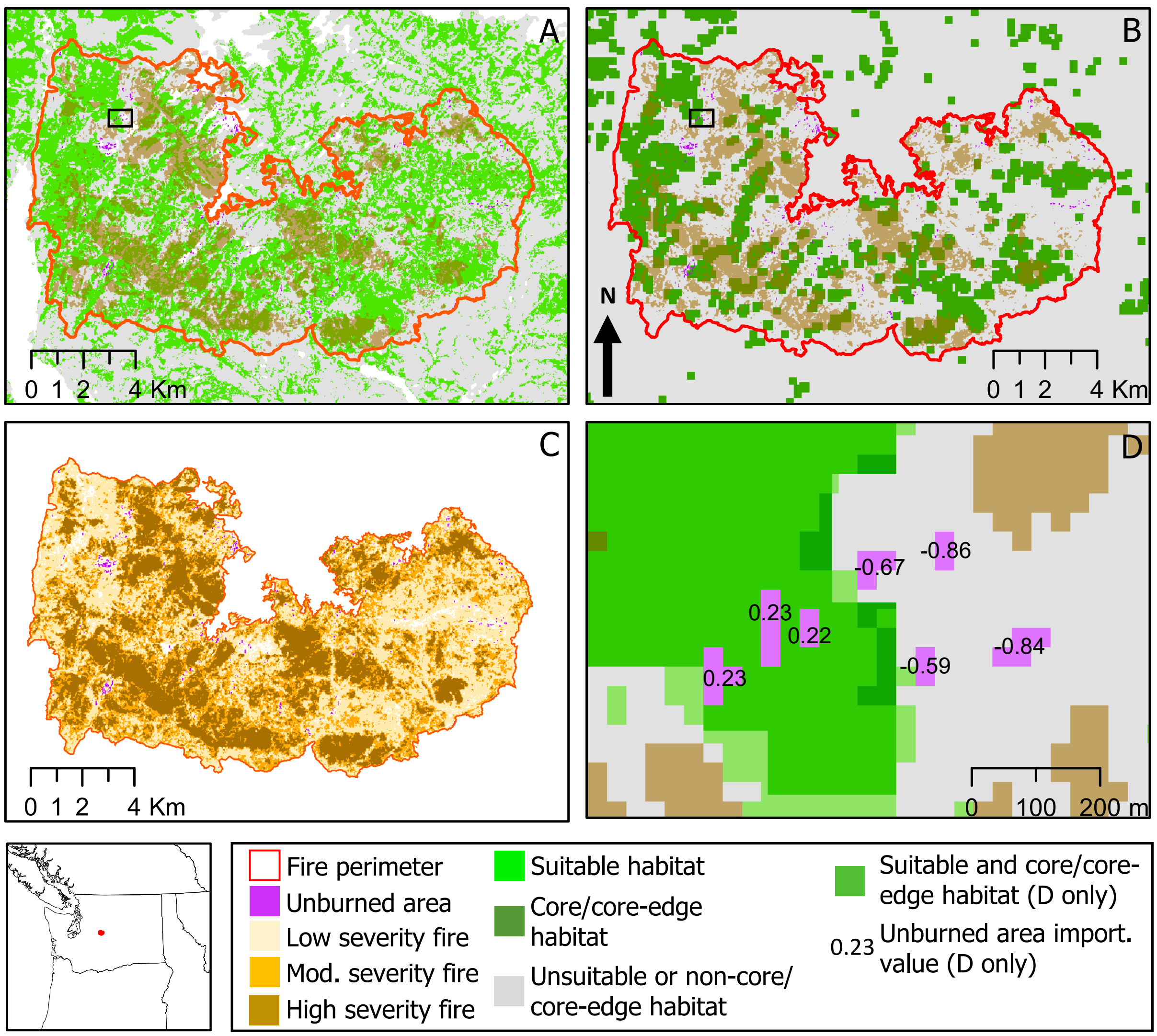

Figure 7. Maps illustrating spatial overlap of high severity fire with A) suitable (including highly suitable) spotted owl nesting and roosting habitat (prefire) and B) spotted owl core and core-edge habitat (prefire) as well as unburned areas in the Jolly Mountain Fire, WA. C) Burn severity in four classes: unburned, low severity, moderate severity, and high severity (see Appendix S1: Table S1 (in Andrus et al. in review) for burn severity thresholds). D) Example fuzzy logic model wildlife importance values for unburned areas, illustrating much higher values for unburned areas within suitable and core/core-edge habitat and lower values for unburned areas in unsuitable habitat (Andrus et al. in review, Forest Ecology and Management).

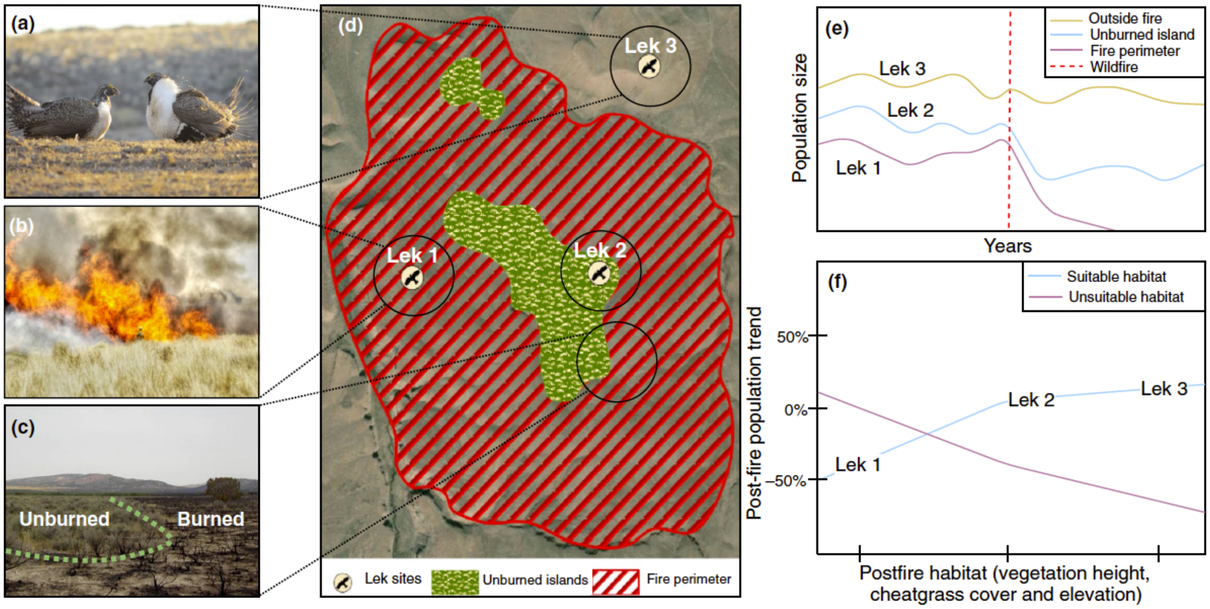

Figure 8. Fire dynamics in the sagebrush ecosystem and hypothesized postfire responses of the sage-grouse to burned and unburned areas. (a) The greater sage-grouse (Centrocercus urophasianus), a characteristic wildlife species of the sagebrush ecosystem in the Great Basin of North America. (b) Wildfires are common in this ecosystem and result (c) in a mosaic of burned and unburned islands. (d) At the landscape scale, lek sites (i.e., mating locations) of the sage-grouse might be located within fire perimeters (lek 1), in unburned islands inside fire perimeters (lek 2), or outside fire perimeters (lek 3). (e) Depending on the location of leks in burned or unburned areas, postfire population trends (growth/decline per year) might be negative (inside fire perimeters) or relatively stable (within unburned islands or outside fire perimeters). (f) The amount of postfire habitat surrounding lek sites might affect postfire population trends positively (availability of suitable sagebrush vegetation) or negatively (amount of unsuitable cheatgrass cover). Images (a) courtesy of Sarah McIntire, University of Idaho, (b) courtesy of Bureau of Land Management (available with a CC BY license), (c) adapted from Jones, Monaco, and Rigby (2015), Figure from Steenvoorden et al. (2019; Ecology and Evolution).

3.3.2 Greater sage grouse

Sage grouse live in fire-prone, sagebrush ecosystems and shifts in climate conditions are altering fire regimes within these systems. Unburned areas have the potential to mitigate the negative effects of fire on wildlife populations (such as the sage grouse) by providing habitat within burned areas for populations to persist and recolonize burned areas. We used the Meddens et al. (2018a) unburned island dataset to assess the postfire response of the greater sage grouse in southeastern Oregon. We tested whether pre- and post-fire male lek attendances were different in burned areas versus unburned areas. We overlaid lek count locations with recent wildfire perimeters and assessed changes in habitat due to the fires. Using time-series analyses of male lek counts, we modeled the effects of the fire at the lek site and in the surrounding areas (Fig. 8). We also analyzed the effect of habitat characteristics such as vegetation height, cheatgrass cover, and elevation.

We found that burned leks often exhibited a decline in male attendance, whereas leks within unburned areas exhibited stable or increasing trends in male sage grouse attendance. Post-fire habitat composition was important as well; sagebrush vegetation height within and around leks as well as elevation had positive effects on sage grouse lek attendance. The proportion of cheatgrass cover exhibited a negative relationship with sage grouse counts. These results indicate that unburned areas and habitat quality are important for sage grouse populations in this region

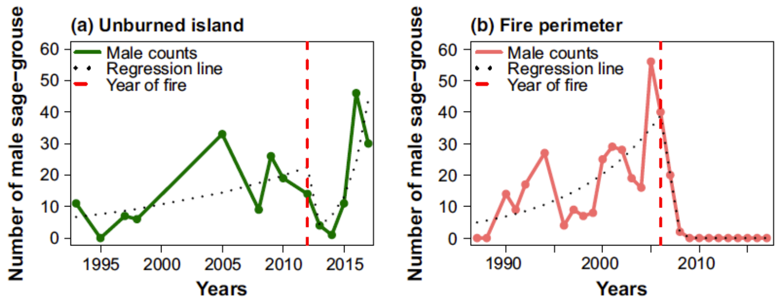

Figure 9. Examples of typical prefire and postfire male attendance trends of greater sage-grouse (Centrocercus urophasianus) leks in two fire categories: (a) unburned island, (b) fire perimeter. The graphs show (observed) male counts over time and (fitted) regression lines before and after a fire event. Figure from Steenvoorden et al. (2019; Ecology and Evolution).

and that management can positively effect these populations by protecting or creating unburned areas in fire-prone ecosystems (Steenvoorden et al. 2019).

3.4 Objective 4: Assess topographical features and management activities related to unburned areas

In our fourth Objective, we (1) assessed topographical features related to the creation and existence of persistent unburned areas in a post-fire landscape using a geospatial query approach and (2) identified management activities related to unburned areas by holding a couple of workshops and an online questionnaire.

For the topographical features related to unburned areas, we note that in a recent study, Krawchuk et al. (2016) found evidence that topographical metrics (such as catchment slope, local aspect, relative position, topographic wetness, topographic convergence, and local slope) can contribute to predicting fire refugia occurrence, yet other factors such as fire weather and environmental setting played equally important roles. However, this study was performed across only seven fires in western Canada. Since persistent unburned areas – as opposed to ephemeral unburned areas (Meddens et al. 2018b) – are more likely to occur at locations that include environmental factors that control the creation of fire refugia, we evaluated the effects of topography on the occurrence of persistent unburned islands (remaining unburned for more than one fire) across the Inland Northwest. We utilized the unburned area dataset developed by Meddens et al. (2018a), extracted the fire perimeters of multiple fires, and identified the locations that did not burn more than once within these fire perimeters (Martinez et al. 2019b). We subsequently overlaid fire regime groups (Table 1; LANDFIRE 1.0.5; https://www.landfire.gov/frg.php; Accessed 10 Sept 2018.) on top of the persistent unburned areas and extracted sampled pixel locations to evaluate the effect of topography on the occurrence of unburned areas.

Martinez et al. (2019b) found that persistent unburned area were more likely than burned areas to be located at the foot of slopes and valleys (Table 2; $P < 0.0001$ for FRG I to IV, see Tabl 1 for details on fire regime groups). However, for areas with a high fire return interval (200+), unburned areas were slightly more likely to be found on slope shoulders and ridges ($P = 0.0035$). Annual grasses and dry ponderosa pine forests showed the greatest difference in median topographic position index between persistent unburned areas and burned areas. Similarly, persistent unburned areas were more likely to be found in areas with lower runoff and a higher likelihood of water accumulation than in burned areas in the areas with more frequent fire.

Persistent unburned areas were more likely to be found in more rugged areas for high frequency fire regimes, while they were more likely to be found in less rugged areas in low frequency fire regimes. There was no significant difference between the distributions in FRG V. Persistent unburned areas were more likely to be found on flatter slopes in high frequency fire regimes; however, persistent unburned areas were more likely to be found on steeper slopes in other fire regime groups (II and V). Persistent unburned areas were more likely to be found on dry (SSW) aspects in most fire regime groups. Although the difference between the TRASP distributions for persistent unburned areas and burned areas in FRG II was insignificant.

In summary, we found that topography was indeed related to the development of unburned areas, thereby accepting the latter part of Hypothesis 4 that topographical features are correlated to the spatial distribution of unburned areas within the landscape. However, some of our results from the topographic analysis differed from what previous studies have found. While many authors have found fire refugia in valley bottoms and gullies (Krawchuk et al. 2016; Leonard et al. 2014; Romme and Knight 1981), we found that there was a significant relationship between topographic position and persistent unburned islands, although the effect was relatively small. We note, however, that prior studies focused on forests, whereas our study area encompassed forests, shrublands, and arid grasslands.

Table 1. Fire regime groups (FRG). (Adapted from Malesky et al. 2018; in Martinez et al. 2019, Fire Ecology)

Fire regime group	**Fire frequency**	**Severity**	**Severity description**	**Example cover type from study area**
I	0 – 35 years	Low/Mixed	Generally low-severity fires replacing less than 25% of the dominant overstory vegetation; can include mixed-severity fires that replace up to 75% of the overstory (typical of perennial grasslands)	Ponderosa pine; dry mixed conifer forest
II	0 – 35 years	Replacement	High-severity fires replacing greater than 5% of the dominant overstory vegetation (annual grasslands and some forests with frequent surface fires)	Grassland
III	35 – 200 years	Mixed/low	Generally mixed-severity; can also include low-severity fires (many forests and shrublands)	Big sagebrush, lodgepole pine
IV	35 – 200 years	Replacement	High-severity fires (forests and shrublands)	Big sagebrush, lodgepole pine
V	200 + years	Replacement/ any severity	Generally, replacement severity; can include any severity type in this frequency range (some moist forests, tundra, and deserts)	Very sparse big sagebrush steppe; spruce-fir forest

Table 2. Two-sample Kolmogorov-Smirnov D statistic and P-values to test significance of difference between the distributions of topographic metrics among unburned islands based on their degree of persistence and Fire Regime Groups (FRG). Orange highlights indicate P > 0.01, and red highlights indicate P > 0.05. (Martinez et al. 2019, Fire Ecology)

Burned vs persistent unburned		**TPI**	**TWI**	**TRI**	**Slope**	**CosAsp**	**TRASP**	**n_1**	**n_2**
All FRGs	D	0.0425	0.0689	0.1108	0.103	0.0483	0.0492	30000	30000
	P	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001		
FRG 1	D	0.1077	0.1352	0.1847	0.1747	0.0544	0.0508	4006	4667
	P	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001		
FRG 2	D	0.1421	0.0736	0.2696	0.2719	0.0992	0.0562	939	354
	P	< 0.0001	0.1234	< 0.0001	< 0.0001	0.0126	0.3906		
FRG 3	D	0.048	0.0751	0.1253	0.1164	0.0748	0.0799	8978	10097
	P	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001		
FRG 4	D	0.0412	0.0726	0.1118	0.1016	0.0475	0.0305	15136	13854
	P	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001		
FRG 5	D	0.0804	0.0748	0.058	0.0625	0.1256	0.1215	941	1028
	P	0.0035	0.0082	0.0736	0.0429	< 0.0001	< 0.0001		

To assess management activities related to unburned areas, we hosted a workshop in Portland, OR in 2017. During this workshop we invited natural resource managers to participate and guide future research identifying fire refugia on the landscape for management purposes. We discussed how fire refugia are formed, including (1) topographic/hydrologic, (2) weather/climate, (3) fuel arrangement, and (4) random effects. By manipulating the spatial arrangements of fuels, managers can influence the formation and creation of refugia. Prescribed burning might increase the chance protecting refugia (i.e., refugia "hardening"), while eradicating of fire-adapted grasses (e.g., cheat grass) might reduce fuel continuity, increasing the formation of fire refugia. Collectively, we identified several pathways by which managers could influence formation of fire refugia: (1) changing grazing allotments, (2) active suppression during wildfires, (3) changing backburn/burnout tactics, and (4) varying the intensity of prescribed burning to promote heterogeneity. Perceived management constraints included: identification of fire refugia within managed units, presence of fire-adapted invasive species, suppression strategies and tactics (e.g., high severity back burns), public/political support and risk aversion, and different jurisdictions with different management goals/targets (summarized in Appendix C).

3.5 Objective 5: Develop management strategies promoting or preserving unburned areas

To develop management strategies promoting or preserving fire refugia, we had in-depth interactions with various managers across the Pacific Northwest. We held two workshops, developed an online questionnaire, and held a meeting at the Idaho Fish and Game station in Lewiston, Idaho. Below, we synthesize the key strategies, management tools, and research needs for managing fire refugia.

In the first workshop (Portland, OR; May 17th, 2017), we identified potential management tools for preserving fire refugia in the landscape that could be employed by managers, pre-, during, and post-fire (Appendix C). To understand how pre-fire management can affect fire refugia formation, we need increased understanding of the effects of climate/weather, topography, fuel arrangements, fire behavior, landscape permeability, pathogens, and drought.

For management utility, identified fire refugia can be integrated into the Interagency Fuel Treatment Decision Support System (IFTDSS) system for fuel treatment planning. Management of fire refugia during active fire incidents are critical for the formation or preservation of fire refugia. Integration of a fire refugia data layers into the Wildfire Decision Support System (WFDSS) will enhance active protection of fire refugia. In addition, better understanding/communication of the importance of refugia or other ecologically significant sites with the Incident Command and line officers will facilitate improved fire refugia preservation. For post-fire management, we need a better understanding of which fire refugia are important; in addition, mapping the distribution of refugia and the probability of restoration success are essential for successful management of these locations. Spatial data on the disturbance history (e.g., presence of invasive species), fire severity, or time since last fire disturbance (persistence) will be instrumental. Two fire refugia of particular interest for future research were identified: (1) a yellow cedar relic site in central Oregon, and (2) the Steens Mountain area. These areas are of increased perceived ecological value and should be considered values-at-risk when active fires are burning nearby.

In the second workshop (Moscow, ID; Jan 16 and 17th, 2019), we further explored management action categories and workshop participants ranked a list of different action categories regarding the management of fire refugia. This list was generated from a brainstorm session and ranked by "*usefulness*" using a Q-sort method (See Appendix D Figure 2). There was agreement across both occupation types (manager and researcher) that planning/prioritizing fire refugia (e.g., creating a GIS database of fire refugia) and performing fuels reductions (e.g., thinning around or within fire refugia) were the most useful management actions. There was also agreement that altering the hydrology (e.g., raising the water table), and repopulation (e.g., collecting seeds or trees within refugia) were the least useful methods. However, during the workshop participants indicated that the definitions of these 14 management categories were sometimes ambiguous and therefore should be interpreted as a general indication of usefulness, but specific management actions could be more suitable. In addition, workshop participants identified high and low value fire refugia using the GoogleEarth platform. Eighty-two individual refugia were identified from five fires within the Pacific Northwest: 51 high value, 12 moderate value, and 20 low value. Most refugia were identified as high (or moderate) value because of their wildlife habitat importance (Figure 1). Participants also valued large refugia, as well as those in riparian or topographically sheltered areas (e.g., "stringers"). There were also a number of fire refugia that were identified as having a low priority for managers. These were mainly chosen because they were disturbed, close to roads, or the fire refugia were at low risk for being burned in the future (e.g., wet meadow, rocky terrain lacking fuel).

Since there is no formal way to incorporate fire refugia into management plans yet, we used an online survey to understand how our stakeholders value fire refugia. Responses (n=33) generally fell within two groups: human infrastructure and wildlife habitat (Fig. 10a). However, there was little consensus about a single important factor for identifying fire refugia (Fig. 10b), suggesting that a region-wide fire refugia importance ranking model is not feasible nor would be considered effective (Martinez et al. 2019a).

Our workshops revealed many opportunities for actionable science on the topic of fire refugia. Key aspects of fire refugia are as yet not well defined; therefore, more research is needed to link unburned islands to key habitat, identify management techniques and constrains, and provide information specific to pre-fire, active fire, and post-fire contexts of

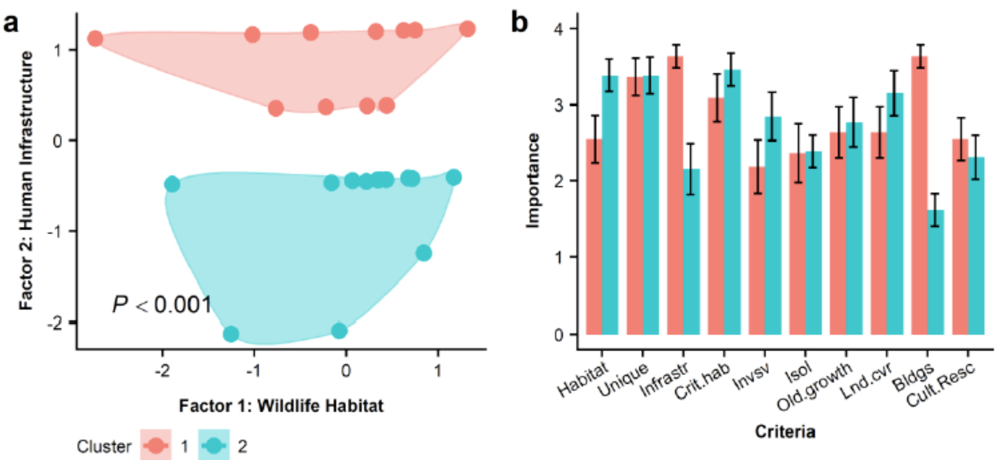

Figure 10. Respondent scores by cluster (a) Respondents plotted along factors, grouped by cluster. (b) Mean and standard error of respondent importance rankings, by cluster. See Table A1 (Martinez et al. 2019a) for descriptions of the abbreviations of the variables. p-values are from MANOVA tests, which test for differences between clusters by respondent's scores (Martinez et al. 2019a, Fire).

fire refugia at a local (or species-specific) level. It appears that the fire refugia concept is just beginning to become a consideration for land managers. While there a great deal of interest among land managers in managing fire refugia, more research is needed in translating the ecological significance of fire refugia into management strategies that natural resource managers can implement. These practices must be broad enough to cover the wide range of values among managers in different regions, ecosystems, and from a variety of agencies with differing missions; however, they must also be specific enough to be applied by individuals in their local areas of responsibility.

4. Conclusions (Key Findings) and Implications for Management/Policy and Future Research

We successfully mapped unburned areas across the Inland and Pacific Northwest (Objective 1), leading to various subsequent studies on how these unburned areas were distributed and associated with topographical, landcover, and species characteristics across the landscape (Objective 2). We investigated how these areas function as refugia for spotted owl and sage grouse (Objective 3) and what the topographical and management activities are related to unburned islands (Objective 4), and how we can promote and/or preserve these areas using management strategies (Objective 5). We feel that this project was highly successful in meeting the proposed objectives. We list a few key findings below and make recommendations on future research regarding this topic.

As climate continues to change, delineation and monitoring higher quality refugia will become increasingly important for managing at-risk natural resources in fire-prone areas. In addition, discovering longer-term trends in unburned area creation and/or expiration will be even more important, as fire seasons lengthen and fuels become drier. Geospatial technologies (such as our established unburned area database) that elucidate trends in unburned areas and subsequent assessments of unburned area quality can help inform pre- and post-fire planning. Over a relatively short timeframe (31 years), we did not find evidence for a trend in unburned area within wildfire perimeters (Meddens et al. 2018a), however we encourage finer spatial resolution and longer temporal analyses. This could lead to further and refined assessments on whether these locations that remain unburned are high-quality functioning fire refugia or whether they might shift to less desirable unburned areas (e.g., unburned areas that contain invasive species).

We developed a system for assessing the importance of unburned areas using an easy, adaptable fuzzy logic model and used spotted owls for our case study. We showed that 44% of the important spotted owl habitat has burned at high severity (Andrus et al. in review). Our model identified remaining patches of quality habitat, which can be used by management agencies for prioritization for monitoring and restoration. In addition, we showed that sage grouse lek sites within unburned areas remain stable, whereas lek counts in adjoining burned areas generally decreased. Greater understanding of the actual mechanisms of unburned areas during and following wildfire is needed. For instance, with the increase of animal tracking data, analyses of animal movement during a fire and the few years following a fire could show the importance (by cover or food resource) of different patches and configurations of fire refugia across the landscape.

The topic of analyzing reburns and persistent fire refugia within multiple burns is an important topic that warrants more research. Although we found some topographical metrics are related to persistent unburned areas (Martinez et al. 2019b), in many cases we could not easily elucidate which factors were important for the existence of persistent unburned areas. Kolden et al. (2017) found that in some cases unburned areas are more likely to burn in a subsequent fire, as the area that is unburned in the first fire might contain more fuel build-up as compared to the surrounding more recently burned matrix. During our workshops fire and fuel managers identified management techniques (such as prescribed burning) to remove fuels around important fire refugia to decrease the fire risk to important fire refugia. Post-fire lidar and longer-term post-fire recovery analyses are needed to assess where tipping points and/or fuel reduction strategies are effective at protecting higher quality refugia.

Our workshops received interest from a broad group of managers affiliated with various aspects of wildfires. As we presented aspects of recent fire refugia research, we learned that managers have already adopted some of our thinking into action, however many of these management actions were not categorized under the umbrella of fire refugia. As the concept of fire refugia is gaining traction in the scientific literature, the concept, to date, has not been included in many management directives or plans. A key recommendation from our projects is the incorporation of fire refugia in resilience-based and adaptive management strategies, and the need for understanding where and when to perform management strategies to maintain and preserve fire refugia. A better understanding of fuel treatment activities in relation to the creation of fire refugia is therefore warranted. Table 3 lists important research needs that will lead to key management strategies and applications regarding fire refugia.

Finally, the aspect of fire refugia overlapping with other types of refugia deserves attention. Fire refugia that also function as drought and insect refugia (i.e., disturbance refugia; Krawchuk et al. 2020) might be of even more importance to a resilient ecosystem than just high-value fire refugia themselves. Multiscale and multi-temporal monitoring with remote sensing data will improve the identification and preservation of these areas. In this JFSP project, we addressed several of these key knowledge gaps related to unburned areas, but more research is needed to comprehensively build upon this work to broadly to address land management agency needs.

Table 3. Future key research needs and their associated management and applications questions for fire refugia (Meddens et al. 2018b, BioScience).

Topic	Key research need	Key management and applications questions
Historic natural variability	Historical range of refugia abundance, size, and complexity across ecotypes	How do we facilitate refugia through ecosystem restoration tactics (e.g., prescribed fire)?
Refugia characteristics	Ranked importance of refugia characteristics by key species	How do we integrate metrics of refugia (e.g., distribution, abundance, physical complexity) into ecosystem function management goals?
Landscape pattern	Refugial connectivity across landscapes; species-specific needs for network size and connectivity	How do we create refugial connectivity on the landscape through forest and fire management activities?
Biophysical determinants	Relationships between refugia longevity and biophysical factors (persistent, predictable, stochastic)	How and where can we establish biophysical barriers to create, enhance or preserve fire refugia on the landscape?
Fire behavior	Models of fire behavior that accurately project refugial formation	Under what conditions can we actively pursue protection or facilitation of fire refugia?
Climate change	Climate change impacts on refugial trajectories, patterns, function and characteristics	How do we identify and protect critical fire refugia as seed sources and biodiversity hot spots?
Successional pathways	Probabilities of different successional pathways for refugia	How do we protect the ecological integrity of fire refugia years to decades post-fire?

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Appendix A: Contact Information for Key Project Personnel

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Appendix B: List of Completed/Planned Scientific/Technical Publications/Science Delivery Products

Articles in peer-reviewed journals

Blomdahl, E.M., Kolden, C.A., Meddens, A.J.H., & Lutz, J.A. (2019). The importance of small fire refugia in the central Sierra Nevada, California, USA. *Forest Ecology and Management*, 432, 1041-1052.

Kautz, M., Anthoni, P., Meddens, A.J.H., Pugh T.A.M., and Arneth, A. (2018). Simulating the recent impacts of multiple biotic disturbances on forest carbon cycling across the United States. *Global Change Biology* 24, 2079–2092, https://doi.org/10.1111/gcb.13974.24.

Krawchuk, M.A., Meigs, G.W., Cartwright, J.M., Coop, J.D., Davis, R., Holz, A., Kolden, C., & Meddens, A.J.H. (2020). Disturbance refugia within mosaics of forest fire, drought, and insect outbreaks. *Frontiers in Ecology and the Environment*, 18, 235-244

Martinez, A., Meddens, A., Kolden, C., & Hudak, A. (2019). An Assessment of Fire Refugia Importance Criteria Ranked by Land Managers. *Fire*, 2, 27

Martinez, A.J., Meddens, A.J.H., Kolden, C.A., Strand, E.K., & Hudak, A.T. (2019). Characterizing persistent unburned islands within the Inland Northwest USA. *Fire Ecology*, 15, 20

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Articles currently in review

Andrus, R.A., Martinez A.J., Meddens, A.J.H. (in review) Assessing the value of unburned areas for wildlife habitat: a case study of northern spotted owls in the eastern Cascade Mountains, *Forest Ecology and Management*.

Reports/Workshop outcomes

Meddens, A.J.H, Martinez, AJ. and Cartwright J.M. (2020). Chapter 8: Database of unburned areas within fire perimeters, *in: A guidebook to spatial datasets for conservation planning under climate change in the Pacific Northwest,* J.M. Cartwright (Ed.) p. 65–71, U.S. Geological Survey, https://doi.org/10.5066/P92L1H7O.

Meddens A.J.H. and Martinez A.J. (2019). Managing for Fire Refugia in the Northwestern United States (Outcomes of the second fire refugia workshop in the Northwest (Jan 16 & 17th 2019, Moscow Idaho), p. 2

Meddens A.J.H., Kolden C.A., Hudak A.T., Ramirez A. and Martinez A.J. (2017). Managing Fire Refugia in the Pacific Northwest: Outcomes of the first Fire Refugia Workshop in the Pacific Northwest (May 17th 2017, Portland, OR. https://arjanmeddens.weebly.com/ranking-unburned-islands.html), p. 2.

Graduate theses (masters or doctoral)

Martinez, A.J. (2019). *Characterizing and Ranking the Importance of Fire Refugia in the Northwestern US*. Thesis for a Master of Science Degree with a Major in Natural Resources, May 2019, University of Idaho, 92pp.

Steenvoorden, J. (2018). *Assessing the Ecological Importance of Unburned Islands in the Conservation and Management of Wildlife Species: A Case Study on Greater Sage-Grouse Populations in the Sagebrush Ecosystems of South-Eastern Oregon.* Master Thesis Earth Science (track Geo-Ecological Dynamics), April 2018, University of Amsterdam, The Netherlands, pp. 68.

Datasets

Meddens, A. (2017). Unburned areas within fire perimeters across the Inland northwestern USA from 1984 to 2014. USGS ScienceBase. Publication date: 2017-08-30, website: https://www.sciencebase.gov/catalog/item/59a7452ce4b0fd9b77cf6ca0

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Picotte, J.J., Arkle, R., Bastian, H., Benson, N., Cansler, A., Caprio, T., Dillon, G., Key, C., Klein, R.N., Kopper, K., Meddens, A.J.H., Ohlen, D., Parks, S.A., Peterson, D.W., Pilliod, D., Pritchard, S., Robertson, K., Sparks, A., Thode, A., (2019). Composite Burn Index (CBI) Data for the Conterminous US, Collected Between 1996 and 2018. https://doi.org/10.5066/P91BH1BZ.

Presentations/webinars/other outreach/science delivery materials.

Meg A. Krawchuk, Garrett W. Meigs, Jennifer Cartwright, Jonathan D. Coop, Raymond Davis, Andrés Holz, Crystal Kolden, Arjan J. H. Meddens (2020). *Disturbance refugia within mosaics of forest fire, drought, and insect outbreaks*. Conservation Biology meeting, Denver July 27-31.

Meddens A.J.H. (2018). *The role of fire refugia in ecosystem recovery*. Physics Colloquium University of Idaho, 22 October, Moscow ID.

Meddens A.J.H. (2018). *The role of fire refugia in ecosystem recovery*. Central Idaho Fire and Fuels Workshop, 11 June, McCall ID.

Meddens A.J.H. (2018). *Management of Fire Refugia in the Northwestern US*. Fire continuum conference, 22 May, Missoula MT.

Martinez A., Meddens A.J.H., Kolden C.A., Lutz J.A., Abatzoglou J.T., and Hudak A.T., (2017). *Spatiotemporal patterns of unburned areas within fire perimeters in the northwestern United States from 1984 to 2014*. Seventh Association for Fire Ecology (AFE) International Fire Congress, November 28 – December 2, Orlando FL.

Meddens, A.J.H. (2017). *Management of Fire Refugia in the Pacific Northwest. Northwest Refugia Research Coalition (RCC) workshop 2*. October 13, Reed College, Portland OR. Kolden, C.A. Seminar, NAU School of Forestry, "Forest Resilience and Fire Refugia", October 4, 2017, Flagstaff, AZ.

Kolden, C.A. Presentation: "Managing for forest resilience under global change: the power of fire refugia." Plenary presentation, Restoring the West Conference 2017: What's working, what's not? October 17-18, Logan, UT.

Meddens, A.J.H. (2016). Presentation: "*The role of fire refugia in ecosystem vulnerability*". Presentation for the NRS Department 501 seminar, University of Idaho.

Kolden C.A., Meddens A.J.H., Abatzoglou J.T., Cansler C.A., and Lutz J.A. (2017). *Refugia under fire: the impacts of climate change on wildfire refugia persistence and resilience.* Ecological Society of America (ESA) annual meeting, August 6-11, Portland, OR.

Website development

Project website: https://labs.wsu.edu/meddenslab/projects/ranking-unburned-islands/, accessed September 24, 2020.

Appendix C: Metadata.

Two datasets were publicly made available from this project on the ScienceBase (https://www.sciencebase.gov/catalog/; accessed November 12, 2020). ScienceBase is a trusted digital repository that provides access to scientific data products and resources. The first dataset includes the unburned islands dataset and is a Landsat-derived geospatial database of unburned islands within 2,298 fires across the Inland Northwestern US (including eastern Washington, eastern Oregon, and Idaho) from 1984-2014. The dataset has been posted, with the metadata provided in FGDC format as discussed in the data management plan. Methods for establishing this dataset are described in Meddens, A.J., Kolden, C.A., Lutz, J.A., Abatzoglou, J.T., & Hudak, A.T. (2018). Spatial and temporal patterns of unburned areas within fire perimeters in the northwestern United States from 1984 to 2014. *Ecoshpere*, 9, Article e02029, DOI: e02029.02010.01002/ecs02022.02029. The data is available through the following url: www.sciencebase.gov/catalog/item/59a7452ce4b0fd9b77cf6ca0 (Meddens, 2017a).

The second dataset includes Composite Burn Index (CBI) Plot Data from a field campaign. The dataset has been posted, with the metadata provided in or Federal Geographic Data Committee (FGDC) format as discussed in the data management plan. These data are used in the detection of unburned areas using Landsat imagery, see for more info: Meddens, A. J., C. A. Kolden, and J. A. Lutz. 2016. Detecting unburned areas within wildfire perimeters using Landsat and ancillary data across the northwestern United States. *Remote Sensing of Environment* 186:275-285. The data is available through the following url: www.sciencebase.gov/catalog/item/59a738e8e4b0fd9b77cf6c81 (Meddens, 2017b).

Data were posted in the USGS ScienceBase as a part of the funding for the creation of the database were also from the USGS Climate Adaptation Science Centers. Therefore, we did not post this data on DataBasin as originally proposed in the Data Management Plan. The PI has contacted the USFS Research Data Archive (http://www.fs.usda.gov/rds/archive/) to request inclusion of the two metadata files into their repository since this repository maintains a record of all data products funded by JFSP. Finally, we also contributed our CBI dataset to a larger combined dataset assembled by Picotte et al. (2019). Intermediate data, computer code, and data processing documents are securely stored (with off-site backups) by the PI and are available upon request (contact: arjan.meddens@wsu.edu).

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Meddens, A. (2017a). Unburned areas within fire perimeters across the Inland northwestern USA from 1984 to 2014. USGS ScienceBase. Publication date: 2017-08-30, website: https://www.sciencebase.gov/catalog/item/59a7452ce4b0fd9b77cf6ca0

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Picotte, J.J., Arkle, R., Bastian, H., Benson, N., Cansler, A., Caprio, T., Dillon, G., Key, C., Klein, R.N., Kopper, K., Meddens, A.J.H., Ohlen, D., Parks, S.A., Peterson, D.W., Pilliod, D., Pritchard, S., Robertson, K., Sparks, A., Thode, A., (2019). Composite Burn Index (CBI) Data for the Conterminous US, Collected Between 1996 and 2018. https://doi.org/10.5066/P91BH1BZ.

Appendix D: Two-pager on the outcomes of the first workshop of this project.

Managing Fire Refugia in the Pacific Northwest

Outcomes of the first Fire Refugia Workshop in the Pacific Northwest (May 17th 2017, Portland Oregon)

[Introduction] Fire refugia are areas with lower fire effects than the surrounding area, where biota (or cultural resources) can persist and expand from during and after a fire event. These areas are important landscape elements that contain habitat for species, can increase ecosystem resilience, and provide ecosystem services by retaining seed sources. Examples of fire refugia include unburned patches of old-growth for spotted owl habitat or unburned patches of sagebrush rangelands important for greater sage grouse.

Natural resource managers are increasingly interested in identifying fire refugia to preserve the ecological function of these areas. Researchers at the University of Idaho and Utah State University have developed an unburned islands database for approximately 2,300 fires across the Inland Northwest from 1984 to 2014 (Fig. 1, Meddens et al, 2016, Meddens et al, in prep).

To make this unburned islands database useful for natural resource management, a means to rank the importance of fire refugia contingent upon management objectives is critical. We invited natural resource managers to participate in a workshop to guide future research in identifying fire refugia on the landscape for management purposes. We discussed three key topics using example fires. Here, we describe the primary outcomes of the workshop.

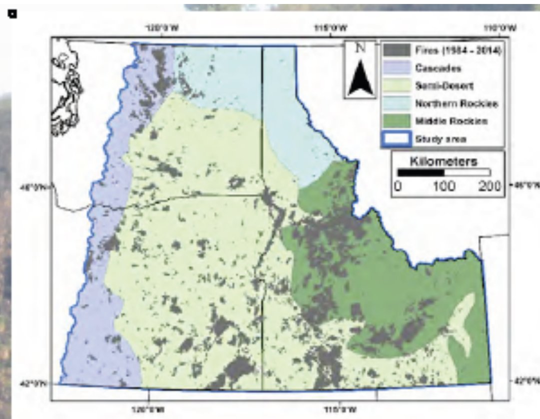

Figure 1: Fire locations of the unburned area database in the inland northwestern USA (Meddens et al, in prep).

➢ Fire refugia formation and management limitations

Fire refugia are formed by (1) topographic/hydrologic, (2) weather/climate, (3) fuel arrangement, and (4) random effects. By manipulating the spatial arrangements of fuels, managers can influence the formation and creation of refugia. Prescribed burning might increase the chance of a given fire refuge to survive a fire (refugia "hardening"), while eradication of fire-adapted grasses might reduce fuel continuity, increasing the formation of fire refugia. Other influences managers could have over refugia formation are: (1) changing grazing allotments, (2) active suppression during wildfires, (3) changing backburn/burnout tactics, and (4) varying the intensity of prescribed burning to promote heterogeneity.

Perceived management constraints included: identification of fire refugia within managed units, presence of fire-adapted invasive species, suppression

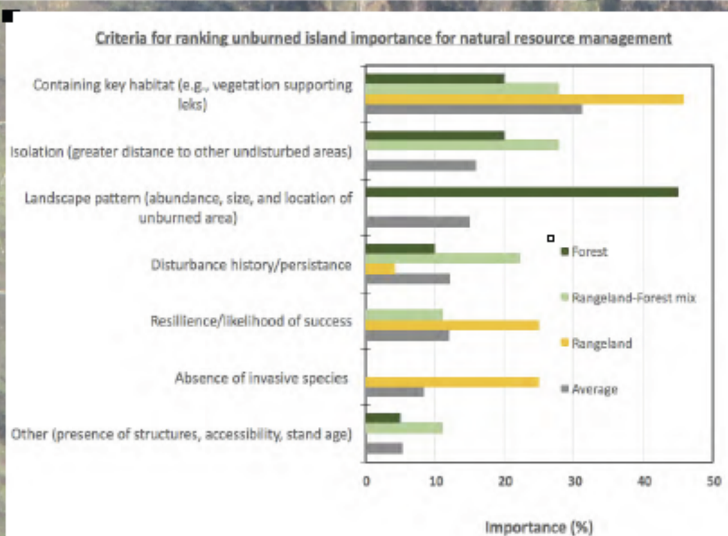

***Figure 2:** Importance (%) of criteria for ranking unburned islands. A group of 14 natural resource professionals was asked to list and rank criteria that could be used for identifying important unburned areas for management purposes across a (1) forested area, (2) a mixed rangeland-forest area, and (3) a rangeland area. A wide range of criteria were identified and are summarized by importance in the bar chart on the left. Unburned areas containing important habitat in isolated locations were generally considered important. Landscape pattern was considered important in forest, whereas invasive species were considered more important in rangelands. Disturbance history/persistence and resilience/likelihood of success where other factors that were identified as important.*

strategies and tactics (e.g., high severity back burns), public/political support and risk aversion, and different jurisdictions with different management goals/targets.

- **Criteria for identifying fire refugia**

Workshop participants ranked criteria for identifying fire refugia across three fires; one fire burned predominantly in closed canopy forest (Table Mountain Fire in central WA, 2012), one fire burned through a mix of rangeland and forest types (South Fork Complex fire in central OR, 2015), and one fire that burned through predominantly rangeland (Buzzard fire in eastern OR, 2015). Unburned areas that contain key habitat for fire sensitive species were deemed most important for identifying fire refugia across the three fires. Location and isolation were found more important in forest and forest/rangeland mix, resilience/likelihood of success and invasive species were more important in rangelands (Fig. 2).

- **Management tools and future research**

[Pre-fire] We need increased understanding of the effects of climate/weather, topography, fuel arrangements, fire behavior, landscape permeability, pathogens, and drought related to fire refugia formation. For management utility, identified fire refugia should be integrated into the IFTDSS (Interagency Fuel Treatment Decision Support System) system for fuel treatment planning.

[During fire] Management decisions during fire can be critical for the formation or preservation of fire refugia. Integration of a fire refugia data layers into the Wildfire Decision Support System (WFDSS) will enhance active protection of fire refugia. In addition, better understanding/communication of the importance of refugia or other ecologically significant sites with the Incident Command and line officers will facilitate improved fire refugia preservation.

[Post-fire] Identification of fire refugia is important post-fire; in addition, mapping the distribution of refugia patches and the probability of restoration success are essential for successful management of these locations. Spatial data on the disturbance history

Figure 3: Identified fire refugia within the Table Mountain Fire, central Washington 2012. Imagery courtesy of Google Earth.

(e.g., presence of invasive species), fire severity, or time since last fire disturbance (persistence) will be instrumental. Two fire refugia of particular interest for future research were identified: (1) a yellow cedar relic site in central Oregon, and (2) the Steens Mountain area. These areas are of increased perceived ecological value and should be considered values-at-risk when active fires are burning nearby.

Conclusion: Fire refugia are important and management agencies can influence the maintenance of these areas. Our workshop revealed many opportunities for actionable science on the topic of fire refugia. Key aspects of fire refugia are as yet not well-defined; therefore, more research is needed to link unburned islands to key habitat, identify management techniques and constrains, and provide information specific to pre-fire, active fire, and post-fire contexts of fire refugia.

Workshop participants: Don Major (BLM), Sarah Canham (BLM), Holly Higgins (BLM), John DeGroot (Nez Perce), Cyndi Sydles (USFWS), Robyn Darbyshire (USFS), Craig Goodell (TNC), Bryce Kellogg (TNC), Amanda Stamper (TNC), Tom DeMeo (USFS) + authors.

Authors: AJH Meddens (ameddens@uidaho.edu) and CA Kolden (University of Idaho), AT Hudak (US Forest Service), Aaron Ramirez (NCEAS) and Anthony Martinez (University of Idaho).

Acknowledgements: Funding was provided by the Joint Fire Science Program and North West Climate Science Center. We thank the OSU Foundation center, the Northwest Fire Science Consortium, and Nicholas Giannettino for their valuable support.

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Meddens AJH, Kolden CA, & Lutz JA. (2016). Detecting unburned areas within wildfire perimeters using Landsat and ancillary data across the northwestern United States. *Remote Sensing of Environment, 186*, 275-285

Meddens AJH, Kolden CA, & Lutz JA (in prep). Spatial and temporal patterns of unburned areas within fire perimeters in the northwestern United States from 1984 to 2014. *In preparation for Ecological Applications.*

Appendix E: Two-pager on the outcomes of the second workshop of this project.

Managing for Fire Refugia in the Northwestern United States

Outcomes of the second fire refugia workshop in the Northwest (Jan 16 & 17th 2019, Moscow Idaho)

Fire refugia are defined as areas less frequently or less severely affected by wildfire relative to the surrounding landscape and important for the persistence of biota. Land managers and researchers were invited to participate in a two half-day workshop to gain insight on the factors that influence land management strategies on fire refugia. The workshop objectives were to (1) establish a list of possible management actions for managing fire refugia and (2) identify examples of the placement of these management activities within a fire. Additionally, we identified unburned islands of high and low values on a GIS during the workshop.

Nineteen participants from across the Pacific Northwest attended the workshop; they included 12 natural resource managers and 7 researchers. Due to the timing of a federal government shutdown, many federal attendees were unable to attend. Agencies represented were: Washington Department of Natural Resources, Washington Department of Fish and Wildlife, USDA Forest Service, Idaho Department of Lands, and Idaho Department of Fish and Game. Additionally, we had representation from the University of Idaho, the University of California Davis, private landowners, and a congressional staffer.

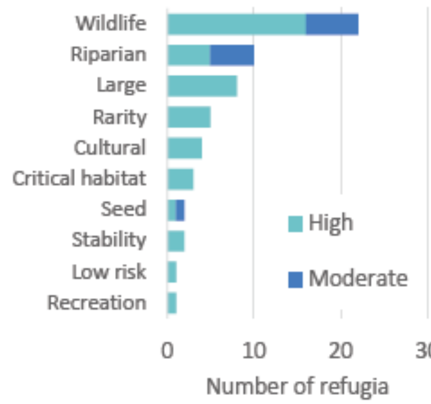

Figure 1: The number of refugia identified as having high or moderate management value by class.

Identifying high and low value fire refugia

During the workshop participants identified high value and low value fire refugia using Google Earth. Eighty-two individual refugia were identified from five fires within the Pacific Northwest: 51 high value, 12 moderate value, and 20 low value. Most refugia were identified as high (or moderate) value because of their wildlife habitat importance (Figure 1). Participants also valued large refugia, as well as those in riparian or topographically sheltered areas (e.g., "stringers").

There were also a number of fire refugia that were identified as having a low priority for managers. These were mainly chosen because they were disturbed, close to roads, or the fire refugia were at low risk for being burned in the future (e.g., wet meadow, rocky terrain lacking fuel).

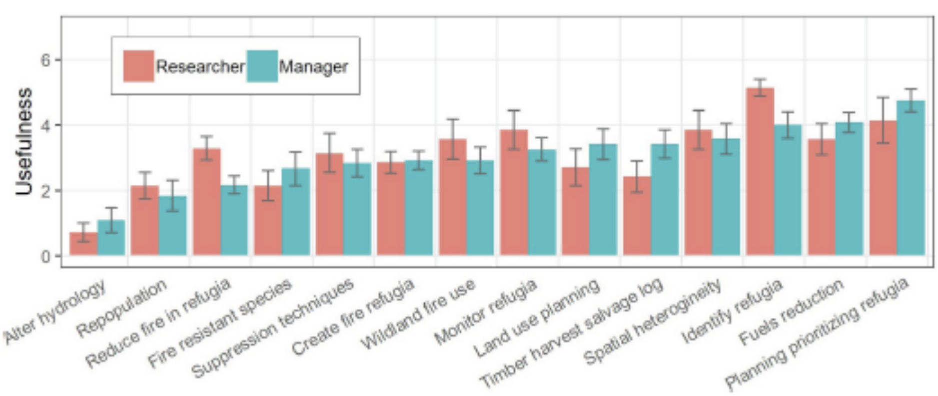

Figure 2: Mean "usefulness" score (from 0 to 7) for different management action categories in promoting or preserving fire refugia. Participants were separated by their occupational group. Standard error bars in grey.

Management actions promoting fire refugia

During the workshop participants developed a list of management action categories by brainstorming management actions to promote or preserve fire refugia. The individual actions were categorized into 14 broader categories. Participants then ranked these actions by their "usefulness" using a Q-sort method (Figure 2).

There was agreement across both occupation types (manager and researcher) that planning/prioritizing fire refugia (e.g., creating a GIS database of fire refugia) and performing fuels reductions (e.g., thinning around or within fire refugia) were the most useful management actions. There was also agreement that altering the hydrology (e.g., raising the water table), and repopulation (e.g., collecting seeds or trees within refugia) were the least useful methods. However, during the workshop participants indicated that the definitions of these 14 management categories were sometimes ambiguous and therefore should be interpreted as a general indication of usefulness, but specific management actions could be more suitable than others given specific circumstances.

Future research topics

At the conclusion of the workshop participants were asked to write down future research topics that would make the most impact in preserving/managing fire refugia. Forty-three research topics (and questions) were identified by the participants. These topics were categorized into eight broader categories (Figure 3). Participants were categorized into manager versus researcher based on their job duties.

Both groups indicated that more research is needed to characterize fire refugia, to gain further insight into the physical and ecological traits and functions of fire refugia. Both groups also indicated a strong interest in further research on the creation and maintenance of fire refugia. Research questions that were posed were generally practical, such as "How do we create artificial fire refugia?"

Conclusion

This workshop provided valuable insight into the values of land managers and how that impacts their decision making. It appears that the fire refugia concept is just beginning to become a consideration for land managers. While there a great deal of interest among land managers in managing fire refugia, more research is needed in translating the ecological significance of fire refugia into management strategies that natural resource managers can implement. These practices must be broad enough to cover the wide range of values among managers in different regions, ecosystems, and from a variety of agencies with differing missions; however, they must also be specific enough to be applied by individuals in their local areas of responsibility.

Acknowledgements

Thanks to all the workshop participants, the College of Natural Resources at the University of Idaho for hosting us, and the Joint Fire Science Program (JFSP, Cooperative Agreement L16AC00202).

University of Idaho
College of Natural Resources

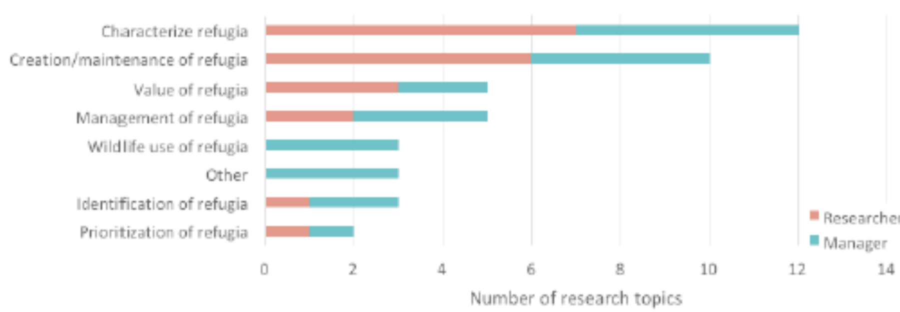

Figure 3: The number of research topics or questions suggested by participants. Topics were separated by the occupational group of the participant.

Authors: A.J.H. Meddens (ameddens@uidaho.edu) and Anthony Martinez (ajmartinez@uidaho.edu)