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Assessing the quality of fire refugia for wildlife habitat

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ABSTRACT

Wildfires have important effects on wildlife habitat. Within fire perimeters, 'fire refugia' are unburned or less severely burned areas that contain residual pre-fire habitat structures and facilitate species persistence following fire. However, fire refugia may vary in their relative quality. The ability to evaluate the relative quality of fire refugia for wildlife habitat may help efficiently allocate resources for post-fire conservation planning, especially for at-risk species. Using spatial overlays of habitat models and burn severity data, we developed the refugia index, a flexible multi-scale, multi-criteria fuzzy logic model to assess the value of unburned areas for wildlife habitat affected by wildfires and other disturbances. We conducted a case study of the northern spotted owl (*Strix occidentalis caurina*) and applied our method to 4278 unburned areas in 15 fires that each burned > 400 ha of spotted owl nesting/roosting habitat in the eastern Cascade Mountains, U.S.A. In our study area, unburned areas represented ~ 1.7% of the area within the fire perimeters. Most fire refugia were low quality, because unburned areas were small relative to the desired nest patch size of spotted owls and contained little suitable nesting/roosting habitat. However, each fire contained a few high-quality fire refugia, because they co-occurred with suitable nesting/roosting habitat and were surrounded by desirable habitat characteristics for spotted owls. Our method illustrates how land managers can use readily available spatial data and analysis tools to understand fire effects on species' habitat (e.g., habitat lost) and prioritize areas for post-fire conservation and management.

1. Introduction

Habitat for many wildlife species is being altered by land use changes (e.g., timber harvesting), disturbances (e.g., hurricanes and wildfires), and climate change (Pimm et al., 2014). Among disturbances, wildfire is a key threat to habitats for many species (Geary et al., 2020; Ward et al., 2020) and fire activity is projected to continue to increase with warming and drying conditions in many locations across the earth (Moritz et al., 2012; Abatzoglou et al., 2018; Bowman et al., 2020). While fires create new habitats for some wildlife species (e.g., snags for cavity-nesting birds; Hutto et al., 2020; Latif et al., 2020), fires also remove vegetation structures that are essential habitats for other species (Kelly et al., 2015; Jones et al., 2016). Many national policies, such as the Northwest Forest Plan in the U.S. (USFS and BLM, 1994), require conservation and restoration of habitats for at-risk species (DSE, 2009; USFS, 2012). Understanding the availability and spatial distribution of habitats for wildlife species affected by fire is, therefore, an important component of post-fire planning process for land managers.

Fire interacts with topography, vegetation, and climate to create complex spatial patterns in vegetation following fire (Agee, 1996) that have varying levels of suitability for wildlife habitat (Chia et al., 2015; He et al., 2019). Fire refugia – unburned or less severely burned areas that allow some species to persist following fire (Meddens et al., 2018b) – have garnered increased attention in recent decades for their capacity to maintain intact habitats and support ecological recovery (Camp et al., 1997; Franklin et al., 2000a; Robinson et al., 2014; Landesmann and Morales, 2018; Krawchuk et al., 2020). Across fires, unburned or low-severity burn areas with low tree mortality (e.g. < 10% tree mortality) can be mapped with remote sensing techniques that identify areas with minimal change in spectral indices relative to the surrounding burn mosaic (e.g., Krawchuk et al., 2016; Meddens et al., 2016, Collins et al., 2019, Chapman et al., 2020). Hundreds to sometimes thousands of unburned areas within the matrix of burned areas are often identified and, combined, these areas may represent ~10% of the area within the burn perimeter (Meddens et al., 2018a). Few studies to date have examined whether unburned areas overlap spatially with suitable habitat for wildlife species that prefer habitat structures associated with older forests (e.g., > 200 years since fire), despite widespread concern about the

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negative effects of fire on habitat for some wildlife species (e.g., USFWS, 2011; Wintle et al., 2020).

Unburned areas likely vary considerably in their capacity to function as fire refugia for wildlife species due to differences in their vegetation structure and composition. Indeed, spatial overlay analysis has identified that landcover of unburned areas may include unburnable surfaces, like roads and rocks, or grasslands and late successional forests (Clarke, 2002; Meddens et al., 2018b; Meigs and Krawchuk 2018; Martinez et al. 2019a). The ability to evaluate the relative quality of habitat in unburned areas for a focal wildlife species would be useful for prioritizing areas for post-fire conservation (Martinez et al., 2019b; Latif et al., 2019). Fuzzy logic models are increasingly used in such environmental decision support contexts (e.g., Gärtner et al., 2008; Reynolds et al., 2014), because they treat model variables and outputs as degrees of truth (membership) rather than assigning membership to a class (i.e., true/false; Sheehan and Gough, 2016), integrate multiple data types and complex relationships, and produce easily interpretable results for multiple stakeholders (e.g., scientists, managers, policymakers). Such tools would be helpful for land managers to transparently and effectively justify conservation and management actions pertaining to wildlife habitat in post-fire landscapes.

Our objectives were to (1) develop a refugia index (RI), a geospatial method to assess the quality of unburned areas for wildlife habitat affected by wildfires (and other disturbances), (2) apply the method and conduct a case study using spatial overlay analysis to examine how the RI (model output) varied with model inputs for a focal species, and (3) investigate how the RI at the individual fire-level was affected by characteristics of the fire and availability of habitat (pre-fire). Our geoprocessing workflow and fuzzy logic model application can be implemented in readily available geospatial software (e.g., ArcGIS and R programming language). We selected the northern spotted owl (*Strix occidentalis caurina*; hereafter, spotted owl) as our focal species, because it is strongly considered in many aspects of forest management in the northwestern region of the continental U.S. (USFS & BLM, 1994; Spies et al., 2019) and the response of spotted owls to fire and persistence of spotted owls in post-fire landscapes is a key management concern (Lesmeister et al., 2019). We applied our method to publicly available spatial datasets of spotted owl habitat suitability, burn severity, and unburned areas in the eastern Cascade Mountains of Oregon and Washington, an area where spotted owl habitat has recently been affected by multiple wildfires (Davis et al., 2016). The RI provides land managers with an assessment of the quality of individual unburned areas to help prioritize areas for post-fire conservation planning.

2. Methods

2.1. Development of refugia index for wildlife habitat

The RI is the output from a multi-criteria fuzzy logic model (Zadeh, 1965) in the Environmental Evaluation Modeling System platform (EEMS; Sheehan and Gough, 2016). EEMS was developed to provide environmental decision support for inherently complex systems, such as forest (Sheehan and Bachelet, 2019) and wildlife (Zabihi et al., 2017) management. A key benefit in the context of wildlife habitat and unburned areas is the capacity of fuzzy models to reduce ambiguous transitions between classes and more effectively address uncertainty inherent in environmental datasets (Burrough, 1989), such as inaccuracies in attribute data or spatial geometries (McKelvey and Noon, 2001).

Following the conventions of fuzzy logic models, we represented our model as a logic tree of hierarchically arranged logical propositions (i.e., refugia index or the value of an unburned area). Propositions are described by fuzzy values (i.e., degrees of truth or each proposition) and are evaluated by operators (i.e., union; Fig. 1) combining multiple fuzzy value inputs (i.e., spatial datasets). The terminal nodes in our logic tree represented the input spatial datasets that in our case were existing habitat models modified with burn severity and timber harvest spatial datasets. Model inputs were divided into two branches that described characteristics within and surrounding unburned areas. Input variables were normalized to obtain fuzzy values using the EEMS framework. First, minimum (−1, fully false) and maximum (1, fully true) thresholds were defined (e.g., Table 1). Then the values between the thresholds were linearly interpolated across the spectrum of truth (Appendix S2: Fig. S1). Fuzzy values representing input parameters were combined using a weighted union operator (weighted mean) into two intermediate propositions (nodes) which were, in turn, combined into one final proposition (root node) to determine the RI (Fig. 1). Model weights for each parameter can be assigned at each proposition. Input variables, operators, and model weights are adjustable depending on the focal species, previous research, expert opinion, and management goals.

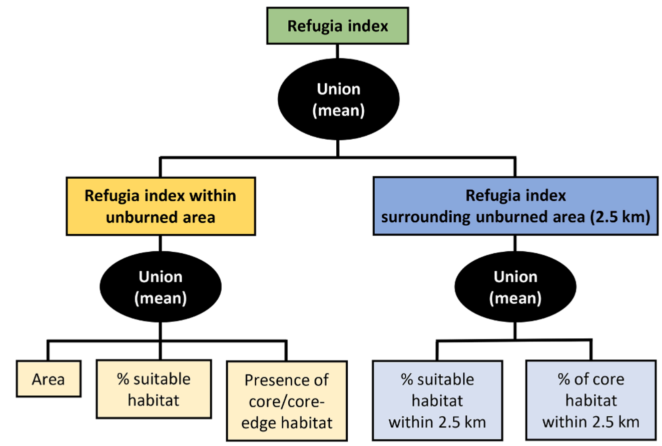

Fig. 1. Fuzzy logic tree for assessing wildlife species' refugia index. The terminal nodes are the input criteria, which were divided into characteristics within the unburned area (light yellow) and characteristics of the habitat surrounding the unburned area (light blue). The final proposition (green) is a union of the two intermediate propositions (yellow and blue). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2.2. Application of habitat value assessment method

2.2.1. Focal species

The northern spotted owl was listed as 'threatened' in 1990 under the Endangered Species Act (USFWS, 1990). The Northwest Forest Plan (adopted in 1994), which provides management direction for all federally administered forests in the Pacific Northwest, was developed to protect and promote late successional reserves (older stands with complex forest structure) that function as habitat for multiple life-history requirements for the spotted owl (USFS & BLM, 1994; Thomas et al., 2006). Spotted owl populations have continued to decline across their range over the past two decades (Dugger et al., 2016) despite many measures to improve habitat conservation, such as substantial reductions in timber harvest on federal lands. In addition to timber harvesting and invasion by barred owls (*Strix varia*) in recent decades, wildfire has significantly reduced suitable habitat for spotted owls (Davis et al., 2016; Reilly et al., 2017), particularly in more fire-prone areas such as the eastern side of the Cascade Mountains.

Fire alters stand structures and tree species compositions suitable for spotted owl nesting/roosting habitat (Lesmeister et al., 2019) that, in turn, affects spotted owl demography (Rockweit et al., 2017; Wan et al., 2018). Spotted owls have high site fidelity (Forsman et al., 1984) and following fire, pre-fire residents may return to previously occupied nesting/roosting habitat in unburned or low severity burn areas (Gaines et al., 1995; Jones et al., 2016). Spotted owls forage across a wide variety of stand types from unburned areas of varying stand age to areas recently burned at all severities (including smaller patches and edges of

Table 1
Criteria and thresholds used to determine refugia index of unburned areas for spotted owl nesting/roosting habitat using the Environmental Evaluation and Modeling System (EEMS) model. Input criteria were normalized to obtain fuzzy values by defining minimum (-1, fully false) and maximum (1, fully true) thresholds and then linearly interpolating values between the thresholds. Values less (greater) than the minimum (maximum) threshold were assigned a value of −1 (1). All input criteria were weighted equally in the intermediate propositions, weights differed in the final proposition (80% for suitability of habitat within unburned area and 20% for suitability of habitat surrounding unburned area).

Input variables	Threshold False	True	Justification
Within unburned area			
Area (of unburned area, ha)	0.18	12.6	Larger unburned areas are more likely to serve as nesting/roosting habitat. Min. size of unburned areas is 0.18 ha (Meddens et al. 2016) and a common nest patch size is 12.6 ha or 200-m radius around the nesting/roosting location (Swindle et al., 1999; Glenn et al., 2017).
% suitable habitat	0%	100%	Owl fitness increases with more suitable nesting/roosting habitat as well as less habitat fragmentation (Franklin et al., 2000b; Davis et al., 2016; Dugger et al., 2016).
Presence of core or core edge habitat	Absent (0)	Present (1)	
Surrounding unburned area			
% suitable habitat	0%	70%	True threshold based on recommended percent of suitable habitat within 2.5-km radius circle (Forsman et al., 2015) or territory (Glenn et al., 2017).
% core and core–edge habitat	0%	80%	Spotted owls prefer approximately 80% nesting/roosting vegetative cover within territory (Glenn et al., 2017).

high severity; Comfort et al., 2016). In more fire-prone regions of the spotted owl distribution, such as the eastern side of the Cascade Mountains, a mosaic of early seral foraging habitat and late-successional nesting/roosting habitat created by mixed severity fire is likely beneficial to the maintenance of owl habitat (Baker, 2015; DellaSala et al., 2015; Franklin et al., 2000b; Hessburg et al., 2007). The risk of spotted owl habitat loss to fire and the need to manage elevated fuel levels from fire suppression to protect habitat is a source for considerable scientific debate throughout the distribution of all spotted owl subspecies (DellaSala et al., 2015; Jones et al., 2016, 2019; Lee, 2018; Peery et al., 2019). Extensive severely burned areas tend to reduce spotted owls' survival and occupancy (Rockweit et al., 2017; Jones et al., 2016), but the existence of fire refugia could help explain persistence by owls in some severely burned landscapes (Lee & Bond 2015). As both area burned and area burned at high severity are expected to increase under climate warming (Davis et al., 2017; Wan et al., 2019), understanding the degree to which fire refugia maintain post-fire habitat might contribute to post-fire conservation planning and management for this focal species.

2.2.2. *Study area*

We applied our method to fires that burned spotted owl habitat in two physiognomic provinces on the eastern side of the Cascade Mountains in Washington and Oregon (Fig. 2). From 1993 to 2012, wildfire accounted for ~ 48% (~27,000 ha) of nesting/roosting habitat loss for the spotted owl on federal lands in the eastern Cascades (Davis et al., 2016). In the study area, spotted owls nest in dry to wet mixed conifer forest in the Douglas-fir (*Pseudotsuga menziesii*) zone and grand fir (*Abies grandis*) zone (Franklin & Dyrness, 1973). Within these forest zones, spotted owls prefer to nest and roost in closed-canopy forests (>50–60% canopy closure) with medium- to large-sized trees and multi-layered canopies (Buchanan et al., 1995; Forsman et al., 2015). Historical fire regimes in the eastern Cascades were variable, but ranged from relatively frequent, low severity fire regimes in lower elevation dry forests to relatively infrequent, stand-replacing fire regimes in higher elevation moist forests with considerable area that experienced mixed-severity regimes (Agee, 1996; Hessburg et al., 2007; Spies et al., 2019).

2.2.3. *Spatial data used in method application*

We used the following spatial datasets in our method: (1) Unburned areas dataset from 2013 to 2018 (Meddens et al., 2018a), (2) spotted owl nesting/roosting habitat suitability (vegetation reference year, 2012; Davis et al., 2016), (3) spotted owl cover type patterns (vegetation reference year, 2012; Davis et al., 2016), and disturbance (burn severity, MTBS, 2020; timber harvest, USFS, 2020). For the purposes of illustrating our model, we selected 15 fires from 2013 to 2019 that burned > 400 ha (mean, 2,065 ha; range, 404–7,734 ha) of suitable spotted owl nesting/roosting habitat. The 400-ha cutoff was chosen because this is an area sufficient to affect multiple spotted owl pairs (Franklin et al., 2000b). We only selected fires after 2012, because the habitat suitability dataset accounts for fires prior to 2012 and land managers often need methods to update spatial datasets (spotted owl habitat suitability model updated periodically, every ~ 5 years) with recent events (e.g. wildfire) for conservation planning. For unburned areas, we compiled the existing unburned areas dataset from 2013 to 2014 (Meddens et al., 2018a) with unburned areas identified using the same methods from 2015 to 2018 (see Appendix S1: Table S1 for Landsat image acquisition dates). Unburned areas for the period 2013–2018 were delineated using the field-validated classification tree of spectral indices derived from Landsat data (30-m raster) following Meddens et al., (2016). This dataset is the presence/absence of an unburned pixel. These pixels were then aggregated with adjacent pixels into unburned areas with a minimum area of 0.18 ha (2 Landsat pixels). The accuracy for unburned area detection was 89% (Meddens et al., 2016). For the purposes of our analysis, the geometry of unburned areas was converted to polygons (from raster) and the area of each unburned area was extracted as a model input. By only examining unburned areas (rather than including low burn severity areas) as nesting/roosting habitat, our method is more conservative than methods including higher levels of burn severity and we provide managers with a clear and consistent definition of fire refugia.

The habitat suitability and cover type patterns datasets were both used as model inputs and here we briefly summarize the methods used by Davis et al. (2016) to create these datasets. In the following paragraph, we detail how the habitat suitability and cover type patterns datasets were modified with the disturbance datasets. The habitat suitability dataset (30-m raster) was created by predicting presence of nesting/roosting behavior by spotted owl pairs using nine gridded forest structure and tree species composition predictor variables in a maximum entropy species distribution model (Davis et al., 2016). Habitats were classified as unsuitable, marginal, suitable, or highly suitable, and we reclassified these classes to suitable habitat (suitable and highly suitable) and unsuitable habitat (unsuitable and marginal). Model validation produced 'area under curve' values ranging from 0.78 to 0.87. The cover type patterns dataset (100-m raster), also developed by Davis et al., (2016), was created to assess the potential effects of fragmentation on spotted owl habitat and classified spotted owl habitat type as non-habitat (background), edge, core–edge, and core. Core habitat (or 'interior habitat') was spotted owl habitat > 100 m from non-habitat,

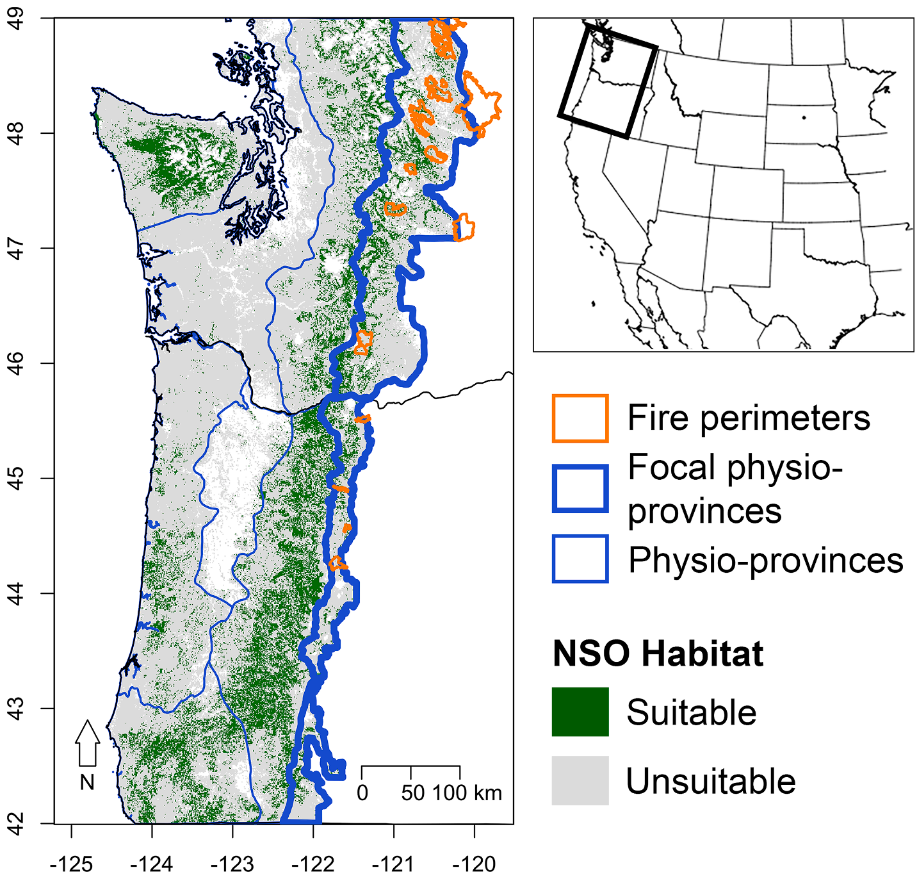

Fig. 2. Map illustrating the extent of fires (orange, n = 15; MTBS 2020) and suitable nesting and roosting habitat for the northern spotted owl (NSO; green; Davis et al., 2016) within the two focal physiographic provinces (thick blue line; USFS, 2013) in the eastern Cascade Mountains of Oregon and Washington, U.S. The inset map shows the location of the study area in the Pacific Northwest. Only portions of fires within the focal physiological provinces were included in the analysis. White areas are not spotted owl nesting/roosting habitat. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

core–edge habitat was adjacent to core or edge habitat (no distance requirement from non-habitat), and edge habitat was on the margins of core–edge habitat and adjacent to non-habitat.

High severity fire and some timber harvesting practices remove suitable habitat and increase habitat fragmentation, thereby affecting spatial patterns in spotted owl habitat (Davis et al. 2016). Areas that burn at high severity (>75% tree canopy cover loss) are generally considered unsuitable nesting/roosting habitat for spotted owls (Comfort et al., 2016; Jones et al., 2016; Lesmeister et al., 2019), because occupancy and survival often decline in these areas following fire (Clark et al., 2013; Rockweit et al., 2017). For burn severity, we used the RdNBR (Relative differenced Normalized Burn Ratio), a commonly used index that assesses relative change in dominant vegetation from pre- and post-fire fire images, to identify areas that burned at high severity (Rockweit et al., 2017). RdNBR was downloaded, if available, from Monitoring Trends in Burn Severity project (MTBS, 2020) or computed using MTBS methods with Landsat data downloaded from Earth Explorer (USGS, 2020). We derived the RdNBR threshold for high severity fire by predicting RdNBR from the composite burn index (CBI; Key and Benson, 2006) and evaluting the RdNBR value (>615) that corresponded to the CBI threshold for high severity fire (>2.25; Appendix S1: Fig. S1, Table S3). Our RdNBR value roughly corresponds to the RdNBR value for high severity fire (basal area morality > 75%; RdNBR > 648) previously found in the southern half of the study area (Meigs et al., 2020). For timber harvest, areas that were 'clear-cut harvest' after 2012 (year of habitat suitability model) were identified using the 'Timber Harvest' dataset (USFS, 2020). In the habitat suitability dataset, areas of suitable habitat were reclassified as unsuitable if they were clear-cut or burned at high severity. Based on the finding that optimal spotted owl habitat within the territory (i.e., surrounding area) was ~ 20% fragmented (Glenn et al., 2017), we reclassified core and core–edge habitat in the cover type patterns dataset if > 20% of the 100-m focal pixel burned at high severity or was clear-cut by downgrading these pixels to non-habitat. Adjacent pixels were also reclassified based on the criteria for core/core–edge habitat (see above) such that core habitat was only adjacent to core–edge habitat and neither were present if core habitat was no longer present (Davis et al., 2016).

2.2.4. Model application

We selected three characteristics within the unburned area (i.e., potential or existing nest patch) and two characteristics of the area surrounding (i.e., territory) the unburned area as model input variables (Fig. 1). For characteristics within the unburned area, we selected area, proportion of suitable nesting/roosting habitat, and presence/absence of core/core–edge habitat. For characteristics of areas surrounding unburned areas, we examined the area within 2.5 km of the unburned area edge and selected the proportion of suitable habitat and proportion of core/core–edge habitat within this area. The distance of 2.5 km approximates the home range of spotted owls pairs on the eastern slope of the Cascades (Forsman et al., 2015) and allows comparison with the distance of 2.9 km used in U.S. Fish and Wildlife Service and Washington State Environmental Policy (*sensu* Forsman et al., 2015).

We used previous research relating spotted owl fitness to habitat characteristics to develop thresholds for our fuzzy logic model (Table 1). We considered each input variable to be positively correlated with higher quality habitat for spotted owls, because greater area of suitable habitat is positively correlated with owl fitness (e.g., annual survival and reproductive success increase with amount of suitable habitat in territory; Dugger et al., 2016). All input criteria were weighted equally in the intermediate propositions; however, weights in the final proposition were 80% for suitability of habitat within unburned area and 20% for suitability of habitat surrounding unburned area. In eastern Washington forests, characteristics of the spotted owl nest patch, such as distance to interior of patch (accounted for by area of burned area and core habitat) and percentage of suitable nesting/roosting habitat within 200-m radius (12.6 ha), were considerably more important predictors of suitable habitat (explained 76.1% of variability) than the surrounding (i.e., territory) area (explained 1.9% of variability; Glenn et al., 2017).

Investigating how characteristics of the pre-fire habitat and fire impacted the refugia index may help land managers in landscape scale planning. As such, we constructed bivariate relationships using generalized linear models to examine how the highest RI values within a fire (mean of upper 95th percentile per fire) were affected by burn severity (low, mod., high), area burned, and percent of the area within the fire perimeter covered by suitable nest/roosting habitat and core/core–edge habitat. Given a relatively small sample size of 15 fires, we only examined bivariate relationships (rather than multiple regression) and evaluated statistical significance with $\alpha = 0.10$ to minimize failure to detect meaningful relationships (i.e., type II error).

3. Results

The RI, an index of the quality of unburned areas for a focal wildlife species (here, spotted owl), was the output of the fuzzy logic model (Fig. 1). In our analysis of 15 fires in the eastern Cascades (Fig. 2), there were of 274 isolated unburned areas per fire (median, range 49 to 545, total 4,278) that were > 0.18 ha in size (minimum size for unburned areas). Unburned areas represented 1.7% (median, range 0.5–8.2%) of the area within fire perimeters (Appendix S1: Table S2). Fire perimeters contained 1,373 ha (median, range 404–7734) of suitable spotted owl nesting/roosting habitat pre-fire and 28 ha (6–439 ha) of core/core–edge habitat pre-fire (Appendix S1: Table S2). Fires burned 96% (median, range 82–99%) of suitable nesting/roosting habitat (all severities combined) of which 44% (median across fires, range 22–70%) burned at high severity (Fig. 3A). Similarly, fires burned 99% (range 84–100%) of core/core–edge habitat (all severities combined) of which 44% (range 9–82%) burned at high severity (Fig. 3B). For example, the Jolly Mountain Fire, which contained ~ 50% suitable habitat pre-fire, burned 29% of suitable habitat at high severity and ~ 27% of core/core–edge habitat at high severity (Fig. 4).

Examining characteristics of model inputs *within* unburned areas across fires, most unburned areas (mean 78% ±2.48 (se) across fires) contained < 1% suitable nesting/roosting habitat (Fig. 5A), but a few unburned areas (8% ± 0.90) in each fire contained > 75% suitable nesting/roosting habitat (Fig. 5A). The presence of core/core–edge habitat occurred within very few unburned areas (3.8% ±1.05, Fig. 5B). Unburned areas were generally small (median 0.27 ha; range 0.18–96.93 ha) and few unburned areas (0.77% ±0.12) were greater than the mean nest patch size (12.6 ha) for spotted owls (Fig. 5C). Examining characteristics of model inputs for areas *surrounding* (<2.5 km) unburned areas across fires, the most suitable unburned areas (>70% suitable nesting/roosting habitat) rarely occurred (5.36% ±3.3 of unburned areas, Fig. 5D). Nearly all unburned areas (99%) were surrounded by < 25% core/core–edge habitat (<1% and 1–25% combine) and no unburned areas (in any fire) were surrounded by > 50% core/core–edge habitat (Fig. 5E).

The RI values for all fires were generally very low (median, −0.87; range, −1.0–0.46; Fig. 5F; Appendix S1: Fig S2) relative to the possible range of model outputs (-1–1). The pronounced peak in the RI at ~ -0.98 (Fig. 5F) resulted from many small (<1 ha) unburned areas (Fig. 5C) without suitable habitat (Fig. 5A, D) or core/core–edge habitat (Fig. 5B). The relatively smaller peaks in the distribution of the RI at −0.7 and −0.4 (Fig. 5F) resulted from slightly larger unburned areas (Fig. 5C) with increasing amounts of suitable habitat (Fig. 5A) and core/core–edge habitat both within and surrounding the unburned area (Fig. 5D, E). The peak at ~ 0.1 (Fig. 5F) generally resulted from > 75% suitable habitat (Fig. 5A) and core/core–edge habitat presence within the unburned area (Fig. 5B) and higher than mean amounts of suitable habitat and core/core–edge habitat in the 2.5 km surrounding the unburned area (Fig. 5D, E). There were a mean of 7 unburned areas per fire (median, range 2 to 21) that had a RI greater than zero (see example for Jolly Mountain fire, Fig. 4D).

The mean of the upper 95th percentile of RI for fires was −0.19 (range −0.46–0.21). The RI (mean of upper 95th percentile) increased with higher percentages of low burn severity (Fig. 6A), while we found no effects of moderate and high severity fire on the RI (Appendix S1: Table S4). The RI also increased in fires with higher percentages of the area within the fire perimeter containing pre-fire suitable habitat (%) and core/core–edge habitat (%) (Fig. 6B, C).

4. Discussion

The primary contribution of this study is the development and demonstration of a method that assessed the quality of fire refugia for wildlife species' habitat based on preferred habitat characteristics within and surrounding unburned areas. Using the spotted owl as our focal species, we identified relatively higher versus lower quality fire refugia for nesting/roosting habitat in 15 fires on the eastern side of the

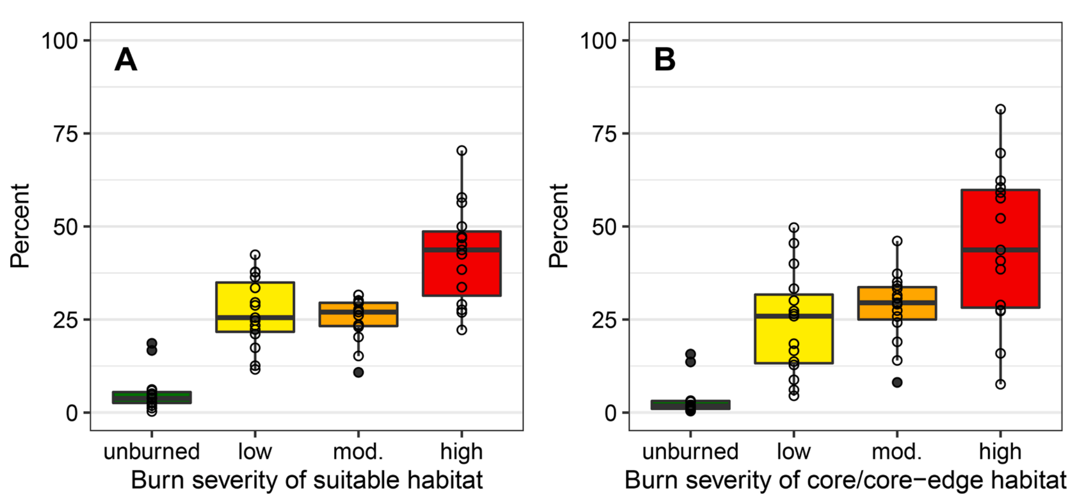

Fig. 3. Percent of A) pre-fire suitable spotted owl nesting and roosting habitat or B) core/core–edge habitat by burn severity class for 15 fires that burned > 400 ha of suitable spotted owl habitat in the eastern Cascade Mountains, illustrating that within fire perimeters suitable northern spotted owl habitat burns more frequently at higher severity. Hollow black circles are values from individual fires. See Appendix S1: Table S3 for burn severity thresholds. In boxplots, the thick black horizontal line within the box is the median, the box represents the interquartile range (25th–75th percentiles; IQR) of the distribution, the whiskers extend no further than 1.5 times the IQR, and the solid black circles beyond the whiskers are outliers.

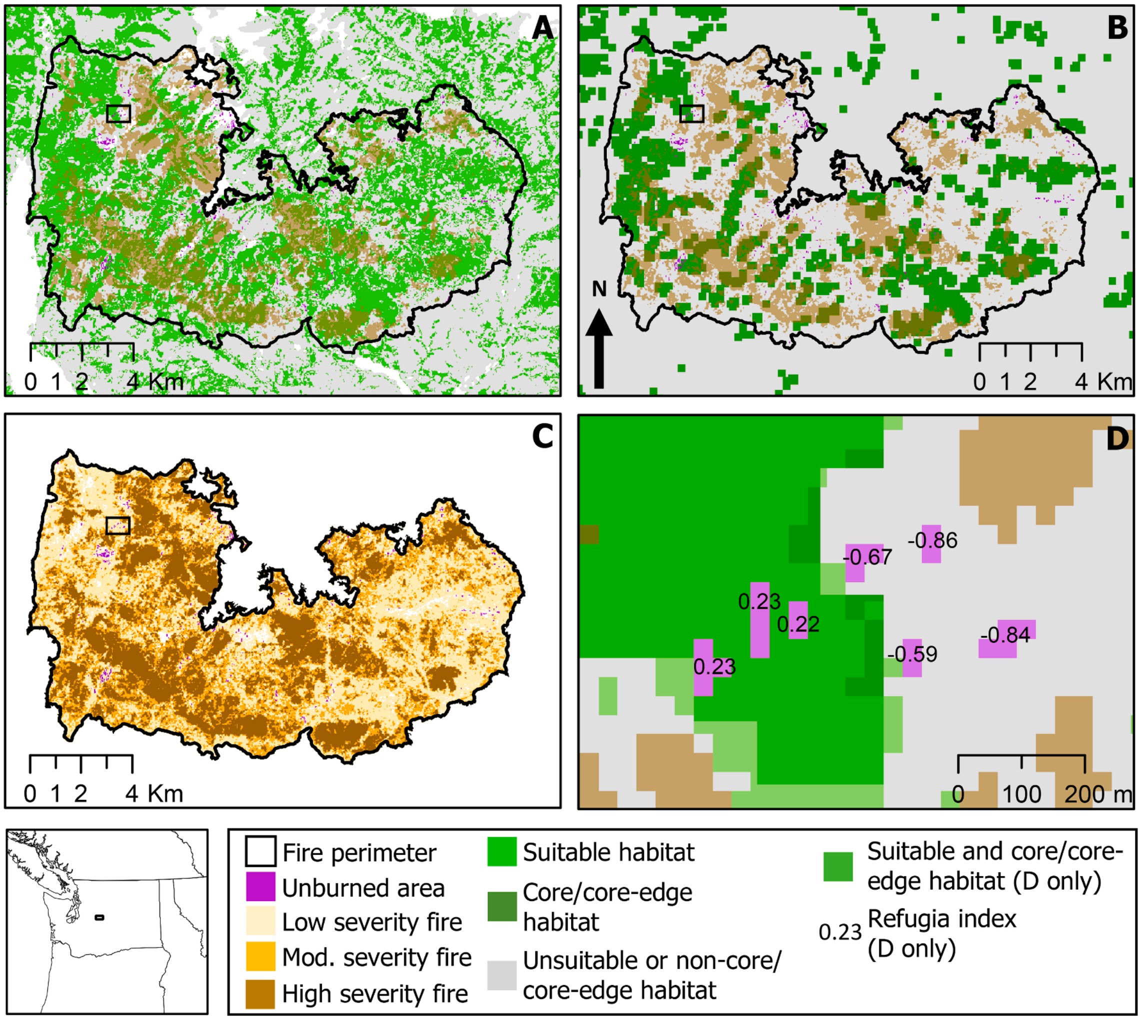

Fig. 4. Maps illustrating spatial overlap of high severity fire with A) suitable (including highly suitable) spotted owl nesting and roosting habitat (pre-fire) and B) spotted owl core and core–edge habitat (pre-fire) as well as unburned areas in the Jolly Mountain Fire, WA. C) Burn severity in four classes: unburned, low severity, moderate severity, and high severity (see Appendix S1: Table S1 for burn severity thresholds). D) Example refugia index from fuzzy logic model for unburned areas (-1 (lower quality) to 1 (higher quality)), illustrating higher quality refugia within suitable and core/core–edge habitat and lower quality refugia in unsuitable habitat.

Cascade Mountains. Our method illustrates how land managers can use readily available spatial data and analysis tools to understand fire effects on species' habitat and use a transparent method to prioritize areas for post-fire conservation.

We identified a few unburned areas in each study fire that exhibited characteristics of higher quality fire refugia, but most unburned areas were low quality fire refugia for spotted owl nesting/roosting habitat (Fig. 4). By comparing spotted owl nesting/roosting habitat preferences (Table 1) to characteristics within and surrounding unburned areas, we improved the understanding of factors limiting the quality of fire refugia for nesting/roosting in unburned areas (Fig. 5). Several unburned areas within each fire contained a high percentage of suitable habitat in our study fires; such inclusions of high-quality habitat within a larger burned matrix may function as fire refugia for spotted owls (Gaines et al., 1995). Most unburned areas were, however, much smaller (median size 0.27 ha) than the average nest patch size (~12.6 ha, Glenn et al., 2017). The small size of unburned areas and loss of core/core–edge habitat likely reduced the distance to the interior of large patches of suitable nesting/roosting habitat, which is generally found to be negatively associated with site suitability for nesting/roosting habitat (i.e., low quality fire refugia; Dugger et al., 2016).

Examining the area surrounding unburned areas, high severity fire removed substantial amounts of suitable and core/core–edge habitat (44% loss) and likely further fragmented areas of nesting/roosting habitat within the fire perimeter (Figs. 3, 5). Such losses of suitable habitat are expected and accounted for in critical habitat management plans (USFWS, 2011) due to their negative effects on, for example, spotted owl survival and recruitment (Rockweit et al., 2017). Nevertheless, most unburned areas were surrounded by < 25% suitable nesting roosting habitat, which is well below the ~ 80% preferred by spotted owls range-wide (Glenn et al., 2017), 55–57% preferred by spotted owls in the eastern Cascades (Forsman et al., 2015), and 40% recommend by Washington State Forest Practices Board Rules (Washington State Environmental Policy Act, 2006). By highlighting unburned areas with both lower and higher quality spotted owl nesting/roosting habitat characteristics, we demonstrate key differences among unburned areas in habitat quality. Understanding such differences may help land managers and biologists identify unburned areas for conservation that have a higher chance of functioning as fire refugia for spotted owl nesting/roosting habitat (or other desired focal species).

Broadening the spatial scale of analysis from the individual unburned area to the entire fire, we found that the higher RI values (mean of 95th percentile per fire) for spotted owl nesting/roosting occurred in study fires with more suitable habitat and core/core–edge habitat pre-fire (Figs. 4, 6). Unburned areas and spatial patterns in burn severity are created by the complex interaction of fire weather, topography, and

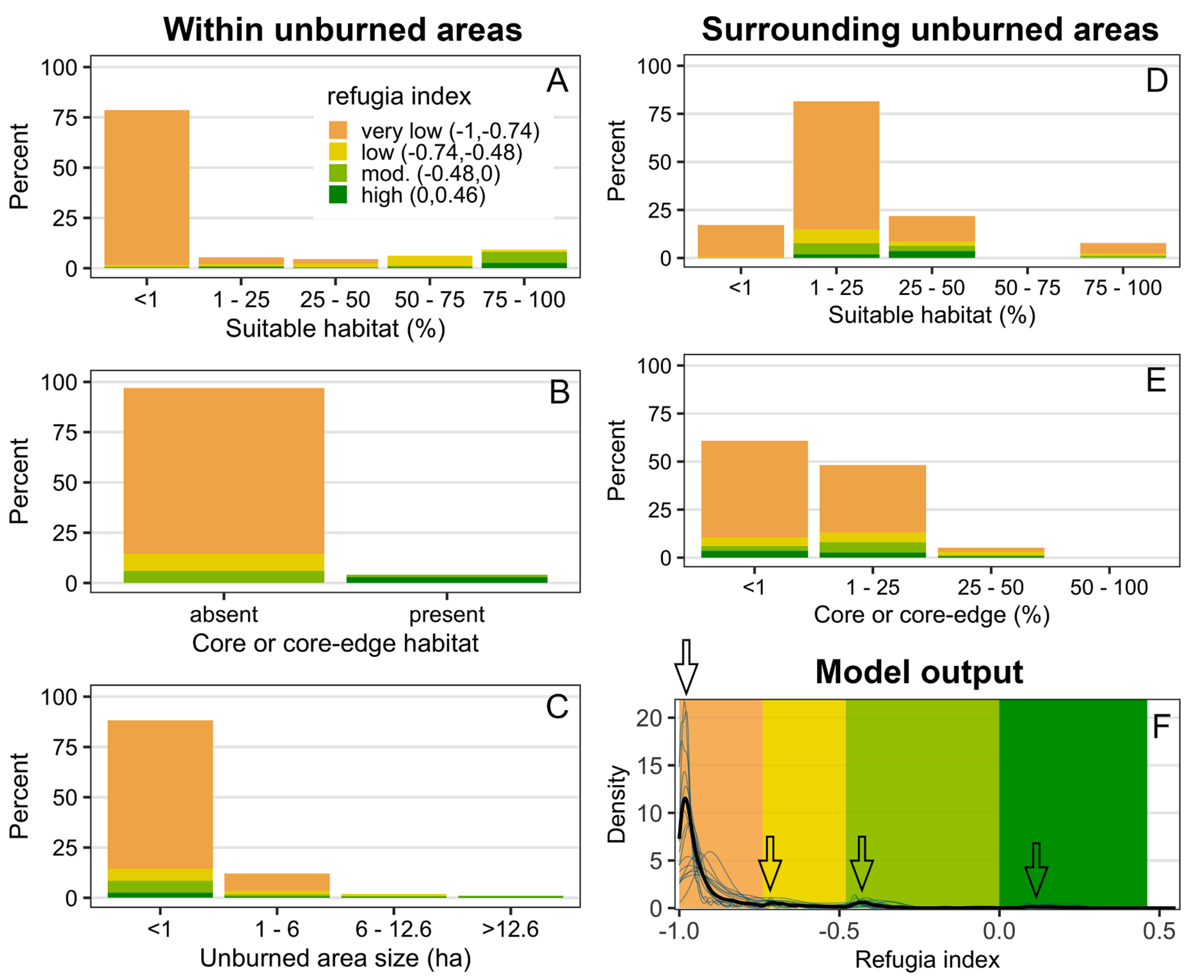

Fig. 5. Mean (A) suitable spotted owl nesting and roosting habitat within unburned areas (%), (B) core or core–edge habitat within unburned areas (present/absent), and (C) size of unburned area by refugia index class across fires. Mean (D) suitable spotted owl nesting and roosting habitat surrounding (<2.5 km) unburned areas (%) and (E) core or core–edge habitat surrounding unburned areas (%) by refugia index class across fires. (F) Mean distribution of refugia index across all 15 fires (thick black line) and distribution of refugia index for each fire (thin blue lines; see Appendix S1: Fig S4 for individual fires). Classes in (A-E) show mean frequency of each class of refugia index within each bar. Range of classes (colors) in (A-E) are from (F) and were delineated to highlight peaks (arrows) in the distribution of refugia index. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

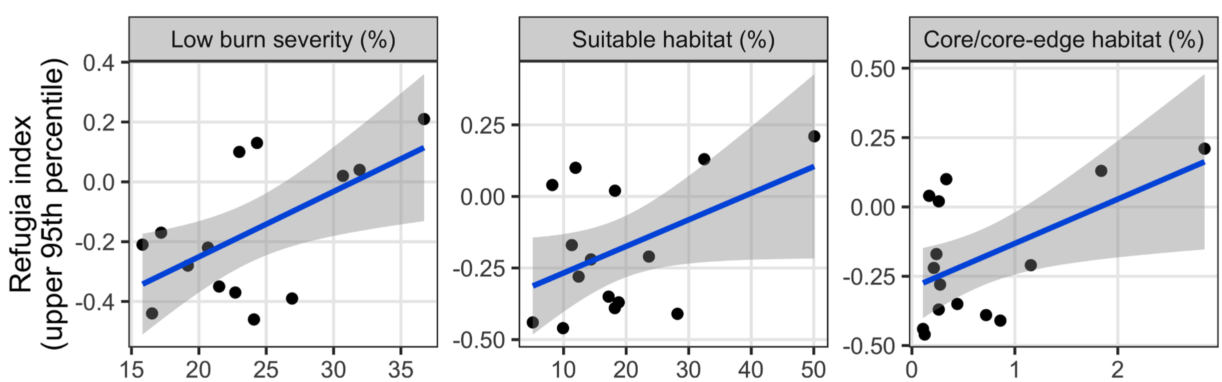

Fig. 6. Bivariate relationships (blue line) examining factors affecting mean of upper 95th percentile of refugia index (sampling unit is fire), including A) low burn severity, B) percent of area within fire perimeter covered by suitable nesting/roosting habitat for northern spotted owls pre-fire, and C) percent of area within fire perimeter covered by core/core–edge habitat for northern spotted owls pre-fire. Linear model and P-values indicate results from generalized linear model, and the title is the x-axis label. Numerical results presented in Appendix S1: Table S4 for all relationships. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

fuels (Krawchuk et al., 2016; Meigs et al., 2020; Parks et al., 2018) and threatened habitats can be prioritized for protection during fires. Forest structures associated with suitable nesting/roosting habitat (i.e., late-successional reserves) were more likely to produce refugia (<10% basal area mortality from fire) in the southern portion of our study area (Meigs et al., 2020) and this may have contributed to higher RI values in fires with more suitable nesting/roosting habitat pre-fire in our study. Additionally, our results suggest that higher RI values for nesting/roosting habitat occur in fires when more area burns at low severity, which tends to occur during more moderate fire weather conditions (Meigs et al., 2020).

Our goal was to use existing datasets in a relatively simple modeling framework to produce a spatially explicit RI to inform post-fire land management. In our method, we omitted some variables due to data availability and specified thresholds in our fuzzy logic model that may have important effects on habitat and demography. Our results need to be considered in this context. First, higher RI values produced by the fuzzy logic model would benefit from field validation to ensure that unburned areas did not burn, contain habitat characteristics suitable for the focal wildlife species, and are used by the focal species (e.g., presence of nesting/roosting spotted owls) more commonly than unburned areas with lower RI values. In the context of spotted owls, areas with prior nesting/roosting activity by spotted owls that did not burn might be considered higher priority for conservation given the tendency for spotted owls to return to prior nesting areas. Second, we could not account for competitive interactions with other species. Again, in the context of spotted owls, competition for resources (e.g., habitat) between the spotted owl and barred owl is a key contributor to range-wide declines in spotted owl populations (Long and Wolfe, 2019; Wiens et al., 2014). Third, our method assessed the RI immediately post-fire and thus does not account for potential changes in habitat that affect focal species demography with time since fire, such as delayed tree mortality or stands increasing/decreasing in habitat suitability. However, we note that our method is flexible and could be readily revised or updated as new information or data becomes available. Fourth, for some wildlife species unburned areas may be too restrictive and the limits for delineating unburned areas should be adjusted to also include, for example, low severity fire. While it is important to consider our RI in the context of these limitations, our method offers a repeatable, transparent, and objective means to evaluate fire effects on wildlife habitat and identify higher-quality fire refugia.

5. Management implications

Wildfires present a challenge for managing at-risk wildlife species, because fires are often beyond the control of land managers (Spies et al., 2019). Understanding the variability in quality of unburned areas to function as fire refugia for a particular species is a key challenge in post-fire management (Martinez et al., 2019a). A flexible and readily adaptable method, such as the one presented in this paper, that incorporates publicly available spatial habitat and disturbance data as well as empirical studies and expert knowledge is a powerful spatial planning tool for science-based management following fire. The current iteration of our method was developed logically for wildlife species that use areas within and surrounding unburned areas, but the approach is broadly applicable to other species with different life-history requirements, such as sage-grouse (*Centrocercus urophasianus*; Steenvoorden et al. 2019) and long-footed potoroos (*Potorous longipes*; NRE, 2000). The capacity to add and adjust parameters (model inputs, operators, and weights) is the primary method by which end users could update the model with new information, apply the model to spotted owls in a specific geographic region or adapt the method to other wildlife species, depending on management objectives and policy. Given limited resource availability for restoration and time required to regrow, for example, late-successional habitat structures, prioritizing conservation of higher quality fire refugia can help reduce the high costs to maintain habitat for a focal species (Bottrill et al., 2009). Furthermore, the spatially explicit nature of our product would allow it to be coupled with existing habitat models assessing, for example, wildlife species specializing in burned landscapes (black-backed woodpecker, *Picoides arcticus*; FIRE-BIRD; Latif et al., 2019) to identify areas (burned and unburned) that may be beneficial to a variety of species versus activities detrimental for many wildlife species (e.g., salvage logging). By explicitly investigating the quality of unburned areas and developing maps of locations of higher quality fire refugia, our method could help support spatial planning and adaptive management in conservation for at-risk species.

CRediT authorship contribution statement

Robert A. Andrus: Conceptualization, Methodology, Data curation, Formal analysis, Visualization, Writing - original draft, Writing - review & editing. **Anthony J. Martinez:** Conceptualization, Methodology, Visualization, Writing - original draft, Writing - review & editing. **Gavin M. Jones:** Writing - review & editing, Visualization. **Arjan J.H. Meddens:** Conceptualization, Methodology, Writing - review & editing, Supervision.

Declaration of Competing Interest

The authors declared that there is no conflict of interest.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.foreco.2020.118868.

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