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Topographic and fire weather controls of fire refugia in forested ecosystems of northwestern North America

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Abstract. Fire refugia, sometimes referred to as fire islands, shadows, skips, residuals, or fire remnants, are an important element of the burn mosaic, but we lack a quantitative framework that links observations of fire refugia from different environmental contexts. Here, we develop and test a conceptual model for how predictability of fire refugia varies according to topographic complexity and fire weather conditions. Refugia were quantified as areas unburned or burned at comparatively low severity based on remotely sensed burn severity data. We assessed the relationship between refugia and a suite of terrain-related explanatory metrics by fitting a collection of boosted regression tree models. The models were developed for seven study fires that burned in conifer-dominated forested landscapes of the Western Cordillera of Canada between 2001 and 2014. We fit nine models, each for distinct levels of fire weather and terrain ruggedness. Our framework revealed that the predictability and abundance of fire refugia varied among these environmental settings. We observed highest predictability under moderate fire weather conditions and moderate terrain ruggedness (ROC-AUC = 0.77), and lowest predictability in flatter landscapes and under high fire weather conditions (ROC-AUC = 0.63–0.68). Catchment slope, local aspect, relative position, topographic wetness, topographic convergence, and local slope all contributed to discriminating where refugia occur but the relative importance of these topographic controls differed among environments. Our framework allows us to characterize the predictability of contemporary fire refugia across multiple environmental settings and provides important insights for ecosystem resilience, wildfire management, conservation planning, and climate change adaptation.

Key words: burn mosaic; burn severity; fire refugia; fire weather; island; predictability; remnant; topography; topo-refugia; unburned; wildfire.

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INTRODUCTION

Wildfires are familiar landscape disturbances in forested ecosystems of western Canada and the United States (USA) that result in mosaics of fire effects. The concept of burn severity is used to quantify biological, physical, and chemical effects of fire and can be broadly defined as the degree to which an ecosystem changes as a result of fire (Lentile et al. 2006, Keeley 2009). Landscape heterogeneity produced by burning, which can include a range in severity from unburned patches to high severity fire, is important to conserving characteristic biodiversity of fire-adapted ecosystems (Agee 1993, DellaSala and Hanson 2015). As a part of the burn mosaic, areas that experience comparatively low-severity fire or remain unburned are landscape legacies that can provide an essential environment for species sensitive to fire, and support populations that contribute to the reassembly of biotic communities after fire (e.g., Camp et al. 1997, Franklin et al. 2000, Burton et al. 2008, Keppel et al. 2012, Robinson et al. 2013, Perera and Buse 2014). Fire islands, residuals, remnants, skips, shadows, refuges, refugia, or unburned patches are all terms used to describe areas at the low end of the burn severity spectrum. Here, we use the term *fire refugia* to describe places that are disturbed less frequently or less severely by wildfire than the surrounding landscape matrix, following Camp et al. (1997) and Wood et al. (2011). Refugia can exist at a range of spatial scales, for example, from an individual plant or small patch of vegetation to broader landscapes. And refugia can occur across a range of temporal scales, persisting only in the short term through a single fire event or in the longer-term through multiple events. The term fire refugia is adapted from the broader concept of refugia as places providing environmental stability and facilitating species persistence as regional biotic and abiotic environments change (Keppel et al. 2012). An understanding of the processes and patterns of fire refugia formation, maintenance, and ecosystem role across multiple spatial and temporal scales is critical as we (society) strive(s) to meet landscape fire management and ecosystem restoration goals, now and into the future.

Fire refugia are features of forest burn mosaics, and topography appears to influence their location in some instances. Topography is a more stable factor than weather or fuels, the other two primary drivers of fire behavior (the fire behavior triangle; Rothermel 1972, 1991, Pyne et al. 1996). Topography's influence on spatial patterns in historical fire frequencies has been revealed in the tree ring record, reflecting the refugial concept, and this influence is stronger in complex terrain compared to gentler terrain (Beaty and Taylor 2001, Heyerdahl et al. 2001). Bottom-up topographic controls have been demonstrated as important determinants of overall patterns of contemporary burn severity (Holden et al. 2009, Taylor et al. 2009, Bradstock et al. 2010, Dillon et al. 2011, Birch et al. 2015, Kane et al. 2015). Predictability of fire refugia from topographic features of the landscape suggests the location of some refugia may have an enduring, deterministic component (Camp et al. 1997, Keeton and Franklin 2004, Wood et al. 2011, Leonard et al. 2014). In comparison to refugia associated with topography, unburned or low-severity patches that occur as a result of fire suppression activities and idiosyncratic variation in fire behavior or weather may be more random, that is, less predictable, in their spatial pattern. Fuel structure may provide predictable protection from burning, either in situ or to adjacent patches (Krawchuk et al. 2006, Burton et al. 2008), but unless topographically mediated, we consider refugia resulting from successional dynamics, demographic processes, and land management (e.g., forest thinning/harvest, prescribed burning) as ephemeral, and of a different class of features than topographic fire refugia. The focus of our research is in understanding topographic controls of contemporary fire refugia at a landscape scale.

Topography can offer protection from fire through the effects of terrain on climate and weather, vegetation, and as fuel breaks to fire spread. Differences in insolation and heat load due to slope aspect and inclination contribute important topoclimatic effects. In the northern hemisphere, moister and cooler north-facing forested slopes can dampen fire behavior (Rothermel et al. 1986); however, these slopes can burn with high severity (e.g., Beaty and Taylor 2001) when conditions are dry. In mountainous areas, places with a higher probability of cold-air pooling have been found to correlate to lower fire frequencies and severities (Wilkin et al. 2016). Forest types found in steep ravine bottoms are hypothesized to differ from adjacent slopes because of protection from fire and biophysical conditions that encourage more mesophilic species and accelerated succession (Romme and Knight 1981). Valley bottoms and basins are often characterized by finer-textured soils, temperature inversions, cold-air drainage and pooling, and increased soil moisture, resulting in vegetation composition and structure (Coop and

Givnish 2007) and topoclimate (Dobrowski 2011) that differs from surrounding areas. Landscape depressions, in general, confer higher soil and plant moisture either from hydrologic or from cold-air pooling and decreased evaporation, resulting in areas wetter and cooler than the surrounding landscape (Ouarmim et al. 2014). Surface and crown fire behavior is directly affected by topography through slope effects (Rothermel 1972, 1991), and fire spread often slows or stops at ridge tops when slope changes (e.g., Holsinger et al. 2016). Topographic fuel breaks (non-fuel) that impede fire spread can include rivers, lakes, and rock exposures (Heinselman 1973, Hellberg et al. 2004, Parisien et al. 2010) that may also provide landscape-level support for topographic fire refugia.

Topographic factors responsible for the formation of fire refugia have been described in the scientific literature across various geographies, but we lack a systematic, quantitative framework to synthesize empirical observations among locations. For example, in northeastern Spain, fire refugia in mixed conifer–oak forests were more common on north-facing slopes than south-facing ones, and undulating terrain had more unburned refugia than did steep or flat terrain (Román-Cuesta et al. 2009). In sub-boreal spruce forests in British Columbia, Canada, the amount of unburned forest associated with topographic draws was consistently high in burn mosaics of relatively flat and mildly undulating terrain (DeLong and Tanner 1996). The burn mosaic of a large fire that occurred in extreme conditions in mountainous temperate, broadleaf eucalypt forests of Victoria, Australia, showed few unburned patches (<1% of burned area) and suggested only deep gullies supported fire refugia (Leonard et al. 2014). Slope position, elevation, degree of slope, and aspect were found to create important settings for refugia in a mountainous, mixed conifer forest landscape in Washington, USA, though “no combinations of variables invariably predict their occurrence” (Camp et al. 1997).

Whether or not a fire refugium persists through a fire is likely a function of drought and weather conditions at play during the fire, as well as the degree of protection a particular location receives from its topographic context. For example, a re-assessment of the refugia locations identified by Camp et al. (1997) showed that subsequent fires burning under anomalously warm and dry conditions consumed most of the purported refugia (Bleeker 2015). Although fire refugia at these locations had persisted through previous fire events, they burned at high severity through the abundant fuels accumulated during the earlier refugial phase. Accordingly, Bleeker (2015) suggested these areas outgrew their refugial status and that topographically protected fire refugia are more likely to exist as a shifting mosaic of “long-term” refugia in this region rather than being truly persistent. Observations that patches of forest persist through fires burning under moderate meteorological conditions but may burn under extreme fire weather/dry conditions are consistent with proposals by Perera and Buse (2014), Ouarmim et al. (2015), and Berry et al. (2015). In particular, Berry et al. (2015) showed the mesic conditions in deeper gullies supported refugia under moderate weather conditions but when conditions were extreme, there were few unburned patches and their location was very hard to predict. Together, these findings suggest an important next step in advancing our understanding of topographic controls on fire refugia is to explicitly integrate information on topographic context and fire weather conditions into empirical study and to test these ideas across multiple fire landscapes.

Based on what we know of fire refugia from existing studies, we developed a set of hypotheses reflecting their occurrence and predictability in relation to coarse filter gradients of topographic complexity and fire weather conditions, and their interaction (Fig. 1). We hypothesize that landscapes with gentler terrain (Fig. 1: FLAT) are likely to burn more uniformly compared to those with higher complexity (RUGGED) due to the heterogeneity in topo-environment; in other words, topographic complexity confers predictability to fire refugia. We also hypothesize that relatively mild (BENIGN) fire weather conditions during burning results in extensive unburned or low burn severity areas generated by a mixture of topographic control and stochastic factors. Predictability of topographic refugia is low because these refugial patches are difficult to differentiate, statistically, from those formed by alternative, or more random, processes. Under MODERATE fire weather, we hypothesize the highest predictability of fire refugia because fire behavior will be most sensitive to topographic controls. In comparison, high or extreme fire weather conditions (HIGH)

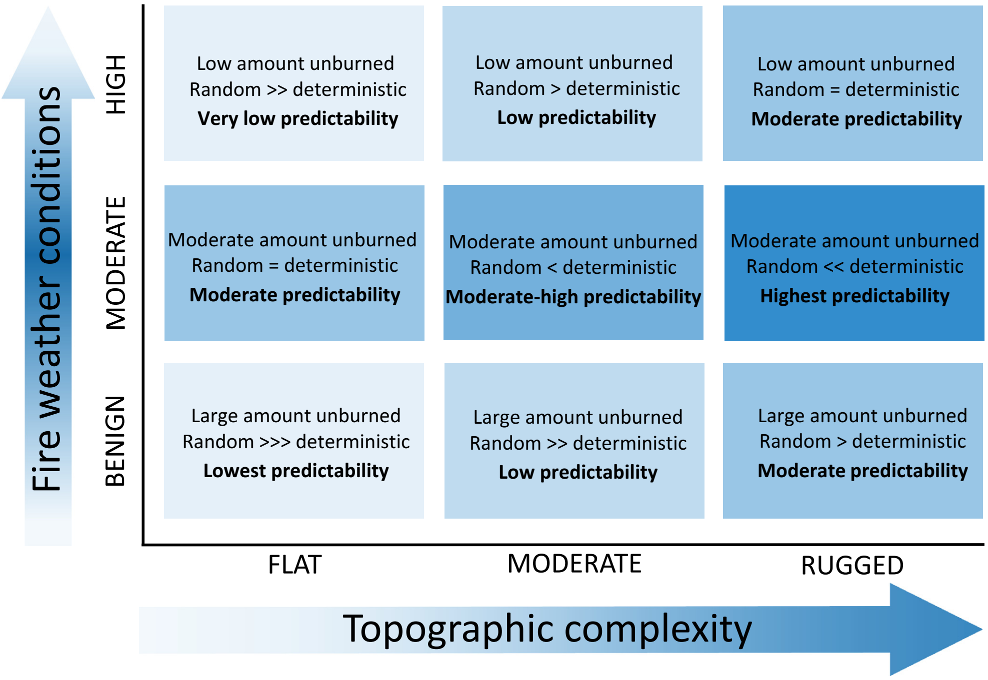

Fig. 1. Our conceptual framework for a gradient in predictability of topographic fire refugia. Darker blues indicate higher predictability; the relationship between refugium predictability and fire weather conditions is hump-shaped; topographic complexity is linearly increasing, together creating a 2-D predictability surface. Here, we generalize the predictability surface into a three-by-three matrix and provide expectations of (1) amount unburned/low severity in these environments, (2) the amount of unburned/low severity as random vs. deterministic, that is, topographic refugium, and (3) the relative predictability of refugia. Relative predictability is bolded and is a primary focus of our analyses. The strata of fire weather and topographic complexity introduced here are used explicitly in the text (e.g., FLAT-BENIGN, RUGGED-MODERATE, HIGH).

produce such intense and erratic fire behavior that protection conferred by topography may be overwhelmed. Accordingly, though we hypothesize topography to still play a role under HIGH conditions, topographic fire refugia will be rarer and more difficult to predict in these conditions than under MODERATE fire weather.

METHODS

We tested our hypotheses using an atlas of satellite-derived burn severity data from recent wildfires in moist conifer-dominated forested landscapes of western Canada. We developed a collection of nine statistical models of topographic fire refugia matching the categories in Fig. 1 at a spatial resolution of 30 m based on a suite of topography-related explanatory metrics. The collection of models allowed us to examine the relationship between refugia and topographic variables across a gradient of fire weather conditions at the time of burning and topographic complexity. We expected the ranked importance of individual topographic metrics to differ among models, but the shape of the relationship between refugia and topography to remain the same. As a preliminary field examination, we linked our model predictions with a small set of field observations from unburned/low-severity fire refugia within three of our study fires to characterize forest structure and evidence of recent or historical fire at these sites.

Study area

Our study included seven wildfires that burned between 2001 and 2014 within the Western Cordillera ecoregion of the Northwestern Forested Mountains of the Ecological Regions of North America (CEC 1997). The fires burned under a variety of fire weather conditions and through landscapes with a range of topographic complexity

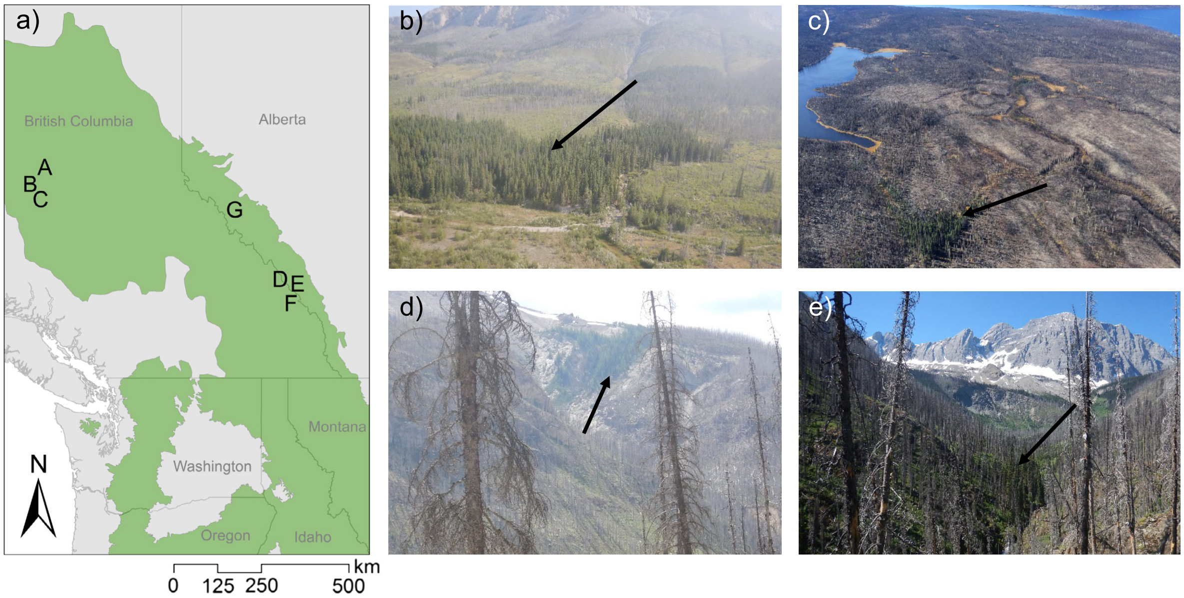

Fig. 2. (a) Seven study fires within the Western Cordillera ecoregion, shown in green. The Binta (A), Chelaslie (B), and Entiako (C) fires burned through landscapes in the northwestern portion of the ecoregion, and Tokumm (D), Mount Shanks (E), Octopus (F), and Syncline (G) fires burned in the east. Photographs show study fires (b–e) that burned through a range of topographic and meteorological environments; potential topographic fire refugia are indicated by black arrows. Relatively FLAT terrain is illustrated in panels (b) and (c), and more RUGGED terrain in panels (d) and (e). Photograph credits: Ellen Whitman and Stuart Sinclair.

(Fig. 2). Whitman et al. (2015) describe the contemporary climate space and fire regimes of the region. The study fires varied in size, year of burn, proportion of unburned/low-severity area, environmental context, and management history (Table 1). Depending on the fire, some or all of the area burned occurred without fire suppression either because of management intent (e.g., limited suppression, modified response) or because the size and conditions did not allow suppression action.

The Binta, Chelaslie, and Entiako fires in the northwest portion of the ecoregion burned through sub-boreal forests dominated by lodgepole pine, *Pinus contorta* var. *latifolia*, in gentle terrain punctuated with a few prominent topographic rises

Table 1. Key attributes and descriptions of the seven fires used in models of topographic fire refugia.

Name	Year	Size (ha)	Unburned	Terrain (m)	FWI	Elevation (m)	Land	FireM
Binta	2010	37 839	0.46	0–1036	0–60.9	801–1439	M	Full
Chelaslie	2014	129 284	0.16	0–1043	3–48.3	854–1816	PP	Modified
Entiako	2012	7 249	0.40	0–412	15.1–38.2	916–1298	PP	Modified
Tokumm	2003	16 137	0.12	4–2063	0.2–43.7	1257–2640	NP	Full
Octopus	2012	999	0.02	86–112	1.3–40.2	1374–2354	NP	Modified
Mount Shanks	2001	3 212	0.16	4–1229	0.9–39.6	1233–2338	NP	Full
Syncline	2003	26 861	0.17	0–1641	0–60.3	1004–2245	NP	Modified

Notes: "Unburned" is the proportion of burned area classified as unburned or burned at low severity using the dNBR metric. "Terrain," "Fire Weather Index (FWI)," and "Elevation" are ranges in the values of terrain ruggedness, daily FWI, and elevation (m) for each fire. "Land" indicates the land management for a fire, where PP is a provincial park (British Columbia), NP is a national park (Parks Canada), and M is forest under harvest tenure. "FireM" indicates the level of fire management, where "Modified" response indicates limited or no suppression over the majority of the fire and "Full" indicates full response within some duration of the fire. The Syncline fire was ignited as a prescribed burn and later escaped prescription and so was considered an unmanaged wildfire.

(Fig. 2; sub-boreal spruce and sub-boreal pine spruce biogeoclimatic zones described in Meidinger and Pojar 1991). These forests experience fires dominated by moderate and high severity, with a historical fire cycle of approximately 100–400 yr (Wong et al. 2004 and citations therein). This portion of the region currently has high proportions of lodgepole pine killed by the mountain pine beetle (*Dendroctonus ponderosae*), and landscapes were in the gray phase of post-outbreak structure at the time of fire.

The Tokumm, Octopus, Mount Shanks, and Syncline fires in the eastern portion of the ecoregion burned through forests dominated by Engelmann spruce (*Picea engelmannii*), subalpine fir (*Abies lasiocarpa*), and lodgepole pine in rugged, mountainous terrain that included areas with steep slopes and rock outcrops, as well as gentler slopes and valley bottoms (Meidinger and Pojar 1991). These forests experience relatively infrequent fires at higher elevations but more frequent, mixed-severity fire at drier, lower elevation sites that together contribute to a fire cycle of approximately 45–270 yr (Wong et al. 2004 and citations therein).

Data

Each cell (i.e., pixel) within the burned areas was categorized to one of nine model stratification units (Fig. 1) based on two coarse-scale filters: topographic complexity and fire weather. Topographic complexity was quantified as terrain ruggedness calculated from the BC Gridded DEM Product (Province of British Columbia 2002) and Advanced Spaceborne Thermal Emission and Reflection Radiometer Global Digital Elevation Map 2 (ASTER GDEM Validation Team 2011). Values were assigned to each 30-m cell estimated as the mean of the absolute differences in elevation between the cell and surrounding cells in its approximately 7-ha neighborhood. We assigned each cell as FLAT (≤200 m), MODERATE (>200 m to ≤400 m), or RUGGED (>400 m) using heuristic breakpoints developed based on orthoimagery. Daily fire weather was assigned to each 30-m cell using spatial models for day of burn estimated from MODIS hotspot data (NASA MCD14ML product, Collection 5) following methods in Parks (2014) linked to daily weather station measurements from the nearest Environment Canada or Parks Canada weather station. We used the calculated noon hour values of the Fire Weather Index (FWI) from the Canadian Forest Fire Weather Index System (Van Wagner 1987) as a metric of fire weather conditions with levels of BENIGN (FWI 0–13), MODERATE (FWI >13–29), or HIGH (FWI >29) assigned based on breakpoints following Alexander and De Groot (1988). Though it would be ideal to have location-specific fire weather observations at fine spatial and temporal resolution and observations of fire behavior, the FWI values provide the best available estimate for burning conditions at these fires. Fires contained samples from all nine stratification units with the exception of the Entiako fire, which contained five classes. For efficiency, we refer to classes of environmental settings using topography or weather labels, or a combination thereof, for example, FLAT, FLAT-BENIGN, MODERATE-MODERATE, RUGGED, HIGH.

Fire refugia were mapped using 30-m grid spacing Landsat TM and ETM change detection images classifying the differenced Normalized Burn Ratio, dNBR, developed using methods in Eidenshink et al. (2007). We derived the binary response variable for our models that represented unburned and lightly burned areas within burn mosaics, with $-200 \leq$ dNBR $\leq 200 = 1$ and all other values = 0.

A set of eight terrain metrics were used as explanatory variables and derived from the 30-m digital elevation model. We calculated the following: catchment area (m^2); catchment flowpath length (m); catchment slope (radians); local aspect (radians); local slope (radians); relative position (0–1: lower to higher elevation within a 500 m radius window); and two indices based on catchment area and slope: topographic wetness index (~1 to 12, a metric of hydrologic pooling, increases with potential soil wetness), and topographic convergence index (~6 to 20, a metric of cold-air drainage, increases with potential for cold-air pooling). Local metrics were calculated using a 3×3 window. Alternative metrics exist to quantify topographic variability but the suite used here captures basic elements of geomorphology for our analyses. All topographic metrics were calculated using the RSAGA (Brenning and Bangs 2016) and raster (Hijmans 2015) packages.

Models

We modeled the probability of refugium occurrence as a function of topographic variables for each of nine models that acted to stratify for differences in terrain ruggedness and fire weather conditions. We developed a boosted regression tree model for each of the nine strata using a binary response and the eight terrain metrics. All of the analyses were accomplished in the R statistical environment (R Core Team 2015). Boosted regression trees were fit using the gbm (Ridgeway 2015) and dismo (Hijmans et al. 2016) packages. Use of random forests or other algorithms would be possible alternatives, but the comparison and integration of evidence from multiple algorithms were beyond the scope of our investigation.

Models were fit to data using a random sample of locations. For each model, we ran a cross-validated boosted regression tree, parameterized to obtain at least 1000 trees, include fitting interactions, and using random subsets of the data (learning rate = 0.001, tree complexity = 5, bag fraction = 0.5).

We evaluated the models based on the receiver operator characteristic area under the curve (ROC-AUC) from the cross-validation samples. The ROC-AUC assesses the sensitivity and specificity of our model, providing a synthetic metric that integrates the model's ability to correctly predict both the presence and absence of refugia; an ideal model would give a ROC-AUC value of 1.0, whereas a model with no predictive ability, that is, random, would have a value of 0.5. Here, we consider values >0.6 to ≤0.7 as fair, >0.7 to ≤0.8 as good, >0.8 to ≤0.9 as very good, and >0.9 as excellent.

The relative influence of explanatory variables and shapes of the relationships were used to interpret the role of topography in supporting fire refugia. The relative influence of explanatory variables was calculated using the metric outlined by Friedman (2001), with a value scaled to sum to 100 and higher numbers representing a stronger influence. We then used a simple ranking system to assess the overall relative influence of each topographic variable. For each model, the top-ranked variable received a value of eight and the lowest-ranked variable received a value of one. The overall rank for each variable was calculated as the sum of ranks from each model. We looked for patterns among models that would suggest generalizable environments where topographic variables ranked higher or lower in their capacity to predict the occurrence of unburned/low severity patches. We reported the deviance explained of the training datasets as context for the relative influence metrics. We plotted marginal response curves to examine and compare the shapes of relationships estimated by the models.

We used the nine models to generate mapped surfaces of the expected probabilities of refugia for each fire, and three fire weather scenarios. For each fire, mapped values are mosaics of probabilities generated from each of the models, populated according the cell's terrain complexity and FWI. We developed three fire weather scenarios to ask how the probability of a refugium might change if a landscape were to burn under alternative fire weather conditions. For each fire weather scenario (BENIGN, MODERATE, HIGH), individual pixels retained their original classification for terrain, and expected values were generated from models for the different fire weather conditions. Data predictions and raster-based analyses were completed using the raster (Hijmans 2015) package. Code and data are for all analyses are available at https://www.sciencebase.gov/catalog/item/5810e721e4b0f497e797a5b5.

Field characterization of fire refugia

Field data were collected from 15 plots from three of our study fires within the Canadian Mountain Parks in the summer of 2014 as a preliminary characterization of the composition of refugia and to acquire evidence of fire (recent and/or historical) at these sites. Five plots were visited at Syncline, six at Tokumm, and four at Mount Shanks. Locations were selected using a combination of a priori reconnaissance based on dNBR mapping to identify unburned/low-severity refugia, and final selection in the field that was constrained by hiking access. Plots were identified without influence from the predictive models. At each 30 m diameter sample plot, we collected field data related to topographic position and context, live and dead elements of stand structure, and evidence of recent and historical fire.

We classified each field site according to the expected values from our statistical models and examined the relationship between our model values and a suite of field characteristics: the duff depth (cm), and diameter at breast height (cm) of the largest tree in each study plot. A historical fire evidence index was computed as sum of presence/absence of soil charcoal (1/0), fire scars (1/0), charred snags (1/0). The relationship between each of the field characteristics and the predicted values from our statistical models served as an assessment of whether refugia locations with higher values from our topographic models exhibited different characteristics from those with lower values.

RESULTS

The ROC-AUC, our metric of each model's ability to predict unburned/low-severity patches based on topographic metrics, ranged from 0.63 to 0.77 (Fig. 3). The highest ROC-AUC values occurred under MODERATE and RUGGED terrain and BENIGN and MODERATE fire weather. The ROC-AUC values suggest we have relatively poor capacity to discriminate topographic fire refugia in FLATter terrain and HIGH fire weather severity (values between 0.63 and 0.68), but comparatively good capacity otherwise (values of 0.72–0.77). The proportion of unburned/low-severity area within each of our strata varied from 0.17 to 0.36 (Fig. 3) and generally followed the rank order we proposed in our conceptual model with more unburned/low severity area in strata classified as BENIGN fire weather and least in HIGH fire weather (Fig. 1). The exception was in RUGGED terrain where proportion unburned/low severity was relatively high in HIGH fire weather (Fig. 3).

Our collection of models illustrated variation in amount of variability explained and the relative importance of individual variables, but relatively similar shapes of the response curves. The percent deviance explained by topographic features ranged from 4% (FLAT-HIGH) to 50% (RUGGED-BENIGN; Table 2). The overall ranked importance of variables from highest to lowest was as follows: catchment slope, local aspect, relative position, topographic wetness, topographic convergence, local slope, catchment flowpath length, and catchment area (Table 2; Fig. 4). Since catchment area and flowpath length ranked poorly across the models, they are not discussed further.

Catchment slope was the most important overall discriminant of topographic fire refugia and ranked in the top three variables for eight of nine models (Table 2); the concave shape of the relationship was consistent among all models (Fig. 4a). Local aspect was most important in more RUGGED terrain (Fig. 4b), and the shape of this relationship varied somewhat among models. Relative position was generally important in predicting fire refugia, ranking in the top three variables for five models. Refugia were more likely to occur either within depressions in the landscape or on convex surfaces, and this pattern seemed to hold for all models (Fig. 4c). Topographic wetness was most important in FLAT landscapes, with

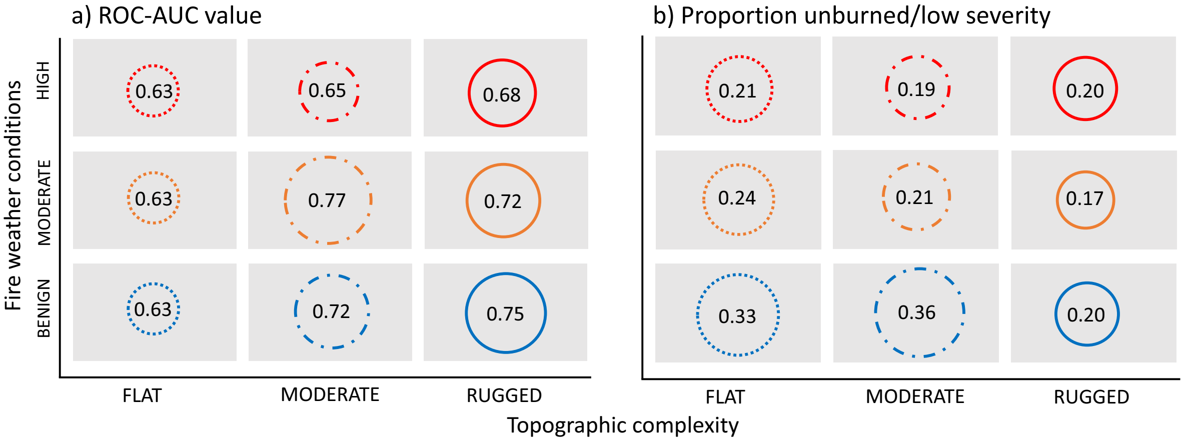

Fig. 3. (a) The receiver operator characteristic area under the curve (ROC-AUC) values and (b) proportion of pixels classified as unburned/low severity within the sample for each of the nine models considered in our conceptual framework. The size of the circle is scaled to the value of the ROC-AUC (in panel a) or proportion (in panel b) it subscribes. The color and line type correspond to the modeled relationships illustrated in Fig. 4.

Table 2. The overall deviance explained and relative influence of each terrain metric for each of nine boosted regression tree models.

Model	Expl (%)	V1	V2	V3	V4	V5	V6	V7	V8
FLAT-BENIGN	12	Slope 20.5	Wetness 16.3	Converg 15.7	Flowpath 12.2	Aspect 11.4	Rel. Pos. 11.0	L. Slope 7.8	C. Area 5.1
FLAT-MODERATE	6	Wetness 24.1	Rel. Pos. 22.3	Slope 14.5	Aspect 12.6	Converg 11.1	Flowpath 5.6	L. Slope 5.3	C. Area 4.5
FLAT-HIGH	4	Wetness 32.1	Rel. Pos. 22.7	Slope 13.5	Converg 12.6	L. Slope 9.3	Flowpath 4.3	Aspect 3.5	C. Area 2.0
MODERATE-BENIGN	29	Aspect 22.0	Wetness 20.6	Slope 17.5	Converg 10.3	Rel. Pos. 8.5	L. Slope 7.5	C. Area 7.2	Flowpath 6.4
MODERATE-MODERATE	29	Slope 24.3	Aspect 22.6	Rel. Pos. 12.5	L. Slope 11.8	Wetness 8.9	Converg 8.5	Flowpath 6.4	C. Area 5.0
MODERATE-HIGH	7	Aspect 33.0	Slope 22.0	Wetness 12.0	Rel. Pos. 11.0	Converg 7.2	Flowpath 5.0	L. Slope 5.0	C. Area 4.8
RUGGED-BENIGN	50	Aspect 21	Rel. Pos. 17.2	Converg 17.0	Slope 13.8	C. Area 11.9	L. Slope 8.6	Wetness 6.6	Flowpath 3.9
RUGGED-MODERATE	24	Slope 26.0	L. Slope 24.5	Rel. Pos. 17.1	Aspect 10.1	Wetness 8.0	Flowpath 5.6	C. Area 5.2	Converg 3.5
RUGGED-HIGH	11	L. Slope 24.4	Slope 19.9	Aspect 19.3	Rel. Pos. 11.5	Converg 9.7	Flowpath 5.9	Wetness 5.1	C. Area 4.2

Notes: Models are labeled using the stratum identifier of topographic complexity and fire weather; for example, FLAT-BENIGN indicates gentle terrain and low fire weather conditions. "Expl" is the percent of variability explained by all variables in the model, calculated from the training data. The relative influence of each terrain variable is a metric scaled to 100, here ranked from highest (V1) to lowest (V8). Explanatory variables include the following: Slope: catchment slope; Wetness: topographic wetness; Converg: topographic convergence; Flowpath: catchment flowpath length; Aspect: local aspect; Rel. Pos.: relative position; L. Slope: local slope; C. Area: catchment area.

higher probability of refugia in wetter areas than in drier ones (Fig. 4d). The probability of refugia was generally a concave response associated with topographic convergence (Fig. 4e), indicating areas with lowest and highest likelihood for cold-air pooling support fire refugia. Local slope ranked quite low globally, but ranked highly in its discrimination of refugia in RUGGED terrain under MODERATE and HIGH fire weather (Fig. 4f). The shape of the relationship between refugia and local slope was generally consistent among models and with similar form to that estimated for catchment slope.

For the fire weather scenarios, maps generated from the Mount Shanks fire illustrate expected probability of refugia under observed conditions (Fig. 5a, e) and three classes of fire weather conditions (Fig. 5b–d, f–h). We used the three weather models to illustrate expected probability of refugia if the entire landscape were to have burned under BENIGN (Fig. 5b, f), MODERATE (Fig. 5c, g), or HIGH fire weather (Fig. 5d, h) conditions. A complete set of fire weather scenarios for all fires is included in Appendix S1.

Field data were sampled from a broad range of site types (Table 3) and illustrated a range of compositional and structural diversity in fire refugia. We assigned a probability of refugium to each field plot using the average value of the modeled probability of refugium within a 100 m radius of plot center. The spatial averaging was used to conservatively integrate any spatial error. Values for the predicted probability of refugia ranged between 0.15 and 0.32 (Table 3). Field plots occurred on a full range of mesoslope positions (eight positions following Luttmerding et al. 1990), but the highest predicted refugia values, according to our models, fell in locations described as crests, gullies, or flat. Among the samples, boxplot analyses showed the median expected probability of topographic refugium occurrence was highest in areas with a low historic fire evidence index (Fig. 6). The relationship between the probability of refugium occurrence and duff depth was not statistically significant (Pearson correlation = −0.14, df = 13, $P = 0.63$), nor was the relationship with size of the largest tree in the plot (Pearson correlation = +0.17, df = 13, $P = 0.54$).

DISCUSSION

Our conceptual framework reveals the overall predictability of contemporary fire refugia varies according to terrain ruggedness and fire weather

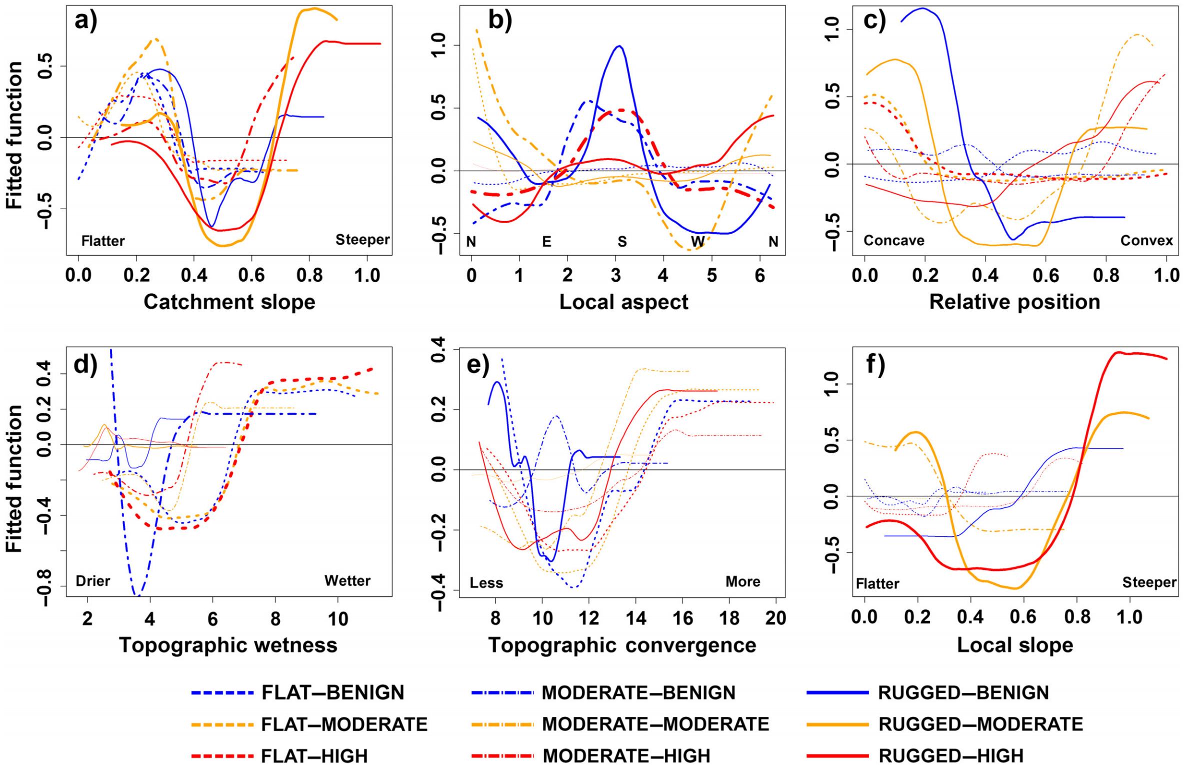

Fig. 4. The shape of topographic relationships predicting the probability of refugia estimated from boosted regression trees, shown using marginal partial dependence plots. The top six explanatory variables are shown in rank order of overall importance from highest to lowest and include (a) catchment slope, (b) local aspect, (c) relative position, (d) topographic wetness, (e) topographic convergence, and (f) local slope. The legend at bottom describes symbology used to illustrate outcomes from each of the nine models. Red symbols indicate HIGH fire weather, orange symbols indicate MODERATE, and blue symbols indicate BENIGN fire weather conditions. The dashed symbols indicate FLAT terrain, dashed dots indicate MODERATE, and solid lines indicate RUGGED terrain. For example, the shape of the response curve for RUGGED terrain and HIGH fire weather conditions (RUGGED-HIGH) is shown as a solid red line for each of the topographic variables (a–f). The width of lines on the plots varies according to the relative influence of each variable in each model (Table 2) so that thicker lines show when a variable was more important. The range of the *y*-axis differs among the panels to aid in viewing the shapes of response curves.

conditions, and the relative importance of topographic factors differs among these broad classes of environments. The study helps to unify a growing collection of observations of when and where landscape-scale topographic fire refugia occur, and advances our understanding of environmental characteristics associated with spatial and temporal patterns in fire mosaics. We use a probabilistic approach to identify topographic locations with higher chances of supporting fire refugia, emphasizing these locations may or may not persist through a particular fire. Importantly, our fire weather scenario analyses illustrate how the probability of occurrence of a refugium varies under different fire weather conditions, with generally lower probabilities under more extreme conditions. This work corroborates previous studies of topographic fire refugia in both the northern and southern hemispheres (e.g., Camp et al. 1997, Wood et al. 2011, Berry et al. 2015) but adds an important new layer of understanding for how environmental context—here topographic and meteorological conditions—affects the abundance, predictability, and spatial pattern of fire refugia.

As we hypothesized, the predictability of refugia was lowest under higher fire weather conditions

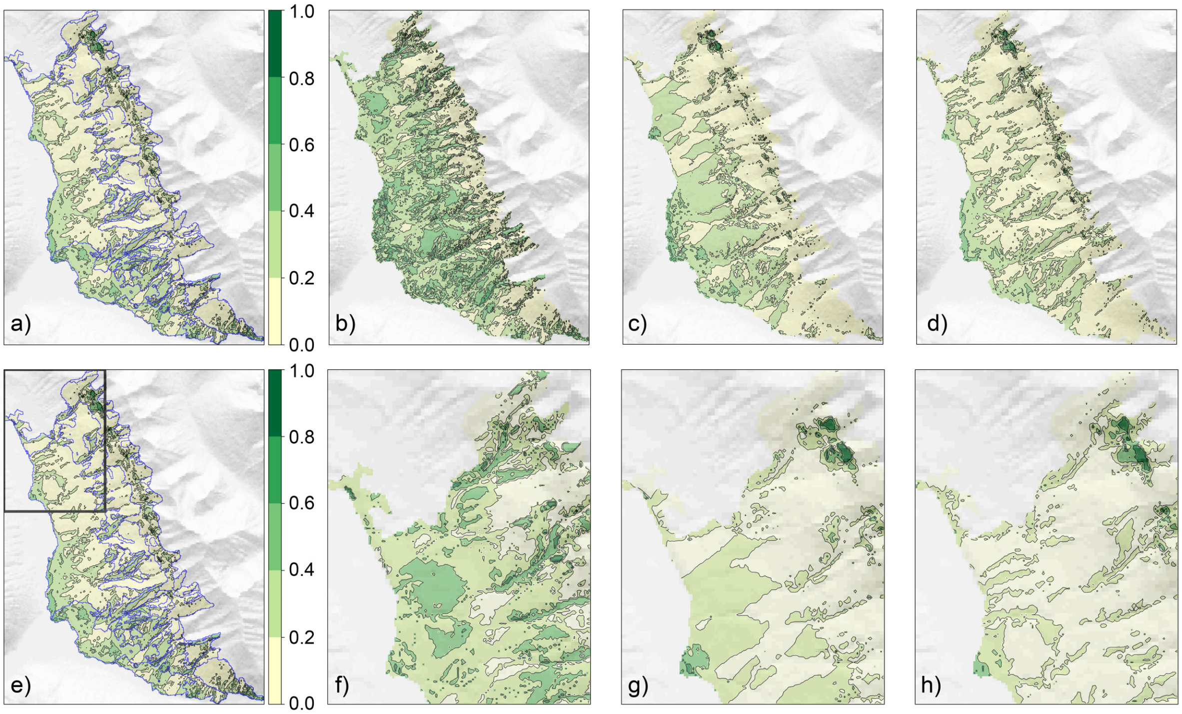

Fig. 5. The expected probability of topographic refugium occurrence estimated from boosted regression trees for the Mount Shanks fire in Kootenay National Park. (a) The probability in occurrence across the entire burn area based on a mosaic of the nine different models, populated depending on the weather and terrain conditions associated with each 30-m cell. Blue lines illustrate the division of burned area into the nine classes of weather and terrain for model development. The model predictions illustrated in (b) through (d) show the spatial pattern of refugium probability as we move from a model scenario based entirely on (a) BENIGN fire weather conditions, to the expected probability for the same area based under (c) MODERATE fire weather, and (d) HIGH fire weather conditions. In general, the models show a reduction in the probability of refugia under higher fire weather conditions. Panel (e) illustrates a focal area chosen to highlight these changes in the probability of topographic refugium under different weather conditions, as seen in (f) BENIGN, (g) MODERATE, and (h) HIGH fire weather.

and increased with topographic complexity. For MODERATE and RUGGED terrain, we saw highest predictability of refugia under the BENIGN and MODERATE weather conditions that then dropped under HIGH meteorological conditions. Predictability was highest under MODERATE fire weather conditions and MODERATE terrain ruggedness, suggesting a sweet spot where refugia are most sensitive to topography. Given the highest ROC-AUC metric value we obtained was 0.77, there remain unrepresented limiting factors to the predictability of refugia, either through topography or other processes. This is not surprising given we did not expect topography to predict all unburned/low severity areas. We hypothesized refugia would be least predictable in flatter landscape settings, and this held true. However, the predictability of fire refugia did not vary with weather conditions in FLAT terrain and this was counter to our hypothesis—we observed the lowest values of our ROC-AUC metric (0.63) across all fire weather conditions. Our fire weather scenario mapping showed discernible decreases in the probability of refugia with increasing fire weather conditions in FLATter terrain (as well as MODERATE and RUGGED terrain) illustrating that while the overall predictability of refugia may not vary with fire weather, their likelihood of occurrence does. As well, the proportion of area that remained unburned/low severity in each fire was greatest

Table 3. Key attributes from 15 field plots in the Tokumm, Syncline, and Shanks fires.

Stratum	P_T	Sl	Asp	Fire	Duff (cm)	dbh (mm)	CBH (m)	Big snag	C	Pos	Elev (m)	Common
FLAT-MODERATE	0.15	9	245	1,0,1	15.0	282	4.75	0	1	Mid	1386	*Pc*, *Pe*
MODERATE-HIGH	0.16	35	80	0,1,1	7.5	243	8.13	0	0	Mid	1703	*Pc*, *Al*
MODERATE-HIGH	0.17	16	2	0,0,1	1.0	513	2.75	0	0	Mid	1121	*Pe*
MODERATE-HIGH	0.17	6	180	0,0,0	6.0	355	8.25	0	0	Low	1044	*Pe*
FLAT-HIGH	0.18	14	220	0,1,0	3.0	513	9.5	0	1	Low	1312	*Pe*, *Bp*, *Pm*
FLAT-MODERATE	0.19	9	185	1,0,0	2.0	328	14.25	0	0	Low	1303	*Pm*, *Pe*
MODERATE-HIGH	0.21	8	335	0,1,1	1.0	898	17.5	0	4	Toe	1494	*Pe*, *Al*
FLAT-HIGH	0.24	38	319	0,0,0	5.0	248	1.5	0	0	Mid	1569	*Pe*, *Al*
MODERATE-HIGH	0.25	17	131	0,0,0	0.5	905	7.5	3	2	Toe	1671	*Pe*, *Al*
FLAT-HIGH	0.26	8	180	0,0,0	10.0	516	6.5	0	0	Toe	1516	*Al*, *Pe*
FLAT-MODERATE	0.28	5	218	0,0,0	4.0	581	12.25	1	2	Level	1267	*Pe*, *Al*
FLAT-MODERATE	0.31	1	240	0,0,1	3.5	265	3.13	0	2	Level	1265	*Pe*
FLAT-HIGH	0.31	Flat	Flat	0,0,0	1.0	467	4.45	0	1	Gully	1023	*Pe*, *S*
FLAT-MODERATE	0.32	Flat	Flat	0,0,0	5.0	545	13.15	0	0	Gully	1039	*Pe*, *Pt*
RUGGED-HIGH	0.32	12	325	0,0,1	10.0	293	8.3	0	0	Crest	1239	*Pe*

Notes: "Stratum" indicates the ruggedness-fire weather combination in which the plot was located. Plots are ordered to an increasing probability of refugia (P_T), the average probability of refugium within a 100 m radius of plot center. "Sl" is slope angle in degrees; "Asp" is slope aspect in degrees; "Fire" is a three-value combination scored as 1 for presence of each of soil charcoal, fire scar, or charred snags within each plot; "Duff" is the mean depth of duff based on four samples one in each quadrat of the plot; "dbh" is diameter at breast height of the largest tree in each plot; "CBH" is average canopy base height from the largest trees, one in each quadrat of the plot; "Big snag" is the number of dead and standing trees >30 cm diameter; "C" is coarse woody debris as the number of large (>30 cm diameter) and rotten pieces of coarse woody debris intersecting 30-m transect across each plot; "Pos" is mesoslope position, following Luttmerding et al. (1990); "Elev" is elevation of plot; "Common" indicates the most common species of trees in the canopy and subcanopy of each plot, labeled with abbreviations: *Al*, *Abies lasiocarpa; Pe*, *Picea engelmanii; Pc*, *Pinus contorta; Pt*, *Populus tremuloides; S*, *Salix* sp.; *Bp*, *Betula papyrifera; Pm*, *Pseudotsuga menziesii*.

under BENIGN weather conditions. Kolden et al. (2015) showed that coarser-scaled climate metrics can explain some variability in spatial patterning of fire refugia as a whole, but did not examine weather and topographic distinctions we assess here. Our results, derived from information pooled from multiple fires, provide evidence of sensitivity of refugia to daily variability in fire weather. An important implication of the weather signal is that if topography is systematically less able to support refugia under more extreme conditions, the occurrence of topographic fire refugia may diminish for many parts of western North America in the future, where more extreme fire weather is projected (Flannigan et al. 2009, Wang et al. 2015). The ecological consequences of fewer, smaller, and/or more isolated fire refugia under changing climate are unclear and warrant further study of the structure of fire refugia and their function as components of resilient ecosystems.

Our analyses provide insight into how enduring topographic features might support refugia in Western Cordilleran forest ecosystems. Catchment slope was important in all models, and the shape of the response curve was always concave suggesting higher probability of refugia on flatter and steeper angles, regardless of the general terrain complexity of the surrounding landscape. Both Wood et al. (2011) and Bradstock et al. (2010) found steep slopes and valleys supported low-severity or unburned refugia, though Román-Cuesta et al. (2009) determined likelihood of refugia increased on intermediate slopes. Steeper slopes might be associated with cliffs, rock outcrops, and scree or gravel slopes that are common in mountain environments and would provide fuel breaks, or breaks in topography where fire approaches up-hill on one side but is less likely to burn down the adjoining slope. Our analyses also showed refugia were more common at low angles of catchment slope, potentially associated with valley bottoms. In certain biogeoclimatic regions, flats/valley bottoms might have higher fuel moisture and/or confer protection from wind (Bradstock et al. 2010), with vegetation (fuel structure and abundance) that usually differs from higher and steeper locations (e.g., Peet 2000). Fire burning on low local slope angles might have slower rates of fire spread, lower intensities (Pyne et al. 1996), and high sensitivity to protective

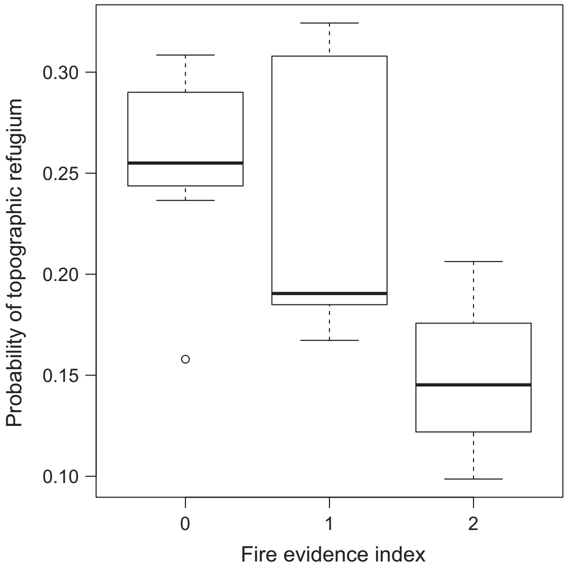

Fig. 6. Box-and-whisker plot showing the distribution in values from our topographic fire refugia probability models for field plots, classified according to a fire evidence index. A value of zero indicates no evidence of historical fire within sample plots, based on soil charcoal, charred trees, or charred snags. A value of one indicates evidence from one of the three criteria; two indicates evidence from two of the three criteria; there were no values of three. Overall, locations with a higher probability associated with topographic setting had a lower historical fire evidence index.

topographic features. Our local slope metric was also important in RUGGED terrain, exhibiting the same response curve as catchment slope.

Slope aspect was important in more complex terrain. Fire refugia were more likely on north-facing slopes under MODERATE fire weather. As northern aspects have relatively low solar insolation and heat loading, these locations may remain unburned due to generally cooler and moister conditions, and long duration of the snowpack on these facets. Cooler aspects have been shown to be good predictors of fire refugia in Tasmanian rainforests (Wood et al. 2011) and western conifer forests of Washington (Camp et al. 1997). However, these north slopes can burn with high severity under warm and dry conditions (e.g., Beaty and Taylor 2001, Bleeker 2015). Counter to expectations, refugia were more likely on south-facing slopes in low (BENIGN) fire weather conditions in MODERATE and RUGGED terrain and in HIGH fire weather conditions in MODERATE terrain. Southern exposures in the northern hemisphere are typically considered warmer and drier, and more flammable. A possible explanation for these counterintuitive findings relates to vegetation on these southern exposures: Though our study focused on forested ecosystems, there are meadows and openings of herbaceous vegetation within these forest mosaics. Drier-warmer south-facing slopes in rugged terrain are more likely to support grassy vegetation than north-facing slopes. Grasses can recover quickly (<1 yr) after fire so that our dNBR metric would identify the area as unburned. We did not comprehensively assess the composition of areas identified as fire refugia in our analyses. We expect these locations include a broad diversity in form and function ranging from old-growth forest to alpine meadows, and further investigation is required to examine these structures more closely.

The relative position metric revealed that refugia were supported both in concavities (depressions, valleys, gullies) and on convexities (hilltops, ridges). In RUGGED terrain, the probability of refugia was particularly high in depressions but only under low and moderate fire weather conditions, a pattern that follows Berry et al.'s (2015) findings in Australian landscapes. Similar to the effects described with aspect and slope, above, vegetation and fuels in these cool, mesic settings may have reduced flammability in comparison with the surrounding landscape, but as weather conditions become more severe, this heterogeneity in moisture levels is lost. At HIGH FWI values, we were likely to see refugia on convexities, and we suspect this response might be related to fuel breaks often associated with steeper slopes. The importance of gullies or depressions/valleys more generally as protection from fire (Romme and Knight 1981, Robinson et al. 2013, Leonard et al. 2014) and for preserving complex forest structure (Collins et al. 2012) has been well documented. Our observation of fire refugia on hilltop convexities, however, seems to be somewhat unique and may be a function of the terrain, or perhaps an interplay with active avalanche regimes that generate systematic fuel breaks (Suffling 1993) in the Cordilleran mountains of our study region.

Topographic wetness and topographic convergence ranked relatively low in our models overall, but still contributed interpretable and logical information about the ways in which topography may affect the patchwork of fire refugia across forest landscapes. The topographic wetness index describes the relative potential for hydrologic pooling, and this factor was important in FLAT and MODERATE complexity classes. As described in relation to other topographic factors, above, the importance of the wetness index may reflect the high moisture content in landscape depressions that can temper fire behavior. Topographic convergence is a metric of cold air drainage and pooling that also dampens fire behavior (Wilkin et al. 2016), and we generally saw a high probability of refugia at higher values, regardless of terrain ruggedness or fire weather.

Field data collections suggested our models have captured relevant attributes of the landscape related to the likelihood of remaining unburned, though these pilot data contain a small sample size. In addition to ground-truthing the satellite burn severity information, the field data provided a preliminary test of our topographic refugia models. The estimated probability of fire refugia occurrence was positively correlated to variation in field measures of forest "oldness." For example, higher probabilities were associated with less or no evidence of historical fire and larger trees (though not statistically significant), the latter potentially indicative of longer time periods of biomass accumulation uninterrupted by wildfire disturbance. One might expect that evidence for longer-term persistence, and through multiple fires, would be found in areas identified by our models as having the highest probability of refugium occurrence under the HIGH fire weather conditions scenario.

Advancing our understanding of the structure and role of fire refugia in burn mosaics will further our knowledge of the importance of ecosystem heterogeneity contributed by all parts of the burn mosaic as components of fire-adapted ecosystems. Some species are dependent on high severity, stand-replacing fire for their persistence. For example, in our study system, lodgepole pine is highly serotinous with cone opening cued by fire (Lotan and Perry 1983), and the black-backed woodpecker, *Picoides arcticus*, relies on the larvae of wood-boring beetles for food that proliferate in fire-killed trees (Rota et al. 2015). As a complement, fire refugia provide important "bridging habitat" (DeLong and Kessler 2000) for a wide range of species during the passage of fire and post-fire (Robinson et al. 2013, Perera and Buse 2014). The degree to which particular fire refugia are indeed refuges, for what taxa, and over what geographic extent, is a focus for the next stages of our research. For example, at a landscape scale, distance to unburned forest canopy has been repeatedly shown to be an important attribute of post-fire establishment of trees (Turner and Dale 1998, Coop et al. 2010, Harvey et al. 2016). Whether a fire refugium is large or small, its composition, configuration, and the nature of the surrounding landscape mosaic will all likely affect each refugium's function in the ecosystem. We posit that the degree to which a refugium is topographically entrained will also be important to its ecological form and function.

Our approach to quantifying fire refugia relied on key assumptions from the data. The 30-m grid spacing of our data captures landscape-scale refugia, but likely did not capture smaller, but potentially ecologically important refugia. Further investigations using high-resolution images such as orthorectified aerial photographs or lidar, in conjunction with field investigations, would provide additional empirical data on the composition and configuration of refugia at finer spatial resolutions. Also, the satellite imagery used to calculate burn severity cannot robustly detect changes below the canopy of trees (Kolden et al. 2012), so places we classified as refugia may have experienced surface, or subcanopy fire. Our use of a range of burn severity values from −200 to 200 dNBR was intended to acknowledge such limitations of the satellite imagery, and we explicitly defined our fire refugia as unburned or burned at low severity. The topographic signal and ecological implication of truly unburned patches could be very different from those that burned at low severity, but our approach did not explore this. Likewise, our topographic metrics focused on terrain features derived from digital elevation models and may not have captured all of the relevant topographic factors in these landscapes, particularly in flatter landscapes where refugia may be more closely tied to physiognomic fuel breaks such as streams and lakes (Heinselman 1973, Hellberg et al. 2004, Nielsen et al. 2016). Although we used the best available data from noon-time records at nearby weather stations, some burn conditions were certainly subject to inaccuracy.

The fire weather metrics we used here does not capture details of airflow and how it interacts with topography that is likely important to protection from fire in complex terrain nor does it capture important variability within each day's burn window; however, these levels of detail are infeasible for the scale of our study. Future use of finer-scaled fire behavior simulations to study refugia formation (Ouarmim et al. 2016) will complement our growing understanding of burn mosaics across multiple scales. We characterized the drivers of fire refugia based on enduring features that should be invariant through time; however, we highlight that the fire data are a modern-day snapshot of burn mosaics that include the fingerprint of historical fire and land management. Our selection of fires that mainly burned within protected areas and that experienced limited or no fire suppression was made in an attempt to focus on landscapes where the contemporary human footprint is less pronounced.

Identifying the locations of topographic fire refugia in forested landscapes can inform forest harvest, fire operations, landscape restoration, and conservation. Forest harvest plans typically have stand-level requirements for variable retention and maintenance of tree islands. Increasingly, thinning is used to reduce the risk of forest fires (Agee and Skinner 2005), often based on the philosophy of emulating natural disturbance. Wildfire management frequently utilizes burnouts as a safety measure to clear flammable vegetation from within the anticipated fire perimeter. Unfortunately, all of these practices may be altering, or removing, critical patches and corridors for the establishment, persistence, and movement of organisms in burn mosaics. In an era of increasing concern over undesirable ecological outcomes of fire, our thinking needs to remain focused on the important landscape heterogeneity generated by burning. This pyrodiversity includes low-severity/unburned refugia through to high severity fire and the landscape mixtures in between (Agee 1993, Perera and Buse 2014, DellaSala and Hanson 2015, Hutto et al. 2016) all as components of fire-resilient ecosystems, though the frequency, extent, and proportions of fire severities differ importantly among vegetation types. Our conceptual framework advances understanding of the predictability, structure, and function of topographic fire refugia as a component of contemporary burn mosaics in western North American forest ecosystems.

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