1. ADMINISTRATIVE INFORMATION:

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2. PUBLIC SUMMARY:

Recent stand-replacing wildfires in late-successional and old-growth (LSOG) forests have increased land manager interest in fire refugia, which could provide vital habitat for threatened and endangered species during a time of rapid change. The overall goal of this project was to *model, map, and share* information essential for the conservation of LSOG forest ecosystems in the U.S. Pacific Northwest, within a diverse co-production team of state and federal land managers. We developed statistical models of contemporary (2002-2017) fire refugia, non-stand-replacing fire (NSR), and high-severity fire based on topography, fuels, fire weather, fire behavior and climate. We used these models to produce probability surface maps for fire refugia, NSR, and high-severity fire under low, moderate, and extreme fire weather and fire growth scenarios. These maps and associated products provide timely information about the likely persistence, change, and loss of LSOG forests under current and future climate conditions.

In moist forests of the Douglas-fir/western hemlock zone, we found high potential for fire refugia in old, high biomass forests across a fairly broad range of fire weather conditions. We document thresholds in extreme weather and fire behavior beyond which refugial probability declined across the landscape, except in protected topographic sites and some coastal areas. Subalpine forests generally were likely to burn at higher severity under most scenarios. In dry forests of the region, fire refugia probability tended to be low. However, intermediate-severity fire was widespread, even under more extreme burning conditions. These results highlight important biogeographic differences in the processes generating and maintaining forests, and in particular, LSOG habitat.

Final products for this project were developed iteratively, with feedback from key partners. All of our refugia products are available through a new web tool, Eco-Vis (https://firerefugia-app.forestry.oregonstate.edu/projects/latest), which facilitates data exploration, download, and advanced visualization.

3. TECHNICAL SUMMARY:

Recent stand-replacing wildfires in late-successional and old-growth (LSOG) forests have increased land manager interest in fire refugia, which could provide vital habitat for threatened and endangered species during a time of rapid change. The overall goal of this project was to *model, map, and share* information essential for the conservation of LSOG forest ecosystems in the U.S. Pacific Northwest, within a diverse co-production team of state and federal land managers. We developed boosted regression tree models of contemporary (2002-2017) fire refugia, non-stand-replacing fire, and high-severity fire in LSOG forests based on topography, fuels, fire weather, fire behavior and climate. We used these models to evaluate the drivers of fire refugia and severity, to produce probability surface maps for fire refugia, non-stand-replacing (NSR), and high-severity fire, and to examine probability shifts under low, moderate, and extreme fire weather and fire growth scenarios.

In the moist Douglas-fir/western hemlock zone, we found high potential for fire refugia in old, high biomass forests across a fairly broad range of fire weather conditions. We document thresholds in extreme weather and fire behavior beyond which refugial probability declined across the landscape, except in protected topographic sites and some coastal areas. Subalpine forests generally were likely to burn at higher severity under most scenarios, in large part due to the prevalence of fire-sensitive species. In dry forests of the region, fire refugia probability tended to be low, with smaller patches of high refugial probability throughout the landscape. However, intermediate-severity fire was widespread in these forests, even under more extreme burning conditions. These results highlight important biogeographic differences in the processes generating and maintaining LSOG habitat. Daily maximum temperature, minimum humidity, and moisture content of 1000-hour fuels were important influences on predicted probabilities. But our models show that fire growth rate was a more important predictor of fire refugia and severity than fire weather variables, highlighting the complex, nonlinear dynamics that drive fire effects during major blowup events. We also show that past timber harvest of LSOG forests has reduced refugial probability across the landscape.

These results provide a comprehensive foundation for understanding the drivers, geographic patterns, management influences, and temporal dynamics of fire refugia, NSR, and high severity fire within forests of the Pacific Northwest. Our data products have undergone review by and are being applied by managers in project-specific and regional planning and analysis. Project deliverables are made available through a new web tool, *Eco-Vis (*https://firerefugia-app.forestry.oregonstate.edu/projects/latest), which facilitates data exploration, download, and advanced visualization of model predictor rasters, predicted probability maps, and response function curves that link them.

4. PURPOSE AND OBJECTIVES:

Wildfire activity is increasing across western North America, heightening concerns about high-severity, stand-replacing fire (Parks and Abatzoglou 2020). In the Pacific Northwest (PNW), the 2017 fire season included numerous large fires that displaced many people and exemplified the challenges land managers face when working to reduce fire risk in mature and old forests. These forests provide critical habitat for threatened and endangered species, including the northern spotted owl and marbled murrelet. Identifying areas with lower a probability of stand-replacing fire is an urgent management priority, particularly given projections of more extreme fire weather under climate change. In this context of rapid change, forest fire refugia—places that experience minimal tree mortality compared to surrounding areas—represent important areas of legacy habitat for species dependent on late successional old growth (LSOG) forest. Maps of likely fire refugia and stand-replacing fire are therefore crucial for effective planning and stewardship of wildlife habitat and biodiversity, maintenance of ecosystem services, and protection of cultural values associated with old forests. This project was designed to address this need of land managers in Washington, Oregon, and California to better understand the patterns and drivers of forest persistence, especially that of old forest, in the face of increasing wildfire activity.

The specific objectives of this project were to:

1. *Model* the probability of topographically associated fire refugia and stand-replacing fire within recently burned LSOG forests of the PNW as a function of local and landscape topographic features under a range of fire weather and climate conditions.
2. *Map* the modeled probabilities of fire refugia and stand-replacing fire across the PNW study area to assess the potential retention and recruitment of late- and early-successional forests as a function of climate and land ownership, including effects on T&E species.
3. *Share* a suite of open-source, online applications for managers, the general public, and other stakeholders to access our maps and analytical tools.

We successfully completed each of these objectives, with minimal modification. Throughout 2021 we have received increasing requests for engagement from land managers and scientists from federal agencies, which suggests growing receptivity and active interest in the fire refugia concept and specific data products. We have participated actively as part of the Late Successional Reserve (LSR) system pre-assessment review and have met with the USFS R6 Ecology Program as well as local forest managers (Gifford Pinchot National Forest) to examine fire refugia map products in the context of regional and local project planning (see Section 9 for details). This has led to fruitful and ongoing extension opportunities to discuss the application of existing products from this project, as well as refinement of project data deliverables based on direct feedback from user groups to meet their needs more effectively.

5. ORGANIZATION AND APPROACH:

Research design

The study area includes forests of western Washington, Oregon, and northern California, encompassing 26,430,005 ha in total (Fig. 1) and including the Coast Range, Cascade Range, and Klamath-Siskiyou Mountains. This project was built around a core framework that employed boosted regression trees (BRT) to model the biophysical drivers of fire refugia and high severity fire in forested areas (Objective 1) and produce probability maps under different biophysical scenarios (Objective 2). Boosted regression trees are a robust and flexible model framework for evaluating complex, high-dimensional relationships (De'ath 2007, Elith et al. 2008) such as those between fire and its drivers. We used change detection maps to characterize burn severity of fires from 2002-2017, based on the relative differenced normalized burn ratio (RdNBR) (Miller and Thode 2007) derived from fire perimeters in the Monitoring Trends in Burn Severity (Eidenshink et al. 2007) and Landsat time series analysis in Google Earth Engine (Gorelick et al. 2017). This range of years was selected based on the availability of the Moderate Resolution Imaging Spectroradiometer (MODIS)- and Visible Infrared Imaging Radiometer (VIIRS)-derived daily fire progression maps required for daily fire weather calculations that provided data on fire weather for model building. We calibrated the continuous RdNBR rasters using regionally-specific field data (Reilly et al. 2016) to create three categories representing different ranges of fire-caused canopy cover loss, including: (1) fire refugia (RdNBR ≤ 166, 0-10% canopy cover loss), (2) non-stand-replacing (NSR) severity (RdNBR=167-648, 11-75% canopy cover loss), and (3) high severity (RdNBR > 648, 75-100% canopy cover loss).

Burn severity field data collection
In 2019, we conducted a field campaign to evaluate spatial models and better understand the biophysical conditions associated with fire refugia. We collected field data at 90 plots that burned in 2017 (two years prior to sampling) in western Oregon across the Willamette, Umpqua, and Rogue-Siskiyou National Forests. We distributed field plots evenly among refugia (low-severity), NSR-severity, and high-severity sites associated with remotely sensed spectral change. We focused on mature forests identified using gradient nearest neighbor imputation maps (Ohmann et al. 2012). We measured forest structure, composition, and fire effects (tree mortality, scorch, canopy closure), as well as key characteristics associated with fire refugia including tree regeneration, distance to nearest live tree seed source, and topographic setting.

Biophysical predictors of fire refugia and burn severity
We developed independent BRT models for fire refugia, NSR, and stand-replacing classes based on a set of topographic, vegetation structure, tree species traits, climate, fire weather, and fire growth biophysical predictor variables (Table 1, Fig. 2). These predictor groups represent a broad cross-section of factors that are consistent with theory and have been found to influence fire severity in other studies (Holden et al. 2009, Krawchuk et al. 2016, Parks et al. 2018). We added independent models of NSR severity to our planned research design, which initially focused on refugia and high-severity fire, after field data and initial model results demonstrated their important role in the severity dynamics of both ecoregions.

We included a number of unique data inputs and analytical features in our models designed to improve model performance, interpretability, and insights about fire refugia dynamics. First, to represent live vegetation structure, we included a mix of standard Landsat vegetation indices, including the enhanced vegetation index and tasseled cap transformations, and a suite of modeled vegetation attributes derived from gradient nearest neighbor (GNN) imputation from Forest Inventory and Analysis plots (Ohmann and Gregory 2002, Ohmann et al. 2012). Landsat-based vegetation indices have been shown to be useful predictors in models of fire severity (Parks et al. 2018, Povak et al. 2020, Taylor et al. 2021), but they can have unclear ecological interpretations as a result of index saturation, mixed pixel effects, and non-orthogonality between index values and specific ecological attributes (Huete et al. 1997, Turner et al. 1999, Hyyppa and Hyyppa 2001, Pflugmacher et al. 2012). In contrast, GNN-derived variables such as canopy cover, tree density, stand biomass, and vertical or horizontal complexity, have clear ecological interpretations that are commonly used and directly interpretable by scientists and land managers alike. We used GNN rasters from 2001, the year that most closely preceded our time series of fires, to represent pre-fire vegetation attributes in our models. We complemented these vegetation structure variables with a tree species functional trait variable, the fire resistance score (FRS; Stevens et al. 2020), to account for differential species responses to fire.

Second, we developed a suite of metrics, estimated from daily fire progression maps (Parks 2014), to characterize the influence of daily fire growth rate in our models of fire refugia and stand-replacing (high-severity) fire. Fire events commonly proceed through a range of critical growth domains characterized by different fire behaviors and ecological outcomes (Peters et al. 2004). Potential for such behavioral switches in fire dynamics are exemplified by major blowup events that have occurred in recent decades (Graham 2003, Peterson et al. 2015, Coen et al. 2018). During these events, the relative importance and interactions between drivers of fire severity may undergo dramatic reorganization (Lydersen et al. 2014, Meigs et al. 2020). Providing model flexibility to account for these critical transitions in fire growth, such as blowups, is important to effective predictive modeling of fire severity. However, the cause and predictability of blowups is still limited (Peterson et al. 2017, Coen 2018), prohibiting direct incorporation of meso-scale atmospheric and meteorological factors in our models. Inclusion of a fire growth term in our models was intended as a useful empirical proxy for these poorly understood cross-scale fire-atmosphere interactions that permitted evaluation of shifting drivers and severity outcomes as fires evolve through these critical transitions. Together, these additions represent a novel attempt to improve our understanding of key bottom-up and top-down drivers of fire severity.

Characterization of fire growth

We characterized fire growth using daily fire progression maps derived from geospatial interpolation of MODIS and VIIRS hotspot detection data (Parks 2014) for each of our study fires. Fire progression maps provide estimates of the daily area burned (DAB), which is itself a metric of fire growth rate. However, because DAB is an area-based growth metric, it is subject to geometric bias related to fire size, i.e. fires with larger perimeters can grow more rapidly than small fires. To address this, fire progression can be expressed as a planar measure of fire growth akin to fireline spread rate. We calculated planar fire growth using two methods. The circular method (Podur and Wotton 2011, Parisien et al. 2013) estimates planar growth by projecting DAB onto a circle and calculating radial growth at a daily time step. This method has been used to improve landscape fire spread models by identifying climatic conditions associated with major fire spread days (Wang et al. 2017, Potter and McEvoy 2021). However, these previous applications have been aspatial, where fire progression within each fire event is aggregated by day, independent of spatial variability occurring along different portions of the flaming front. To account for this, we modified the circular planar fire growth method by calculating it for each DAB patch separately, where patches were defined as all contiguous pixels with the same day of burning. The circular method also does not account for the length over which fire spread occurs, instead assuming even spread along the entire length of a circular perimeter. To incorporate irregular fire spread dynamics along the flaming front in our planar fire growth estimates, we developed a perimeter-based calculation of planar fire growth based on the shared perimeter length between daily DAB patches (Fig. 3). We included these three metrics, DAB, circular estimation of planar fire growth (FG_CIRC), and perimeter-based estimation of planar fire growth (FG_P_MEAN), in our severity models to represent the influence of fire growth dynamics.

Ecoregional stratification

This region spans a diverse range of forest types including the Douglas-fir/western hemlock forests of the western Cascades, subalpine forests of the Cascade Crest, ponderosa pine, dry mixed-conifer and lodgepole pine forest of the eastern Cascades, and dry and moist mixed-conifer, mixed-evergreen and deciduous forests of southwest Oregon and northern California (Franklin and Dyrness 1973). Understory vegetation composition, fuel complexes, landscape vegetation patterns, and fire-vegetation responses also vary geographically, creating unique fire environments that are challenging to incorporate directly with remote sensing data. To allow sufficient model flexibility to capture these unique fire-vegetation interactions, we subdivided our study area into two separate modeling regions, fire prone (FP) and non-fire-prone (NOFP) using an ecoregionalization method driven by broad-scale biogeographic patterns of fire-resistant and fire-sensitive tree species. The combined use of ecoregionalized refugia models and pixel-level functional traits (i.e. the FRS model term) represents a multi-scale treatment of vegetation composition designed to capture both broad-scale biogeographic and stand-scale vegetation influences on refugial models. Our ecoregional boundary delineation method also had to address biogeographic climatological differences in the fire environment (Davis et al. 2017) that influenced the sample size of fire events, or total burn area, available for modeling. As defined by existing meso-scale ecoregionalization schemes, many ecoregions encompassing wet forests in the northwest portion of the study area had no, or few, fires available for modeling. Thus, our ecoregionalization method sought to strike a balance between the area required to obtain a robust sample of fire events and sufficient model flexibility to capture biogeographic differences in fire refugia dynamics. We defined ecoregional boundaries using GNN tree species basal area rasters to define the basal area-weighted distribution of fire-prone and fire-sensitive functional groups (Table 2) for all forested pixels in our study area. For this analysis, we selected GNN imputations for the year 1986, the earliest year for which GNN reconstructions are possible, to reduce the impact that modern fires and other disturbances might have on vegetation conversion between forest types or non-forest conditions. We calculated the percent of total basal area in each forested pixel comprised by the sum of fire-prone species (% fire-prone BA) and then classified each pixel as fire-prone if the % fire-prone BA was ≥ 10% or non-fire-prone otherwise. This classification approximated a presence/absence of fire-prone species. To further generalize this binary map and produce a broad delineation of the extent of fire-prone and non-fire-prone species, we overlaid it with a 5km hexagonal grid, calculated the percent area of each hexel (e.g. hexagonal grid cell) in each class, and again used a 10% threshold to classify fire-prone and non-fire-prone hexels. This spatial smoothing procedure eliminated many fine-scale gaps. Residual gaps were manually removed, resulting in a single contiguous ecoregional polygon encompassing fire-prone (FP) and non-fire-prone (NFP) ecoregions.

Fire severity model construction

For each of our two ecoregions, we built independent models for refugia, NSR, and high-severity fire and for scenarios with and without fire growth as a predictor term (2 ecoregions * 3 severity classes * 2 fire growth scenarios = 12 models total). Models that included fire growth terms were useful for evaluating the ecological outcomes and shifting interactions between fire severity drivers during critical transitions in fire growth. However, fire growth is not as intuitive to managers as other time-varying fire severity drivers, such as daily weather conditions, and is more difficult to link directly to projected climate change. For this reason, we constructed models with different sets of time-varying predictors, those that incorporated fire weather only (fire weather models) and those that incorporated both fire weather and growth (fire growth models), along with vegetation and topographic predictors.

We built a sample pixel dataset from a random, spatially-distributed set of 95,932 burned pixels (< 1% of potential pixels) from fire perimeters in the Monitoring Trends in Burn Severity project (Eidenshink et al. 2007) spanning all years between 2002-2017. Consistent with previous studies (Kane et al. 2015, Harvey et al. 2016, Zald and Dunn 2018), sample pixels were spaced by a minimum of 200 m to reduce the influence of spatial autocorrelation. We culled this initial sample by applying a GNN non-forest forest mask (Meigs and Krawchuk 2018) for the 2001 year to remove any unforested pixels prior to our time series of fires, removing pixels < 100 m from fire perimeter boundaries and those burned more than once. This resulted in 74,789 model pixels in total (10,927 for NFP and 63,862 FP).

We used boosted regression tree models to evaluate the drivers of fire refugia, NSR, and high-severity classes and to build probabilistic maps of each variable for our study area. Boosted regression trees are a machine learning method that is well suited for addressing high-dimensional ecological problems (De'ath 2007, Parisien and Moritz 2009, Krawchuk et al. 2016). All models were constructed for a binary response variable (e.g. refugia/no refugia, high severity/not high--severity) using a 10-fold cross-validation procedure (Elith et al. 2008) to evaluate the number of optimal trees and assess model performance using independent data. The bag fraction was set to 0.5, tree complexity to five to allow high level interactions, and the learning rate to 0.01, resulting in well over 1,000 trees for all models. We used the area under the receiver operating characteristics curve (AUC) and the percent deviance explained, a form of pseudo R^2, estimated from the cross-validated folds to evaluate model performance. To cull models to a more parsimonious form, we implemented a three-step variable reduction procedure. Models with all predictor variables were first run and trimmed in a backwards elimination procedure (Elith et al. 2008) that excluded the lowest ranking variable until the cross-validated predictive performance reduction exceeded one standard error of the full model. From this reduced list of predictors, we then excluded highly correlated ($r \geq 0.7$) variables within each predictor class (e.g. vegetation, fire weather, etc.), retaining only a single correlated predictor within each group with the highest variable importance score in the simplified model. Compared to pre-screening of correlated variables, this approach had the benefit of allowing the models to select the top predictors from amongst highly correlated variables. Final models were run on this final set of culled predictor variables.

Modeling the drivers of fire growth
Because fire growth emerged as a key driver of fire severity (see Results), we constructed BRT models following the methods above, but for fire growth as a response variable, independent of fire severity, using the same set of vegetation, topographic and fire weather variables as predictors. We view this analysis as a first step towards testing the robustness of predictive models of major blowup events that influence fire severity, evaluation of its drivers, and examination of the hierarchical interactions between fire growth and severity.

Mapping probability surfaces
We used the final set of models to create a suite of region-wide probability surface maps for fire refugia, NSR, and high-severity fire, under a range of potential fire growth and fire weather conditions. For models including fire growth, where fire weather variables were not highly influential (see *Results*), we produced scenario maps for low, moderate and extreme fire growth conditions, based on the 10^{th}, 50^{th} and 90^{th} percentile of fire growth conditions observed in our study region and period. For models without fire growth, we produced maps for a full factorial range of low (10^{th}), moderate (50^{th}) and extreme (90^{th}) conditions of the two top-ranked fire weather variables. Weather variables exhibit important temporal and spatial co-variance structures that are key to influencing local fire dynamics and outcomes. To preserve some of this covariance structure in our probability maps we created rasters for each predictor using pixel-wise percentile calculations based on fire season (July-September) conditions during 1986-2018. Restricting the percentile calculations to the fire season ensures that our scenarios represent the range of conditions and covariance structures that exist when fires tend to occur (Parks et al. 2018). Pixel-wise percentile calculations constrained predictions to the local range of variation for each variable, while permitting expression of natural geographic variation in each variable (Fig. 2). The most consistently top-ranked fire weather variables were daily maximum temperature (TMMX) and minimum relative humidity (RMIN), so we used these two variables to produce a consistent suite of fire weather scenario maps for both ecoregions and all severity classes. All other fire weather variables were fixed at the 50^{th} percentile for all scenario runs. For all scenarios, we used GNN vegetation rasters from 2017, the most recent year available, to represent the probability surfaces that most closely reflect current vegetation.

6. PROJECT RESULTS

Field observations of fire effects across the burn severity gradient
The large extent of the study region and limited resources for field sampling precluded a full quantitative evaluation of spatial models based on the 90 field plots we sampled in 2019. However, the field plots did enable us to quantify key attributes associated with fire refugia in mature forests and assess the relationship between field-based and remotely sensed estimates of burn severity. For example, we found a strong linear association between basal area mortality observed on the ground and burn severity observed by Landsat satellites (R^2 = 0.83). The refugia and high-severity classes exhibited less variance than the moderate-severity class (Fig. 4). This result highlights that remotely sensed maps of fire refugia and stand-replacing fire are relatively reliable, whereas a wide range of fire effects is possible in sites mapped as NSR severity.

Final models
Fire growth and weather models exhibited moderate to good (AUC=0.58-0.75) performance across all fire severity classes and ecoregions (Table 2). However, some consistent and noteworthy differences emerged. Mean model performance was best for high-severity models, followed closely by refugia models, with consistently lower values for NSR models. Lower performance for NSR models is likely related, at least in part, to the challenge of modeling intermediate levels of tree mortality using NBR-based metrics (Fig. 4). Fire growth models were more parsimonious and performed better than fire weather models (Table 2), suggesting that fire growth is a critical driver of fire severity dynamics. Models for the fire-prone (FP) ecoregion outperformed those from the non-fire-prone (NOFP) ecoregion and included more predictors for models of all severity classes, suggesting more complex fire severity dynamics.

Drivers of fire refugia, NSR, and high severity fire effects
Landsat vegetation indices were identified as important predictors in initial models. However, we found that models using GNN vegetation structure variables performed equally well, produced response curves with clearer ecological interpretations, and resulted in models with predictor variables that are widely used, translatable, and accessible in forestry, management, and ecology. We therefore excluded Landsat vegetation indices from further analysis.

The variable selection and reduction routine produced a fairly consistent suite of vegetation and topographic predictors for all 12 models (Figs. 5-6, Table 3). Live stand biomass, fire resistance score, and relative position, were top predictors in most models. Refugial probability increased, and high severity probability decreased, with increasing biomass in the non-fire-prone ecoregion. A similar pattern occurred in the fire-prone ecoregion, except that this pattern reversed at very high biomass, and stand density exerted a joint, inverse influence on refugia. Together, these results suggest that older stands with a large tree component in both ecoregions, and lower stand density in the fire-prone ecoregion, were important sources of fire refugia. FRS exhibited a consistent pattern across all models and ecoregions, with an abrupt threshold response (FRS=0.4-0.5) towards increased refugia and NSR probability occurring where Douglas-fir and fire-resistant pines were abundant. Refugia and NSR probability increased, and high-severity fire decreased, in lower topographic positions such as valley bottoms and sites with higher cold air-pooling potential. While the drivers of fire refugia and

NSR severity were similar, response curves for NSR models often exhibited higher probabilities over a wider range of predictor variables. We interpret this as evidence that fire refugia are more strictly constrained to a narrow range of predictor variable conditions than NSR severity.

RMIN, TMMX, and FM1000 were the most consistently selected fire weather variables across models, with drier, hotter conditions and lower fuel moistures resulting in lower fire refugia probability and higher probability of high severity. Fire weather variables exerted much weaker influences in fire growth models than in models that included fire weather alone. Daily area burned—a simple measure of fire growth—was consistently included as a top predictor in fire growth models, outperforming either of the planar methods of fire growth estimation. Models of the drivers of daily area burned showed reduced performance compared to the suite of severity models. Fire weather factors were the dominant predictors of daily area burned, with few topographic and no vegetation predictors retained in the final model.

Patterns of refugia, NSR and high-severity probability

Predictive maps showed a striking pattern of moderate to high fire refugia probability across much of the non-fire-prone ecoregion in all but the most extreme fire weather or growth conditions and relatively low refugia probability in forests of the fire-prone ecoregion independent of fire weather or growth scenario (Figs. 7-8). Under moderate and extreme fire weather conditions, the largest areas of high fire refugia probability were concentrated along the Coast Range and northern portion of the study area, with smaller pockets of refugia distributed throughout the entire study area in topographically protected sites and in old forest patches (Fig. 9a-c). NSR severity in this ecoregion exhibited intermediate probability under all fire weather and growth scenarios, except extreme fire growth. High-severity fire probability increased in tandem with the extremity of burning conditions, but was predicted at low to intermediate levels across most of the Douglas-fire/hemlock forest in the non-fire-prone ecoregion. In fire-sensitive forests, such as the subalpine forests along the Cascade crest and north Cascades, high-severity fire was predicted across most scenarios.

In the fire-prone ecoregion, high refugia probability was fairly widespread for the low extremity fire weather scenario (Figs. 7-8), but occurred in a much patchier, fragmented pattern than in the non-fire-prone ecoregion (Fig. 9d-e), consistent with the fine-scale heterogeneity of forest structural characteristics in these forests. Refugia probability was greatly reduced across the ecoregion under moderate to high extremity scenarios. NSR severity probability, in contrast, was relatively high across most scenarios. High severity probability was quite low in the low extremity scenarios, with gradual increases across the moderate and high extremity scenarios. Under the extreme scenario, high severity fire was predicted at intermediate levels across much of the ecoregion, although fine-scale patterning reflecting the vegetation and topographic heterogeneity was still evident.

Fire weather and fire growth scenarios demonstrated similar broadscale biogeographic patterns for low and moderate extremity scenarios, as well as for the high extremity scenario in the fire-prone ecoregion. However, their behaviors diverged markedly for the extreme scenario, where fire growth models showed much stronger, study area-wide decreases in refugia and increases in high severity probability (Fig. 8). This scenario of extreme fire growth represents major blowup conditions, which may be similar to that experienced during the 2020 Labor Day fires in the Pacific Northwest, where fire behavior and effects are driven by large-scale synoptic influences not included in our models. Under these conditions, the probability of fire refugia, and NSR severity to a lesser extent, was reduced to low levels and high-severity fire increased to high levels across much of the Pacific Northwest. These results demonstrate the utility of the fire growth term in our models for capturing non-linear, cross-scale dynamics that are often poorly captured in models driven by surface fire weather conditions alone.

7. DISCUSSION:

Inclusion of multi-scale species composition, fire growth dynamics, and ecologically tractable vegetation variables constitute important contributions to the broader effort to understand fire severity drivers and develop more robust, dynamic predictive modeling approaches. The multi-scale treatment of species composition revealed an important pixel-level tree species composition influence on fire severity that was shared between ecoregions, while the species-based ecoregional delineations permitted unique model structures for biogeographic regions. Ecoregionalization was also effective in providing a sufficient sample size of burned pixels for model construction in the wetter portions of our study area, which have been excluded in previous studies (Parks et al. 2018). This is an important outcome, as climate-driven changes in the fire dynamics of these ecoregions are uncertain (Littell et al. 2010, Donato et al. 2020), in large part due to data limitations resulting from the regime of infrequent, extreme events. While more data in fire-limited portions of our study area will undoubtedly benefit future efforts, our results provide important initial insights into fire dynamics and fire-driven outcomes for LSOG forests in moist forest ecosystems of the PNW.

Here, we highlight several key discoveries emerging from this work that inform our central research objectives and collaborative partnerships.

1. Contrasting ecoregional refugia dynamics: forests in both ecoregions exhibited broad similarities in the final set of predictors and relative shape of the response function curves. For example, refugia were more likely in both ecoregions for older forests with intermediate to high biomass in lower relative slope positions that burned under milder fire weather conditions. However, our models reveal striking ecoregional differences in the patterns of fire refugia and severity probability that emerge from the unique biogeographic expressions of underlying predictors and higher dimensional variable interactions between them. Our models predicted high refugial probability for the non-fire-prone ecoregion under a range of weather conditions. This is consistent with observational evidence from fires in recent decades that fire refugia comprise an important component (almost 40%) of total burn area (Meigs and Krawchuk 2018). Together, these results suggest that there is broad potential to maintain fire refugia in moist forests of the PNW, depending on the fire weather and growth conditions under which fires occur. In these moist forests, refugia are maintained by topographic and vegetative conditions that promote patchy burning, safe-sites, or more fire-resistant microclimates, except under extreme fire weather conditions. In contrast, our models predicted limited, patchy areas of fire refugia for forests of the fire-prone ecoregion. Instead, the NSR severity class was a prominent feature of our model outputs across most fire weather conditions. Lower refugial probability in forests of the fire-prone ecoregion, where fire-resistant species are more abundant, may seem, at first, counterintuitive. However, this can be explained by different fire severity-mediated pathways to old forest development between the two ecoregions. In fire-prone forests, few areas avoid fire consistently and fire refugia are limited under all fire weather scenarios. However, the NSR severity class is prominent under most fire weather conditions, resulting in widespread surviving residual tree structures. These disturbance-mediated old forest pathways captured in our statistical models are consistent with old growth forest dynamics theory in each region (Franklin et al. 2002, Spies et al. 2006, 2018, Tepley et al. 2013). High probability of high-severity fire in fire-sensitive forests in both ecoregions is likely a function of high fire-susceptibility of the dominant tree species in these forests, potentially coupled with a tendency in these climate-limited systems for fires to occur under more extreme weather conditions that promote severe fire.

2. Old forest and large tree habitat is an important source of refugia: Live tree biomass was one of the most consistently selected top predictor variables for our models. Fire refugia probability exhibited a strong threshold increase in both ecoregions at biomass levels characteristic of old growth forest (Grier and Logan 1977). An overlay of our fire refugia maps with trends in northern spotted owl nesting and roosting habitat over the period 1993-2019 shows a net increase of areas mapped as high fire refugia probability and only a marginal decrease in areas predicted as moderate probability, compared with a large decrease in low refugia probability areas (R. Davis, Region 6 Monitoring Lead for Older Forests & Spotted Owls, personal communication). Thus, both modeled and empirical results suggest that old forest is an important positive feedback on fire refugia.

3. Non-stand-replacing fire severity is an important source of large tree habitat: Our models reveal that NSR severity fire was the dominant process generating residual, post-fire structure in fire-prone ecoregions. Although our models demonstrate an important role for fire refugia in the non-fire-prone ecoregion, they also predict high NSR severity probability across both ecoregions under all fire weather and growth scenarios, including the most extreme conditions. These results suggest that NSR severity fire is a critical component of legacy tree structure in burned forests across the PNW. Future research on the structural characteristics, habitat quality and use of forests affected by low- to moderate-severity fire is an important future research direction.

4. Multi-decadal depressions in fire refugia probability, and increases in high-severity fire, resulting from past timber harvest: Our models showed a clear and lasting imprint of past timber harvest on fire severity probability. Particularly in the non-fire-prone ecoregion, previously harvested areas showed notable decreases in fire refugia probability, and increases in high severity probability, for several decades after harvest. This finding is consistent with other studies of high-severity risk in managed forests of the region (Zald and Dunn 2018, Evers et al. 2021), but adds an important new perspective through the joint evaluation of refugia and high severity fire. This is a critical land use legacy impact that provides context for current fire severity dynamics and can inform future fire refugia and forest management strategies.

5. Fire management strategies can promote (or diminish) fire refugia: Our models provide clear evidence that fire refugia outcomes are strongly contingent on fire weather and burning conditions. Importantly, they identify broad windows of *fire season weather*, based on data from 1986-2018, where mild to moderate conditions promote high refugia and NSR probability. This highlights the risks assumed when aggressive suppression strategies are used to constrain much of the annual area burned to the most extreme weather conditions, when direct fire control fails. Instead, it suggests that more proactive use of prescribed fire or adaptive management of natural ignitions could be an important part of promoting the persistence of fire refugia in PNW forests. Intentional fire management strategies that take advantage of these opportune fire weather windows may be especially important as climate change causes increasingly warm, long, and dry fire seasons.

6. Extreme fire growth trumps extreme fire weather: Extreme surface fire weather conditions (e.g. hot, dry, and windy) and extreme fire growth events, such as major blowups documented in recent years (Lareau et al. 2018, Abatzoglou et al. 2021), are often conflated. While these phenomena are often related, their causes are complex and driven by nonlinear, cross-scale dynamics that are not yet well understood and are difficult to predict (Peterson et al. 2017, Coen 2018). Our fire weather and growth models were designed to provide alternative views of the temporal drivers of fire severity, where the latter account for eruptive fire behaviors that are difficult to capture mechanistically. The variable selection and reduction routine we implemented retained the daily area burned term over both planar fire growth metrics. This suggests that meso-scale fire-atmosphere dynamics that drove major eruptive fire growth episodes were more important than local-scale fire behavior represented by the planar metrics. Predictions from the fire weather and growth models were broadly congruent, especially at low to moderate extremity scenarios. However, fine-scale differences in the mapped predictions were apparent even in these scenarios and large differences existed for the extreme scenarios, with fire growth models predicting much higher severity (and lower refugia and NSR probability). The conceptual model of nested fire growth-severity relationships we developed (Fig. 10) reflects that fire severity-mediated outcomes are more sensitive to, and directly influenced by, fire growth than to fire weather. As a result of this, our fire weather models may, in fact, underestimate fire severity under blowup conditions. A notable example that demonstrates this potential underestimation and the utility of the fire growth models is the 2020 Labor Day fires. Fire weather conditions during the 2020 fires were substantially more extreme than anything in our model training dataset (Abatzoglou et al. 2021, Higuera and Abatzoglou 2021), which included data from 2002-2017. As a result, extreme, rare weather conditions like that which drove the 2020 fires may not be reflected in our model predictions. This is evident in the prevalence of intermediate probabilities of high-severity fire predicted by the fire weather models, even under the most extreme scenario. In contrast, the fire growth model predicted widespread high-severity fire in the non-fire-prone ecoregion under the extreme scenario that is more consistent with the observed severity patterns resulting from the 2020 fires. This is a striking result. It suggests either that similar fire behavior was captured in our training dataset, despite the lack of similarly extreme fire weather conditions, or that the fire growth model more effectively captured a threshold response in the growth-severity relationship that was useful in predicting outcomes for an unprecedented event. This decoupling of fire weather and behavior is an important operational and conceptual tool that should be informative in real-time fire management decisions, post-fire ecological assessments, and fire severity modeling.

7. Opportunities for fire refugia and old forest structure under extreme burning conditions: Although fire refugia extent in the non-fire-prone ecoregion was greatly reduced under extreme fire conditions, our models identify some consistent areas of refugial persistence. Under extreme fire growth, refugia are strongly constrained to valley bottoms and areas of cold air-pooling, especially in the non-fire-prone ecoregion, with areas of intermediate refugia probability extending further upslope in the fire-prone ecoregion. Biogeographic areas of moderate to high refugia probability existed in portions of the Coast Range, Olympic Peninsula, northwestern Cascades, and portions of the southeastern Cascades. Companion work to this study (Downing et al. 2021) that evaluated the drivers and biogeography of refugia in repeatedly burned areas found that a similar set of topographic factors was associated with persistent refugia. Knowledge of these fire refugia areas that may persist under more extreme burning conditions or repeated burns are a critical anchor to consider in future LSOG reserve design and management planning. Another important application of refugia maps is examination of the overlap between fire refugia areas, which represent important stable habitat for spotted owls, and habitat selection or use by key competitors such as barred owls (Wiens et al. 2021). Areas of significant overlap between refugia and barred owl use could help prioritize barred owl removal efforts where it is most important for spotted owls.

8. CONCLUSIONS AND RECOMMENDATIONS:

We successfully met our proposed research and deliverable goals (Objectives 1-2), as well as most of our key partnership goals (Objective 3). Consistent and frequent engagement with the full range of collaborators and partners was delayed during transition in the lead postdoc on the project, which impacted the planned co-production activities. However, the postdoc change also brought new perspectives and expertise that are reflected in many of the research outcomes. Once the staffing transition was underway in 2020, interaction with key partners (see Section 9), especially around the topic of fire refugia product applications to northern spotted owl habitat management, became an important part of our project activities. These partner engagements have resulted in important discussions about how to apply refugia products, as well as modifications to our data products and delivery systems to address feedback we have received. Several partner engagement activities are ongoing or are planned for the near future, including product outreach with managers and scientists from The Nature Conservancy (K. Metlen), Bureau of Land Management (B. Hollen), and Forest Service (C. Friesen).

Important next steps that we have identified include:

- More robust accounting for spatial autocorrelation influences on refugia and severity models.
- Improved representation of vegetation structure (bottom up) and fire meteorology (top down) in refugia and severity models.

- Investigation of the post-fire forest attributes, habitat value and use for LSOG species, and patterns of non-stand-replacing burn severity areas.
- Development of science products and evaluation of planning/operational challenges to flexible fire management policies that could allow fire during low-moderate fire conditions (e.g. fire weather or fire growth), when fire refugial probability is high and ecological benefits could be maximized.

9. MANAGEMENT APPLICATIONS AND PRODUCTS:

The principal audience and co-production partners in this work have been federal and state land managers, conservation NGOs, and other scientists involved with management of LSOG species. Management of LSOG species has been a focal point in the Pacific Northwest due to the challenges presented by a legacy of timber harvest, introduced species, and increasing fire activity and severity in recent decades. Refugia concepts have figured prominently in discussions of conservation planning for LSOG species and products from this project are among the first to emerge to address these regional evaluation and planning needs. Recent large, severe fire events have demonstrated the abrupt long-term changes that can occur and have focused attention on fire refugia as a key conservation priority. As refugia products emerged during the last year, we have engaged with management partners to feature and describe them, receive feedback, refine products, and provide customized outputs for specific project landscapes and planning areas. The primary interests in refugia products expressed to us so far have centered around: (1) where to plan vegetation treatments so as to augment fire refugia or avoid negatively impacting refugia, and (2) better understanding of where in the landscape, or under what conditions, fire refugia are likely to persist. We have worked extensively with regional Forest Service teams as part of a pre-assessment, review and landscape evaluation of the Late Successional Reserve (LSR) system in the Northwest Forest Plan (NWFP), with a goal of developing forward-looking habitat reserve networks for LSOG species. One of the three working groups in the NWFP LSR redesign pre-assessment is focused on disturbance refugia, and fire refugia is a key topic for that working group. We have served as integral members of this team to provide data products, advise on multi-resource, landscape analyses methods, and review outputs. We have also shared our work with the USFS Region 6 Ecology Program team and individual National Forests (Gifford Pinchot, Little White Salmon project area) to examine how fire refugia products may be used in project-level management planning. We are planning to engage in future outreach and translational science with the R6 Ecology Program, BLM co-producers (e.g., Bruce Hollen), The Nature Conservancy co-producers (e.g., Kerry Metlen), and in broad dissemination of tools facilitated by Cheryl Friesen (USFS). Additional details are listed below.

Partner engagement activities and contact information

1. USFS Late Successional Reserve Assessment (weekly meetings beginning 7/14/2021)
    - Goal: Provide the USFS Old Forest Assessment Team with a landscape level analysis of fire refugia probability to ensure that future late successional forest reserve designs are centered in areas where older forest is predicted to be the most resilient to current and future disturbances. We provided refugia and high-severity probability maps, collaboratively developed customized

refugia products, and participated extensively in advisory roles on regional reserve design and integrated analyses.

- Key member of the Disturbance Refugia working group, responsible for developing tailored refugia models and other outputs and presenting to the group.
- Worked closely with Ray Davis (R6 Monitoring Lead for Older Forests & Spotted Owls), Joshua Chapman (R6 Wildlife program leader), Betsy Glenn (Partnerships Ecologist, NW CASC), Matt Reilly (Research Forester, WWETAC), Garrett Meigs (WA Department of Natural Resources), Andrew Yost (OR Department of Forestry), Stacy Drury (R5 Research Fire Ecologist), Yang Zhiqiang (Rocky Mountain Research Station).

2. USFS Region 6 Ecology program meetings (3/2/2021, 4/28/2021).
   - Goal: Multiple meetings to discuss the content and potential applications of fire refugia data products for regional planning project management, research applications.
   - Main contact: Tom DeMeo (R6 Regional Ecologist and CFLRP Coordinator) and other R6 Ecologists.
3. USFS Little White Salmon Project team (Gifford Pinchot NF) (1/20/2021, 6/22/2018).
   - Goal: Discuss application of fire refugia products to vegetation management planning in the Little White Salmon Project area, Gifford Pinchot National Forest, Washington. There was specific interest in how the refugia and high-severity maps could be used to inform landscape planning for a suite of wildlife and plant species of concern that are associated with both old growth, closed canopy forest and open oak woodland, grassland, and early seral environments.
   - Main contacts: Audrey Maclennan (Assistant Regional Analyst, USFS), Jessica Hudec (R6 Ecologist, western WA Region), Andrea Montgomery (South Zone botanist, Gifford Pinchot National Forest).
4. Washington Department of Natural Resources (bimonthly meetings beginning 1/2021)
   - Goal: Sharing of concepts and tools for development of fire refugia modeling methods and map production for eastern Cascade forests.
   - Ongoing research co-production to develop fire refugia modeling and mapping methods.
   - Main contact: Garrett Meigs.
5. Co-production survey and responses from collaborators (12/15/2018).
   - Main contacts: Richard Tveten (Restoration Ecologist, Washington State Department of Fish and Wildlife), Ariel Cowan (Oregon Department of Forestry, now OSU Extension Fire Program), Kerry Metlen (Nature Conservancy), Christina Donehower (Oregon Department of Fish and Wildlife), Mark Brown (USFS), Andrew Yost (Oregon Department of Forestry).

A primary science delivery and decision support tool that we developed for this project is *Eco-Vis* (Ecological Visualization Web Tool; https://firerefugia-app.forestry.oregonstate.edu/projects/latest). *Eco-Vis* is designed to provide basic data access and a download platform for probabilistic maps of fire refugia and severity developed in this project, as well as a dynamic mapping and exploration environment (Fig. 11). A novel feature of *Eco-Vis* is a visualization tool, the Model Inspection Window, that permits detailed exploration of the underlying predictor variable maps and response functions that describe how predictor variables influence the prediction surfaces. We considered this a critical feature of the science extension. Boosted regression tree models are a robust modeling method for complex, high-dimensional ecological problems. But the inherent complexity of these models can obscure the specific relationships between predictors and predictions, especially in explicit geographic terms that are critical to managers. This is especially problematic for managers who need ecologically informative maps, but also are interested in understanding why predictions manifest as they do for specific geographies and how their management decisions may influence these outcomes. Eco-Vis is designed to provide users with tools to explicitly visualize these relationships between input (predictors), outputs (probability maps) and modeled relationships (response curves) in a geographically explicit environment.

10. OUTREACH:

Presentations, webinars, workshops:

1. Naficy, C. E., G. W. Meigs, M. J. Gregory, D. M. Bell, M. A. Krawchuk. "Fire within the fire: the role of fire growth rate on patterns of fire refugia, severity and their drivers in forests of the Pacific Northwest." Special Session. Annual Meeting of the Ecological Society of America. Long Beach, CA. August 1-6, 2021.
2. Krawchuk, M.A. 2021. Disturbance refugia within mosaics of forest fire, drought, and insect outbreaks. Alpine Biomass Collaborative Meeting. Virtual/Alpine, CA. May 4th 2021 (invited oral presentation).
3. Naficy, C. E., G. W. Meigs, M. J. Gregory, D. M. Bell, M. A. Krawchuk. "Dissecting the firestorm: contingency of fire severity drivers and refugial probability on critical fire growth rates." Northwest Climate Conference. Virtual meeting. April 6-8, 2021.
4. Krawchuk, M.A., Meigs, G.W., Cartwright, J., Coop, J.D., Davis, R., Holz, A., Kolden, C., and Meddens, A.J.H. 2020. Disturbance refugia within mosaics of forest fire, drought, and insect outbreaks. North American Congress for Conservation Biology. Virtual/Denver, CO. July 37-31st (invited oral presentation).
5. Krawchuk, M.A. 2020. Fire refugia: what are they, where are they, and why do they matter? OSU COF Forest Health State of the State. Corvallis, OR. Feb. 26/27th (Invited oral presentation).
6. Krawchuk, M.A. 2020. Fire refugia in western forested ecosystems: what are they, where are they, and why do they matter? Botany and Plant Pathology Seminar Series, Corvallis, OR. Feb. 20th (Invited oral presentation).
7. Cartwright, J.M., Krawchuk, M.A., Lawler, J.J., Meigs, G.W., Michalak, J., Morelli, T.L., Ramirez, A. 2020. Refugia from climate change: emerging concepts and application. American Geophysical Union Annual Meeting. Virtual. Dec. 1-17th (poster).
8. Meigs, G.W., and Krawchuk, M.A. 2019. Fire refugia in PNW forests: conceptual framework and mapping applications. Washington Forest Collaborative Summit. Wenatchee, WA. Nov. 6-7th. (Invited oral presentation).
9. Meigs, G.W., Harvey, B.J., Krawchuk, M.A. 2019. Improving burn severity mapping for landscape conservation: incorporating biophysical gradients, uncertainty, and functionally significant patches in burned forests. International Association of Landscape Ecology – North America, Annual Meeting. Fort Collins, Colorado. April 7-11. (Oral Presentation).

10. Refugia Research Coalition: Frontiers Special Issue Workshop. NW Climate Science Center, USGS, The Nature Conservancy, UC Riverside, NE Climate Adaptation Science Center. Led by Drs. Toni Lyn Morelli and Cameron Barrows. Berkeley, CA, October 17-19, 2018.
11. Meigs, G.W., and Krawchuk, M.A. 2018. Spatial prediction of old-growth forest fire refugia in the US Pacific Northwest. ForestSAT Biennial Meeting. College Park, MD. October 1-5, 2018. (Poster).

Articles published:
1. Meigs, G.W., Dunn, C.J., Parks, S.A., and Krawchuk, M.A. 2020. Influence of topography and fuels on fire refugia probability under varying fire weather in forests of the US Pacific Northwest. Canadian Journal of Forest Research https://doi.org/10.1139/cjfr-2019-0406.
2. Krawchuk, M.A., Meigs, G.W., Cartwright, J., Coop, J.D., Davis, R., Holz, A., Kolden, C., Meddens, A.J.H. 2020.Disturbance refugia within mosaics of forest fire, drought, and insect outbreaks. Frontiers in Ecology and the Environment 18:235-244 Special Issue on Climate Change Refugia https://doi.org/10.1002/fee.2190 .

Forthcoming articles:
1. Naficy, C. E., G. W. Meigs, M. J. Gregory, D. M. Bell, M. A. Krawchuk. *In prep*. Drivers, patterns and dynamics of fire refugia: a disturbance-informed management context for late successional species in the Pacific Northwest.
2. Naficy, C. E., R. Davis, Y. Zhiqiang, M. J. Gregory, G. W. Meigs, D. M. Bell, S. Healy, M. A. Krawchuk. *In prep*. Forest management influences on regional fire refugia dynamics in forests of the Pacific Northwest.
3. Naficy, C. E., M. J. Gregory, D. M. Bell, M. A. Krawchuk. *In prep*. Geographic and temporal trends in eruptive fire behavior and severity dynamics.

Websites:
- Fire Refugia project web page: https://firerefugia.forestry.oregonstate.edu
- *Eco-Vis* web tool: https://firerefugia-app.forestry.oregonstate.edu/projects/latest
- USGS ScienceBase: https://www.sciencebase.gov/catalog/item/5b50b401e4b06a6dd185e1c2

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Table 1. List of candidate predictor variables used in BRT models, grouped by vegetation, topography, climate, fire weather, and fire growth classes.

Variable class	Variable abbreviation	Description
vegetation	AGE_DOM[1]	GNN; age of the dominant tree layer.
	BA_GE_3[1]	GNN; basal area of trees ≥ 3 cm DBH.
	CANCOV[1]	GNN; canopy cover.
	DDI[1]	GNN; density diversity index (DDI). Index of canopy strata diversity (i.e. diversity of size classes).
	QMD_HT25[1]	GNN; quadratic mean diameter of trees > 25 ft. tall.
	OGSI[1]	GNN; old growth structural index (OGSI). Index of old growth structural characterstics.
	TPH_GE_3[1]	GNN; density (trees/ha) of trees ≥ 3 cm DBH.
	BPH_GE_3_CRM[1]	GNN; stand biomass of all trees ≥ 3 cm DBH.
	EVI[2]	LANDTRENDR fitted annual medoid composite of Enhanced Vegetation Index (EVI).
	TC1[2]	LANDTRENDR fitted annual medoid composite of Tasselled Cap 1 (brightness).
	TC2[2]	LANDTRENDR fitted annual medoid composite of Tasselled Cap 2 (greeness).
	TC3[2]	LANDTRENDR fitted annual medoid composite of Tasselled Cap 3 (wetness).
	FRS[3]	multi-variate trait-based fire resistance score (FRS) based on basal area weighting of tree species composition.

Table 1 continued.

topography	CAREA[4]	area (m^2) of hydrological catchment.
	CFLOWPATH[4]	hydrologic flow path length (m); related to watershed area and complexity.
	CASPECT[4]	azimuth of the hydrological catchment (radians); a coarse-scale representation of aspect.
	CSLOPE[4]	mean slope of hydrological catchment (radians); a coarse-scale representation slope.
	ASPECT[4]	azimuth of slope at local scale (radians).
	SLOPE[4]	fine-scale slope steepness (°).
	RELPOS[4]	relative topographic position (0–10); measure of the elevational position of a pixel relative to other pixels within 500 m radius.
	TCI[4]	Topographic convergence index (TCI); measure of cold-air pooling potential.
	SWI[4]	Topographic wetness Index (TWI); measure of hydrological pooling associated with potential soil wetness.
	HEAT_LOAD[4]	Heat load index (HLI); measure of incident radiation based on slope, aspect and latitude.
climate	PDSI[5]	mean summer Palmer Drought Severity Index (PDSI); standardized measure of drought conditions.
fire weather	TMMX_RAW[6]	daily maximum near-surface air temperature (TMMX); expressed as °C.
	ERC_RAW[6]	daily energy release component (ERC) for fuel model G; moisture-related measure of potential energy release.
	BI_RAW[6]	daily burning index (BI); measure of containment difficulty related to related to flame length.
	FM1000_RAW[6]	daily moisture content of 1,000 hour fuels (FM1000); measure of large fuel aridity.
	VS_RAW[6]	daily wind velocity (VS); expressed as meters/second.
	RMIN_RAW[6]	daily minimum relative humidity (RMIN).
	PR_RAW[6]	daily precipitation (PR).
fire growth	DOBLOB_AREA[2]	daily area burned (DAB) derived from daily fire progression maps
	FG_CIRC[2]	planar fire growth estimated using the circular method derived from daily fire progression maps
	FG_P_MEAN[2]	planar fire growth estimated using the perimeter method derived from daily fire progression maps

1 - Ohmann & Gregory 2002; 2 - this study; 3 - Stevens et al. 2020; 4 - Krawchuk et al. 2016; 5 - Abatzoglou et al. 2017; 6 - Abatzoglou et al. 2013.

Table 2. Performance statistics and predictor variables for refugia, non stand-replacing (NSR), and high-severity models, stratified by ecoregion and inclusion.

	Non fire-prone ecoregion						Fire-prone ecoregion					
Severity class	Vegetation	topography	fire weather	fire growth	AUC	% dev. explained	Vegetation	topography	fire weather	fire growth	AUC	% dev. explained
Fire growth												
refugia	BPH_GE_3_CRM, FRS, CANCOV	RELPOS, TCI, ASPECT	RMIN	DAB	0.67	7	BPH_GE_3_CRM, FRS, CANCOV, TPH_GE_3	RELPOS, CASPECT, TCI, CSLOPE	FM1000, TMMX, RMIN, VS	DAB	0.72	11
NSR	FRS	TCI	NA	DAB	0.60	3	FRS, CANCOV	TCI, RELPOS	FM1000, RMIN	DAB	0.62	4
high	FRS, BPH_GE_3_CRM, TPH_GE_3, CANCOV	RELPOS, ASPECT, TCI, CSLOPE	RMIN	DAB	0.72	14	FRS, BPH_GE_3_CRM, TPH_GE_3, CANCOV	RELPOS, CSLOPE, TCI, CASPECT	FM1000, TMMX, RMIN	DAB	0.75	18
No fire growth												
refugia	BPH_GE_3_CRM, FRS, CANCOV	RELPOS, ASPECT, TCI, CSLOPE	RMIN	NA	0.65	6	FRS, BPH_GE_3_CRM, CANCOV, TPH_GE_3	RELPOS, CASPECT, TCI, SLOPE	FM1000, TMMX, RMIN, VS, BI	NA	0.70	10
NSR	FRS, TPH_GE_3	TCI	RMIN, FM1000	NA	0.58	2	FRS, CANCOV	ASPECT, CSLOPE, TCI	FM1000, RMIN, VS,	NA	0.61	3
high	FRS, BPH_GE_3_CRM, TPH_GE_3, CANCOV	RELPOS, TCI, ASPECT, CSLOPE	RMIN, TMMX	NA	0.69	11	FRS, BPH_GE_3_CRM, TPH_GE_3	RELPOS	RMIN, TMMX, FM1000, VS	NA	0.73	15

Table 3. List of indicator species used in the ecoregional delineation analysis. Note that only fire-prone species were used in the analysis; the non-fire-prone region was defined as the inverse of the fire-prone region. Species listed for the non-fire-prone ecoregion are provided to describe its vegetation composition. Note also that Douglas-fir (*Pseudotsuga menziesii)* was common in both ecoregions and for this reason was not used as an indicator species. Only major tree species were included in the list for both ecoregions, but other species were present in lower abundances.

Fire-prone	Non fire-prone
• *Sequoia sempervirens*	• *Pseudotsuga menziesii*
• *Sequoiadendron giganteum*	• *Picea sp.*
• *Pinus sabiniana*	• *Abies sp.*
• *Pinus ponderosa*	• *Pinus contorta*
• *Pinus jeffreyi*	• *Tsuga mertensiana*
• *Pinus lambertiana*	• *Thuja plicata*
• *Pinus monticola*	• *Taxus brevifolium*
• *Pinus attenuata*	• *Acer macrophyllum*
• *Calocedrus decurrens*	
• *Juniperus occidentalis*	
• *Quercus chrysolepis*	
• *Notholithocarpus densiflorus*	

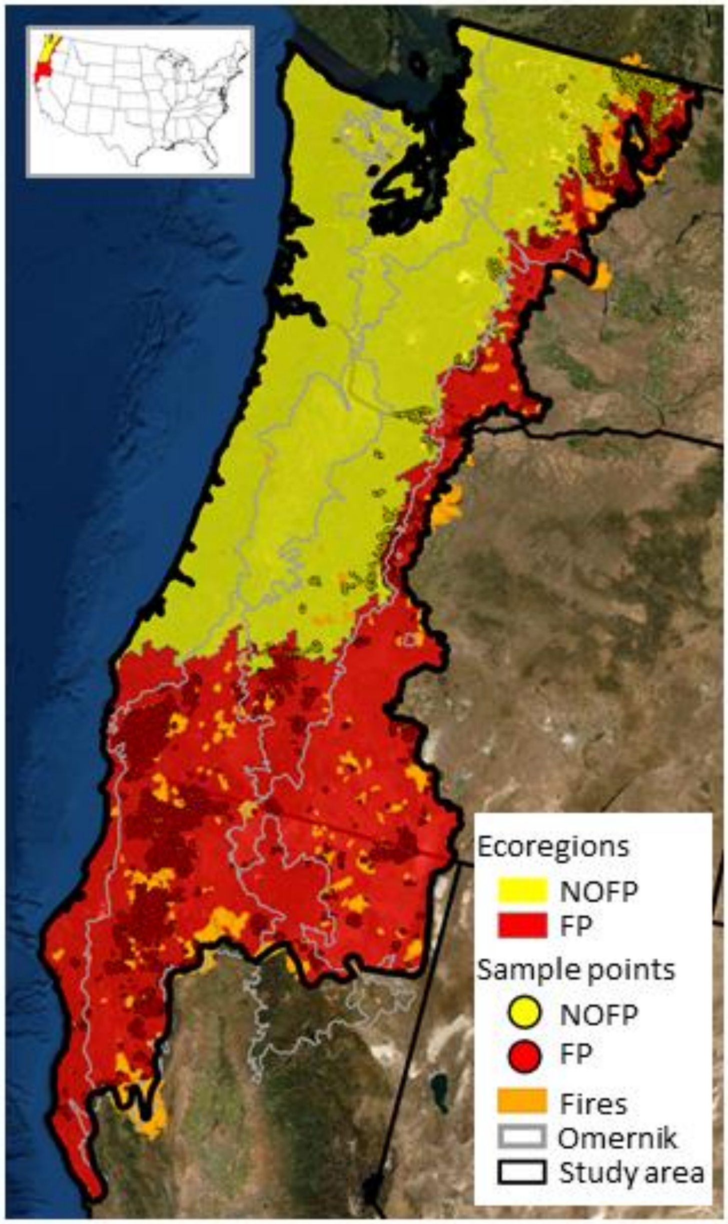


Figure 1. Study area map showing the study extent, ecoregional boundaries, sample pixels used for modeling, and study fires 2002-2017 included in our analysis. EPA level III ecoregions (Omernik 1987) are also displayed for comparison with ecoregions derived for this study. NOFP=non-fire-prone ecoregion; FP=fire-prone ecoregion.

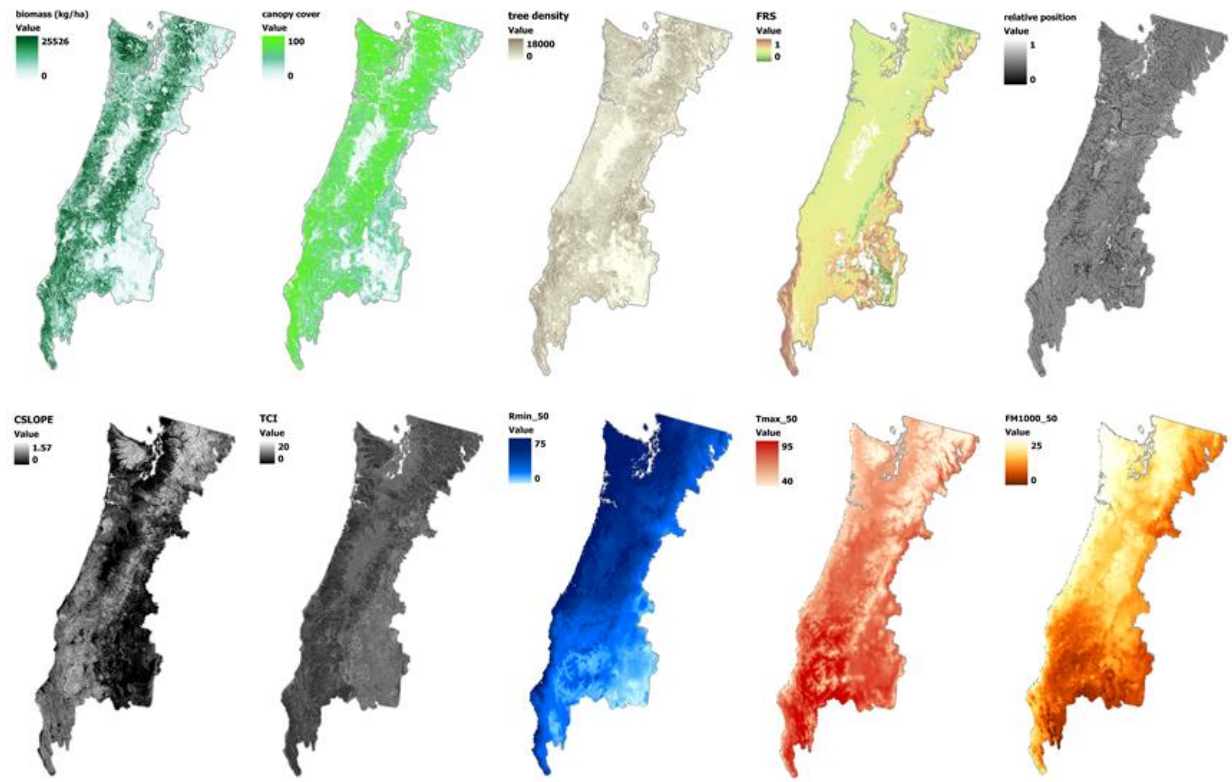


Figure 2. Raster surfaces for many of the top predictor variables in our final models. Note that the fire weather rasters depicted here are the pixel-wise 50th percentile calculations for time-varying variables used in the fire weather scenarios.

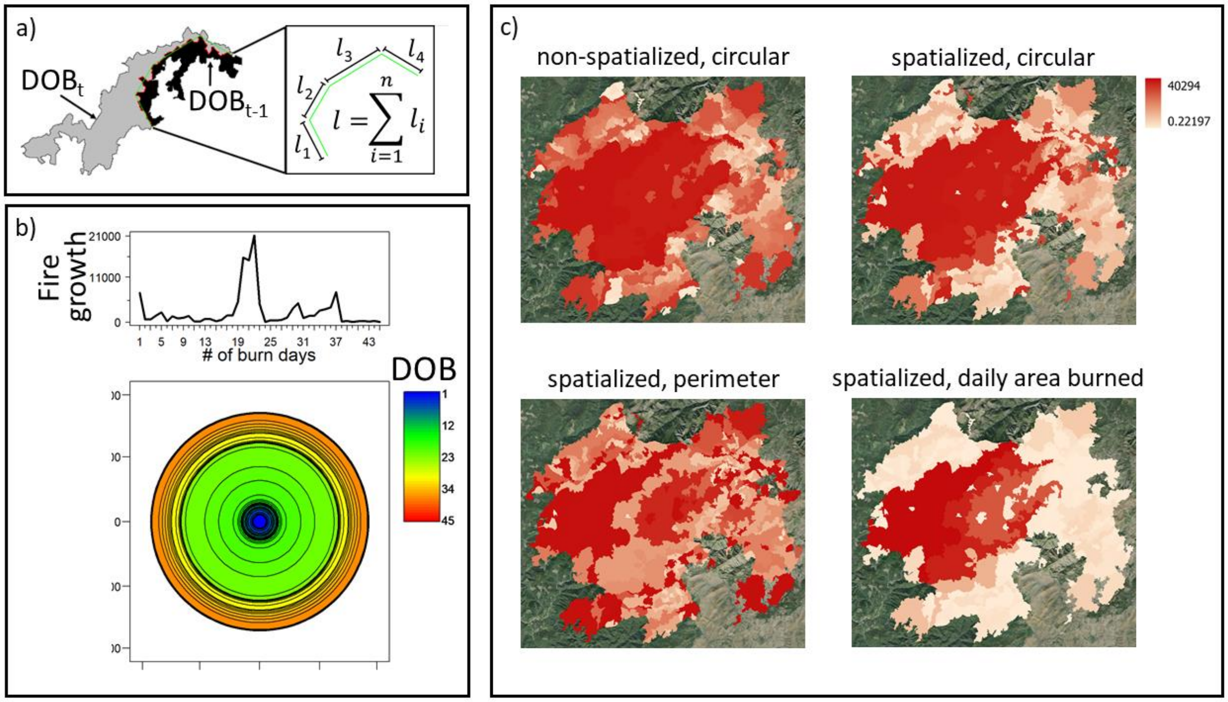


Figure 3. Fire growth characterization methods and outputs derived from analysis of daily fire progression maps. Panel (a) shows the daily fire perimeters for two consecutive days-of-burn, DOB_t and DOB_{t-1}. The inset shows the smoothed estimation method for the perimeter method. Panel (b) shows the non-spatialized circular method for conversion of daily area burned to planar fire growth for the Chetco Bar fire of 2017, along with a time series of the resulting daily fire growth patterns in the line graph above. Panel (c) shows rasters of the non-spatialized circular method (upper left) and spatialized circular (FG_CIRC, upper right), perimeter (FG_P_MEAN, lower left), and daily area burned (DAB, lower right) methods of fire growth characterization for the Chetco Bar fire.

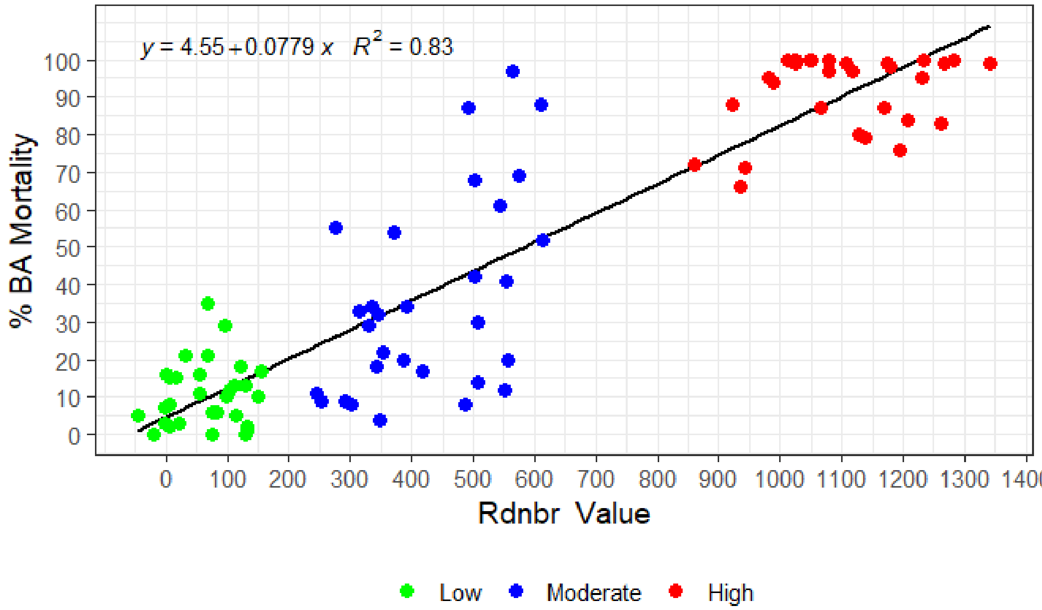
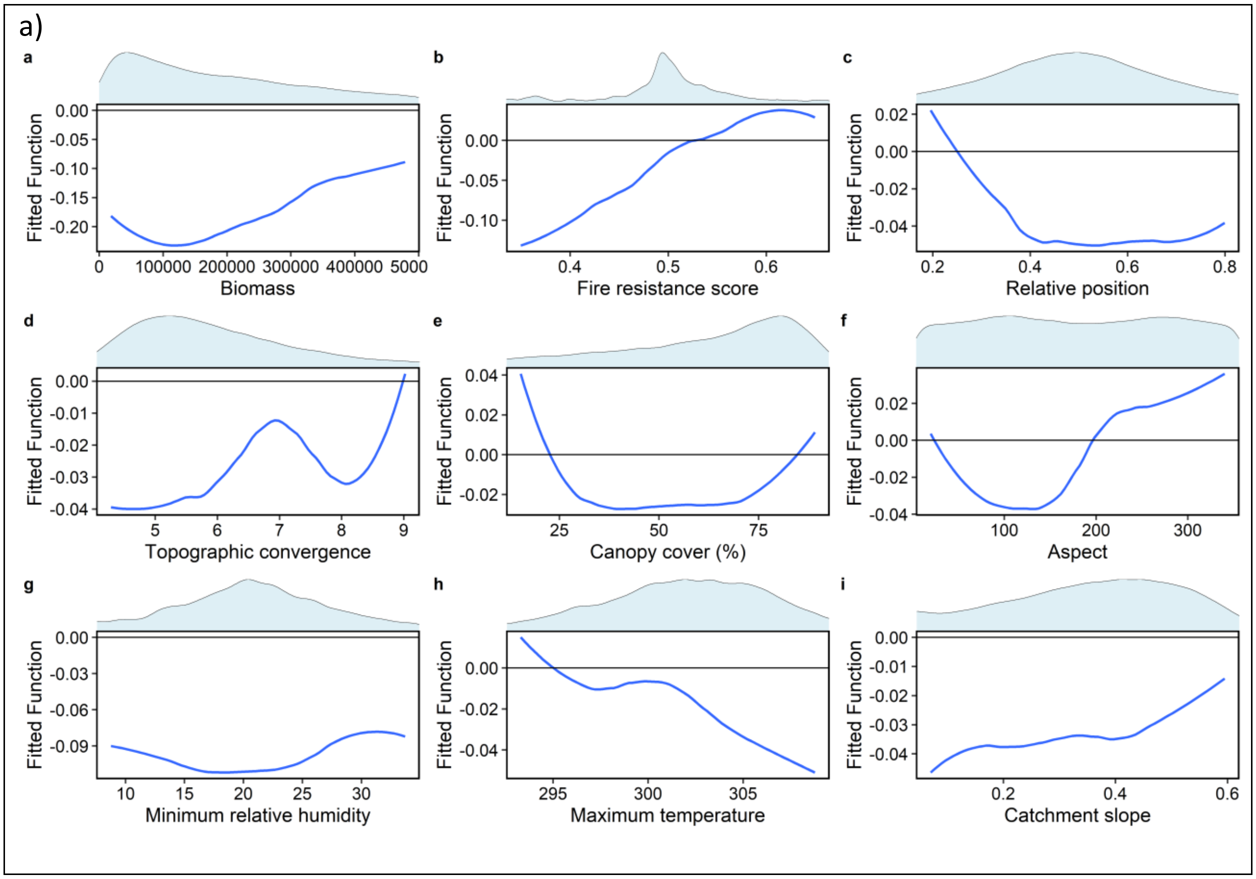


Figure 4. Field plot data of fire-caused percent basal area (BA) mortality versus Landsat RdNBR values color-coded for refugia, NSR and high-severity classes.


a)
a
b
c
d
e
f
g
h
i
Fitted Function
Biomass
Fire resistance score
Relative position
Topographic convergence
Canopy cover (%)
Aspect
Minimum relative humidity
Maximum temperature
Catchment slope

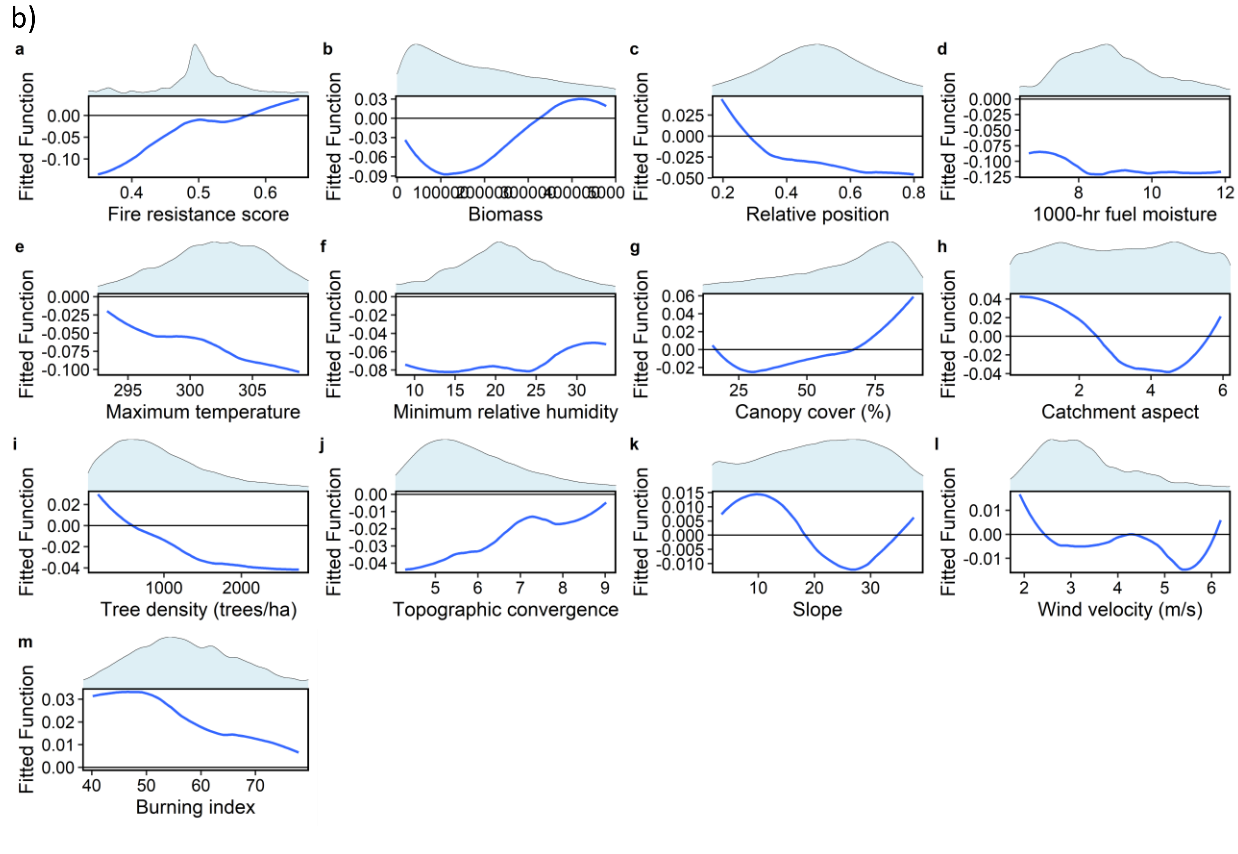
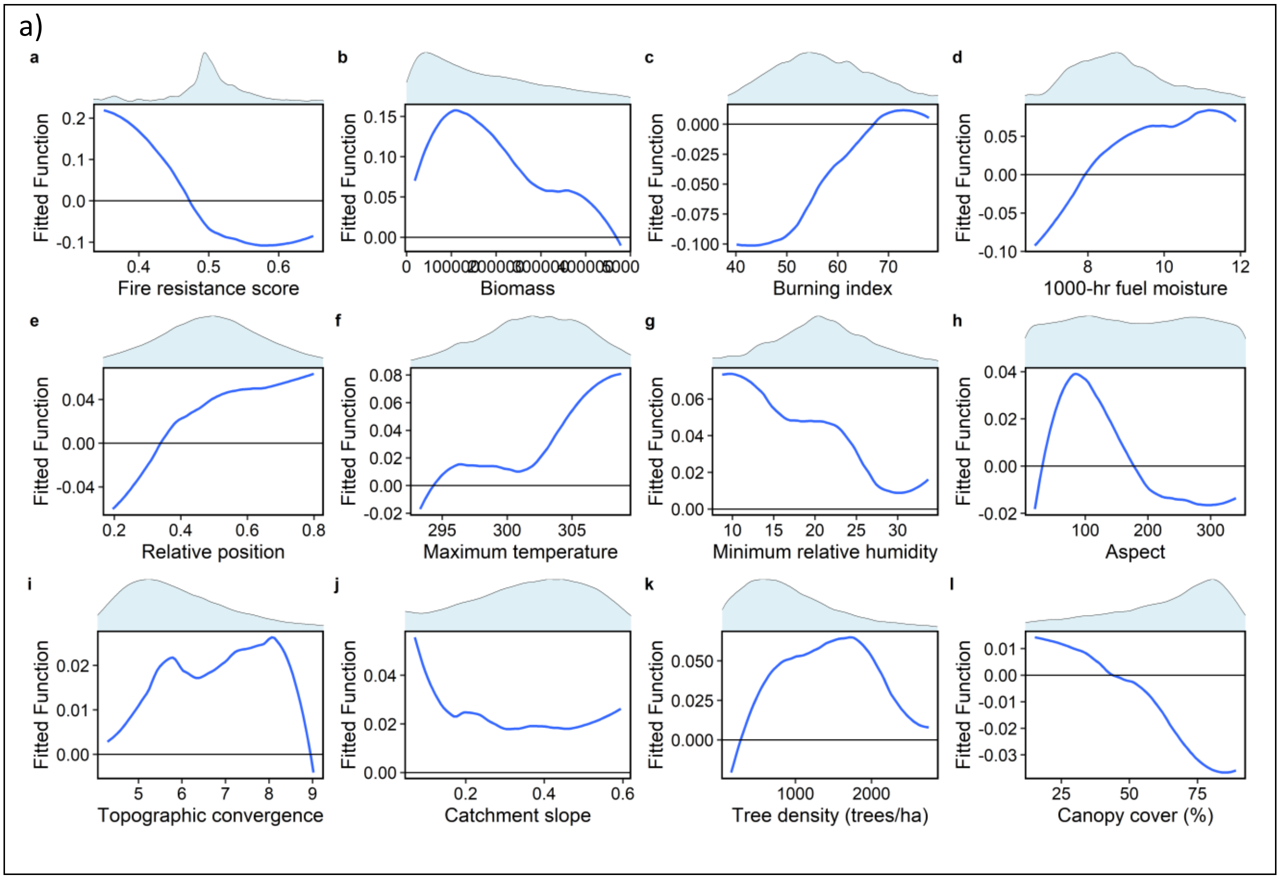


Figure 5. Partial dependence plots for refugia fire weather models for (a) the non-fire-prone and (b) fire prone ecoregions. Partial dependence plots show the conditional influence of each predictor variable on the refugia model, while holding all other predictors constant. Density plots above each panel show the data distribution of each predictor in our modeling dataset.



a)
a
b
c
d
e
f
g
h
i
j
k
l
Fitted Function
Fire resistance score
Biomass
Burning index
1000-hr fuel moisture
Relative position
Maximum temperature
Minimum relative humidity
Aspect
Topographic convergence
Catchment slope
Tree density (trees/ha)
Canopy cover (%)

b)

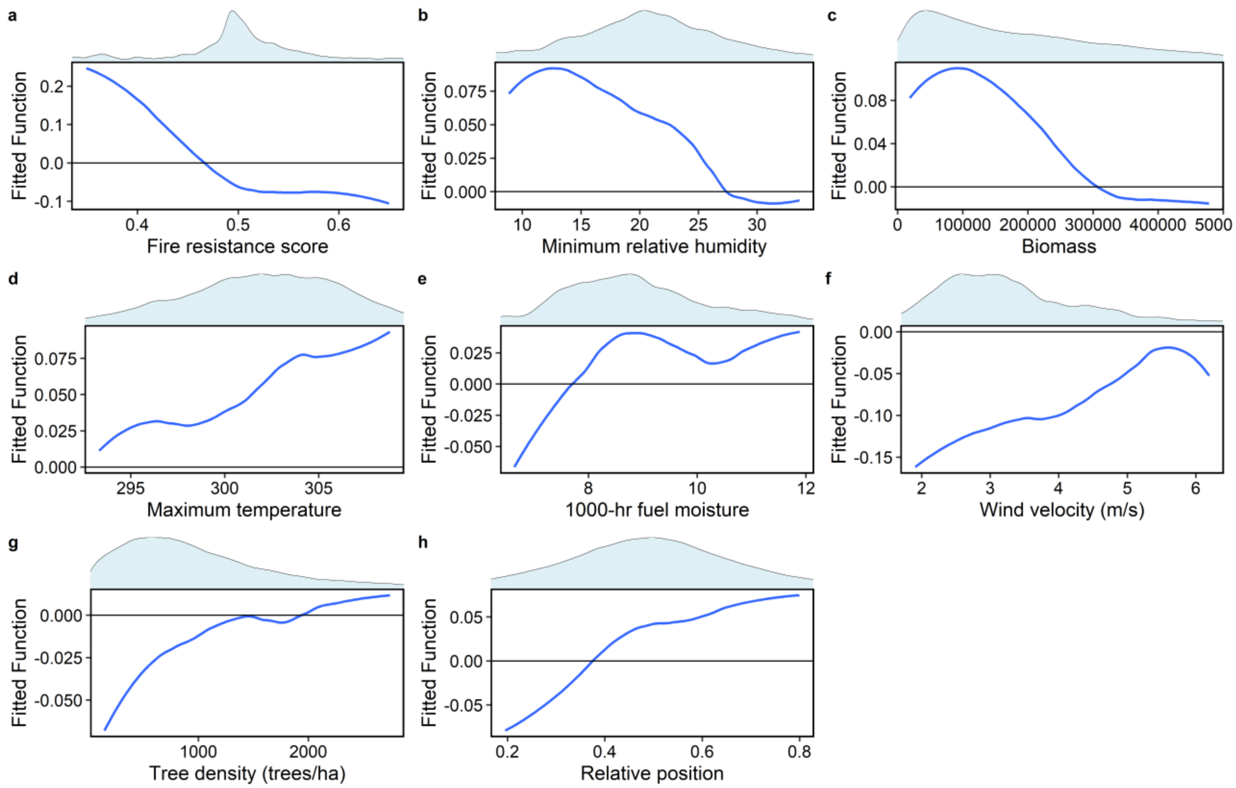


Figure 6. Partial dependence plots for high-severity fire weather models for (a) the non-fire-prone and (b) fire prone ecoregions. Partial dependence plots show the conditional influence of each predictor variable on the high-severity model, while holding all other predictors constant. Density plots above each panel show the data distribution of each predictor in our modeling dataset.

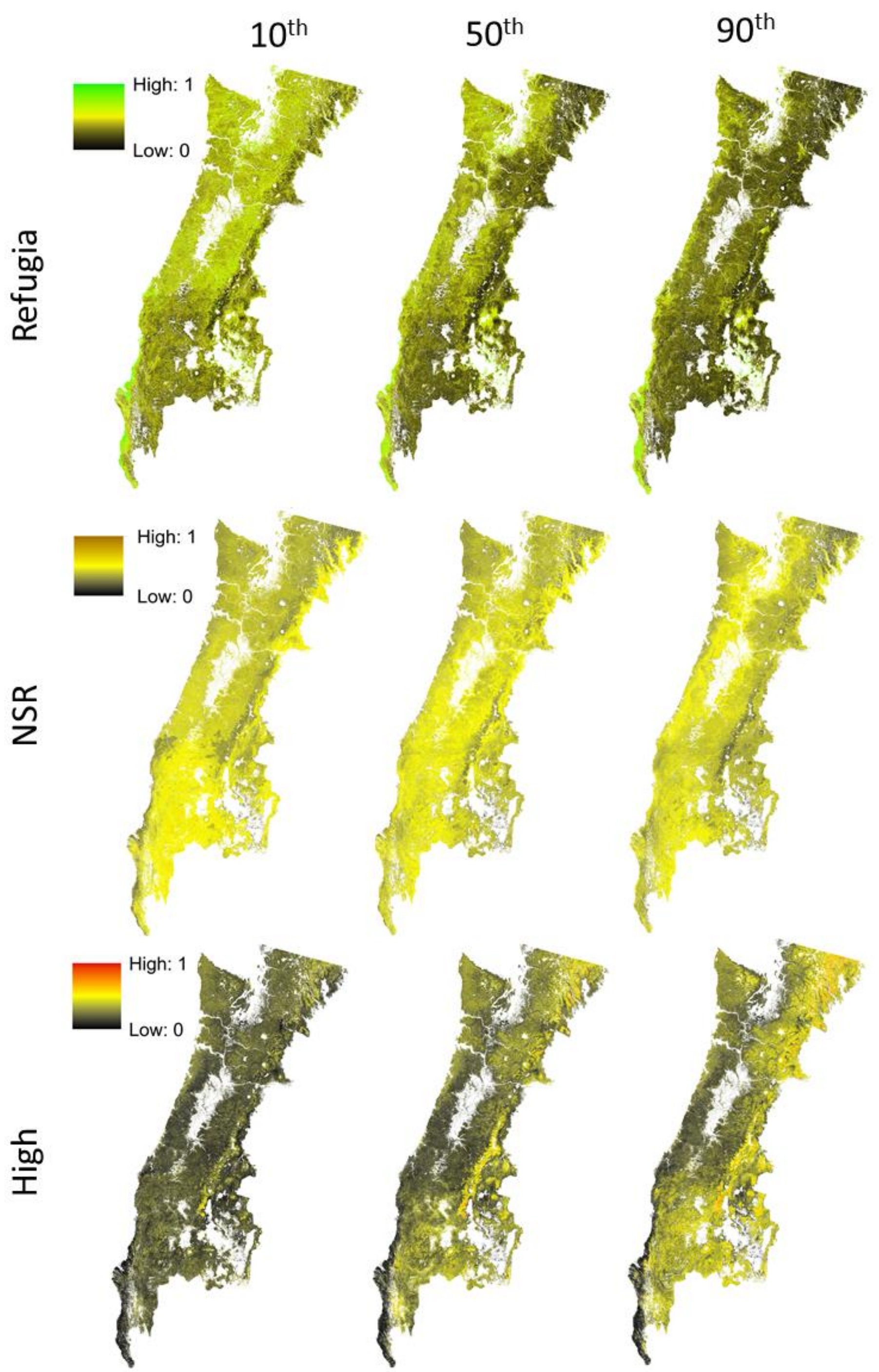


Figure 7. Probability surface maps of fire refugia, NSR severity, and high-severity under low (10th percentile), moderate (50th percentile), and extreme (90th percentile) *fire weather conditions* over the period 1986-2018 based on models with no fire growth term. Fire weather scenarios were driven by TMMX and RMIN, the most consistently ranked top fire weather variables across all model runs, except for NSR models, where FM1000 was used in place of TMMX.

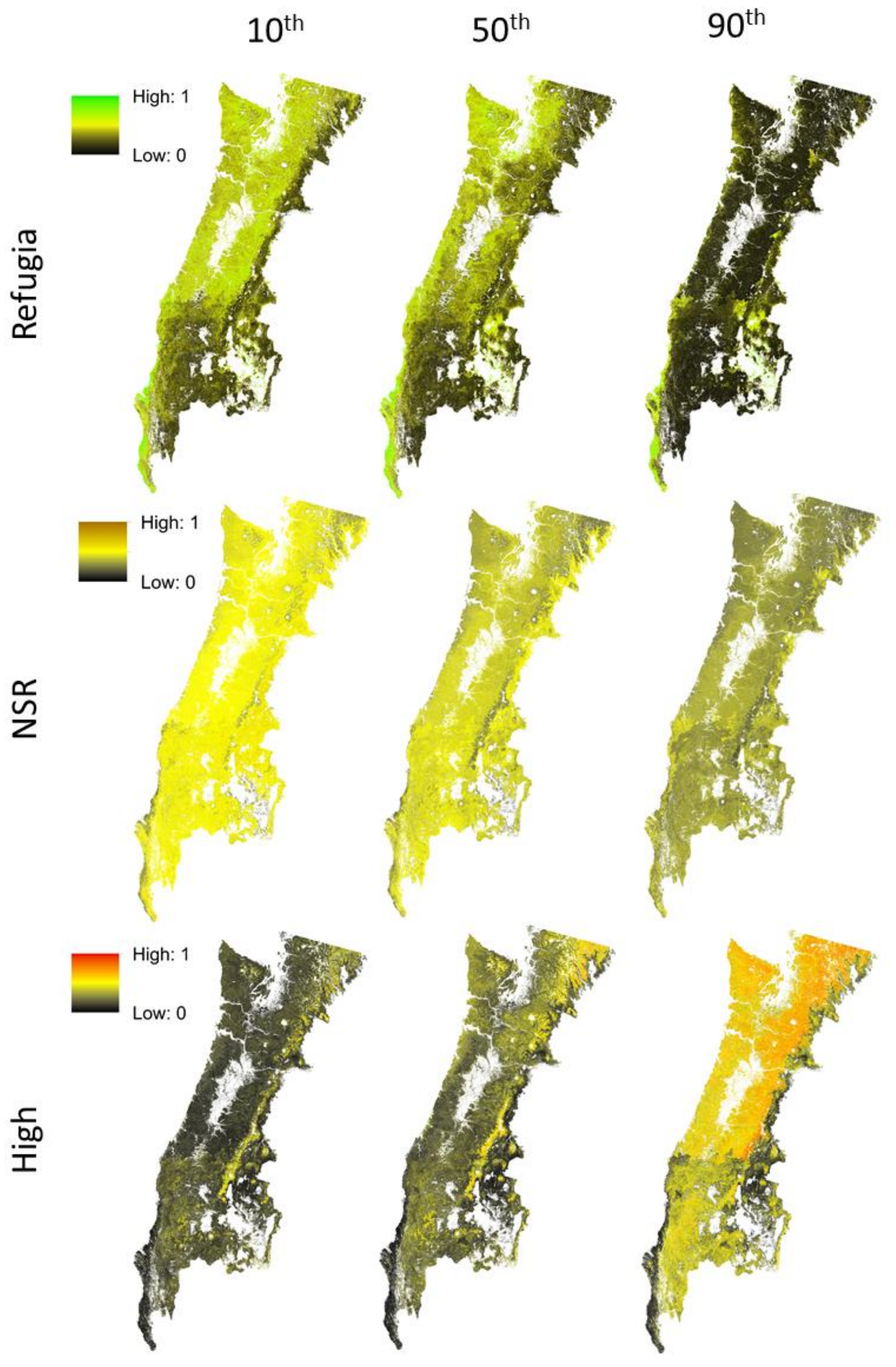


Figure 8. Probability surface maps of fire refugia, NSR severity, and high-severity under low (10th percentile), moderate (50th percentile), and extreme (90th percentile) *fire growth and weather conditions* over the period 2001-2017 and 1986-2018, respectively. DAB and RMIN were the two top time-varying predictors in these model runs.

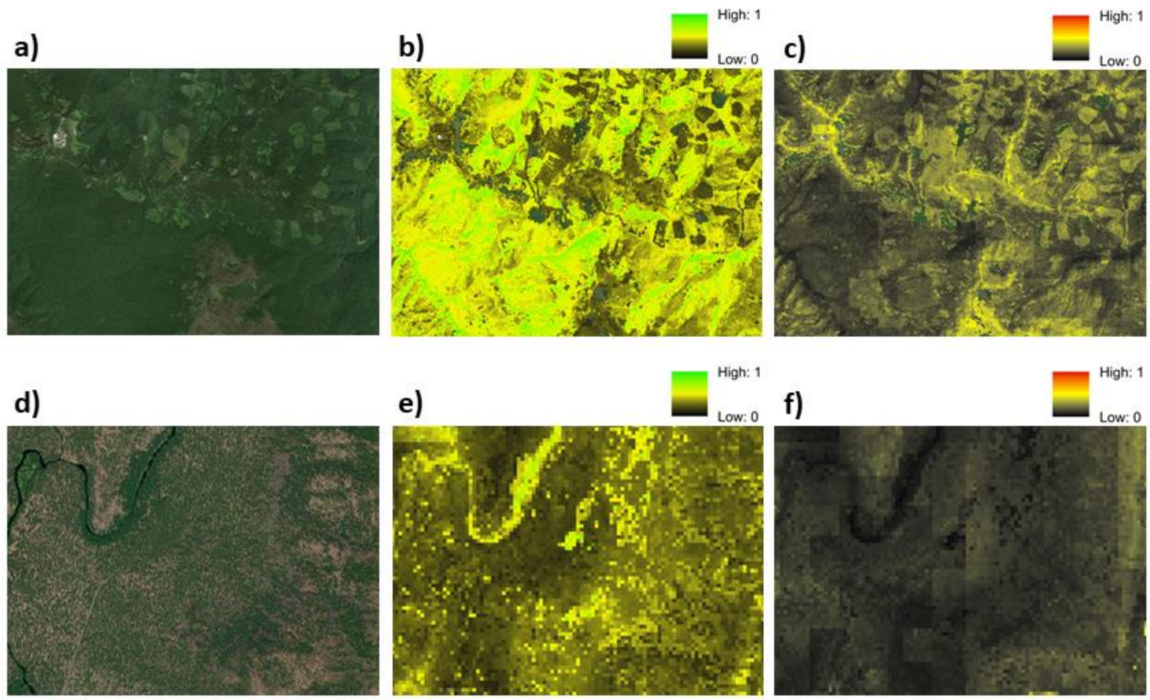


Figure 9. Mid-scale view of an area in the (a-c) non-fire-prone ecoregion and (d-f) fire-prone ecoregion, showing (a,d) an true color satellite image, (b,e) modeled fire refugia, and (c,f) modeled high severity fire probability. In the non-fire-prone ecoregion, note the concentration of refugia along low-lying topographic positions and the long-term reduction of refugial probability resulting from past timber harvest. In the fire-prone ecoregion, note the fine-scale spatial patterning of refugia, the prevalence of intermediate refugial probability, and the low probability of high severity fire.

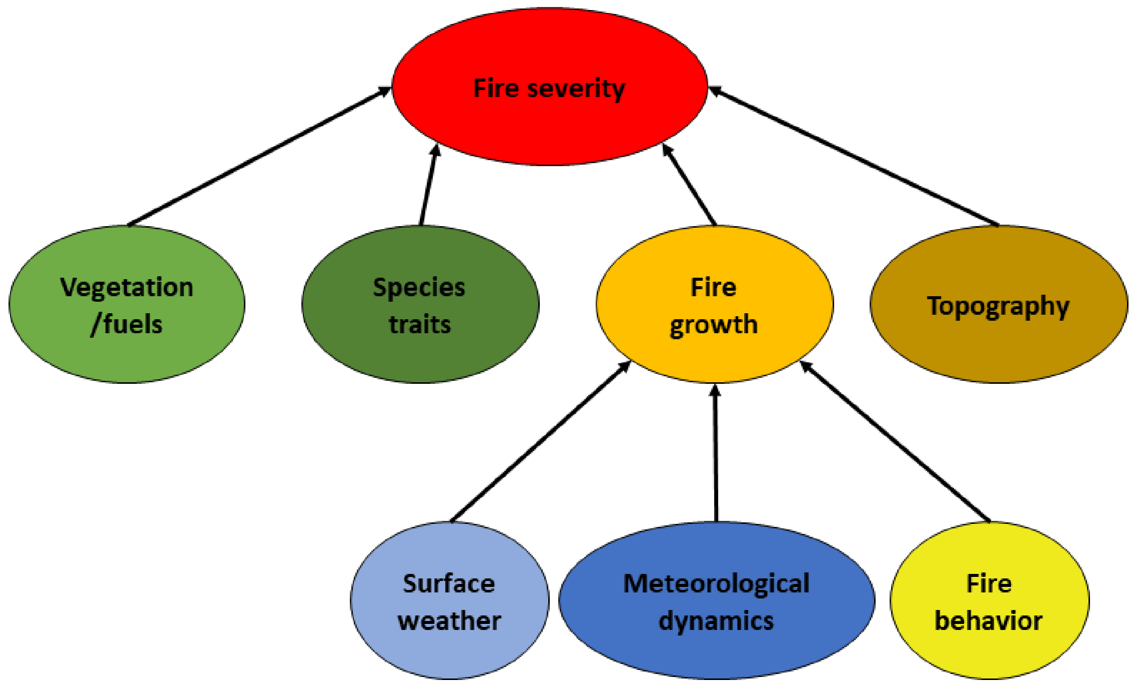
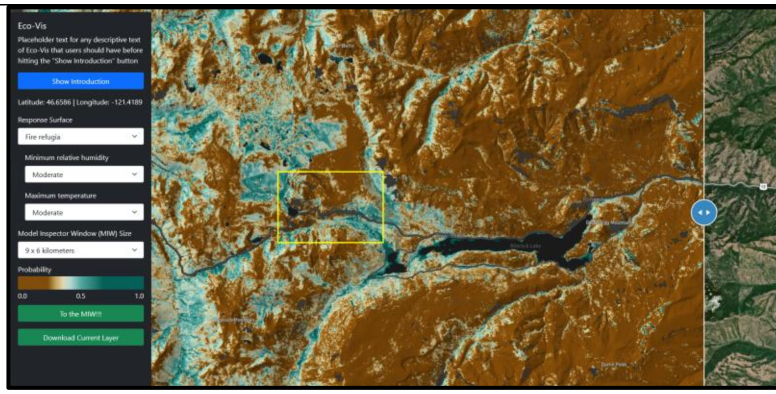


Figure 10. Conceptual model of the nested drivers of fire growth and fire severity. In this model, fire growth is strongly driven by the proximal influences of surface weather, meteorological dynamics, and fire behavior. Fire severity, in turn, is driven by vegetation characteristics, fire growth, and topography.



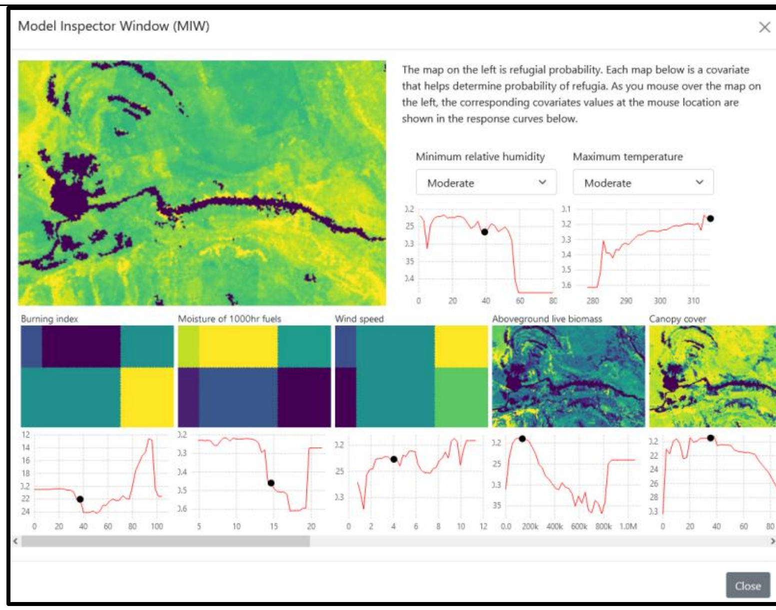


Figure 11. Screen captures of *Eco-Vis (*https://firerefugia-app.forestry.oregonstate.edu/projects/latest), showing (upper panel) the navigation pane, which permits selection and exploration of probability surface maps, and (lower panel) model inspection viewer that links model response curves and geospatial predictor data to a user-selected inset of the probability surface map and exploration of probability response surface changes under different fire weather scenarios.