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Wildfire Exposure Analysis on the National Forests in the Pacific Northwest, USA

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We analyzed wildfire exposure for key social and ecological features on the national forests in Oregon and Washington. The forests contain numerous urban interfaces, old growth forests, recreational sites, and habitat for rare and endangered species. Many of these resources are threatened by wildfire, especially in the east Cascade Mountains fire-prone forests. The study illustrates the application of wildfire simulation for risk assessment where the major threat is from large and rare naturally ignited fires, versus many previous studies that have focused on risk driven by frequent and small fires from anthropogenic ignitions. Wildfire simulation modeling was used to characterize potential wildfire behavior in terms of annual burn probability and flame length. Spatial data on selected social and ecological features were obtained from Forest Service GIS databases and elsewhere. The potential wildfire behavior was then summarized for each spatial location of each resource. The analysis suggested strong spatial variation in both burn probability and conditional flame length for many of the features examined, including biodiversity, urban interfaces, and infrastructure. We propose that the spatial patterns in modeled wildfire behavior could be used to improve existing prioritization of fuel management and wildfire preparedness activities within the Pacific Northwest region.

KEY WORDS: Burn probability; exposure analysis; national forests; risk assessment; wildfire risk

1. INTRODUCTION

Wildfires cause widespread social, economic, and environmental damage in much of the world, burning in excess of 350 million ha annually in some years.(1) Loss of human life, residential structures, utilities, public assets, and critical habitat for endangered species are all specific examples of features impacted by wildfires. The application of risk science to analyze wildfire impacts is relatively new compared to other natural disturbances, and the demand for quantitative risk-based tools and assessments has grown dramatically in recent years as impacts from wildfires on human and ecological resources continue to escalate.(1) Many government entities are engaged in risk assessments and decision support modeling to map wildfire risk and prioritize investments for fire protection and fuel management. There are many recent efforts to build risk frameworks and conduct assessments in fire prone regions around the world.(2–10) Researchers in the United States in particular have advanced risk-based assessment tools to support a wide range of fire and fuel management planning from individual wildfire incidents to national,

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strategic interagency programs.[11–13] These latter advances have been fueled by new simulation systems that can help estimate wildfire likelihood for large (10,000–200,000 ha), highly stochastic wildfire events[14] that leverage large geospatial datasets on fuel,[15] weather,[16] and social and ecological features.[6] Large wildfires account for the majority of area burned and damaged in the United States,[11] and thus modeling their potential effects is important in risk assessments.

Using large fire simulation methods, quantitative and probabilistic risk assessments have now been demonstrated at a range of scales for management applications in the United States on the 77 million ha national forest network.[17–19] These assessments quantified risk as:

$$E(Lj) = \sum_i p(f_i) RF_j(f_i), \qquad (1)$$

where:

$p(f_i)$ = probability of a fire at intensity level i
$RF_j(f_i)$ = response function for resource j at fire intensity level i, and
$E(Lj)$ = expected loss for resource j.

The formula can be modified to consider a net value change rather than only losses to account for beneficial fire effects in fire adapted ecosystems.

Despite new advances in wildfire risk-based assessment tools, there remain many barriers to incorporating risk analyses into agency decisions regarding fuel management priorities.[12] The most recent federal legislation regarding fuel management priorities has called for increased use of risk-based methods.[20–22] The current process for allocating the ca. 340 million USD annual investment for fuel management activities among the 10 Forest Service Regions is guided by a comprehensive decision support system loss[23] that avoids explicit calculation of expected loss, and is prone to adjustments to meet objectives other than mitigating wildfire risk.[23:2379] A larger problem is that downscaling regional budgets to national forests and districts within forests use a wide range of ad hoc methods, none of which is tiered to a comprehensive risk assessment. Although several risk assessment systems have been proposed,[24,25,17] none has been fully adopted by land management agencies as a replacement for ad hoc methods for prioritizing funding for fuel management projects. Part of the adoption issue is that none of the proposed systems clearly interprets, risk assessment outputs (hazard, likelihood, susceptibility) in terms of specific landscape fuel management strategies[26] to mitigate risk.

In this article, we used wildfire simulation modeling to analyze spatial variation in wildfire exposure to an array of social and ecological features within and adjacent to the national forests in the Pacific Northwest, USA. We define exposure analysis[27] as the exploration of predicted scale and spatiotemporal relationships of causative risk components. Wildfire exposure analysis is a necessary step in risk assessment, but does not include explicit quantification of wildfire-related loss. The primary goal of the work is to demonstrate the broad application of risk science for the specific purpose of prioritizing fuel management activities in the region. Wildfire occurrence is substantial on the national forests, with approximately 1.2 million ha burned between 1992 and 2009. Fuel reduction activities are a major component of the management activities, with annual investments of about 29.4 million USD (between 2002 and 2010) for treatments on roughly 68,000 ha (0.7%). The current fuel budget allocation among the forests is based on coarse evaluations of the current fire exposure and the prior year's budget. In contrast to previous studies in other regions and countries, we specifically examined risk components posed by large, naturally ignited fires (>100 ha), rather than small fires of anthropogenic ignitions.[4,28,3] We first summarized recent historical fire data to examine baseline variation among the forests in ignition frequency and burn probability. These historical fire data in relation to fuel reduction investments were used to understand the broad relationship between fuel management funding and historic wildfire exposure. We then quantified risk components (Table I) from simulation outputs to examine the current wildfire exposure to key social and ecological features in the study area. Variation in risk components among forests and features was then examined in the context of prioritizing fuel treatment investments, and developing specific landscape fuel treatment strategies for managing wildfire risk.

2. METHODS

2.1. Study Area

The primary study area consisted of the 16 national forests (10.6 million ha) in Oregon and Washington, USA (hereafter Region; Fig. 1). We included the adjacent wildland urban interface (SILVIS WUI[29]) within 5 km of a national forest

Table I. Definitions of Risk Components to Describe Wildfire Exposure

Risk Factor		Definition	Type
BP	Burn probability	Annual likelihood of burning given a random ignition in the study area.	Likelihood
HIBP	High intensity burn probability	Annual likelihood of burning at high intensity (>2.4 m flame length).	Likelihood/Intensity
CFL	Conditional flame length	Average flame length given a fire occurs.	Hazard
AHHAZ	Area high hazard	Annual area exposed to high intensity (>2.4 m flame length) fire given a fire occurs.	Hazard
AHE	Area high exposure	Annual area exposed to high intensity fire (>2.4 m flame length).	Risk

Notes: Components were quantified on a pixel (270 × 270 m) basis and then summarized for selected features listed in Table III.

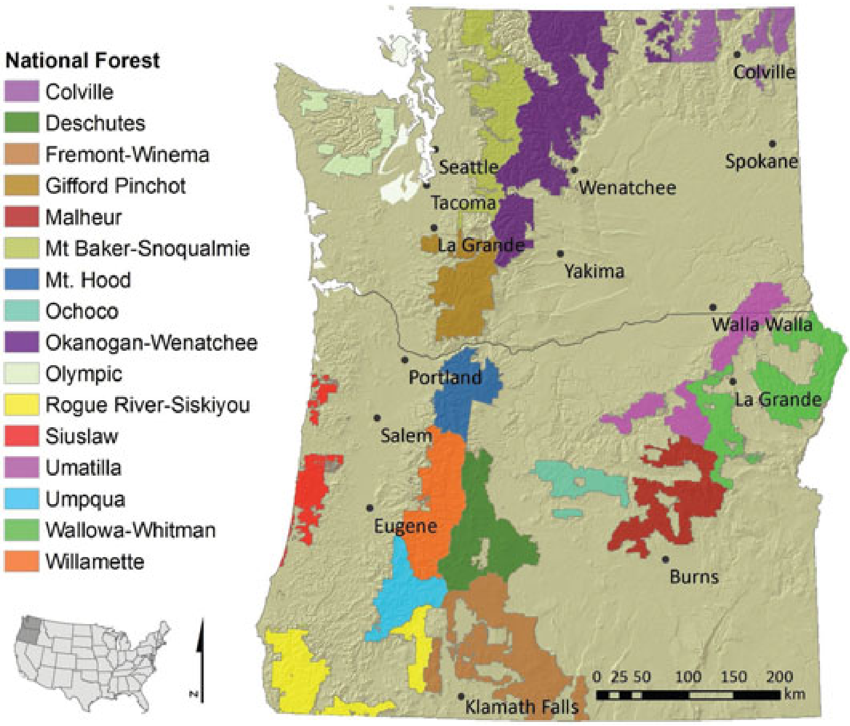

Fig. 1. Vicinity map of the study area and national forest boundaries in Oregon and Washington.

boundary for a separate analysis of wildfire exposure to human populations (0.5 million ha). About 9.6 million ha of the national forest land is classified as burnable according to Landfire data.[15] The forest network is divided by the Cascade Mountain range into two major ecological types, with primarily dry pine forests to the east, and wetter, mixed conifer forests to the west. The forests have been subjected to several recent biological assessments[30–33] concerning threats to an array of ecologically important features.

2.2. Fire History Analysis

We obtained a fire history database from the Fire Program Analysis[34] that was developed for fire simulation research[14] from federal and state agency fire suppression records. These data consisted of ignition location, date, final fire size, and a number of other attributes. We summarized burned area and fire occurrence as a function of fire size and ignition type (lightning versus anthropogenic). We also related ignitions and area burned to total fuel treatment investments. The latter data were obtained from administrative reports from Fire and Aviation Management in the Pacific Northwest Region office in Portland, Oregon (L. Mayer). Empirical burn probability was calculated as the annual area burned as a proportion of the total burnable area.

2.3. Estimation of Wildfire Risk Components

We estimated spatially explicit wildfire likelihood and intensity estimates using simulation methods (FSIM model).[14] The simulations were performed as part of the Fire Program Analysis.[34] In general, the FSIM program generates daily wildfire scenarios for a large number of hypothetical wildfire seasons using relationships between the historical energy release component (ERC) and fire occurrence. The wildfires are then simulated using synthetic weather streams derived from time series analysis of historical weather. The ERC and weather data are derived from local weather stations. FSIM uses the MTT algorithm to calculate fire growth by Huygens's principle where the growth and behavior of the fire edge is modeled as a vector or wave front.[35,36] Rates of fire spread and crown fire initiation are predicted by the appropriate fire behavior equations.[37,38] Surface and canopy fuel data were obtained from the national Landfire data grid.[15] The surface fuel data consisted of stylized fuel models as described elsewhere.[39] Although the fire behavior models incorporated into FSIM are widely used, it is important to recognize their limitations.[40,41] The main issue is that they represent fire behavior using quasi-empirical equations that do not account for fire-atmospheric interactions, and do not model fuel combustion and heat transfer processes. Another major concern is the modeling of crown fire, a process that is poorly understood.[42,40] Despite these limitations, extensive application has demonstrated that the Huygens's principle and the MTT algorithm can be used to replicate large fire distributions and perimeters over a range of fuel types and weather conditions.[43–48,14,49] The modeled outputs include raster data on annual burn probabilities (BPs) and expected fire intensity. The components of the models and major assumptions are briefly described below, while more detailed descriptions can be found elsewhere.[14]

The simulations were stratified by the 17 federal interagency fire planning units (FPU) within the study area as per the protocol for FPA. Most national forests were contained within a single FPU, except for the Malheur, which spanned two. Weather data were derived from one remote automated weather station (RAWS)[16] per FPU. The station was selected based on local Forest Service fire staff recommendations. For each FPU, the daily probability of a fire was predicted by logistic regression of historical fire occurrence and ERC over 20 years of weather data.[14] The weather stream for each simulated fire was generated using the results of a time series analysis of daily RAWS weather data.[14] Specifically, estimates were derived for the seasonal trends, the autocorrelation (dependency of a day's ERC value on previous days), and the daily standard deviation. These estimates were then used to generate synthetic daily weather streams for each day of simulation. Wind data (speed by direction) were also derived from the RAWS stations and tabulated by month as a joint probability distribution. The resulting distribution was then randomly sampled to obtain daily wind data. Selected weather stations had a minimum of 20 years of weather data and were judged to best reflect fire weather and seasonal and daily climatology for the FPU.

We assumed random ignition locations for simulated fires, consistent with FPA large fire simulation methods.[14] Large fire events within the study area have been primarily caused by lightning (Fig. 2), and there are insufficient large fire incidents to detect spatial patterns if they existed. Each fire's growth and behavior were simulated from its ignition day through the remainder of the season, or until containment was achieved as predicted based on historical large fires and their recorded sequence of daily activity.[50] The containment model was developed from an analysis of the daily change in fire size to identify intervals of high spread and low spread for each fire. The containment probability model was found to be positively related to periods of low fire spread.[50]

Fire simulations were performed at 270×270 m pixel resolution, a scale that permitted relatively fast simulation times and incorporated important spatial variation in fuel data. Outputs from FSIM consisted of the annual burn probability in six flame length (FL) classes (Table II). These outputs were used to calculate several secondary risk components as described below. Simulations were completed on a farm of 64 bit SMP workstations located at the EROS Data Center in Sioux Falls, South Dakota.

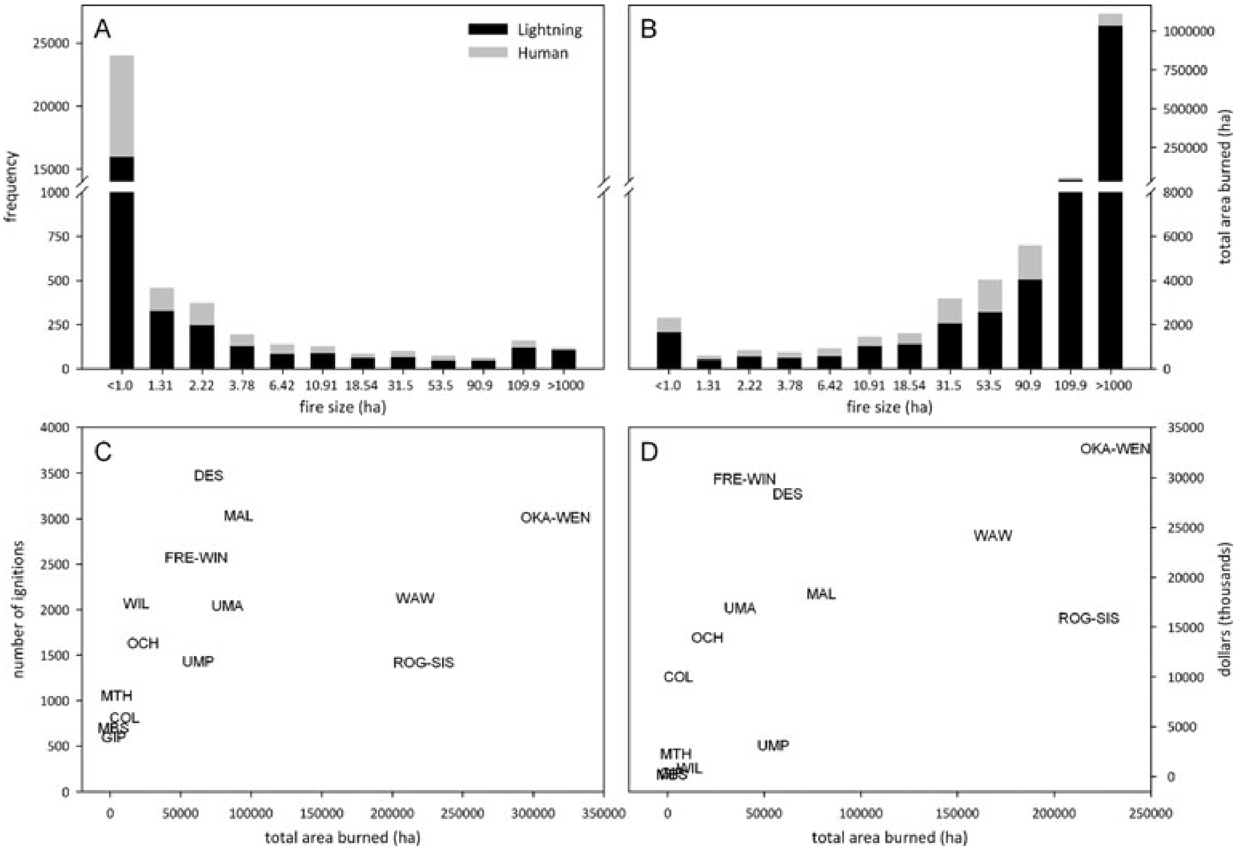

Fig. 2. Historical fire size by (A) frequency, and by (B) total area burned between 1992 and 2009 for lightning and human caused fires; and total area burned by (C) number of ignitions, and by (D) fuel treatment expenditures between 2000 and 2009 for the national forests in Oregon and Washington. Note breaks in *y*-axes. COL = Colville, DES = Deschutes, FRE-WIN = Fremont-Winema, GIP = Gifford Pinchot, MAL = Malheur, MBS = Mt. Baker-Snoqualmie, MTH = Mt. Hood, OCH = Ochoco, OKA-WEN = Okanogan-Wenatchee, ROG-SIS = Rogue River-Siskiyou, UMA = Umatilla, UMP = Umpqua, WAW = Wallowa-Whitman, WIL = Willamette.

Table II. Flame Length Class Categories

Flame Length Category	Range (m)	Midpoint (m)
FIL1	0 to 0.6	0.31
FIL2	0.6 to 1.22	0.91
FIL3	1.22 to 1.8	1.52
FIL4	1.8 to 2.4	2.13
FIL5	2.4 to 3.7	3.05
FIL6	3.7+	3.7

Notes: Definitions of flame length class as defined in the Fire Program Analysis.[34] Flame length was calculated from fireline intensity outputs from FSIM.[14] The upper break point for flame length category FIL4 (2.4 m) was used as the threshold to define high hazard and high exposure. The midpoint for FIL6 was chosen as the lower end of the FIL6 range.

Validation of the fire simulations were examined in several ways. As noted above, individual fire perimeters have been replicated under a range of conditions in several previous studies. A comparison of historical versus predicted fires was described as part of the FSIM model validation.[13] Although refinements to FSIM and the input data continue within the federal wildfire management agencies, the outputs used in the current study are adequate for demonstrating methods to map variation in wildfire exposure and the broad application for risk assessment for fuel management planning.

2.4. Spatial Data on Infrastructure, Urban Interface, and Biodiversity

We obtained data on eight features that described infrastructure, urban interface, and biodiversity within the study area. These features were selected based on their importance to wildland fire protection goals in the Forest Service, and the

Table III. Data Layers on Social and Ecological Features Included in the Study

Theme	Feature class	Source
Infrastructure	Utilities	USDA Forest Service (FS) FSGeodata Clearinghouse-Vector Data Gateway http://fsgeodata.fs.fed.us/vector/index.html
	Developed Sites	USDA Forest Service (FS) FSGeodata Clearinghouse-Vector Data Gateway http://fsgeodata.fs.fed.us/vector/index.html
	Constructed Features	USDA Forest Service (FS) FSGeodata Clearinghouse-Vector Data Gateway http://fsgeodata.fs.fed.us/vector/index.html
	Recreation Areas	USDA Forest Service (FS), FSGeodata Clearinghouse- Vector Data Gateway http://fsgeodata.fs.fed.us/vector/index.html
Urban Interface	Wildland Urban Interface	University of Wisconsin – Madison http://silvis.forest.wisc.edu/maps.asp
Biodiversity	Riparian Habitat Conservation Areas	Pacific Northwest Research Station – USFS http://www.icbemp.gov/
	Spotted Owl Home Range	Northwest Forest Plan Interagency Regional Monitoring Program http://www.reo.gov/monitoring/data-mgt-plan/index.shtml
	Threatened, Endangered, & Sensitive Plant Sites	USDA Forest Service (FS) Data not available for public download

availability of consistent data over the study area (Table III). Data were summarized by district and feature type (or species name where appropriate). Details regarding the data sources and definitions follow.

2.4.1. *Infrastructure*

Infrastructure included utilities, developed sites, constructed features, and recreation sites. Data were obtained from the Automated Lands Program (ALP) operated by the Forest Service in cooperation with the BLM. Data were downloaded in February 2010. Utility data included water lines, communication lines and sites, power lines, pipelines, and transmission lines, and consisted of 999 point and polygon features. Developed sites were land parcels developed for specific nonrecreational purposes, including Forest Service ranger stations, guard stations, lookouts, and administrative sites, and included 481 polygons. Constructed features are nonrecreational sites and included dams, reservoirs, fences, and similar features. Each site was buffered 1.6 km (1 mi) to include land around the site that could potentially influence wildfire risk and included 221 polygons. Recreation infrastructure depicts areas where legal restrictions or rights exist for regulating general recreational use and included 707 polygons. The data do not distinguish developed and primitive campgrounds.

2.4.2. *Urban Interface*

We obtained spatial data on the WUI from the University of Wisconsin Silvis project.[29] The WUI data included both interface and intermix communities (Table IV). Intermix areas have continuous vegetation of more than 50% of the area and more than one house per 10 ha (25 ac). Interface areas have housing in the vicinity of contiguous vegetation with a density >1 house per 16 ha (40 acres), and less than 50% vegetation, and are within 2.4 km (1.5 mi) of area that is more than 75% vegetated. The University of Wisconsin Silvis project buffered interface areas 2.4 km (1.5 mi) to account for the spread of firebrands. We included all WUI lands within a 5 km buffer from national forest lands.

2.4.3. *Biodiversity*

Spatial data were obtained for key biological conservation reserves in the study area, including: (1) riparian habitat conservation areas (aquatic) delineated for the protection of bull trout and steelhead,[32] (2) northern spotted owl home range,[33] and (3) designated populations of threatened and endangered plant species (USFS Region 6 Data Resource Management).

Riparian habitat conservation areas (aquatic) are buffers around streams and rivers to protect critical habitat for a number of anadromous fish species, including steelhead trout (*Onchorynchus*

Table IV. Wildland Urban Interface Categories and Definitions

Description	Proximity to vegetation	Attribute value
Low density interface: Areas with housing density ≥ 6.177635 (housing units/km^2) and <49.42108 (housing units/km^2), vegetation ≤ 50%, within 2.414 km of an area with ≥ 75% vegetation.	Interface	Low_Dens_Interface
Medium density interface: Areas with housing density ≥ 49.42108 and <741.3162, vegetation ≤ 50%, within 2.414 km of an area with ≥ 75% vegetation.	Interface	Med_Dens_Interface
High density interface: Areas with housing density ≥ 741.3162, vegetation ≤ 50%, within 2.414 km of an area with ≥ 75% vegetation.	Interface	High_Dens_Interface
Low density intermix: Areas with housing density ≥ 6.177635 and <49.42108, vegetation >50%.	Intermix	Low_DensyIntermix
Medium density intermix: Areas with housing density ≥ 49.42108 and <741.3162, vegetation >50%.	Intermix	Med_Dens_Intermix
High density intermix: Areas with housing density ≥ 741.3162, vegetation >50%.	Intermix	High_Dens_Intermix
Very low density with vegetation: Areas with housing density >0 and <6.177635, vegetation >50%.	Non-WUI	Very_Low_Dens_Veg
Uninhabited with vegetation: Areas with housing density = 0, vegetation ≥ 50%.	Non-WUI	Non-WUI

Notes: Definitions as defined by the SILVIS[(29)] data.

mykiss gairdneri) and bull trout (*Salvelinus confluentus*). Management activities are generally prohibited and subject to review by the National Marine Fisheries Agency for compliance with habitat conservation objectives. The conservation reserves were established in 1995 when the Forest Service and Bureau of Land Management[(51)] signed two decisions that altered how aquatic habitat was managed within the Interior Columbia Basin.[(32)] Aquatic habitat was defined by a 121.5 m (398.6 ft) buffer on each side of the stream for fish bearing streams, and a 60.75 m buffer for permanently flowing nonfish bearing streams and wet areas greater than 0.4 ha. Aquatic areas were mapped by each forest district, resulting in 42,789 polygons.

Northern spotted owl home ranges were obtained from the USDA Forest Service (Ray Davis, USDA-FS, personal communication 2010). Home range size varied by the location within an owl province according to the methodology developed by the USFWS.[(33)] The data included 5,049 home range sites. Each home range was between 1,000 and 1,500 ha depending on the location.

Spatial data on threatened, endangered, and sensitive plant populations (threatened flora) were obtained from Forest Service records maintained as part of the USFS regional botany program. Six perennial forb species were selected to represent species known to be threatened by wildfire (Forest Service botany staff, personal communication): longbeard mariposa lily (*Calochortus longebarbatus*), fernleaf goldthread (*Coptis aspleniifolia*), clustered lady's slipper (*Cypripedium fasciculatum*), lesser yellow lady's slipper (*Cypripedium parviflorum*), northern twayblade (*Listera borealis*), and Wilcox's penstemon (*Penstemon wilcoxii*). Data were downloaded in June 2010 and consisted of 2,274 population centroids. Each point location was matched to one pixel (7.29 ha) of the FSIM simulation outputs.

2.5. Risk Components—Definitions

We calculated a number of metrics (i.e., risk components; Table I) from the simulation outputs to describe fire intensity (i.e., hazard), likelihood, or a combination of the two. Risk components were calculated by intersecting the FSIM output for burn probability by intensity class with the spatial data layers for each of the features described above. FSIM outputs consisted of an overall burn probability and a frequency distribution of FLs in 0.5 m classes for each 270 m × 270 m pixel. Burn probability was defined as:

$$BP = B/n, \tag{2}$$

where B is the number of times a pixel burns and n is the number of simulated fires. The BP for a given pixel is an estimate of the annual likelihood that a pixel will burn given a random ignition within the study area. Fire intensity[52] is predicted by the MTT fire spread algorithm and is dependent on the direction the fire encounters a pixel relative to the major direction of spread (i.e., heading, flanking, or backing fire), as well as slope and aspect.[36] Randig converts fireline intensity (FI; kW/m) to FL (m) based on Byram's[52] equation:

$$FL = 0.775(FI)^{0.46}. \quad (3)$$

The FL distribution generated from multiple fires burning each pixel was used to calculate the conditional flame length (CFL):

$$CFL = \sum_{i=1}^{8} (BPi/BP)(FLi), \quad (4)$$

where FL_i is the flame length midpoint of the ith category, and BPi is the probability of fire in flame length i. Conditional flame length is the probability weighted flame length given a fire occurs and is a measure of wildfire hazard.[18] We then calculated high intensity burn probability (HIBP) as the annual burn probability for FL classes 5 and 6, representing the probability of a fire with a >2.4 m FL. We also calculated area high hazard (AHHAZ) and area high exposure (AHE) as:

$$AHHAZ = \left(\frac{BP_5 + BP_6}{BP}\right) Area \quad (5)$$

and

$$AHE = (BP_5 + BP_6)\, Area, \quad (6)$$

where BP_5 and BP_6 are the marginal burn probabilities for FL classes 5 and 6 (>2.4 m; Table II). AHHAZ measures the area expected to be exposed to high intensity fire (FLs >2.4 m) given a fire occurs; AHE estimates the annual area exposed to high intensity fire, and measures the expected loss assuming total loss at or above a 2.4-m FL. Our choice of 2.4 m as an FL threshold was based on a number of factors, including previous research building fire effects loss functions.[18] For instance, FLs >2.4 m will generally result in significant torching, crown fire activity, and tree mortality in the extensive mixed conifer forests in the Region. A complete loss of key features such as northern spotted owl habitat, old growth forests, and fire sensitive plant species would generally be expected. In addition, fire protection efforts for key features are compromised since direct attack on fire perimeters is not attempted at or above our threshold.

2.6. Summary Analysis

We summarized and graphed historical fire information between 1992 and 2009 to describe fire size distribution, especially with respect to large fires. We also calculated average fuel reduction expenditures by forest between 2000 and 2009 and compared those to fire size for the same time period to examine how past fuel reduction expenditures were related to wildfire exposure, as measured by total area burned.

To examine broad spatial patterns in risk components we mapped the risk components defined above. We converted AHHAZ and AHE to percent of area within each pixel. Scatter plots of mean burn probability versus CFL were created for each feature class to examine covariation in risk components, and to identify the forests with the highest exposure for the risk components. Feature class data were averaged by district and feature subtype, except for recreation and spotted owl nest sites. The large numbers of data points for each feature (except threatened flora) required subsampling to obtain interpretable plots. Hence, we selected polygons >500 ha for each feature, and further randomly subsampled 10% of the spotted owl nest sites. We then summarized AHHAZ and AHE on a forest and regional basis to understand how the total risk was partitioned within and among administrative units. Scatter plots were also used to examine area high hazard as a percentage of total feature class burnable area in each forest, and as a percentage of total feature class burnable area in the Region. For instance, a conservation strategy for endangered species might establish a higher priority to protect spotted owl nest sites over a broad geographic range (many national forests), versus focus protection efforts on the few forests that contain the majority of the total nests.

We also examined spatial variation in wildfire risk components among subwatersheds (hydrologic code 6, HUC6) within the study area. Subwatersheds range from 800 to 2,000 ha in area and are used by many national forests as a land unit for prioritizing fuel management and restoration activities.[24] For this analysis, we calculated AHHAZ and AHE as a percent of total burnable area within each subwatershed, and used boxplots to describe the variability.

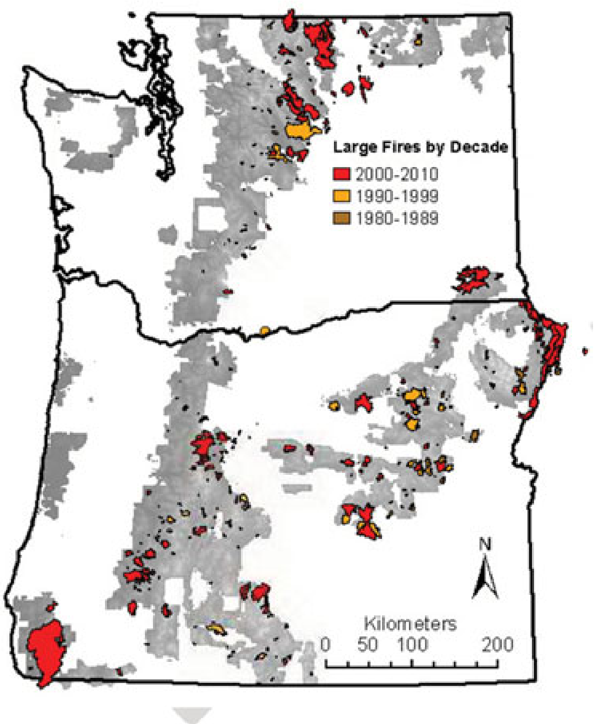

Fig. 3. Map of historical large (>100 ha) fire perimeters for the national forests in Oregon and Washington color-coded 1980–1989, 1990–1999, 2000–2010 (Data Resource Management, Forest Service Regional Office, Portland, Oregon).

3. RESULTS

3.1. Recent Fire History

Fire history data showed substantial variation in area burned and historical ignitions among forests, including the eastside forests that have experienced the largest fires, though large fires were distributed throughout the Region over the period examined (Fig. 3). The annual burn probability including only burnable lands was 0.006 in the Region between 1992 and 2009. Most of the fires were small, and the largest fires accounted for the majority of the area burned (Figs. 2A and B). Lightning fires were the predominant cause, though there was significant area burned by human-related ignitions across the Region (Figs. 2A and B). There were on average about 960 lightning ignitions per year, or about 1 per 1,000 ha per year. By contrast, there were on average about 480 human caused ignitions per year, or about 0.3 per 1,000 ha per year. Fire sizes tended to be higher on the Rogue River-Siskiyou, Okanogan-Wenatchee, and Wallowa-Whitman compared to most other forests, and smaller on the forests west of the Cascade crest (i.e., Mt. Baker-Snoqualmie, Gifford Pinchot, Mt. Hood, Siuslaw, and Willamette) (Fig. 2C). The number of ignitions was positively related to the total area burned (Fig. 2C), though there were many exceptions to the pattern. For instance, the Deschutes (DES) had the highest number of ignitions during the period examined, but a relatively low total area burned, while the Rogue River-Siskiyou (ROG-SIS) experienced a relatively low number of ignitions yet had a relatively large total area burned. The latter finding was caused by a single large fire event (2002 Biscuit Fire, ca. 200,000 ha) within the forest.

In terms of investments in fuel management activities, there was a general trend for greater investment in forests that experienced a larger area burned over the period examined (2000–2009; Fig. 2D). Exceptions to the trends included the Rogue River-Siskiyou, where investments were lower than average, versus the Fremont-Winema (FRE-WIN), where investments were higher than average (Fig. 2D). Although the Deschutes was allocated a relatively large fuel reduction budget and had the highest number of ignitions, the forest also had a lower total area burned (Figs. 2C and D). Much of the Deschutes has been extensively roaded and managed over the past century, and the trend might result from effective fire suppression capability. This trend was not apparent with the Okanogan-Wenatchee (OKA-WEN), which had both the largest expenditures on fuel reduction, yet also experienced the largest total area burned (and a high number of ignitions; Figs. 2C and D). Individual, large, uncharacteristic wildfires, however, probably introduced some of the variability in the relationship.

Maps of the large historical fires around the Region (Fig. 3) show that, except for the two coastal forests (Olympic, Siuslaw), large fires were a common occurrence, especially east of the Cascade Mountain crest. For instance, the Okanogan-Wenatchee had 18 fires >1,000 ha over the period examined, the average size being 12,000 ha. The Deschutes had half as many (nine fires), averaging about 6,700 ha. The Rogue River-Siskiyou had a higher average fire size than other forests (with only three large fires), as a result of the Biscuit Fire (202,000 ha), with an average fire size of 72,300 ha.

3.2. Spatial Patterns in Risk Components

Maps of wildfire risk components (Figs. 4–6) show considerable spatial variation among forests

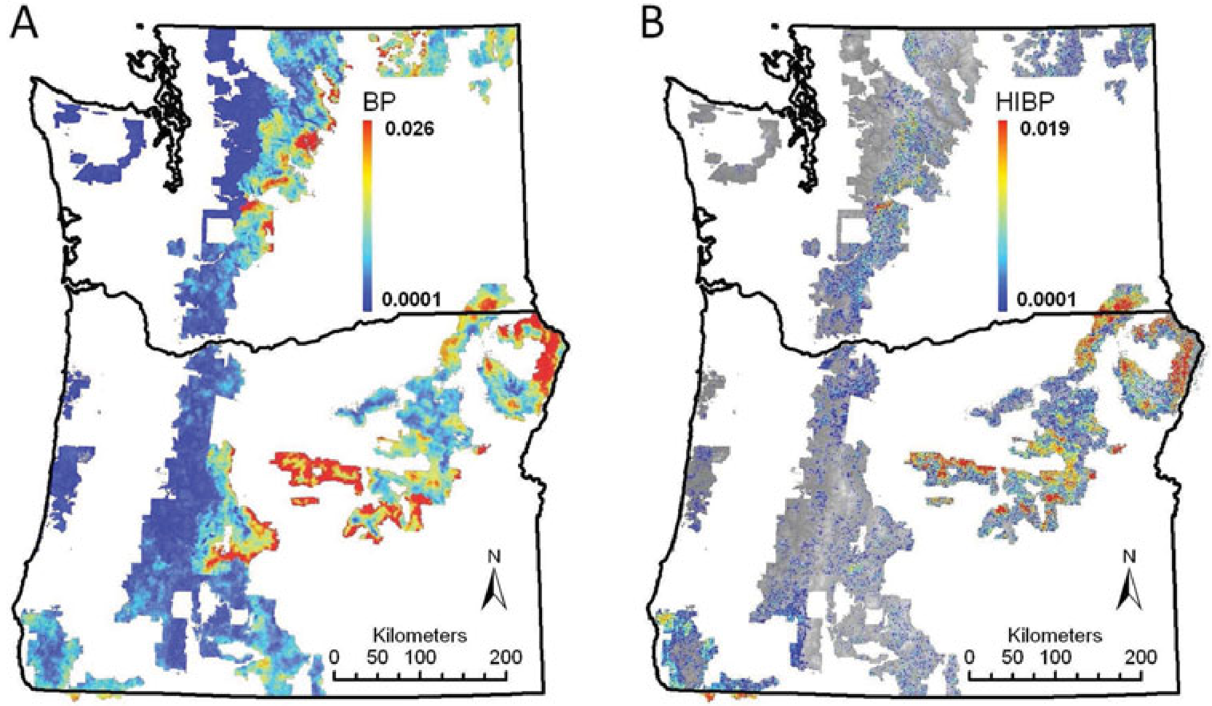

Fig. 4. Maps of burn probability (A) and high intensity burn probability (B) derived from simulation outputs for national forests in Oregon and Washington. High intensity was defined as flame lengths >2.4 m.

within the Region. As expected, the highest BPs were observed in drier forests east of the Cascade crest where fire regimes are characterized by frequent and low intensity fire.[53] Particularly high BP were observed for the forests in the Blue Mountains (Umatilla, Wallowa-Whitman, Malheur; middle right, Fig. 4A). The map of HIBP clearly shows substantial spatial variation in the likelihood of relatively high intensity fire (Fig. 4B). By contrast, spatial variation in CFL (Fig. 5A) and percent area high hazard (PHHAZ; Fig. 5B) were markedly different than BP. High CFL was observed for southwest Oregon, much of the Blue Mountains, and many of the forests on the west slopes of the Oregon Cascade Mountains. Percent area high exposure (PAHE; Fig. 6), which incorporated both likelihood (BP) and FL, showed extensive areas on the Umatilla, Wallowa-Whitman, and Malheur (middle right, Fig. 6) where values reached 1% per year, meaning that there is a 1 in a 100 chance of a fire with FLs that exceeded 2.4 m.

3.3. Variation at the Subwatershed Scale

Boxplots of subwatersheds for percent AHHAZ and percent AHE clearly show differences among forests in both median values and variability (Fig. 7). The plots show a grouping of four forests that have particularly high values for both variables (Umatilla, Wallowa-Whitman, Malheur, and Rogue River-Siskiyou), although the Ochoco showed higher values for percent AHE than the Rogue River-Siskiyou. High variability among subwatersheds and a greater number of outliers were evident for percent AHHAZ compared to percent AHE, and outlier subwatersheds were common for many of the forests.

3.4. Variation in Burn Probability and Flame Length Within Feature Classes

Scatter plots of BP versus CFL for selected feature classes showed the two risk components were highly variable among and within the feature classes (Fig. 8). For instance, infrastructure features (Fig. 8A) had high CFL (>90th percentile) on some forests (Umatilla), versus high BP on others (Okanogan-Wenatchee). For the recreation features (Fig. 8B) a number of sites on the Umatilla, Wallowa-Whitman, Rogue River-Siskiyou, and Malheur, exceeded the 90th percentile for both BP and CFL. Recreation features on the Fremont-Winema

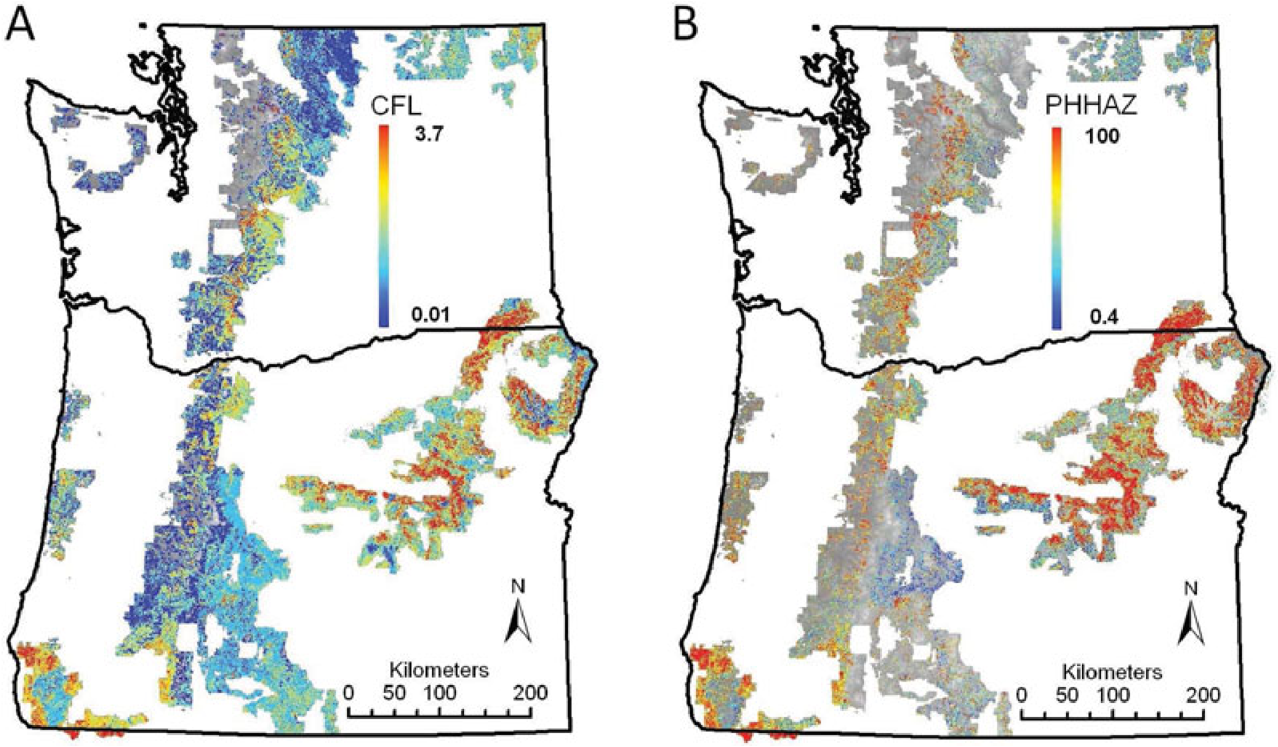

Fig. 5. (A) Conditional flame length and (B) percent area high hazard maps for Oregon and Washington derived from simulation outputs. Conditional flame length (CFL) is the average flame length of all fires that burned a pixel and is a measure of hazard, or the potential for losses from fire given a fire occurs. Percent area high hazard was calculated as the percent of each pixel expected to be exposed to high intensity fire given the pixel burned. High hazard was defined as flame lengths >2.4 m.

and Mt. Hood showed relatively low BPs (Fig. 8B). The Okanogan-Wenatchee recreation areas had the lowest values for CFL (Fig. 8B).

In contrast to infrastructure and recreation there was only one WUI class that had both CFL and BP above the 90th percentile (Malheur). The scatter plot of BP versus hazard for the WUIs in the Region showed generally lower CFL than the other feature classes. The WUIs with BP values exceeding the 90th percentile were observed primarily on the Okanogan-Wenatchee, while those with CFL above the 90th percentile were located on the Rogue River-Siskiyou and Umatilla (Fig. 8C).

Scatter plots for aquatic habitat (critical riparian habitat for bull trout and steelhead) included in the study (Fig. 8D) showed that only one forest (Ochoco) exhibited relatively high BP and CFL. Interestingly, the Fremont-Winema had aquatic habitat features with relatively low BP and CFL, despite the location of the forest on the fire prone area east of the Cascade Mountains.

Scatter plots of CFL and BP for the selected threatened and endangered plant populations (threatened flora; Fig. 8E) suggested a weak positive relationship between the two risk components. Similar to the WUI areas, extreme values were observed for BP and CFL, but none of the features exceeded the 90th percentile for both. Thus the threatened flora features were located on sites with a wide variation in expected fire behavior in terms of likelihood and intensity.

Scatter plots of BP versus CFL for northern spotted owl home range (Fig. 8F) showed on average low BP and CFL compared to the other features studied, a result of owl habitat preferences for mesic mixed conifer forests with lower predicted spread rates for old forest owl habitat, where stands are generally less flammable due to dense canopies and higher fuel moistures, and dampened wind speed.[54,55] The coastal versus interior forests were clearly grouped, and the bulk of the variation was observed for BP rather than CFL. Nest sites with relatively high

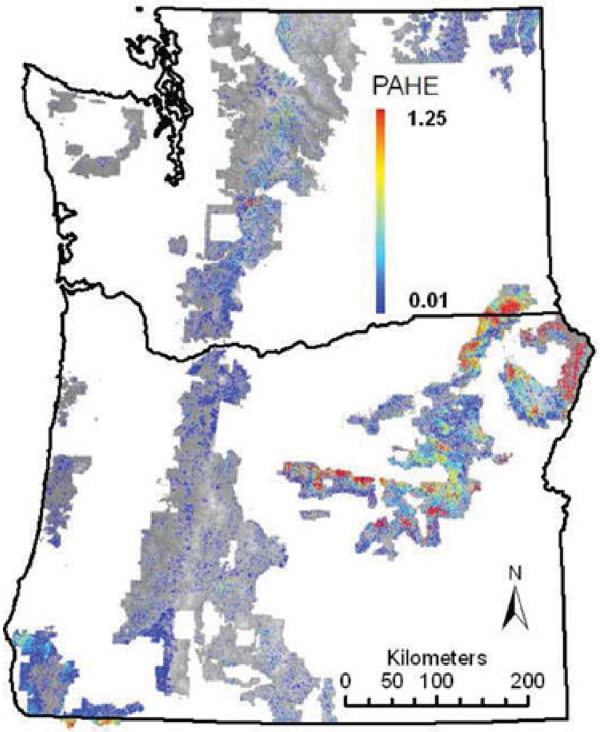

Fig. 6. Percent area high exposure map for Oregon and Washington derived from simulation outputs. Percent area high exposure is the annual percent of each pixel exposed to high intensity wildfire. Percent area high exposure was calculated as the sum of the conditional burn probabilities by flame length >2.4 m multiplied by area.

values for BP were observed on both the Okanogan-Wenatchee and Mt. Baker-Snoqualmie (Fig. 8F), and are located within the dry forest ecotype.

Covariation in the exposure components was evident in scatter plots for some forests and features, but not others (Fig. 8). Among all forests, BP and CFL were positively associated for aquatic and recreation features (Fig. 8). For other features, some association between BP and CFL was apparent within individual forests (Fig 8c, WUI), but not for the feature as a whole.

Covariation indicates that increased likelihood is accompanied by higher intensity, and results from the fact that features are represented by many fuel models, each having predicted rates of spread and intensity. When the two risk components vary together among the population of fuel models that represent polygons of a specific feature, covariation in the scatter plots will be evident.

3.5. Variation Among Forests in Area Risk and Hazard

The total area of risk and hazard was compared among forests to assess aggregate levels of the risk components. These comparisons incorporated the effect of differing amounts of burnable area (Fig. 9A). AHHAZ and AHE showed wide variation among the forests (Figs. 9B and C). The Wallowa-Whitman had the highest AHHAZ and AHE, mostly due to large area of WUI and aquatic reserves. Forest-scale differences in BP and CFL were clearly related to location relative to the crest of the Cascade Mountains, with many of the westside forests showing relatively high AHHAZ and relatively low AHE. The result reflects the fire ecology of the Region, where the mixed-conifer forests on the West Cascades have relatively high fuel loads and burn at high intensity if ignited under severe fire weather conditions (high ERCs); however, these conditions rarely occur due to the maritime influence on weather conditions in the summer months.

3.6. Comparative Risk and Hazard at the Region Versus Forest Scale

The effect of measuring risk at different administrative scales was examined by expressing AHHAZ and AHE as a percentage of the total feature class for each forest Versus within the entire Region (fig. 10). In this way, risk can be examined in terms of local (forest) versus larger province (Region) scale and priorities. For instance, from a conservation standpoint, it could be argued to allocate investments to forests with the highest density and overall number of owl nest sites, versus dispersing fuel management activities to protect widely dispersed owl populations over a larger area. Several forests showed relatively high percent area high hazard (AHHAZ) to the local feature classes (Fig. 10A), but these same forests had a relatively low AHHAZ on a regional basis (Fig. 10B, e.g., Ochoco). Conversely, the Wallowa-Whitman contributed both to high total exposure in the Region as well as the forest. The AHE data show more consistent trends at the two different scales (Figs. 10C and D), meaning that when both likelihood and intensity are combined, all forests contribute more or less equally to the total regional risk. Among the feature classes, owl habitat contributed more to hazard than exposure.

Scatter plots of AHHAZ (Fig. 11A) and percent area high exposure (Fig. 11B) calculated on a

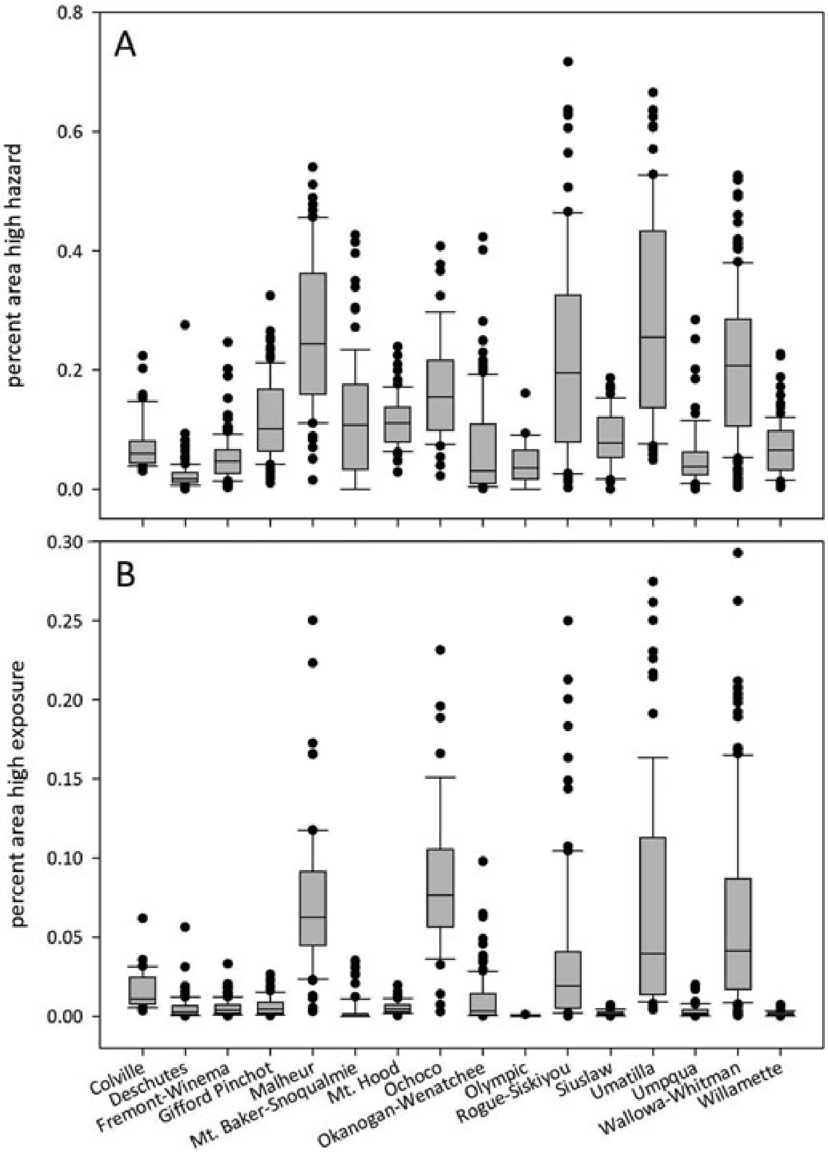

Fig. 7. Box plots of (A) percent area high hazard and (B) percent area high exposure for hydrologic code 6 (HUC 6) subwatersheds for the national forests in Oregon and Washington. Subwatersheds are used by national forests as land units for planning and prioritization of projects. Percent area high hazard was calculated as the percent of each subwatershed expected to be exposed to high intensity fire given the subwatershed burned. High hazard was defined as flame lengths >2.4 m. Percent area high exposure was calculated as the annual percent of each subwatershed exposed to high intensity fire.

forest versus regional basis for national forests in Oregon and Washington show that both exposure and hazard are generally correlated between the two scales. However, exceptions were noted, especially for the biodiversity feature classes, where a number of the forests showed exceptionally high exposure at either the regional or forest scale, but not both. Aquatic habitat on the Wallowa-Whitman showed exceptionally high hazard on a regional basis, and relatively low hazard on the forest, yet the threatened flora showed the highest hazard locally, and contributed very little to regional hazard. In contrast, the Ochoco showed a disproportionately high threatened flora exposure Regionally (regional PAHE = 0.03, outlier not shown), with very low local exposure. Thus, high exposure was apparent in pockets around the Region, suggesting a relatively fine spatial pattern, and significant within-forest variation among feature classes. For instance, the Wallowa-Whitman has several feature classes with relatively low forest and regional exposure, yet also the highest exposure for WUI and aquatic habitat on the two spatial scales.

Area high exposure and area high hazard calculated for feature classes within forests (Fig. 11C) were generally correlated, that is, the annual area expected to be exposed to high intensity fire for a given feature was correlated with the area exposed

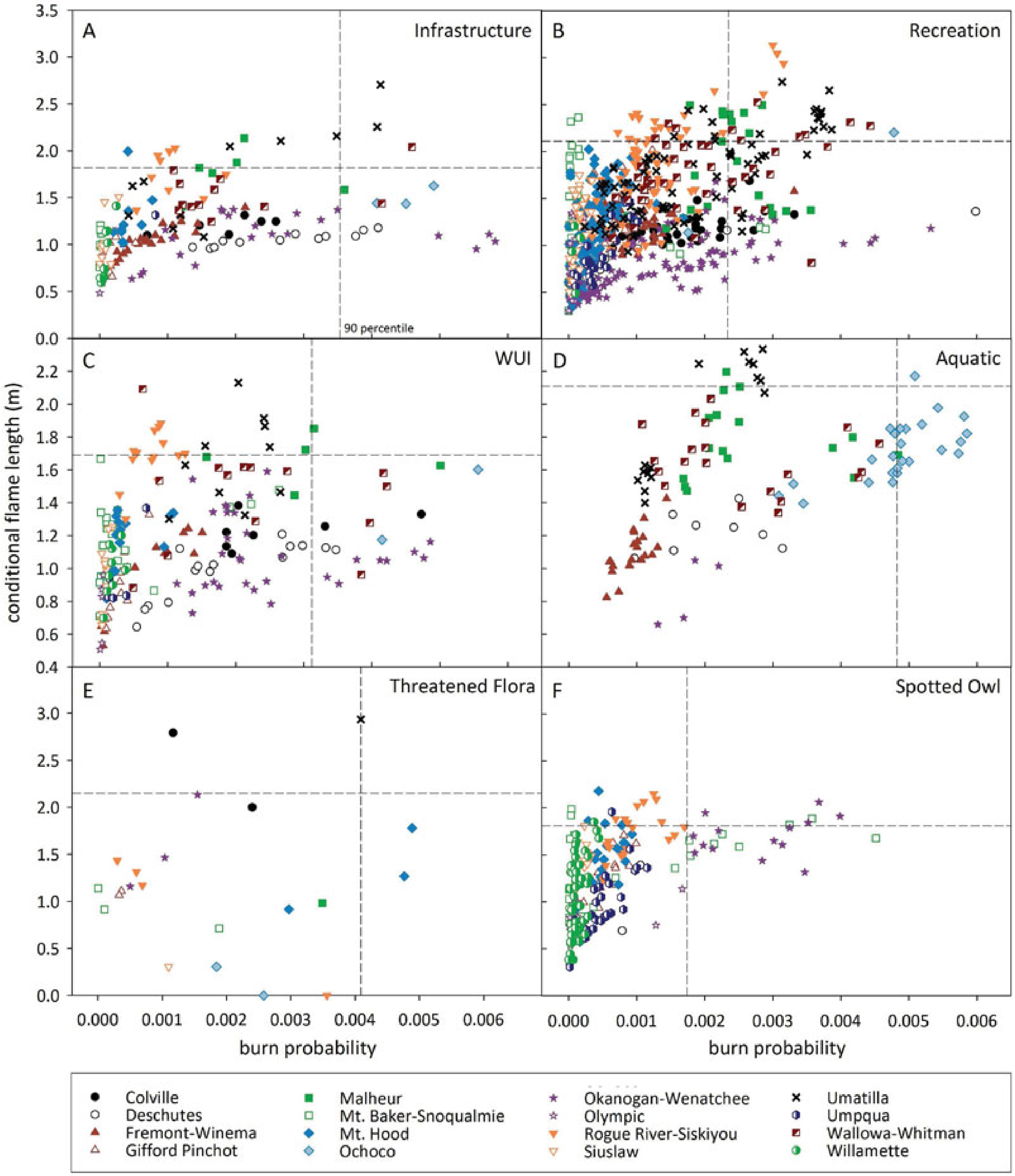

Fig. 8. Scatter plot of burn probability (a measure of wildfire likelihood) versus conditional flame length (a measure of wildfire hazard) for (A) infrastructure, including utilities, constructed features, and developed sites; (B) recreation sites; (C) wildland urban interface (WUI); (D) riparian habitat conservation areas (aquatic); (E) threatened, endangered, and sensitive plant populations (threatened flora) for six selected species (see text); and (F) spotted owl nest sites for the national forests in Oregon and Washington.

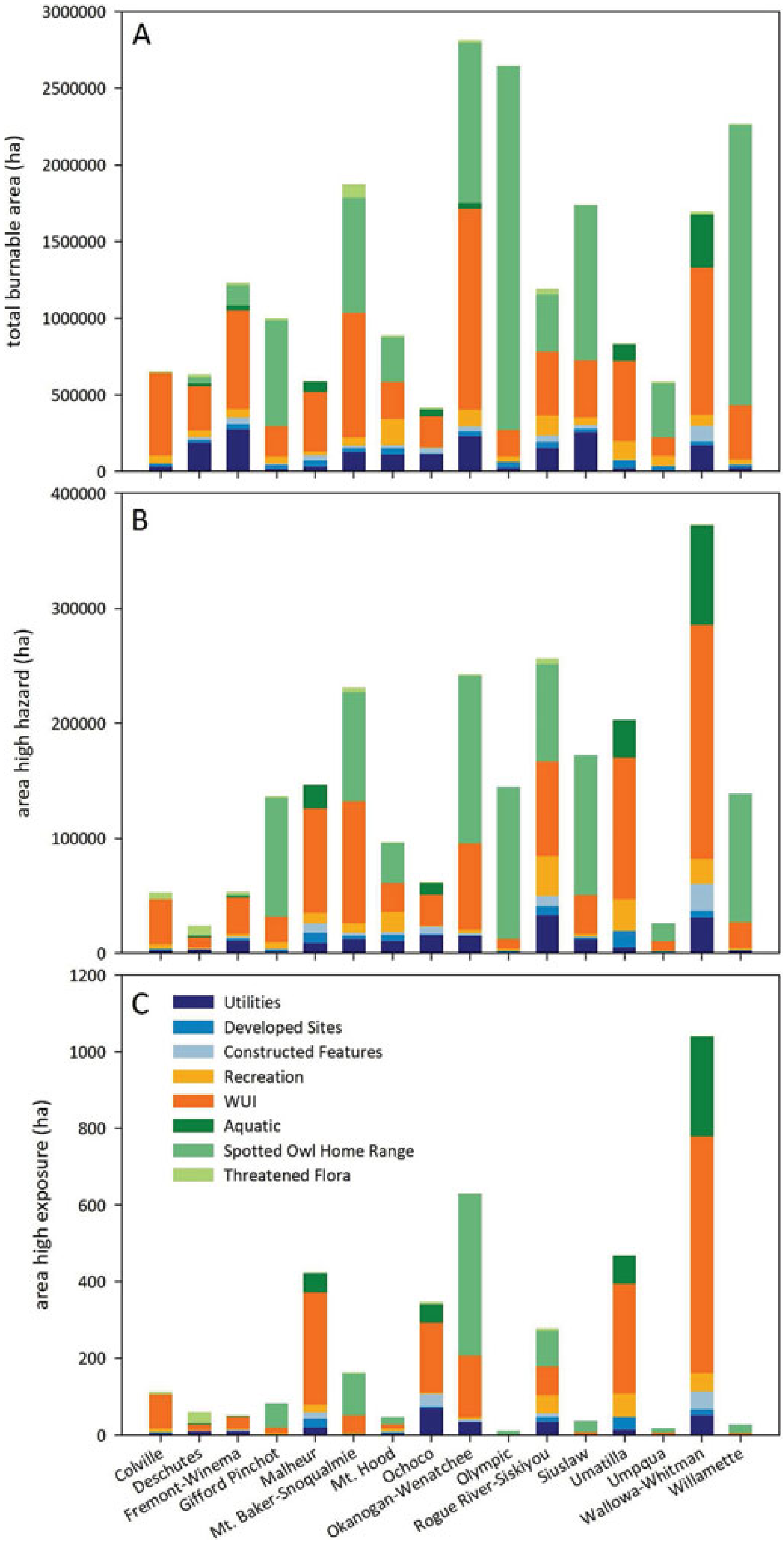

Fig. 9. (A) Total burnable area, (B) area high hazard, and (C) area high exposure in hectares in each feature class by national forest in Oregon and Washington. Area high hazard was calculated as the area within each feature class expected to be exposed to high intensity fire (>2.4 m flame length) given the feature class burned. Area high exposure was calculated as the area of each feature class exposed to high intensity fire.

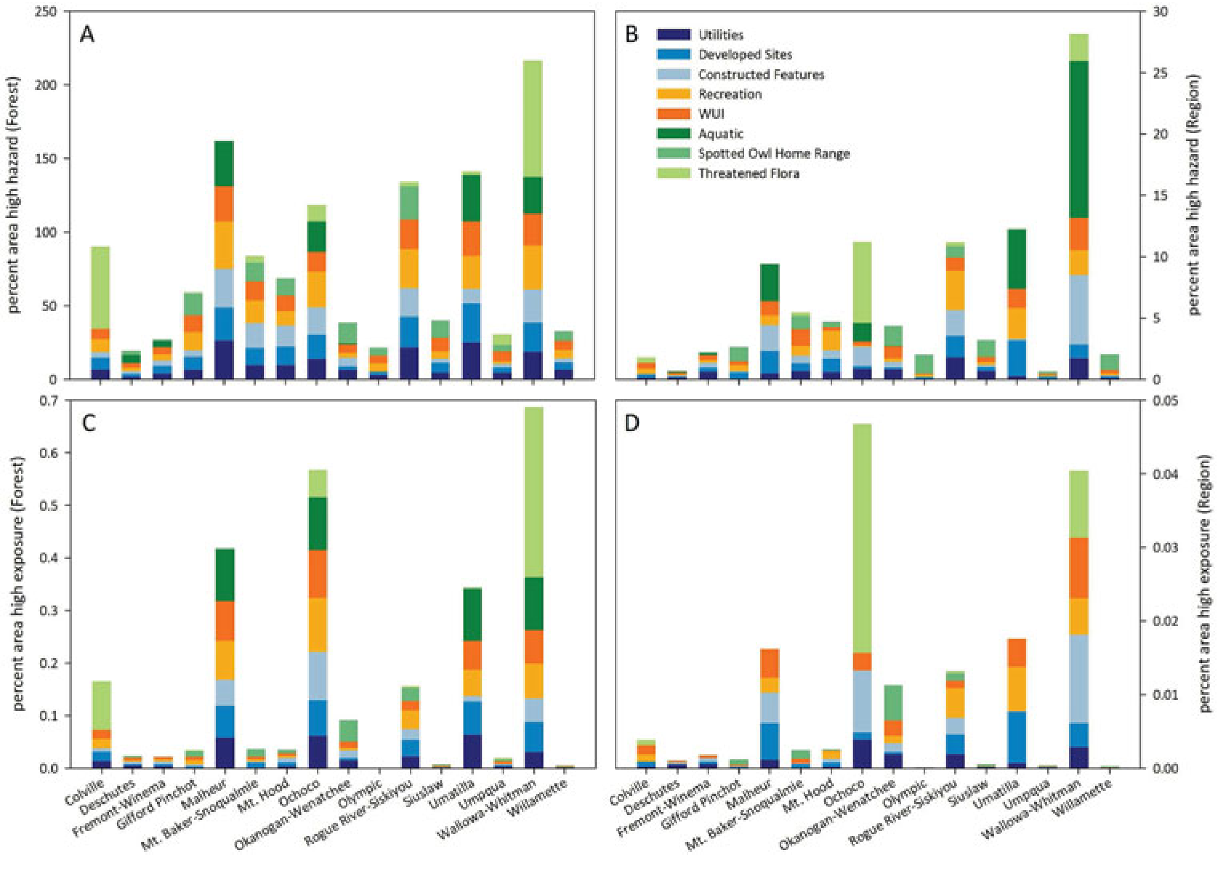

Fig. 10. Percent area high hazard calculated on a Forest (A) and Region (B) basis, and percent area high exposure calculated on a Forest (C) and Region (D) basis for national forests in Oregon and Washington. Percent area high hazard was calculated as the percent of each feature class within the Forest/Region expected to be exposed to high intensity fire (>2.4 m flame length) given the feature class burned. Percent area high exposure was calculated as the annual percent of each feature class within the Forest/Region exposed to high intensity fire.

to high hazard. However, many exceptions were evident, such as the spotted owl nest sites on West Cascade forests (Fig. 11C, e.g., Willamette, Olympic, Siuslaw).

4. DISCUSSION

We employed simulation modeling to examine wildfire exposure to key social and ecological features within the national forests of Oregon and Washington. We quantified risk components (BP and FL) from simulated wildfire events and intersected them with an array of ecosystem services and other important features on national forests and adjacent WUI. The analysis has the potential to inform ongoing allocation of fuel management investments among and within national forests to mitigate the growing incidence of wildfire.[12] The risk framework can be applied to address a range of important forest management issues, including carbon sequestration from fuel treatments[56] and the design of habitat conservation networks.[57] Similar frameworks could be developed for other forest disturbance processes as well.[58]

The outputs from the simulation modeling are consistent with historical fire frequency and current knowledge about fire ecology within the study area.[59,14] However, the simulation approach generated fine-scale maps of risk components that previously have not been available to fuel management planners in the Region tasked with the problem of allocating fuel management budgets to address growing wildfire losses. One potential source of error is the use of relatively few (17) weather stations to derive wind parameters, especially in the mountainous areas where wind patterns are highly variable. However, the simulations can be

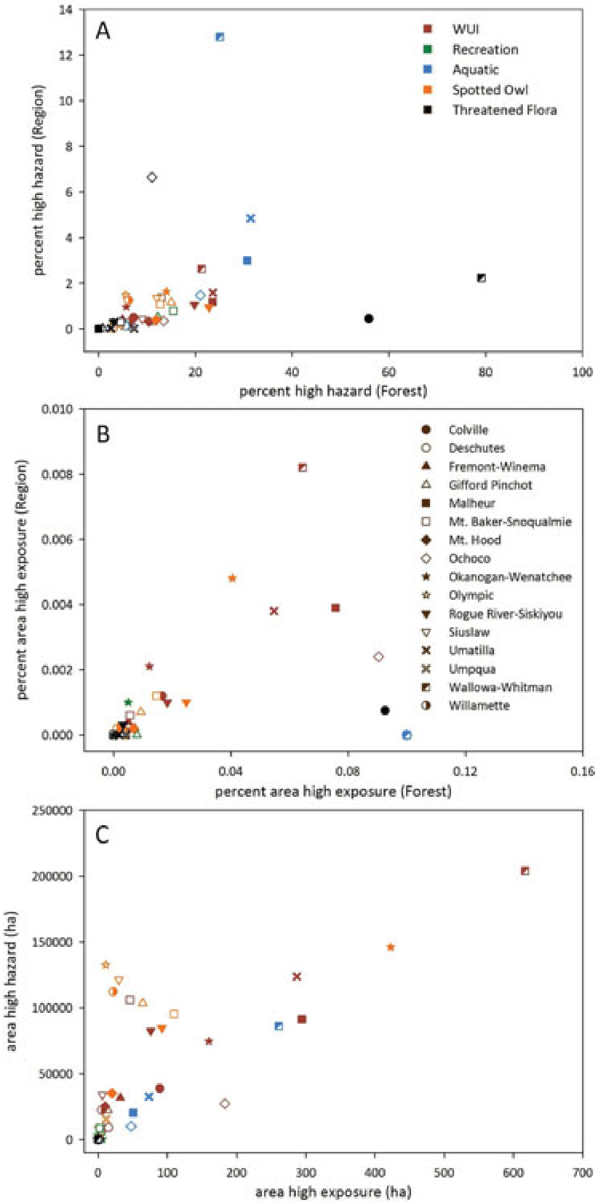

Fig. 11. Scatter plot of percent high hazard (A) and percent area high exposure (B) calculated on a forest versus regional basis, and scatter plot of area high exposure versus area high hazard (C) for national forests in Oregon and Washington for WUI and biodiversity features. Symbol colors denote feature class and symbol shapes denote national forest. Percent area high hazard was calculated as the percent of each feature class within the Forest/Region expected to be exposed to high intensity fire (>2.4 m flame length) given the feature class burned. Percent area high exposure was calculated as the annual percent of each feature class within the Forest/Region exposed to high intensity fire.

refined as part of downscaling the outputs to inform local planning efforts. Wind data in particular can be processed through terrain models to provide detailed wind vectors to account for localized winds.[60] Despite the inherent uncertainty associated with wildfire risk management,[61] the results provide a framework to incorporate wildfire risk and exposure into the existing agency process for prioritization of fuel management investments. The forests in the study area contain similar social, ecological, and conservation reserves as many other forests in the 77 million ha national network, and thus the methods are broadly applicable.

The study illustrates variation in different components of risk, and also shows that emphasizing one versus the other will lead to a different assessment of potential wildfire impacts. Many previous studies on wildfire impacts to specific ecosystem services including carbon, critical habitat, social values, and fire resilient forests[62,63,56] did measure wildfire likelihood as part of the analyses, but ignored how the landscape arrangement of fuel, topography, and weather affects large fire spread and resulting burn probability. Ignoring large fire spread and likelihood can lead to substantially different conclusions about the location and timing of potential fire impacts, as illustrated in our spatial patterns of fire hazard (CFL) versus likelihood (BP). Clearly, both components are required to describe spatial patterns and variation in wildfire exposure and risk.

The application of risk science has seen steady growth with emerging wildfire issues, and numerous risk and exposure assessments have been reported by researchers in the United States, Portugal, Spain, Australia, New Zealand, and India.[2–7,25,64,28,17,65] In contrast to most of these studies, we measured exposure from large, infrequent fires of natural origin, rather than from small, frequent anthropogenic-caused fires. While the latter fire type is a common situation in a global context,[1] the former account for most of the burned area and damage on national forests in the United States. Large fires spread over long distances (e.g., 10–30 km), and thus their potential impacts are poorly represented by models that are based on localized risk components (e.g., ignition probability) rather than large landscape properties (e.g., contagion of fuel).

Most wildfire risk systems devised for managers rely on coarse methods for quantifying fire effects, including qualitative indicators, or discrete response functions that describe percentile loss of a feature at different fire intensities, as determined by expert opinion.[66] Examples of quantitative response functions are rare, although the approach has been demonstrated for above-ground carbon, old growth, and northern spotted owl habitat.[67,18,48] There are well-developed first-order fire effects models to develop response functions for tree mortality, erosion, carbon, and other ecosystem properties,[68] as well as residential structure ignition models.[69] Quantitative risk analyses can leverage these models to advance wildfire risk analyses for a range of wildfire policy issues. However, in lieu of quantitative response functions, we used a simpler approach where a complete loss was assumed when the FL equaled or exceeded a threshold value of 2.4 m. At or above our threshold, direct attacks on the heading portion of wildfire perimeters are generally not attempted, and therefore fires are free burning. We also limited our analysis to features that in general are highly susceptible to fire. For instance, reviews of residential structure and infrastructure loss from a recent fire determined that 83% of the total loss was from surface fire.[70] Significant loss of biodiversity features included in the study would also be expected above the threshold FL. For instance, fire behavior exceeding our threshold of 2.4 m would in general be associated with significant loss to northern spotted owl habitat, as defined by national forests in the Region.[48] It is important to note that we did not assume equal susceptibility among the features studied, but rather provided a way to compare features (WUIs, plant populations, conservation reserves) in terms of the relative exposure to wildfire. Downscaling the results for more local fuel management and risk abatement will require decisions about what specific features most merit protection given their estimated exposure to wildfire. Although the use of quantitative response functions has many merits, we argue that exposure analyses are not only sufficient to inform risk management strategies, but also offer some advantages. First, the simplicity of exposure analyses can facilitate the important process of communicating wildfire risk to people who are potentially affected by wildfires on national forests. Second, most of the area burned in large, destructive fires experiences high intensity fire, above and beyond fire intensity thresholds for complete loss. Third, response functions are difficult to develop with any degree of certainty for many ecosystem services, such as visual quality, ecological integrity, and others, adding to the overall uncertainty of the assessment for highly stochastic wildfire events.

We believe that risk science can play an important role for managing wildfire losses beyond the spatial risk assessment as described in the current work. Specifically, the magnitude and variation in risk components can be used within a planning framework to guide the development of landscape fuel treatment strategies (location, amount, spatial pattern of treatments). In the current federal planning process,[26] both stand and landscape treatment strategies are developed with consideration to fire management goals, current fire exposure, and the spatial arrangement of the features at risk. Stand management concerns thinning and prescribed fire[71,72] to address localized hazard in terms of surface and crown fire. Landscape management concerns the coordination of these activities[26,73,74,18,75] to achieve fire management goals at a scale commensurate with large fires (e.g., 10,000 to 200,000 ha). Fire management objectives are important as well, and determine whether mitigation emphasizes restoring natural fire regimes, or suppression to protect highly valued resources, or a strategy in between. For instance, the extensive dry forest restoration programs in the interior West[76] are concerned with eliminating pockets of high intensity fire so that future natural and prescribed fire can be managed as a fuel treatment process. The goal is to increase BP of low intensity fires to presettlement periods. At the other end of the spectrum, fuel management goals for protecting fire sensitive conservation networks are to reduce burn probability over large areas by slowing fire spread rates, thereby improving the odds that weather conditions will permit containment.[77,78] Here, the optimum strategy is to block the fastest wildfire paths, and the dimensions of the individual units are chosen such that the time to burn the unit equals the time to burn around it.[74] Protecting fire susceptible values like WUIs, localized centers of biodiversity, and infrastructure, in areas of extreme hazard (high BP and CFL) requires localized fuel management to create fuel breaks that serve as protection points for fire suppression. Each of the above fuel management strategies can leverage risk science and specific risk assessment products to maximize the attainment of fire management goals in the respective wildfire scenarios.

Although we did not consider potential benefits from wildfire in this study, frequent, low intensity fire is a key disturbance process in the fire adapted dry forests in the interior portion of the Region.[59] These fires promote the development and sustainability of old growth ponderosa pine stands that provide an array of ecosystem services, including important wildlife habitat.[79] In the case of the northern spotted owl, wildfire can increase prey diversity and abundance[80,79] by creating patches of foraging habitat. However, fire impacts on critical nesting habitat are more often deleterious than beneficial due to reductions in canopy closure and structural attributes, as evidenced by the recent decline in habitat from wildfires.[81]

The results from this study were used to illustrate alternative approaches to rank wildfire exposure for the purpose of prioritizing fuel management. We compared the exposure to each feature relative to each forest, versus all the forests in the Region (Fig. 11A, B). The trade-off question pertains to prioritizing localized high exposure on each of the forests, versus allocating to specific forests that have most of the regional exposure. Both allocations can be justified depending on the specific feature. While specific forests contribute more to the total regional exposure than others, all forests have features with relatively high exposure. The appropriate allocation scheme of investments depends on the feature of interest. For instance, maintaining viability for Region-wide habitat networks (e.g., northern spotted owl) might prioritize dispersed treatments to maintain regional connectivity, rather than focusing on a single forest with the highest overall exposure. The choice of scale has less importance for decisions that involve ecosystem services, such as carbon sequestration, where spatial location does not affect the value.

Simulation modeling is a necessary component of wildfire risk assessment in areas like the western United States where large, infrequent wildfire events are the main drivers of long-term risk. Prioritizing fuel treatment locations at the national scale is the subject of considerable effort and debate[82,73] and the current work can clearly provide a more defendable approach to quantify large wildfire risk and guide investments in fuel treatment programs at the national forest scale.[83] Scatter plots clearly show variation within and between forests for the different wildfire risk components, and their respective contribution to wildfire risk. In terms of specific application to conservation planning, the outputs provide an entry point for risk management on fire-prone forests where wildfire events are uncertain in terms of location, timing, and severity. Risk component plots and maps reveal spatial patterns in risk components that can be integrated into new or existing biological conservation strategies, though an analysis of this type has not previously been discussed or applied to federally listed species.[84,85,33] The interaction among spatial patterns in disturbance regimes and existing conservation networks are key inputs to understanding long-term structural connectivity of landscapes. Future analyses could incorporate a management opportunity map and model the effects of different fuel treatment programs on wildfire exposure at the regional scale.

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