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Analyzing wildfire exposure and source–sink relationships on a fire prone forest landscape

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ABSTRACT

We used simulation modeling to analyze wildfire exposure to social and ecological values on a 0.6 million ha national forest in central Oregon, USA. We simulated 50,000 wildfires that replicated recent fire events in the area and generated detailed maps of burn probability (BP) and fire intensity distributions. We also recorded the ignition locations and size of each simulated fire and used these outputs to construct a fire source–sink ratio as the ratio of fire size to burn probability. Fire behavior was summarized for federal land management designations, including biological conservation reserves, recreational sites, managed forest, and wildland urban interface. Burn probability from the simulations ranged from 0.00001 to 0.026 within the study area (mean = 0.0023), and exhibited substantial variation among and within land designations. Simulated fire behavior was broadly related to gradients in fire regimes, although the combined effects of fuel, topography, and simulated weather resulted in fine scale patterns not reflected in ecological and vegetation data. Average BP for the northern spotted owl (*Strix occidentalis caurina*) nesting sites ranged from 0.0002 to 0.04. Among the 130 different wildland urban interface areas, average BP varied from 0.0001 to 0.02. Spatial variation in the source–sink ratio was pronounced, and strongly affected by the continuity and arrangement of surface and canopy fuel. We discuss the management implications in terms of prioritizing fuel management activities and designing conservation strategies on fire prone landscapes within the 177 million ha national forest network.

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1. Introduction

The growing incidence of catastrophic wildfires and other disturbances over the past decade has led to the loss of important ecological assets within many of the US national forests (Hayasaka et al., 2006; Isaak et al., 2010; Laverty, 2003; Millar et al., 2007; Moeur et al., 2005; Reeves, 2006; Spies et al., 2006; USFWS, 2008). Large fires on national forests have also spread onto private lands and caused significant losses, especially in the wildland–urban interface (WUI). The progression of federal fire policies to address growing wildfire threats have all called for accelerated fuel management programs on federal lands (Cohesive Strategy, 2010; Finney and Cohen, 2003; FLAME, 2010; Franklin and Agee, 2003; HFRA, 2003; NFP, 2000; Reinhardt et al., 2008; Stephens and Moghaddas, 2005). A number of risk-based methodologies have been proposed to help map wildfire risk and set priorities for fuel management investments (Ager et al., 2010; Calkin et al., 2010; Finney, 2005; Thompson et al., 2011). These approaches all fit within the broader risk framework developed by the US Environmental Protection Agency (EPA, 1998), which consists of four primary steps: (1) problem formulation, (2) exposure analysis, (3) effects analysis, and (4) risk characterization. By far, the largest challenge for wildfires is exposure analysis, which explores the predicted scale and spatiotemporal relationships of causative risk factors (Fairbrother and Turnley, 2005). For instance, risk factors such as wildfire likelihood and intensity are difficult to predict for large stochastic wildfires at scales meaningful to fuel management planners (e.g., 5000–100,000 ha).

Recent advances in mechanistic wildfire modeling (Andrews et al., 2007; Finney et al., 2009, 2011; FPA, 2010) have led to a number of new tools and approaches for applying risk frameworks to the fuel management problems. In this paper, we demonstrate how mechanistic wildfire simulation models can be used to explore wildfire exposure to an array of typical national forest land designations and conservations reserves. These land use designations and conservation reserves are intended to provide an array of ecosystem services (recreation, wildlife, water, timber, research, etc.) and were created as part of the National Forest Management Act (NFMA, 1976) and subsequent legislation (ESA, 1973; ROD, 1994; USDC, 1998). We defined exposure analysis as the

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exploration of the predicted scale and spatiotemporal relationships of causative risk factors (EPA, 1998). Wildfire exposure is a necessary step in risk assessment, but does not include the quantitation of expected wildfire impacts. We focused on three causative risk factors (burn probability, flame length, fire size) for the Forest land designations, conservation reserves, and adjacent WUI. We examined wildfire transmission issues with a source–sink ratio to determine whether some land designations were more likely to transmit exposure than others. We also compared quantitative outputs for burn probability and fire intensity to fire regime data that are widely used by fire ecologists and managers to prioritize fuel management activities. The study advances the application of wildfire risk assessment to better understand wildland conservation, restoration, and protection issues on fire prone landscapes.

2. Methods

2.1. Study area

The study area encompasses the Deschutes National Forest near Bend, Oregon, and consists of 653,035 ha managed by the USDA Forest Service (Fig. 1). The Forest contains ecological gradients, social and ecological values, fire regimes, and conservation issues that are typical for many other national forests. The Forest spans a steep ecological gradient from the Cascade Crest on the western edge to the high desert on the east, and was typed into 18 ecological classes by Volland (1985). The low elevation, relatively flat pumice plains are dominated by dense stands of lodgepole pine (*Pinus contorta*), transitioning to ponderosa pine (*Pinus ponderosa*) and Douglas-fir (*Pseudotsuga menziesii*) with increasing elevation to the west. At around 2000 m elevation the forest species intergrade to Shasta fir (*Abies concolor*), mountain hemlock (*Tsuga mertensiana*), and western white pine (*Pinus monticola*), and eventually transition (>2400 m) to primarily mountain hemlock (*T. mertensiana*) near treeline.

The Forest has experienced over 8400 wildland fire ignitions since 1949, with 99% caused by lightning (Finney, 2005). Wildfire activity has seen a major jump since 1990, with four large fire events (Fig. 1a), including the B&B Complex and Davis fires that combined burned 15 inhabited northern spotted owl nest sites and 8041 ha of a designated critical habitat unit.

2.2. Land designations

We built a land designation map (Table 1, Fig. 1b) that contained land allocations as specified in the Deschutes National Forest Land and Resource Management Plan (USDAFS, 1990) and subsequent modifications by the Northwest Forest Plan (ROD, 1994), and PACFISH (Henderson et al., 2005). The map reflects the typical array of land management designations found on forests throughout the national forest system and contained: (1) bald eagle habitat (EAG); (2) deer habitat (DHB); (3) old growth management (OLD); (4) research natural areas (RNA); (5) special interest areas (SIA); (6) visual corridors and vistas (VIS); (7) recreation sites (REC); (8) wilderness areas (WIL), established by the Wilderness Act of 1964; and (9) general forest matrix (GFM). The latter designation has historically been the focus of commercial timber harvest and other silvicultural activities (Table 1). The matrix

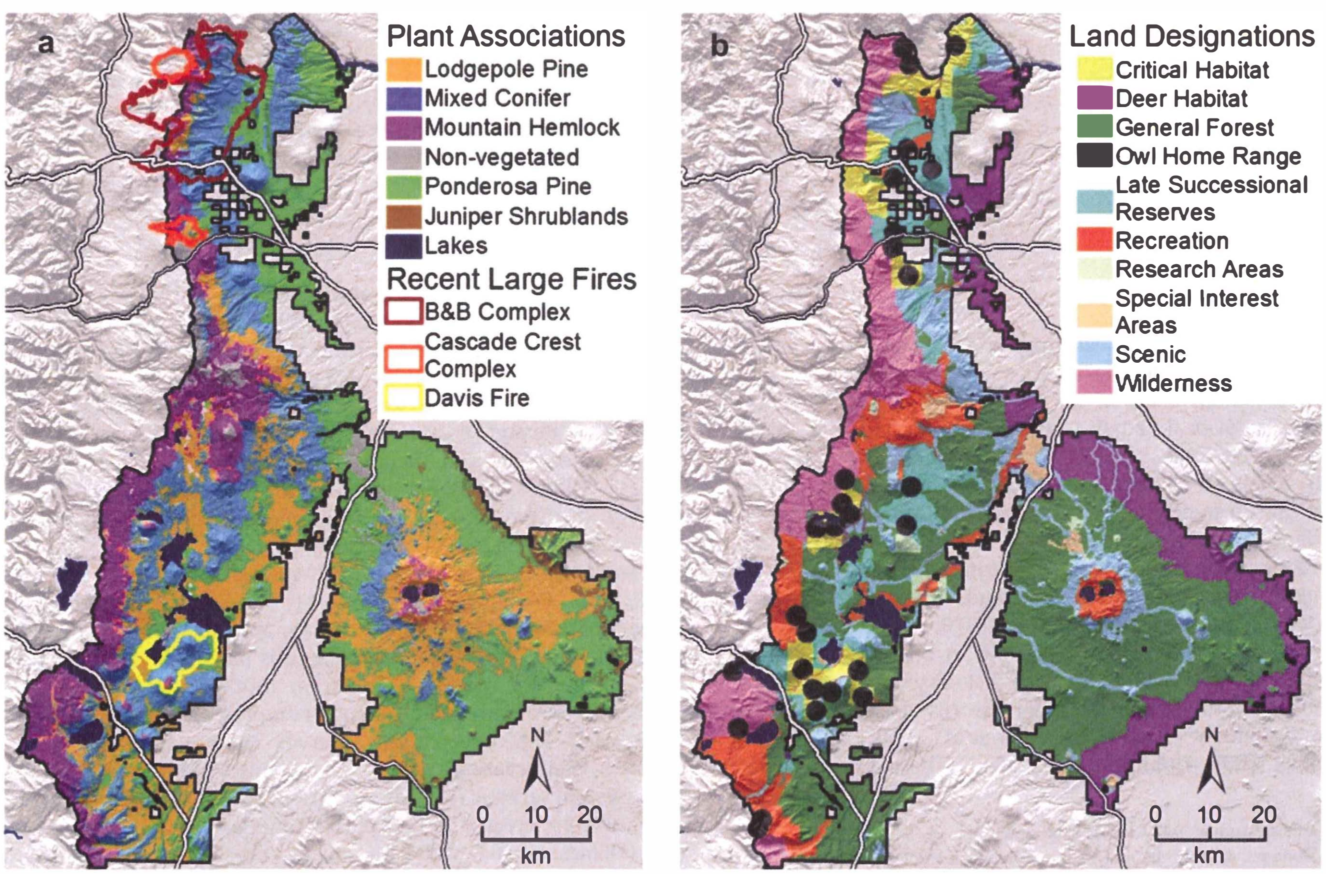

Fig. 1. Potential vegetation and recent wildfire perimeters (a) and land designations (b) on the Deschutes National Forest. Wildfire perimeters are shown for the Davis, B&B Complex, and Cascade Crest Complex wildfires used for calibrating simulations (Table 4, Beaty Butte fire was outside the study area). Potential vegetation (Volland, 1985) was not discernable for alpine, hardwood, meadow, and riparian types, and was excluded from the legend.

Table 1
Land designations on the Deschutes National Forest and the area treated (1989–2009) and burned by wildfire (1900–2009). Treated area includes all harvest, underburning, and fuel mastication activities. Patches represent physical polygons within each land designation. Patches for land designations that covered large contiguous areas (>4000 ha, REC, WIL, GFM, DHB) were created by sampling 177 ha circular areas as described in Section 2.

Land designation (abbreviation)	Total area (ha)	Average patch area (ha)	Number of patches	Treated area 1989–2009 (%)	Burned by wildfire (%)
Riparian conservations area (FSH)	14,389	306	47	0	17
Active spotted owl home range (HRA)	8079	1154	7	0	14
Potential spotted home range (HRP)	33,280	1145	29	0	25
Spotted owl critical habitat unit (CHU)	24,917	3560	7	0	58
Bald eagle habitat (EAG)	5027	186	27	103	21
Deer habitat (DHB)	83,790	177	23	36	30
Late successional reserves (LSR)	39,131	2609	15	50	27
Old growth management areas (OLD)	13,655	161	85	39	16
Research natural areas (RNA)	4787	598	8	40	12
Special interest areas (SIA)	7347	565	13	12	13
Wilderness (WIL)	68,324	177	5	0	16
Recreation (REC)	65,960	177	21	20	5
Visual retention (VIS)	77,370	1005	77	75	17
General forest matrix (GFM)	21,6774	177	88	81	9
Wildland urban interface (WUI)	81,537	685	119	na	5

remains important for timber production and provides connectivity between late- and early-successional forests, contributing to the structural diversity in the area. All land designations contained some proportion of non- or sparsely-vegetated land (Table 1) which is an important factor in the consideration of wildfire spread. Conservation reserves for the northern spotted owl (ROD, 1994) included both designated home ranges (~1.9 km radius circular, 1172 ha) around all known past and present owl nest sites, and seven critical habitat units (CHU, Table 1 and Fig. 1b). The former consists of 22 potentially viable nesting sites (HRP) deemed by biologists as suitable for occupation, and seven active nesting sites (HRA). The CHUs cover 24,917 ha and are located on the western portion of the Forest (Table 1, Fig. 1b). The Northwest Forest Plan (ROD, 1994) created a network of late-successional reserves (LSR, Fig. 1b) to maintain existing and develop future old growth ecosystems. Lastly, aquatic conservation areas (FSH) were added to the Forest's land designations as part of the PACFISH and INFISH Biological Opinion (Henderson et al., 2005), and consist of 47 stream reaches with a 121.5 m buffer on each side of the stream (Table 1, Fig. 1b).

Wildland urban interfaces (WUI) surrounding the Forest were mapped by the interagency Central Oregon Fire Management Service and the State of Oregon. The WUI was defined by a 2.4 km (1.5 mi) buffer around all private land parcels containing structures. The WUIs included 119 polygons summing to 81,537 ha (Table 1).

2.3. Vegetation and fuel data

We created a wildfire simulation boundary that encompassed the Forest and a 10 km buffer on all sides. In this way we captured the impacts of wildfire ignitions in the proximity of the Forest. Surface and canopy fuels were obtained from the national LANDFIRE dataset (Rollins, 2009, www.landfire.gov, retrieved 26 August 2009) and included elevation (m), slope (degrees), aspect (azimuth), fuel model (Scott and Burgan, 2005), canopy cover (percent), canopy base height (m), canopy height (m), and canopy bulk density (kg m^{-3}). LANDFIRE is a standardized fuel dataset available for the conterminous US and widely used for wildfire modeling and research on federal and other lands (Krasnow et al., 2009; Rollins, 2009). The LANDFIRE data are regularly used to model potential fire behavior for fuel treatment projects and other NEPA planning efforts on the Deschutes and adjacent national forests (Ochoco, Fremont-Winema).

2.4. Ecological classification and fire regime

Spatial data on the ecological classification as mapped by Forest staff (Volland, 1985) were used to determine the dominant forest cover types within each land designation (Fig. 1a and Table 2). The fire regimes (Table 2, Hann and Bunnell, 2001; Schmidt et al., 2002) for each land designation were also determined Forest data. The Forest derived the latter from the Volland (1985) ecological classification. Fire regime is a combination of the expected fire frequency and intensity under pre-settlement conditions (Hessburg and Agee, 2003).

2.5. Wildfire simulations

We simulated wildfires using the minimum travel time (MTT) fire spread algorithm of Finney (2002) as implemented in a command line version of FlamMap called "Randig" (Finney, 2006). The MTT algorithm replicates fire growth by Huygens' principle where the growth and behavior of the fire edge is modeled as a vector or wave front (Finney, 2002; Richards, 1990). Fire spread is predicted by the Rothermel (1972) surface fire spread model equations, and crown fire initiation is according to Scott and Reinhardt (2001). Extensive application has demonstrated that the Huygens' principle, in general, and the MTT algorithm in particular, can accurately predict fire spread and replicate large fire boundaries on heterogeneous wildlands (Ager et al., 2007; Arca et al., 2006; Carmel et al., 2009; Knight and Coleman, 1993; LaCroix et al., 2006; Massada et al., 2009; Sanderlin and Van Gelder, 1977; Finney et al., 2011). The MTT algorithm was parallelized for multi-threaded processing, making it feasible to perform Monte Carlo simulations of many fires (>100,000) and generate burn probability surfaces for very large (>2 million ha) landscapes. The MTT algorithm is widely applied for strategic and tactical wildfire management planning throughout the US (Andrews et al., 2007; FPA, 2010; WFDSS, 2010). Randig was created for the specific purpose of simulating discrete burn periods within large fires under constant weather, in contrast to simulating continuous spread of a wildfire over many days and weather scenarios. A small number of large wildfires account for the majority of area burned in the US (Andrews, 2005; Calkin et al., 2005), and relatively few burn periods within these large fires account for the majority of the total area burned. On the Forest, data on mapped fires (>1.18 ha) between 1908 and 2003 shows that a mere 10% of the fires accounted for 74% of the total burned area (156,648 ha). Between 1970 and 2004, 1.2% of all fires on national forests were larger than 121 ha

Table 2
Percent area by plant association type (Volland, 1985) and fire regime for the land designations on the Deschutes National Forest. Fire regime data obtained from the ecology staff on the Deschutes NF. Fire regime definitions are: group I (0–30 years frequency, low severity), group II (0–30 years frequency, high severity), group III (35–200 years frequency, low to mixed severity), group IV (35–200 years frequency, high severity), and group V (200 years frequency, high severity).

Land designation	Plant association type					Fire regime group					
	Ponderosa pine	Lodgepole pine	Mixed conifer	Other	Non-vegetated	I	II	III	IV	V	na
FSH	18	23	21	32	6	9	0	12	8	1	70
HRA	1	12	64	21	2	1	0	60	11	20	7
HRP	2	12	67	16	3	1	0	62	11	14	11
CHU	10	9	70	9	2	9	0	69	9	8	5
EAG	42	20	33	3	2	42	0	34	19	2	3
DHB	81	6	0	13	0	80	12	0	6	0	1
LSR	25	12	52	10	1	25	0	52	11	9	2
OLD	40	35	24	1	0	40	0	24	34	0	1
RNA	25	25	31	13	6	25	0	32	25	13	6
SIA	20	7	6	4	63	20	3	6	7	0	63
WIL	0	13	12	61	14	0	0	12	13	56	19
REC	6	28	14	36	16	6	0	14	27	34	20
VIS	29	36	30	4	1	28	1	30	36	3	2
GFM	38	41	18	1	2	38	0	18	40	0	4
WUI	na	na	na	na	na	2	0	0	1	0	97

(300 ac), but those fires accounted for 93.2% of the total area burned (Andrews, 2005). Wildfire suppression effects on fire perimeters are minimal during these extreme events (Finney et al., 2009; Flowers et al., 1983; Podur and Martell, 2007).

We simulated 50,000 burn events within the study area using random ignition locations that were assumed to be lightning caused. There was no evidence of spatial correlation in the ignition locations of large fires within the study area (Fig. 1 in Finney, 2005). Wildfire spread was modeled at a 90 m spatial resolution. The number of ignitions and resulting fires was sufficient to generate a cumulative burned area in the study area about 113 times, and individual pixels were burned on average 120 times. Simulation parameters (Table 3) were patterned after escaped wildfires within the study area and surrounding national forest lands (Table 4). We created five wildfire scenarios that were defined by wind speed, azimuth, burn period, and frequency (Table 4). These first two parameters were derived from historical observation rates during peak fire season (July–August) in the area (Table 4) from the Lava Butte weather station (5 km south of Bend, OR), and from input from Forest Service fire managers. Fuel moisture was derived for 97th percentile weather scenarios, also from the Lava Butte weather station. We then simulated wildfires to determine a burn period distribution that generated a fire size distribution consistent with historical fires (Table 4, Fig. 2). For the latter, daily fire progression data were obtained from the Incident Status Summary ICS-209 reports required for fires administered by US federal land management agencies. We built a frequency distribution of daily progression for 16 events from four large fires and compared it to the simulation outputs. We included only extreme fire spread events, defined as growth more than 1000 ha. We determined that a 480-min burn period created a reasonable facsimile of the observed fire size distribution and mean fire size (3295 ha for simulated versus 3779 ha for observed, Fig. 2). Qualitative comparisons of simulated versus historic fire perimeters showed a reasonable resemblance in terms of shape and size (Fig. 3). The simulated fires contained larger and smaller fire sizes, the former resulting from ignitions that started on the Forest and burned to the east into rangelands with fast spreading grass fuel types, and the latter were caused by ignitions that started on fuel surrounded by non-burnable land types (lava, lakes, scree, development).

Randig outputs consisted of an overall burn probability and a frequency distribution of flame lengths in 0.5 m classes for each 90 × 90 m pixel. Burn probability was defined as:

$$BP = F/n \tag{1}$$

where F 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 likelihood that a pixel will burn given a random ignition within the study area and burn conditions similar to the historic fires as described above. Fire intensity (Byram, 1959) 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 (Finney, 2002). Randig converts fireline intensity (kW m^{-1}) to flame length (FL, m) based on Byram's (1959) equation:

$$FL = 0.775(FI)^{0.046} \tag{2}$$

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

$$CFL = \sum_{i=1}^{20}\left(\frac{BP_i}{BP}\right)(F_i) \tag{3}$$

where F_i is the flame length midpoint of the ith category. Conditional flame length is the probability weighted flame length given a fire occurs and is a measure of wildfire hazard (Ager et al., 2010).

Table 3
Weather and fuel moisture parameters used for wildfire simulations. Wind scenarios were developed from historical weather data and sampled according to the probability values for wildfire simulations. Fuel moisture values were also derived from historical weather by Deschutes National Forest staff.

Wind scenario			Fuel moisture (%)		
Direction (°)	Speed (k h^{-1})	Probability	Fuel category	Fuel model GR2	All other fuel models
270	40.2	0.35	1-h	1	1
335	40.2	0.35	10-h	2	2
225	32.2	0.25	100-h	5	5
90	32.2	0.05	Live herbaceous	60	40
			Live woody	90	60

Table 4
Description of four large fires (Fig. 1a) in the vicinity of the study area used to calibrate wildfire simulations. Data were obtained from the Incident Status Summary (ICS-209) reports (http://famtest.nwcg.gov/fam-web/).

	Davis	B&B	Cascade Crest	Beaty Butte
Start date	28-Jun-03	19-Aug-03	19-Aug-06	12-Jul-00
Fire size (ha)	8572	36,733	8616	10,724
Largest daily fire growth (ha)	4452	5419	6468	5908
Number of burn periods >0 ha	8	21	12	4
Number of burn periods >1000 ha	1	12	1	2

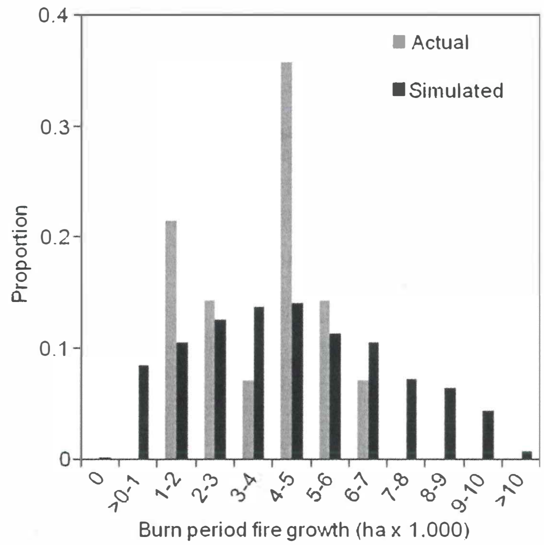

Fig. 2. Histogram of burn period area observed from 16 extreme fire spread events for four large fires (Davis, B&B, Cascade Crest, and Beaty Butte, Table 4), and the fire size distribution from simulating 50,000 fires on the study area.

Randig also generates text files containing the fire size (FS, ha) and ignition x–y coordinates for each simulated fire. These outputs were used to analyze spatial variation in fire size.

To measure wildfire transmission among land designations, we created a source–sink ratio (SSR) of wildfire calculated as the ratio of fire size generated by an ignition to burn probability:

$$\mathrm{SSR} = \log(\mathrm{FS}/\mathrm{BP}) \quad (4)$$

The SSR ratio measures a pixel's wildfire contribution to the surrounding landscape (FS) relative to the frequency with which it is burned by fires that originated elsewhere (BP) or were ignited on the pixel. In relative terms, pixels that have a high burn probability but do not generate large fires from an ignition are wildfire sinks, and those that generate large fires when an ignition occurs and have low burn probability are wildfire sources.

Since Randig does not report specific crown fire behaviors (passive, active), we used a static FlamMap simulation (each pixel burned independently) with the average azimuth and wind speed used in the Randig weather distribution to model crown fire activity and examine differences among the land designations.

2.6. Statistical and graphical analyses

We calculated average values for BP, FS, and CFL for each polygon within each land designation. We considered each polygon as a "patch", having specific socio-ecological function on the Forest (nest site, stream reach, old growth stand, home range, recreation site, WUI), within a larger network. Thus the patches were meaningful spatial units to understand variation in wildfire risk. For land designations with relatively few and large polygons (GFM, DHB, WIL, and REC), we created comparable circular patches with randomly located 177 ha (750 m radius) samples. We generated a sample set of the patches so that 10% of the total area in each land designation was covered (Table 1). The specific patch area for the samples was chosen based on the average polygon sizes of other land designations. We graphically examined the relationship between patch size and both variation and mean value for the simulation output variables and found no evidence of scale-related effects due to size variation in the patches as defined here.

We analyzed variation in BP, FS, and CFL among land designations to determine the relative wildfire exposure. For statistical purposes, we randomly sampled 10% of the pixels within each land designation (Hawth's Tools, Beyer, 2004). The 10% sample was deemed sufficient to represent each land designation in terms of fire behavior ouputs, and the reduced data set allowed for efficient statistical analyses. To address the question of fire sources versus sinks, we examined the relationship between the logarithms of FS and BP by fitting the following generalized additive model:

$$y = a_k + s(xloc, yloc) + s(\log(\mathrm{BP}), by = k) + \mathrm{error} \quad (5)$$

where y is log(FS); a_k is the intercept for the kth land designation; $s(xloc,yloc)$ is a 2-dimensional smooth spline function estimating spatial trends in the data that may be due to covariates not included in the model, and that may be contributing to spatial correlation in the dependent variable; and $s(\log(\mathrm{BP}), by = k)$ is a different smooth function for each of the land designations describing potentially different source to sink relationships for each k. The errors are assumed to be independent and homoscedastic. Residuals from this model were examined for further spatial correlations not accounted for by the spatial term in Eq. (5). The inclusion of x and y in the model was intended to remove the effect of the arrangement of land designation patches relative to each other in the simulation outputs.

A similar model as in Eq. (5) was then used to examine differences in overall fire exposure among the land designations. We defined exposure as the probability of a fire of a given flame length (Eq. (1)). We fit smoothed splines for each land designation to estimate BP at each flame length interval (dependent variable log(FL)).

3. Results

3.1. Spatial variation

Fire simulation outputs for burn probability (BP, Fig. 4a) showed complex patterns that were generally related to the dominant forest type and Landfire fuel model (Fig. 1a). Areas with high BP were found in several locations around the Forest, although the largest concentration was in the ponderosa and lodgepole pine forests on the eastern half of the Fort Rock Ranger District (southeast portion of the Forest), where long fetches of contiguous, fast burning fuel created conditions favorable for large fire growth. Burn probability was lower in and around areas that had been recently burned by wildfire, especially in the vicinity of the 2003 B&B Complex (northwest corner, Figs. 1a and 4a). Sharp transitions in BP were observed at the interface of burnable and non-burnable land

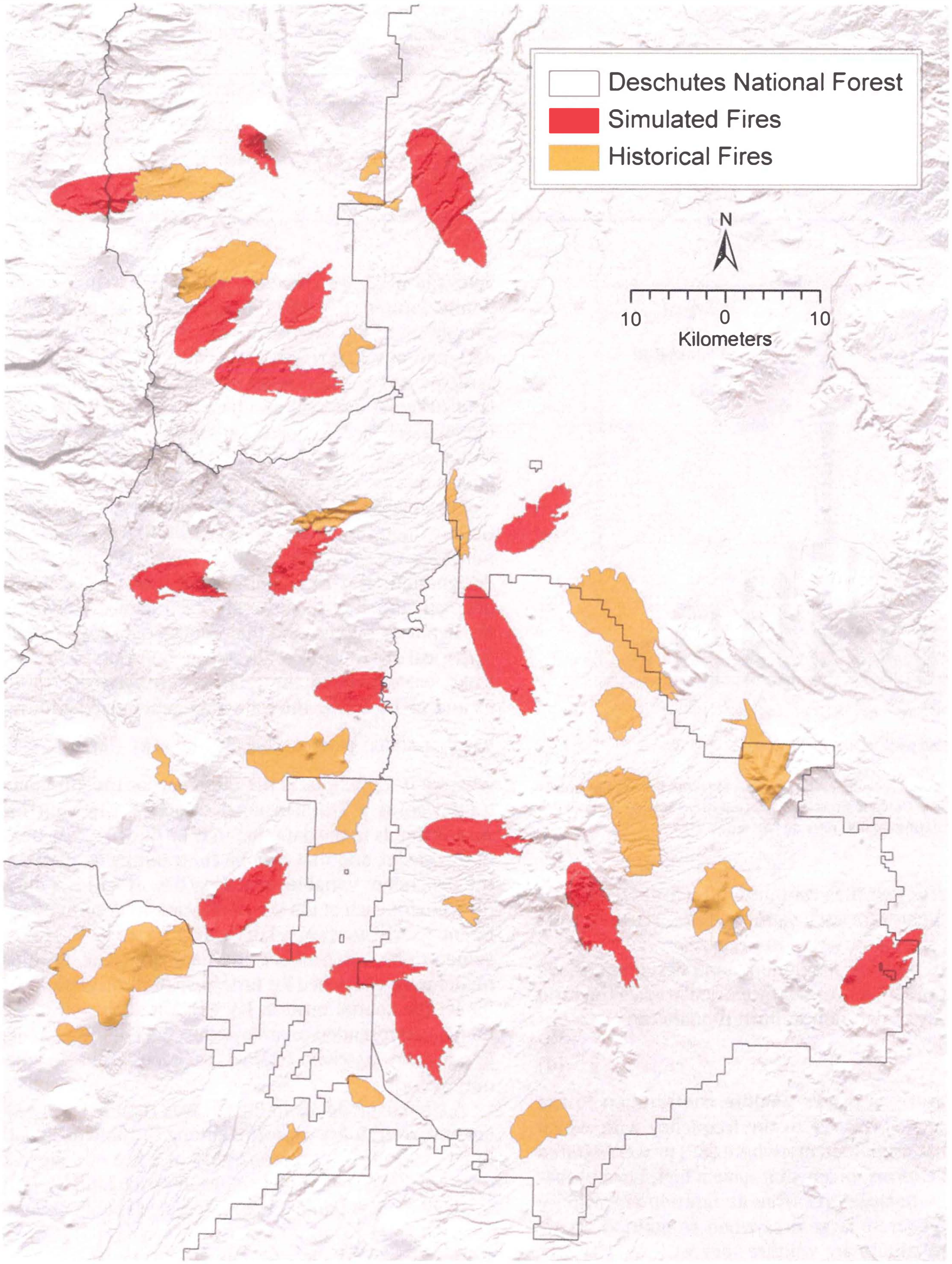

Fig. 3. Comparison of historical and modeled fire perimeters for a portion of the study area. Historical perimeters are shown for fires greater than 500 ha. Modeled fire perimeters are a sample from the 50,000 fires simulated for study (Fig. 2). The modeled fires in the figure were selected from the larger sample to illustrate the similarity in shape between simulated and historical fires. Simulation parameters for wind speed and direction were sampled from a distribution as described in Section 2.

types (lakes, lava flows, scree, urban development). The average modeled wind directions for fire simulations (ca. 270°, Table 3) led to BP shadows on the lee (east) side of non-burnable features, especially around lakes on the southwest portion of the Forest (Fig. 4a).

Spatial patterns in conditional flame length (CFL, Fig. 4b) showed that the mixed conifer, mountain hemlock, and lodgepole pine forests exhibited higher CFL (>5 m), and crown fire activity as well (Fig. 1 and Table 5). Juniper shrublands and ponderosa pine forests showed lower values (1–2 m). Sharp transitions in CFL were directly related to changes in forest type and fuel model, especially where dry ponderosa pine forests transitioned into stands of mixed conifer.

As with BP, the spatial patterns in fire size (FS, Fig. 4c) reflected continuity of fuel along the east-west direction, and the highest values were associated with large patches of contiguous fuel. Fire size also showed pronounced spatial variability within the Forest (Table 5 and Fig. 4c) and ranged from about two to 10,821 ha with a mean of 4512 ha. Sharp transitions in FS were observed where non-burnable features (e.g., lakes) blocked fire growth. Many of

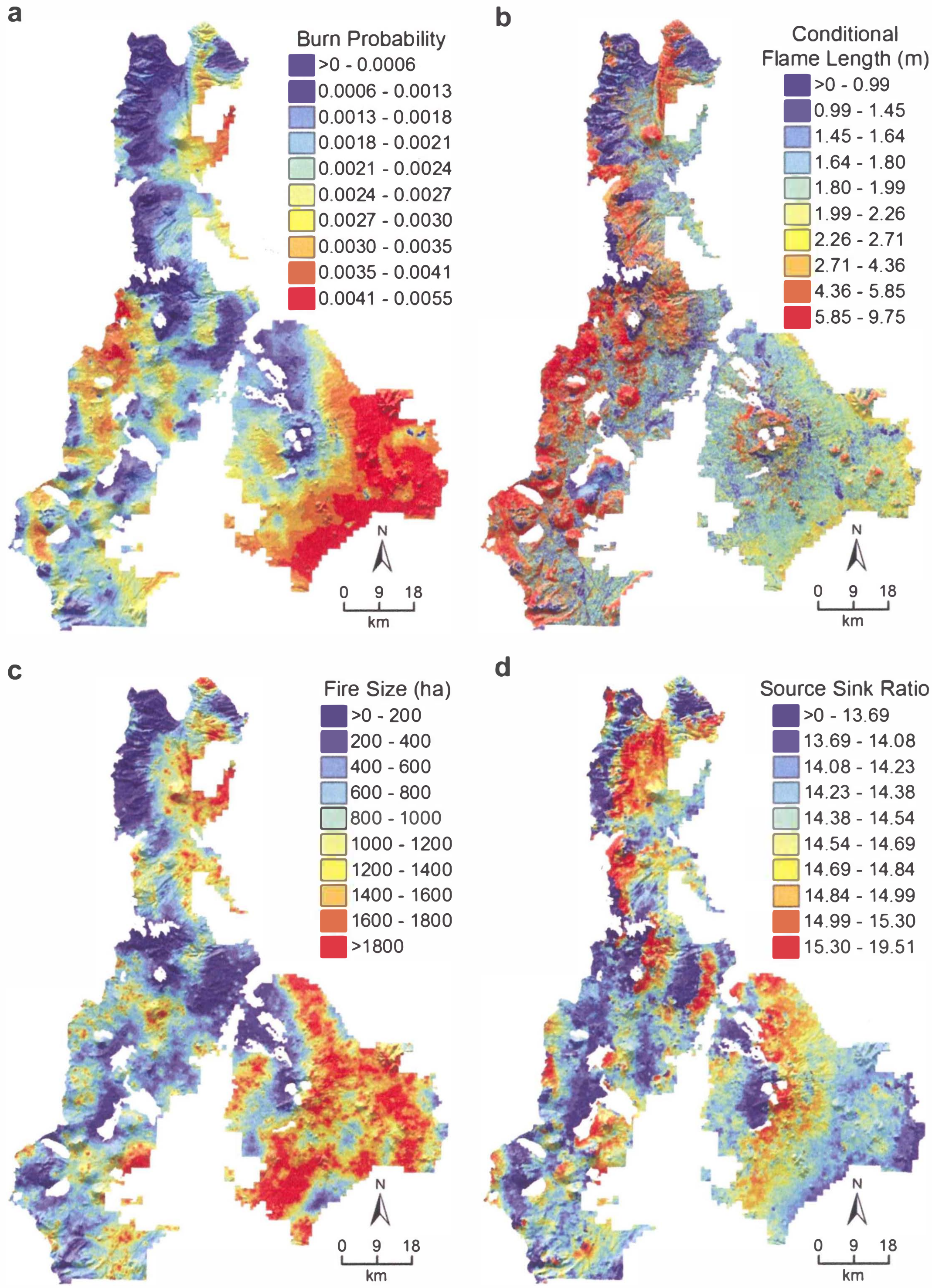

Fig. 4. Map of burn probability (a), conditional flame length (b), fire size (c), and source sink ratio (d) for the study area. Burn probability is the chance of a pixel burning given a random ignition in the study area and simulation conditions described in Table 2. Conditional flame length is the average flame length observed on a given pixel (90 × 90 m). Fire size (ha) shows the area burned from each ignition point. The fire size data were smoothed with a nearest neighbor procedure to fill intervening areas that did not receive an ignition. Source–sink ratio (SSR) was calculated as the log of the ratio of fire size (c) to burn probability (a). Points with large values had ignitions that generated large fires relative to the probability of being burned by other pixels (burn probability). Conversely, pixels with small values generated small fires relative to the probability of being burned by a fire originating elsewhere.

the largest fires were generated by ignitions on the eastern portion of the project area, upwind of large areas of contiguous ponderosa pine stands with a shrub (e.g., antelope bitterbrush, *Purshia tridentata*) understory and high predicted spread rates. The smaller fires resulted from ignitions adjacent to non-burnable features.

The source sink ratio (SSR, ratio of fire size to burn probability) measured the relative contribution of fire to the landscape from a given pixel relative the burn probability (Fig. 4d). The simulation outputs suggested that several regions of the Forest were sinks (small SSR), versus sources (large SSR). Sink areas for fire were evi-

Table 5
Fire simulation results from Randig by land designation for the Deschutes National Forest. BP is burn probability, and CFL is the conditional flame length, as described in Section 2. Maximum values represent the maximum average value observed among individual patches within each polygon. Active crown estimates were obtained from a FlamMap (Finney, 2006) as described in Section 2.

Land designation	Mean BP	Max BP	Mean CFL (m)	Max CFL (m)	Mean fire size (ha)	Max fire size (ha)	Active crown fire (%)
FSH	0.0018	0.0033	2.84	4.74	3566	5309	29
HRA	0.0025	0.0034	5.06	5.9	3494	4285	71
HRP	0.0023	0.0041	4.38	6.36	3833	6751	60
CHU	0.0019	0.0036	2.99	4.29	3229	4137	35
EAG	0.0019	0.0029	2.64	5.23	2842	5175	33
DHB	0.0033	0.0052	1.78	2.61	6140	9626	2
LSR	0.0017	0.0026	2.79	4.72	3469	6594	44
OLD	0.0028	0.0046	2.62	6.74	5211	9100	25
RNA	0.0019	0.003	3.41	5.22	4027	6001	43
SIA	0.0024	0.0047	1.76	2.31	4023	7764	15
WIL	0.0016	0.0041	3.42	7.11	2812	6081	68
REC	0.0019	0.0038	3.72	6.47	3508	6316	51
VIS	0.0023	0.0045	2.56	6.68	4174	8145	26
GFM	0.0029	0.0047	2.15	5.52	5597	9858	13
WUI	0.0018	0.0049	1.59	3.67	3228	7726	5
Forest	0.0024	0.0055	2.9	9.75	4512	10,821	28

dent around non-burnable features that blocked the progression of fire across the landscape. These areas received fire from the surrounding landscape, but ignitions did not generate large fires that burned elsewhere. Areas on the upwind side of long fetches of fuel and located in the lee (generally east) of non-burnable features were source areas. These latter areas generally occurred on the east side non-burnable lands (lakes, scree, lava flows). A large north-south band of relatively high SSR was observed for the southeast portion of the forest, where ignitions generated large fires in areas of moderate burn probability (Fig. 4d).

3.2. Patch variation within land designations

Scatter plots of average patch values for simulation outputs showed a wide range of fire behaviors within all of the land designations (Figs. 5 and 6). Land designations located predominately in the dry ponderosa pine forest (WUI, DHB, Fig. 5a and b) exhibited a wide range of BP (0.001–0.005), but in general, a relatively low CFL (1–2 m). The general forest matrix (GFM), which contains a broader mix of forest types (ponderosa and lodgepole pine, mixed conifer) showed a similar pattern, except for a cluster (15%) of patches that had a midrange for BP and higher CFL (3–5 m). In contrast, land designations located predominately in the mixed conifer, mountain hemlock, and lodgepole pine cover types (HRP, WIL, LSR, Fig. 5b and c), exhibited substantial variation in both BP and CFL. For instance, the average BP for the active and potential owl sites (HRP, Fig. 5b) was clustered between 0.0020 and 0.0035 (excluding 4 sites burned in the B&B Complex) with a CFL primarily between 4 and 6 m. In contrast, BP for deer habitat patches (DHB) ranged from 0.001 to 0.005, with a lower average CFL (1–2 m). Patches with the highest CFL were generally from wilderness (WIL) land designations.

The plot of average patch fire size (FS) versus BP (Fig. 6) showed that, in general, fire size and burn probability were positively correlated, a finding that was expected since larger fires lead to higher burn probability. However, variation among patches in FS at specific BP values was evident (vertical spread, Fig. 6), resulting from arrangement and continuity of fuel and vegetation around each patch. Larger average patch fire sizes for a given burn probability equates to a high SSR (Fig. 4d), and suggested that specific patches generate larger fires relative to the frequency at which they burn. Spatial variation in the relationship between BP and FS can be observed at a range of scales within the study area (Fig. 4d), with higher values of SSR in localized patches, and relatively large areas on the Forest. The range of fire sizes for a given BP is illustrated by WUI patches (Fig. 6a) where average fire size ranges from near zero to almost 8000 ha for a BP value of about 0.001. Deer habitat (DHB) and general forest matrix (GFM) show similar variation at the patch scale, as illustrated in Fig. 6b, and the map of SSR (Fig. 4d).

3.3. Variation among land designations

The results of the regression analysis to estimate burn probabilities (BP) by conditional flame length (CFL), after removing spatial trends (Fig. 7) suggested that the likelihood of a fire at a given CFL differed among the designations. Differences in the likelihood of burning among the land designations depended on the flame length examined. For instance, BP was higher at low CFL for several designations (GFM, DHB), and, to a lesser extent, higher at the high CFL for others (WIL, HRA, HRP). In general, the GFM and DHB areas showed higher probability of burning for a wide range of CFL values. Northern spotted owl nest sites (HRP, HRA) had relatively high BP only at the highest CFL. Comparing the land designations grouped into human values versus ecological and wildfire reserves (Fig. 7), the various wildlife habitat reserves had the highest BP at both low and high CFLs. A wide range of relationships between BP and CFL were observed for the ecological reserves (Fig. 7c), although none of them had a higher BP than GFM, except when the CFL exceeded 4 m.

Regression of fire size (FS) as a function of BP suggested differences in the source–sink relationships among the land designation (Fig. 7). In general, a larger FS at a given BP for a land designation was interpreted as a fire source versus sink. The differences among land designations were consistent with patch scale observations (Fig. 6), although the spatial regression model removed location effects and suggested a clearer interpretation. Steeper slopes for particular land designations suggested larger fire sizes were generated at a given BP. Shallow slopes for particular land designations indicated that increases in fire likelihood (BP) were not accompanied by larger fire sizes, meaning that individual pixels transmitted less fire from an ignition, relative to the frequency of incoming fires. Among the land designations, DHB, OLD, and GFM all had relatively large fire sizes for a given BP. Special interest areas (SIA), wilderness (WIL) and recreational sites (REC) had the smallest values for fire size for a given BP. The relationship between BP and fire size was strongly influenced by the connectivity of the fuel and the position of a pixel relative to fire shadows created by non-burnable features. In the case of eagle habitat (EAG), the shallow, non-linear trend resulted from the proximity of the habitat polygons around large lakes in the southwest corner of the study area.

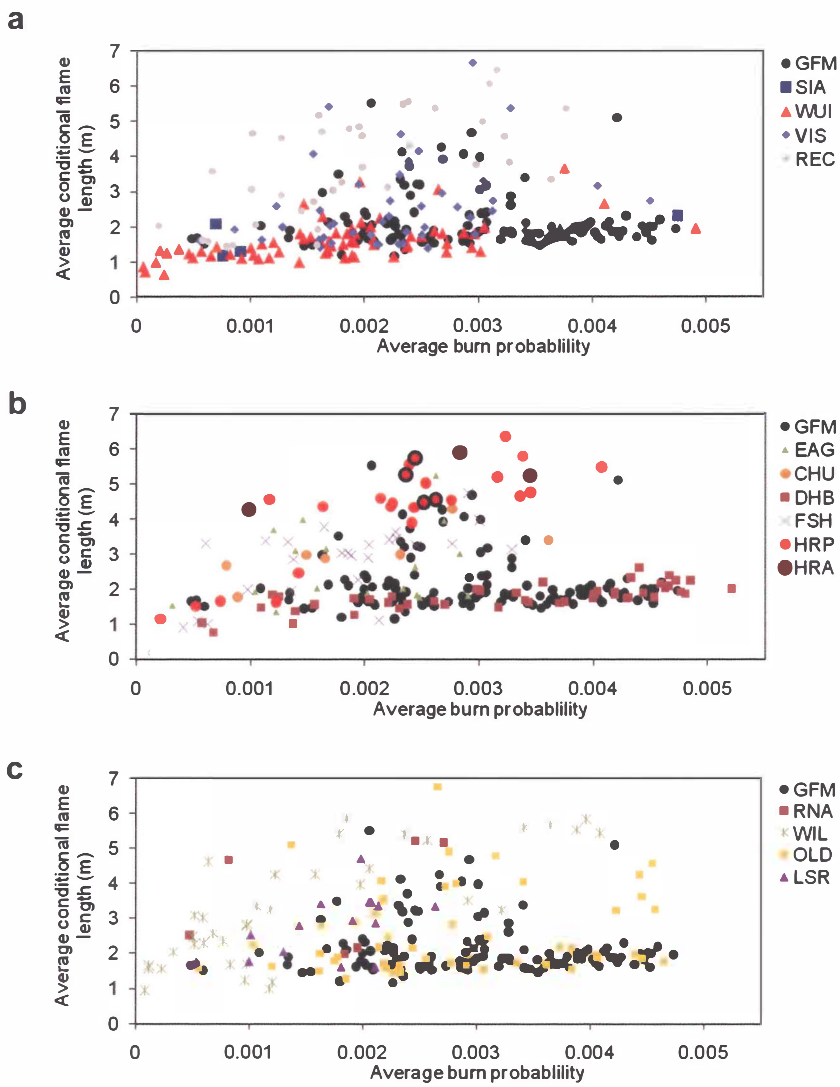

Fig. 5. Scatter plot showing patch-scale variation within selected land designations for burn probability versus conditional flame length. Each point represents a patch for a given land designation (Table 1), plotted according to the average burn probability and expected flame length. Each panel contains a group of land designations. (a) Human values (GFM = general forest matrix, REC = recreation sites, WUI = wildland urban interface, VIS = visual corridors and vistas); (b) Wildlife habitat (DHB = deer habitat, EAG = eagle habitat, FSH = aquatic reserves, HRA and HRP are active and potential northern spotted owl home range sites, respectively); (c) Ecological values (OLD = old growth areas, WIL = wilderness areas, LSR = late successional reserves, RNA = research natural areas). GFM is shown on all panels for comparison purposes.

Locations associated with habitat patches on the east side of the lakes were protected from fires burning in the west to east direction (the average fire spread direction), whereas ignitions from these locations were capable of generating fires that burned large areas to the east.

3.4. Crown fire behavior

FlamMap simulations predicted that 59% of the burnable area would exhibit either an active (crown to crown spread) or passive crown (torching) fire behavior under the conditions simulated (Table 5). The percent area of active crown fire activity (Table 5) ranged from a low of 2% for deer habitat (DHB), to 71% for active owl home ranges (HRA), and the crown fire activity outputs were consistent with the overall patterns found in CFL. Crown fire activity was consistent with the fire regime classification for most of the land designations (Tables 2 and 5). The northern spotted owl home ranges (HRP, HRA) and late successional reserves (LSR) in particular had a high percentage of area with crown fire behavior, and were classified mostly in the mixed severity fire regime (Tables 2 and 5). However, the fire regime data did not reflect the crown fire estimates from FlamMap for the GFM, where 40% of the area was classified into a severe fire regime, and crown fire behavior was only predicted for 13% of the area. The fact that over 80% of the area had experienced vegetation management treatments in the past decade (Table 1) likely contributed to this result.

4. Discussion

Although some of the results are specific to the Deschutes National Forest, there are similar ecological gradients, fuel configurations, management histories, social and ecological values, fire regimes, conservation issues, and restoration goals in much of the 177 million ha national forest network. The current study focused on quantifying wildfire exposure from large, stochastic and natural fire events, in contrast to other work concerned with anthropogenic ignitions and relatively small fires (e.g., Martinez et al., 2009; Syphard et al., 2008). Moreover, the modeling considers the distribution of heading, flanking, and backing fire behaviors and their respective frequencies, which is not the case in static wildfire simulations of individual stands or pixels. We found significant differences in wildfire exposure among land designations,

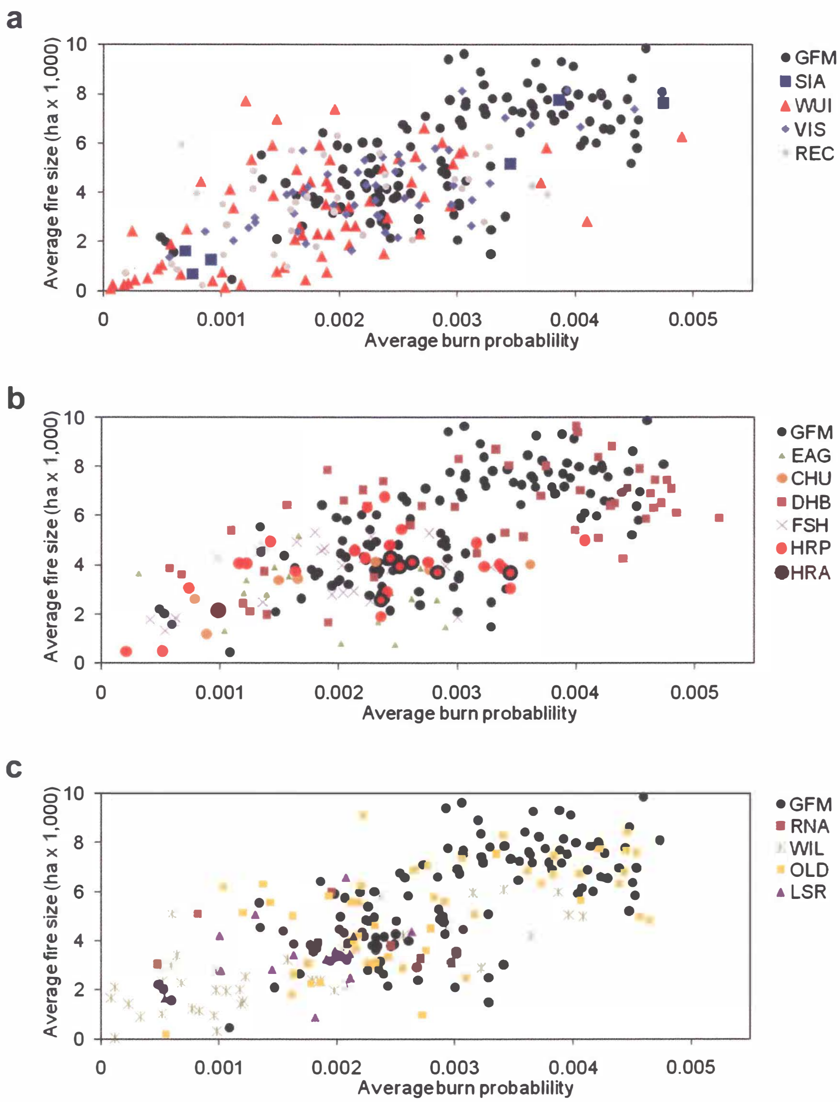

Fig. 6. Scatter plot showing patch-scale variation within selected land designations for burn probability versus fire size. Each point represents a patch for a given land designation (Table 1). Each panel contains a group of land designations. (a) Human values; (b) Wildlife habitat; (c) Ecological values. Land designation codes are as in Fig. 5.

conservation reserves, and urban interfaces. These differences can be used to help prioritize management activities and inform conservation, restoration, and risk management planning. The bulk of the previous work on wildfire risk has largely relied upon analyses of fire occurrence from spatial ignition data (Loboda and Csiszar, 2007; Martinez et al., 2009; Preisler et al., 2004; Syphard et al., 2008) and modeling fire intensity (hazard) (Chuvieco et al., 2010; Keane et al., 2010). While informative, these latter approaches do not fully account for landscape properties that contribute to the spread of large fires (e.g., 10,000–200,000 ha), which account for the majority of the area burned on western US national forests. Studies on potential wildfire impacts on ecosystem services such as carbon, wildlife habitat, social values, and fire resilient forests (Hurteau et al., 2008; Perry et al., 2004;) have not considered spatial variation in wildfire likelihood as part of their assessments. Ignoring large fire spread and likelihood can lead to substantially different conclusions about the location and timing of potential fire impacts, a fact that is illustrated in our spatial patterns of fire hazard (Fig. 4b) versus likelihood (Fig. 4a).

Current restoration and conservation strategies rely on qualitative descriptions of fire regime and condition class (NFP, 2000) that do not capture important spatial patterns in wildfire exposure. The departure from historical range of variability is a main decision variable in dry forest restoration programs (NFP, 2000), and wildfire simulation can be used to generate fine scale maps of these and other information used in the prioritization process. For instance, current fire return interval can be estimated from burn probability outputs (Finney et al., 2011) and compared to historical estimates from ecological data (Rollins, 2009) to measure departure from historical conditions. Although Landfire fire regime maps for the study area (Rollins, 2009) were similar to the burn probability outputs, the outputs also suggested finer scale decoupling of the fire regime components resulting from the arrangement of fuel (e.g., fire barriers such as lakes). Changes in burn probability and flame length not tied to fire regimes were evident in many areas where the flow of fire was interrupted by developments, and non-burnable fuel types.

The core motivation for the study was to compare relative wildfire exposure among conservation reserves, actively managed landscapes, and surrounding urban interfaces. We found relatively high BP and low CFL for the primary managed land designation (GFM) on the Forest, a finding that can be attributed to a long history of intense harvesting practices, and in part due to the ecological setting of the managed forest. The managed forests are located in the

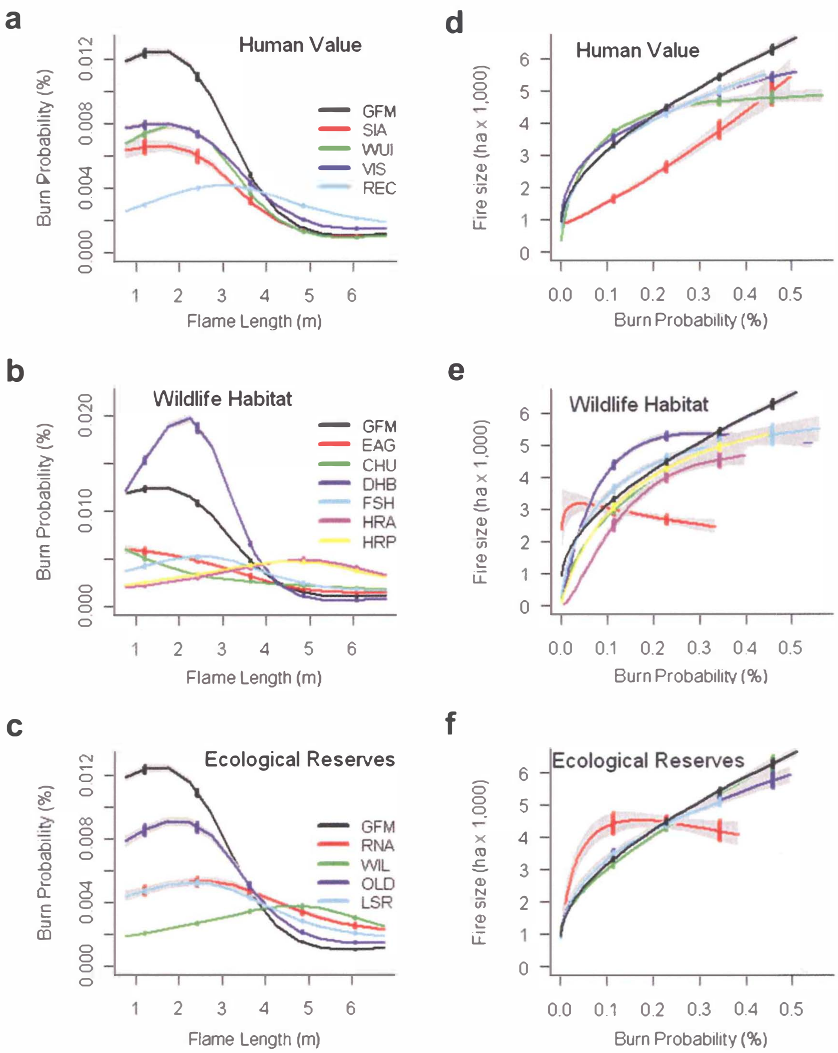

Fig. 7. Results of regression to analyze differences among land designations in burn probability (a–c) and fire size (d–f). Each panel contains a selected group of land designations, with the general forest matrix included on all panels for comparison. Panels on the left show that the relationship between burn probability and flame length varies among the land designations. Panels on the right show that the source–sink relationship varies among land designations as well. Abbreviations are as in Fig. 5. Note that *y*-axis scale in (b) differs from (a) and (c). Gray shaded areas are 95% confidence intervals.

lower elevation dry forests that have fast burning grass, shrub and herbaceous vegetation and high rates of predicted surface fire spread. Harvesting activities have contributed to these conditions (Agee, 2002; Naficy et al., 2010; Reinhardt et al., 2008), especially the relatively low and uniform CFL. On the other hand, owl and fish conservation reserves (HRA, HRP, FSH, and LSR) showed about the same or lower BP, but substantially higher CFL (Fig. 5). In general, many conservation reserves are in mixed conifer forests characterized by higher levels of surface, ladder, and canopy fuel. The simulations quantitate observations by Weatherspoon et al. (1992) and Countryman (1955), for old forest owl habitat, where stands are generally less flammable due to dense canopies and higher fuel moistures, owing to dampened wind speed in closed canopy forests (Rothermel, 1972). Northern spotted owl habitat reserves (CHU, HRA, HRP, LSR) all had a relatively high percentage of area expected to burn as a crown fire (average = 52%) and a relatively low percentage of area classified in high severity fire regimes (Table 2). Although the CHU reserves had the lowest average burn probability among the land designations (0.0015, Table 5), they have the highest observed loss due to historical fires (58%, Table 1), primarily due to the 2003 B&B Complex fire (Fig. 1a and Table 4). The same trend was also observed for other owl reserves (HRP, HRA), and is likely caused by their location in areas where suppression operations are difficult (wilderness restrictions, fewer roads, steep terrain).

We included WUIs in our study to compare wildfire risk on public lands adjacent to the Forest. Current community wildfire protection planning incorporates localized wildfire behavior (hazard), and ignores exposure that is potentially transmitted over long distances from large fires originating elsewhere. The simulation outputs suggested wide variation in wildfire exposure to the 128 WUI's parcels adjacent to the Deschutes. The scatter plots of exposure (Fig. 5a) can be used to prioritize risk management activities both on and off the Forest to address wildfire protection issues.

We analyzed the potential for transmission of risk with the source–sink relationship (SSR, Fig. 4d). Areas with high SSR generated large fires relative to the frequency that they burned, and can be considered progenitor areas for large fires. Conversely, sinks are areas that burned from fires originating elsewhere, relative to the amount of fire they contribute to the larger landscape. Conservation strategies located in source areas have a greater propensity to transmit fire and potentially impact other social and ecological values. Reserves located in sink areas are more prone to fires and potential impacts from fires that originate elsewhere. The SSR can also be interpreted from the slope of the plots between burn probability (BP) and fire size (FS), where steeper slopes suggest higher rates of fire transmission at a given burn probability. Land allocations located around natural fuel breaks (e.g., EAG, Fig. 7e) showed large variation in the SSR and no correlation between BP and FS. Although the results suggested variation in SSR, transmission of exposure can only be inference from the map outputs (Fig. 4c and d). For instance, it would appear that management of the GFM land designation on the Fort Rock Ranger District (southeast block) has a direct bearing on fire occurrence in the adjacent deer habitat (DHB).

In terms of conservation planning for species such as the spotted owl, burn probability and intensity maps may help identify occupied home ranges that are at risk to high intensity wildfire, and identify fire refugia (Arabas et al., 2006; Camp et al., 1997) within habitat conservation networks. We observed wide variation in burn probability among the active spotted owl nesting sites (Fig. 5b), and between the critical habitat units designated by the Fish and Wildlife Service (USFWS, 2008). Incorporating wildfire exposure assessments has not been discussed in the context of conservation plans for federally listed species (Noss et al., 2006; Spies et al., 2006; USFWS, 2008). On many national forests, the cumulative impacts of natural and anthropogenic disturbances increasingly threatens the survival of many species, and active management to protect remaining habitat might be necessary (Spies et al., 2006).

Properly calibrated, fire simulation methods offer a dramatic increase in information content for conservation, restoration, and ecological planning on fire-prone landscapes. Simulation modeling like that described here is now being conducted for the conterminous US (FPA, 2010; Finney et al., 2011), and thus it will be possible to repeat detailed exposure assessments to study a range of wildfire management problems on all ownership. A robust risk framework is also essential to analyze and prioritize specific strategies to adapt to fire-prone landscapes, such as fuel management and fire protection strategies, and expose the inherent risk to humans that live in wildland interfaces. The core fire spread model used in this study has been integrated into several aspects of fire planning on federal lands (see Ager et al., 2011; Calkin et al., 2010; Finney et al., 2011; FPA, 2010). Emerging patterns from additional case studies will help inform ongoing debates about locating and protecting conservation reserves (Spies et al., 2006), protecting WUIs (Ager et al., 2010), achieving ecological restoration goals (Brown et al., 2004; Noss et al., 2006; Pyke et al., 2010), understanding spatial factors that control fires (Parisien et al., 2010) and linked disturbances on fire prone landscapes.

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