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Analyzing the transmission of wildfire exposure on a fire-prone landscape in Oregon, USA

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ABSTRACT

We develop the idea of risk transmission from large wildfires and apply network analyses to understand its importance on a 0.75 million ha US national forest. Wildfires in the western US frequently burn over long distances (e.g., 20–50 km) through highly fragmented landscapes with respect to ownership, fuels, management intensity, population density, and ecological conditions. The collective arrangement of fuel loadings in concert with weather and suppression efforts ultimately determines containment and the resulting fire perimeter. While spatial interactions among land parcels in terms of fire spread and intensity have been frequently noted by fire managers, quantifying risk and exposure transmission has not been attempted. In this paper we used simulation modeling to quantify wildfire transmission and built a transmission network consisting of land designations defined by national forest management designations and ownership. We then examined how a forest-wide fuel management program might change the transmission network and associated metrics. The results indicated that the size, shape, and fuel loading of management designations affected their exposure to wildfire from other designations and ownerships. Manipulating the fuel loadings via simulated forest fuel treatments reduced the wildfire transmitted among the land designations, and changed the network density as well. We discuss how wildfire transmission has implications for creating fire adapted communities, conserving biodiversity, and resolving competing demands for fire-prone ecosystem services.

1. Introduction

Designing effective fuel treatment strategies to achieve the goals of new US federal wildfire policy (USDA-USDI, 2013) will be a major challenge to land managers given the diversity of ecological and social environments within and around federal tracts of land. These areas are increasingly impacted by large wildfires that overwhelm suppression activities under extreme weather conditions, and subsequently spread over long distances (e.g., 20–50 km) that span ownerships, administrative boundaries, diverse ecological conditions, and fuel structures. For example, the 215,000 ha Wallow fire in the southwest US spread over 50 km during a two week period in 2011, burning through two states, two native American reservations, three national forests, and private land. The spread of fires specifically from public to private lands is a common event with over 1 million ha of private land burned from fires starting on the western US national forests over the past 23 years (Ager et al., 2014). Federal wildfires that spread to the urban interface cause the bulk of human and financial losses and are the primary driver behind the escalating federal fire suppression budget (Bailey, 2013). Within the national forests, large fires also burn through highly variable fuel conditions as a result of forest planning efforts and related legislation (Wilkinson and Anderson, 1987; Duncan and Thompson, 2006) that restrict management activities on portions of the Forests to meet biological conservation and amenity objectives.

From a fire management perspective, the long distance spread of fire across anthropogenic and ecological boundaries complicates the development of policies designed to reduce associated financial and ecological losses. Clearly, from the perspective of a private landowner living within a wildland interface, information on where large fires are most likely coming from, who owns the land, and the capacity and willingness to manage fuels (Fischer and Charnley, 2012) should be a key part of the development of a community wildfire protection plan. Thus risk must be partitioned into

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in situ (owned by the landowner) versus *ex situ* (risk being transmitted from fires that start elsewhere), in order to determine the causal factors and optimal fuel management strategy. Managing wildfire risk on the diverse set of land designations on national forests presents a similar problem, where, for instance, fire risk from wilderness areas can impact conservation networks, recreation areas, infrastructure, and areas managed for wood production.

The concept of risk transmission is well developed for many disciplines, including the study of the spread of diseases in humans, plants, and animal populations (Sander et al., 2002) where, for instance, one organism transmits a disease to another. However, applying these concepts to wildfire is problematic without specific definitions of what constitutes transmission. Specifically, if a fire ignited in one land parcel burns another, risk may or may not be transmitted depending on the definitions and the factors responsible for fire crossing the boundary. These latter include, but are not limited to spatial heterogeneity in landowner behavior, fuel loadings, wind direction, responsibility for fire suppression, parcel size and arrangement, management practices, and ignition probability.

In this paper we first present a quantitative definition for the transmission of both wildfire risk and exposure (SRA, 2006), and discuss technical issues that complicate their estimation. Wildfire risk concerns the prediction of expected loss, where exposure concerns the juxtaposition of threatened resources in relation to predicted fire occurrence without estimating potential losses (SRA, 2006). We then describe an experiment to quantify wildfire exposure on a fire-prone national forest, and how exposure might be altered by a fuel treatment scenario that reduces fuel loadings and predicted fire behavior. We combined concepts in risk science with wildfire simulation methods (Finney et al., 2011b; Ager et al., 2012a), and network analysis (Christley et al., 2005) to characterize fire transmission among the land ownerships and Forest Service land designations, and identify contributing factors. We then simulated a large scale fuels management scenario and examined how the treatments changed fire transmission among national forest land designations and to private land. We were specifically interested in understanding the origin of wildfire threats to conservation reserves and adjacent wildland urban interface (WUI), and the potential to alter impacts from fuel treatments on the managed portion of the national forest. We discuss the results in the broader context of managing risk from large fires on multi-owner landscapes, and how network analyses could help inform both existing community wildfire protection planning efforts and newer federal wildland fire policies (USDA-USDI, 2013).

2. Methods

2.1. Transmission of risk and exposure

We define risk transmission when the conditions in one parcel result in amplified expected loss (SRA, 2006) in one versus the other. Consider two adjacent land parcels, A and B, of equal size and shape and conditions with respect to fire spread rate, intensity, ignition probability, suppression capacity, and potential loss (ecological, financial or other), and a random direction of wind. The net expected transmission of risk between the two parcels will be equal, despite ignitions in A burning parcel B and vice versa. Changing any one of the factors listed above creates the potential for unequal risk transmission among the parcels. Some of these factors are natural (e.g., wind direction) while others are ecological (e.g., fire regime), or anthropogenic (e.g., fuel management, urban development, or parcel geometry). The challenge at hand is to determine the magnitude of transmission among land parcels defined by administrative or ownership boundaries and identify the relative importance of the contributing factors. For instance, in the context of federal land management policy, understanding how ongoing fuel management and restoration programs potentially affect risk transmission among land designations (e.g., conservation reserves, recreation areas, etc.) would be important factors to consider in the implementation of federal wildland fire policy.

Transmitted risk can be quantitatively defined and measured with the following formula modified from Finney (2005), where we include both the source parcel (ignition) and the affected parcel where losses occur:

$$E(L) = \sum_{j \notin A} \sum_{i=1}^{n} RF_{ij}(P_{ij}) \qquad (1)$$

where $E(L)$ is the expected loss (risk), RF_{ij} is the loss from fire intensity class i in pixel j, A is the set of all pixels of a given land parcel, P_{ij} is the probability of a fire of intensity i from an ignition in pixel j located outside A.

Local risk (i.e., that from fires ignited within the parcel) versus transmitted risk can be calculated by substituting $j \in A$ into the first term, thereby providing a way to examine the relative contributions of the contributing sources, local versus transmitted. Benefits from transmitted fire could also be considered in the case of fire-adapted forests where fire confers a positive value by reducing fuel loadings and fire intensity. Dropping the response term RF_{ij} leads to a measure of wildfire exposure (SRA, 2006) that is commonly used in risk analysis when it is difficult to predict fire effects on ecosystem services, and when describing the juxtaposition of fire and values of concern is sufficient to inform fuel management or other mitigation strategies (Ager et al., 2012a). As with risk, many variant formulae can be constructed by using probability estimates that measure annual versus conditional burn probability that assumes a specific event (e.g., a single ignition). From an application standpoint, the key difference between risk and exposure is that the former requires intensity information for each pixel, while the latter does not. Existing simulation methods in models such as FlamMap, Randig, and FSIM store perimeter footprints and ignition locations for each fire, but pixel-specific intensity values are not retained for both computational and storage space reasons. Processing fire intensity outputs for >100,000 fires would overwhelm typical geo-processing capabilities with desktop computers. While it is possible to obtain estimates of intensity by modeling static fire conditions (wind speed, wind direction) for every pixel in a landscape (Finney, 2006), the marginal benefits over quantifying exposure from fire as in the current study would be small, in our opinion. Thus we limited the current analyses to measurements of wildfire exposure (henceforth fire transmission), while also considering both exposure and risk transmission in the larger discussion of managing wildfire risk.

2.2. Study area

The study area was the 756,634 ha Deschutes National Forest in central Oregon (Fig. 1) and surrounding lands contained within a 4 km buffer. The proclaimed boundary is a smoothed version of the administrative boundary that considers inholdings as part of the Forest, and thus contained extensive privately owned land (121,000 ha) and WUI (43,000 ha) in addition to the national forest land. The 4 km buffer included lands from adjacent national forests, private land, tribal entities, and the BLM (Fig. 1). The physiographic gradients, diversity of vegetation, climate, and management resemble the setting around many national forests throughout the western US, and are described in detail elsewhere (Ager et al., 2012b). The Forest contains extensive stands of lodgepole pine (*Pinus contorta*), ponderosa pine (*Pinus ponderosa*), Douglas-fir (*Pseudotsuga menziesii*), white fir (*Abies concolor*) and

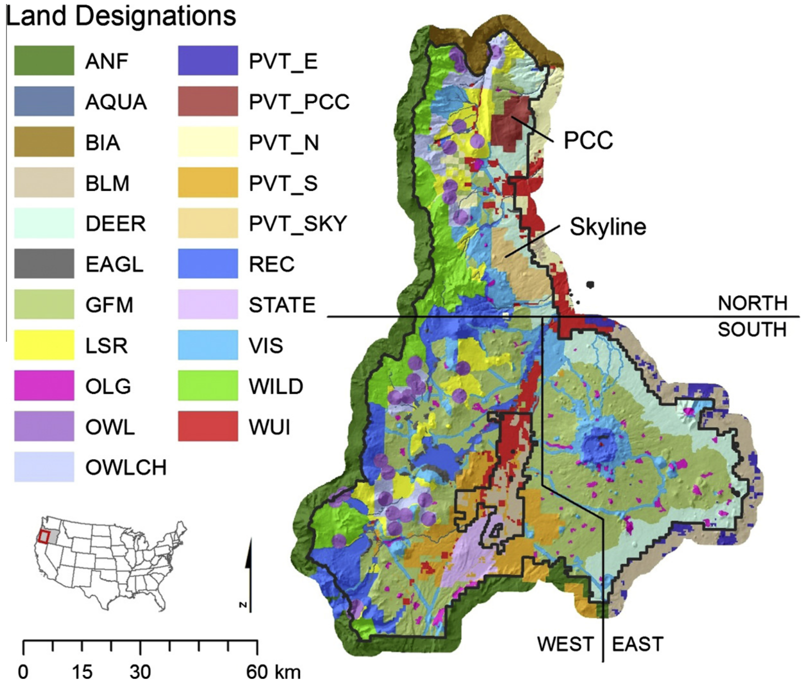

Fig. 1. Land designations on the Deschutes National Forest and surrounding lands from the Land and Resource Management Plan and updated by the Northwest Forest Plan (USDA Forest Service, 1990) and PACFISH (Henderson et al., 2005). Horizontal and vertical lines indicate boundaries to further subdivide privately owned (PVT), non-WUI parcels based on region (north versus south, or east versus west) for network analysis. See Table 1 for land designation descriptions.

mountain hemlock (*Tsuga mertensiana*). The Forest has experienced over 8400 wildland fire ignitions since 1949, mostly caused by lightning during the summer months. Wildfire activity has seen a major jump in the past decade with almost 2000 ignitions and 10 large fire events that combined burned 74,250 ha between 2002 and 2011.

2.3. Land management designations

We chose federal Forest Planning land designations within the Forest as the basis to study transmission for several reasons. First, previous work showed strong differences in fuels and fire behavior (spread rate, intensity) among the land designations (Table 5 and Fig. 5 in Ager et al., 2012b), due to differences in both fire regimes, ecological settings associated with the different designations, and past management activities. Secondly, all of the 155 national forests are stratified into a similar scheme of land designations, making the study relevant to the broader network of national forests. Finally, the contrasting management objectives among the land designations, where some are dedicated to wood production and others are managed for ecological and amenity protection, set the stage for identifying management conflicts in terms of long-term wildfire management goals on the Forest.

The Forest is stratified into land management designations (Table 1, Fig. 1) according to the Deschutes National Forest Land and Resource Management Plan (USDA Forest Service, 1990), the Northwest Forest Plan (USDA and USDI, 1994) and PACFISH (Henderson et al., 2005). The lands surrounding the Forest (4 km buffer) included land managed by the Bureau of Land Management (BLM), Bureau of Indian Affairs (BIA), the State of Oregon (STATE), adjacent national forests (ANF), and private entities (PVT). We further subdivided the PVT lands in terms of their inclusion within wildland–urban interface (WUI) as mapped by the interagency Central Oregon Fire Management Service and the State of Oregon. Here the WUI was defined by a 2.4 km (1.5 mi) buffer around all private land parcels containing structures. The WUIs in the study area covered 43,871 ha and are primarily located along the northeast boundary of the Forest and in the central southern portion of the study area (Fig. 1). Five important tracts of private land are present within the study area and were also identified as unique parcels within the PVT land designation. The Skyline forest is a 15,434 ha private tract (PVT_SKY) west of the city of Bend that was a commercial tree farm for the past 80 years and is now being acquired by the Land Trust as a Community Forest (Deschutes Land Trust, 2014). The Private South land designation (PVT_S) is a 69,895 ha mix of non-industrial private lands and small privately owned tracts located around La Pine in the south central portion of the study area. The Private East (PVT_E) designation includes 13,203 ha of private land adjacent to the Forest along its eastern boundary. The Private North (PVT_N) designation is a 23,203 ha collection of WUI parcels along the northeast portion of the study area. A fifth private tract is the Ponderosa Cattle Company (PVT_PCC) near the town of Sisters and is managed for wood and livestock production.

2.4. Vegetation and fuel data

Surface and canopy fuel data were obtained from the national LANDFIRE dataset (Rollins, 2009), and included elevation, slope, aspect, fuel model (Scott and Burgan, 2005), canopy cover, canopy base height, canopy height, and canopy bulk density (LANDFIRE, 2013). 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 planning efforts on the Deschutes. LANDFIRE data were used to model the fuels for the existing conditions, and then modified to reflect the fuel management scenarios described in Section 2.5.

2.5. Fuel management scenarios

Formulating a Forest-wide restoration scenario on a large national forest such as the Deschutes is a complex problem owing

Table 1
Land designations in the study area and associated values for transmitted fire estimated with wildfire simulation. Abbreviations for land designations used in the text are shown in the left column after the name of each designation. NonTF = the area of self-burning per ignition. TF-IN = the area burned per ignition from other designations. TF-OUT = the area burned per ignition in other designations. Additional description of the calculations for transmitted fire are in the methods Section 2.7.

Land designation	Total area (ha)	Fuels management	Area burned per ignition (ha)					
			Untreated			Treated		
			NonTF	TF-IN	TF-OUT	NonTF	TF-IN	TF-OUT
Adjacent national forest (ANF)	100,174		1025	1649	1441	1045	1194	2373
Aquatic conservation (AQUA)	8592	No	126	487	2553	94	332	1534
Bureau of Indian Affairs (BIA)	19,510		1421	232	925	1404	245	2165
Bureau of Land Management (BLM)	63,547		1444	4753	1721	1434	4019	2968
Deer habitat (DEER)	85,851	Yes	1768	5534	2522	980	2836	2458
Bald eagle habitat (EAGL)	5078	Yes	281	157	1935	50	42	465
General forest matrix (GFM)	220,124	Yes	2051	8416	1927	748	3509	1426
Late successional reserve (LSR)	44,295	Limited	803	1988	1979	205	777	710
Old growth management (OLG)	14,138	No	255	640	3769	195	332	2255
Owl nest sites (OWL)	31,749	No	684	1555	2242	624	1300	1729
Owl critical habitat (OWLCH)	25,235	No	459	984	1607	445	920	1454
Private East (PVT_E)	13,204		661	665	2483	657	545	2854
Private North (PVT_N)	23,203		949	3187	1868	913	2168	1466
Private Ponderosa Cattle Company (PVT_PCC)	10,207		1557	2302	4154	1524	1629	2755
Private South (PVT_S)	69,895		1710	3468	2354	1665	2686	3,629
Private Skyline (PVT_SKY)	15,434		1744	468	1535	1679	210	2594
Recreation sites (REC)	73,666	Limited	884	1559	1609	875	1138	1871
State (Gilchrist State Forest, STATE)	17,479		2080	937	3128	2164	911	4960
Visual corridors and vistas (VIS)	82,348	Yes	676	3236	2327	379	1631	1264
Wilderness (WILD)	68,362	No	1034	934	1405	1053	918	2231
Wildland urban interface (WUI)	43,871		811	2058	1726	776	1365	2023

to a diversity of forest types, management objectives, and land designations. Our approach used detailed information from existing management programs on the Forest, including stand scale (i.e., 10–200 ha) prescriptions, and a landscape scale priority scheme. We modeled a scenario that resulted in mechanical treatments on about 20% (131,000 ha) of the Forest (Fig. 2), primarily on the General Forest Matrix (GFM) land designation. Experimental evidence suggests that this level of treatment can significantly reduce wildfire spread and intensity (Finney et al., 2007), although simulation studies to date have not modeled fuel treatments at the scale of a national forest. At current rates of treatment on the Forest, about 16 years would be required to implement the treatment, or 8 years if the current rate were doubled.

The stand prescriptions were multipurpose in that they addressed both wildfire behavior and ecological departure from pre-settlement conditions. Fuel treatment prescriptions consisted of a thinning from below followed by a surface fuel reduction treatment and prescribed fire. The prescriptions were modeled with the Forest Vegetation Simulator and Fire and Fuels Extension (FVS-FFE, Rebain, 2010) for a sample of 4194 mapped stands using data from recent stand exams on the Forest. The stand simulation results were subsequently translated to the LANDFIRE data to build fuel landscapes for the wildfire simulations as described below. The simulated treatment regime was specific to each of the major cover types on the Forest as determined from forest vegetation maps. We simulated a sequence of thinnings from below to a threshold set by either trees per ha, stand density index, or basal area depending on the cover type (Table 2). Prescribed fire parameters were chosen to replicate typical fall prescribed burning on the Forest (Table 3). We assumed the surface fuel reduction treatment removed 90% of fuels between 2.54 cm and 30.48 cm in diameter. The post-treatment stand characteristics in terms of fuels required by the simulation models (canopy base height, canopy height, canopy cover and canopy bulk density) were then compared to untreated characteristics for the same year to determine adjustment factors (Table 4). After discussions with local fuel planners we chose a timber-litter (TL2) fuel model (Scott and Burgan, 2005) to represent treated stands.

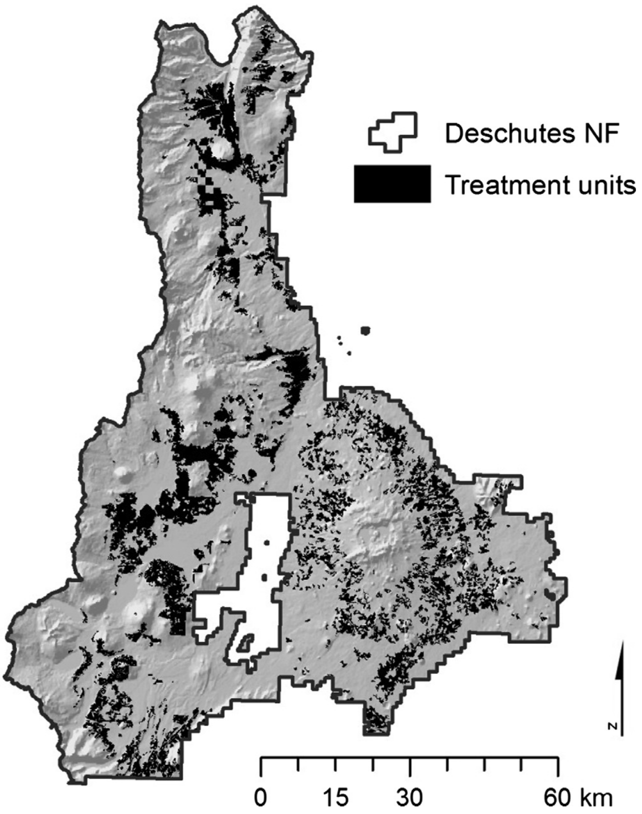

Fig. 2. Map of simulated fuel treatment locations on the Deschutes National Forest. Treatments were primarily in the general forest (GFM) and deer habitat (DEER) management designations. The treated area was about 20% of the total area of the Forest.

We located the treatments on the Forest using a priority scheme based on wildfire hazard (Table 5) and fire regime group (Table 6). The priority scheme is similar to that used on the Forest where stands are selected for treatment based on their current fuel loadings and expected fire behavior relative to pre-settlement conditions. Wildfire hazard was based on the potential for a stand to

Table 2
Specifications for thinning prescriptions modeled in the Forest Vegetation Simulator-and Fire and Fuels Extension (FVS-FFE) to estimate changes in surface and canopy fuels. Prescriptions varied by dominant forest cover type based on operational practices on the Deschutes National Forest. Abbreviations: ponderosa pine (PIPO), white fir (ABCO), lodgepole pine (PICO), diameter at breast height (DBH).

Forest cover type	Species	Diameter threshold	Thinning sequence
Ponderosa pine	PIPO	<25.4 cm DBH	Thinned to 32 tree ha^{-1}
	ABCO and PICO	<53.3 cm DBH	All removed
	All	<53.3 cm DBH	Removed until basal area <13.7 m^2 ha^{-1}
Lodgepole pine	All species	<17.8 cm DBH	Thinned to 57 trees ha^{-1}
	PICO	17.8–53.3 cm DBH	Thinned to stand density index 150
Mixed conifer and mountain hemlock	All species	<17.8 cm DBH	Thinned to 12 trees ha^{-1}
	PICO	17.8–53.3 cm DBH	All removed
	ABCO	17.8–53.3 cm DBH	Thinned to stand density index 238

Table 3
Fuel moisture and weather conditions used for underburns simulated in the Forest Vegetation Simulator and Fire and Fuels Extension (FVS-FFE). The underburns followed the thinning treatment and surface fuel reduction treatment as described in the text.

Fuel moisture (%)							Weather	
1-h	10-h	100-h	1000-h	Woody	Herbaceous	Duff	Temp (°C)	Windspeed (kph)
12	13	14	15	90	120	125	21	6.4

Table 4
Adjustment factors developed from Forest Vegetation Simulator and Fire and Fuels Extension (FVS-FFE) simulations to modify LANDFIRE fuel grids to reflect treatments. Pre-treatment fuel grids for layers are multiplied by the values below to create the post-treatment landscape for fire simulation. Fuel models (Scott and Burgan, 2005) for treated stands were assigned fuel model TL2 (182) for all forest cover types.

Forest cover type	Fuel variable			
	Canopy cover (%)	Canopy base height (m)	Canopy height (m)	Canopy bulk density (kg m^{-3})
Ponderosa pine	0.4	3.9	1.0	0.2
Lodgepole pine	0.3	4.5	0.6	0.2
Mixed conifer	0.6	3.2	0.9	0.5
Mountain hemlock	0.6	3.8	0.9	0.4

exhibit crown fire and high flame length and was determined from a FlamMap simulation (Finney, 2006). FlamMap can simulate the burning of each pixel (or stand) in a landscape under uniform weather assuming a heading fire direction (in contrast to simulating the spread of individual fires across stands and pixels as described in Section 2.6). Weather conditions for these wildfire hazard simulations are described in Tables 5 and 7 and were based on values derived from the Forest fuels specialists. Pre-settlement conditions were described using fire regime group (FRG) data (Hann et al., 2008; LANDFIRE, 2009). The two variables were then used to determine an overall treatment priority for each stand polygon (Table 6). Stands were selected for treatment until the total treated area equaled 20% of the Forest (Fig. 2). The treatments were then implemented in the fuels data to create a treated representation of the landscape. The average size of the treated stands was 18.5 ha (range 2–373 ha).

Table 5
Wildfire hazard classification scheme developed to prioritize stands for treatment. See also Table 6. Fire behavior was estimated from a static FlamMap simulation using LANDFIRE data. The FlamMap simulation used static conditions to burn each pixel independently (versus discrete fire events used to measure transmission; see Table 7) with a wind speed of 38.6 kph and 225 degree azimuth and fuel moistures outlined in Table 7.

Type of fire	Flame length (m)				
	0	>0–1.2	>1.2–2.4	>2.4–3.4	>3.4
No fire	none	none	none	none	none
Surface fire	none	low	low	moderate	high
Passive crown fire	none	low	moderate	high	extreme
Active crown fire	none	moderate	high	extreme	extreme

Table 6
Treatment prioritization scheme to select stands for treatment based on current wildfire hazard (Table 5) and fire regime group (FRG). Assignment of priorities for FRG classes was adopted from that used on the Deschutes National Forest. FRG 1 = high; 3 = moderate; 2, 4, 5 = low; and other = no treatment needed. Stands were treated according to priority level until the total treated area target was met for the Forest. Fire regime definitions are: 1 = 0–30 years frequency, low severity; 2 = 0–30 years frequency, high severity, 3 = 35–200 years frequency, low to mixed severity, 4 = 35–200 years frequency, high severity, 5 = 200 years frequency, high severity.

Fire regime	Wildfire hazard			
	Low	Moderate	High	Extreme
2, 4, 5	low	low	mod	mod
3	low	mod	high	high
1	mod	high	very high	very high

2.6. Landscape wildfire simulations

We applied the wildfire modeling methods used in Ager et al. (2012b) and simulated 200,000 wildfires on both the treated and untreated landscape using the minimum travel time (MTT) fire spread algorithm (Finney, 2002), as implemented in the program Randig. The MTT algorithm is implemented in a number of other wildfire behavior models including FSIM (Finney et al., 2011b), FSPro (Finney et al., 2011a) and FlamMap (Finney, 2006). Simulation conditions (Table 7) were developed from historical wildfires within the study area and surrounding national forest lands as described previously (Ager et al., 2012b). Ignitions were assumed to be lightning caused and randomly located. There was no evidence of spatial correlation in the ignition locations of large fires

Table 7
Parameters for simulating wildfire events with Randig to measure transmission and exposure among land designations. Wind scenarios were developed from historical weather data and sampled according to the probability values for wildfire simulations (Ager et al., 2010). Fuel moisture values were also derived from historical weather by Deschutes National Forest staff.

Wind scenario			Fuel moisture (%)		
Direction (degrees)	Speed ($k\,h^{-1}$)	Probability	Fuel category	Fuel model TL2 (182)	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

within the study area (Fig. 1 in Finney, 2005). Simulated wildfire perimeters bore a close resemblance to historical fires within the study area (Fig. 3A). The effect of the fuel treatments on simulated wildfire growth using the MTT algorithm is shown in Fig. 3B for a sample of simulated wildfires.

2.7. Analysis

Randig generates a number of fire simulation outputs including a shapefile containing the perimeter of each fire, and a flame length probability file (FLP). The FLP is a gridded point file containing an estimate of the burn probability within 20 0.5 m fire intensity classes. The burn probability (BP) for a given intensity class is the ratio of the number of times a pixel burned to the total number of fires simulated and represents the likelihood of a pixel burning given one random ignition within the study area. Conditional flame length (CFL), which measures the average flame length at which a pixel burned, was calculated from the FLP data as:

$$CFL = \sum_{i=1}^{20} \left(\frac{BP_i}{BP} \right) (F_i) \tag{2}$$

where BP_i is the probability of a fire at the i^{th} flame length category, BP is the burn probability, and F_i is the flame length midpoint of the i^{th} flame length category. We used both BP and CFL to examine the effects of treatments by differencing the pixel values between the treated and untreated scenarios and then mapping the output.

To quantify transmission, the fire perimeter outputs and ignition locations were intersected with the land designation map. This allowed a cross-tabulation of the total area burned in each land designation by ignition source designation. We then divided the area burned by the number of ignitions in the source designation to estimate the average per fire transmitted. This removed the effect of differential numbers of ignitions among the designations (ignitions were located with a random uniform density within the study area). The resulting metric quantified transmitted fire (TF) for a fire ignited in land designation i that burned across a boundary into j as

$$TF_{ij} = AB_j / N_i \tag{3}$$

TF_{ij} measures the average area burned in a surrounding land designation j given an ignition in i under the conditions used to simulate wildfires described in Section 2.6. We note that there are many other ways transmission could have been quantified by using various proportions and probabilities, and after experimenting with several approaches we deemed the current metric as the most parsimonious and interpretable measure of exposure. The individual TF_{ij} value for each pair of land designations was used to populate a transmission network as described below. We then summed TF_{ij} for each land designation to partition fire into three categories: total incoming fire, outgoing fire, and self-burning. Specifically, summing TF_{ij} for designation i (ignition source) over j designations yielded the total amount of transmitted fire to other land designations, henceforth TF-OUT. Summing over all ignition sources i for a particular designation j estimated the total incoming fire per ignition outside the designation, TF-IN. The area of non-transmitted fire per ignition ($i = j$) is the non-transmitted fire (NonTF) and measures the area

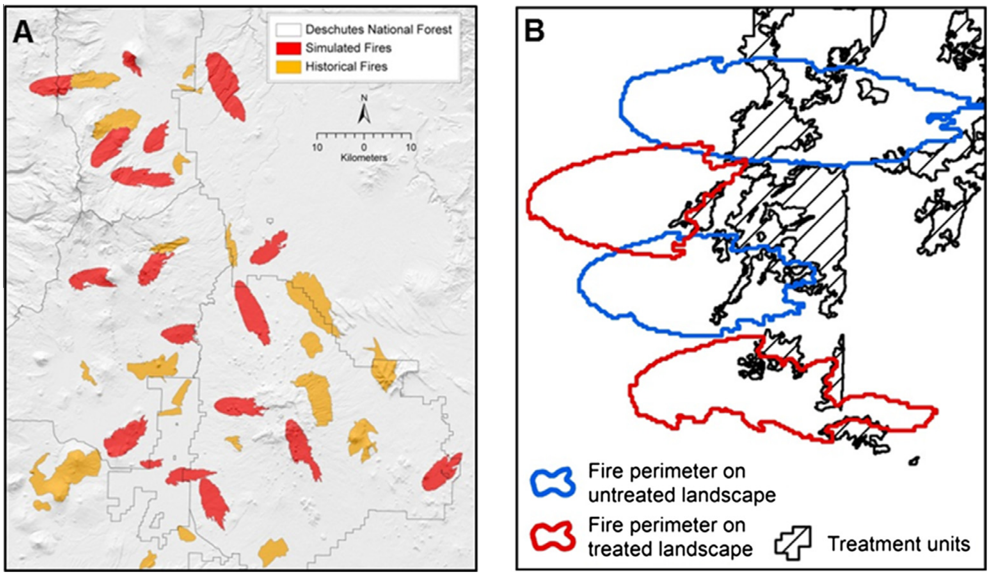

Fig. 3. (A) Comparison of historical and modeled fire perimeters within the study area. (Figure from Ager et al., 2010.) Historical perimeters are shown for fires greater than 500 ha. (B) Example of treatment effects on wildfire perimeter growth. Blue perimeters were simulated without treatments; red perimeters were simulated with hatched areas treated.

burned by ignitions within the land designation (i.e., self-burning). Note that all three measures above are size independent measures, such that more ignitions in a larger land class polygon will not translate into larger values of either of the variables in a smaller, adjacent polygon due to more ignitions in one versus the other. The three summary metrics were then used to compare fire transmission among the various land designations for both the treated and untreated landscape. We were particularly interested in how treatments changed the transmitted wildfire exposure to conservation and other reserves where fuel management is not permitted (43% of the Forest), and to private lands.

Individual values for TF_{ij} (Eq. (3)) were then used to build a network to both visualize and quantify the connectivity among specific land designations. Network methods are increasingly being used in conservation planning and biogeography to understand landscape connectivity and how social organizations affect land use planning (Minor and Urban, 2008; Bascompte, 2009; Cumming et al., 2010; Kininmonth et al., 2011; Guerrero et al., 2013; Mills et al., 2013). Networks are comprised of nodes and linkages; in our case the nodes corresponded to land designations and the linkages represented the transmission (TF_{ij}) of fire igniting in designation *i* and burning onto *j*. Nodes consist of multiple polygons for a given land designation, and hence the linkages measure the transmission of all the polygons to the polygons of other land designations. The transmission between two nodes is directional, thus *TF* from node *i* to *j* does not equal *TF* from node *j* to *i*. Note that TF-OUT and TF-IN metrics described above are sums of incoming and outgoing for all linkages at a node, not transmission between pairs of land designations (TF_{ij}).

We used network software to calculate whole network and node-specific measures pertaining to the frequency and strength of linkages. Node degree measures the number of linkages for each node and is widely used in network analysis to indicate how central a node is in the network, and is often interpreted as an indicator of connectivity and influence (Borgatti et al., 2013). The number of nodes present in the network compared to the maximum possible is the node density, which represents the overall connectedness in the network. We also calculated the number of linkages transmitting fire into the designation (Degree-IN), and the number of linkages the designation was transmitting fire to other nodes (Degree-OUT). Node degree is the total number of linkages for a node (land designation), while Degree-IN and Degree-OUT are the number of incoming or outgoing linkages. All network measures and corresponding graphic representations were calculated in Visone (Borgatti et al., 2002; Brandes and Wagner, 2004).

2.8. Effect of fuel treatments

We described the effects of fuel treatments by mapping differences in burn probability and conditional flame length, and by calculating average number of land designations burned per fire on the treated and untreated landscapes. We also examined the change in NonTF, TF-IN, and TF-OUT between the treated and untreated landscape in scatterplots and network diagrams. The change in the percentage of total network linkages (network density) and average node degree (number of linkages) was also calculated. Of specific interest in these analyses was the relative effect of treatments on conservation and amenity reserves versus managed forests, as well as the effect of treatments on transmission from public to private lands.

2.9. Effect of parcel geometry and size on transmission

To examine how parcel size and geometry were related to wildfire transmission metrics we calculated average polygon size and perimeter to area ratio (i.e., shape of the polygon) for each land designation. These two metrics along with node degree were compared to the percent transmitted fire calculated as (TF-IN + TF-OUT)/(TF-IN + TF-OUT + NonTF) * 100, and to the ratio of TF-IN to TF-OUT. We were focused on comparisons of land designations that have different geometries and parcel sizes, such as linear aquatic reserves along riparian areas (AQUA), versus circular owl nest reserves (OWL), and large tracts of private land (PVT_S, PVT_SKY) in terms of incoming wildfire, and thus vulnerability from fire in surrounding land designations. For this purpose we examined scatterplots of total transmitted fire, transmission ratio and average polygon size and perimeter to area ratio.

2.10. Historical fire transmission

We used historical fire perimeter and ignition location data to analyze and compare observed and simulated transmission. The purpose of this analysis was to document the wildfire transmission among land designations from historical fires and provide coarse summary statistics for comparison. The data were obtained from the Deschutes National Forest data library (Dana Simon, Deschutes NF) and contained 55 wildfires larger than 1.2 ha that occurred between 1980 and 2011. Fire sizes ranged from about 7 to 31,349 ha with a mean of 1777 ha (compared to a mean of 3668 ha for the simulated fires). Historical fire perimeters were intersected using the same methodology as the simulated wildfire outputs for comparison. We then calculated summary metrics including the average number of land designations burned per fire, and the average area burned by fires ignited in other designations (TF-IN). We did not estimate pairwise TF metrics between land designations nor build a network representation due to the relatively small sample size.

3. Results

3.1. Historical wildfire transmission

Historical fires from the period 1980 to 2011 burned across the boundaries of 3.3 of the 21 land designations, with a maximum of 13 observed for one fire that burned about 31,000 ha. Area burned by non-local ignitions (i.e., started in a different land designation, TF-IN) ranged from 0% to near 100%, with an average of 62%. In other words, 62% of the area burned in any one designation was from an ignition located in a different designation. The highest value was observed for OWLCH (10,089 ha) burned mostly by WILD. The historical area burned in five of the land designations (BIA, EAG, PVT_E, PVT_N and PVT_SKY, see Table 1 for abbreviations) was entirely from non-local ignitions. Of the remaining land designations, LSRs received the most fire from ignitions outside of the land designation, with 99% of the total area burned caused by fires that started elsewhere. On average, historical fires that crossed designation boundaries burned seven other designations. Overall, the historical data indicated that most fire events spanned multiple land designations, and that the transmission of exposure has been a common event on the Forest.

3.2. Simulated wildfire transmission

Simulated fires on average burned across the boundaries of 4.3 different land designations with a few fires burning through a maximum of 13 out of the 21 total land designations. Summaries of TF-IN and TF-OUT, which measure the average incoming and outgoing area burned per ignition (Table 1 and Fig. 4A) varied widely among land designations and generally accounted for the majority of the total fire activity (sum of TF-IN, TF-OUT and NonTF, Table 1). In general, area burned by non-local ignitions (TF-

IN) averaged 34% (2153 ha) of the total fire activity among the designations, with the highest value observed for the general forest matrix (GFM, 8416 ha). The highest TF-OUT value was 4154 ha for the private parcel PVT_PCC (Table 1), and on an average 46% (2153 ha) of the total fire activity per designation was transmitted to another designation. NonTF (non-transmitted fire) ranged from a low of 126 ha for aquatic reserves (AQUA) to a high of 2080 ha for STATE, and averaged 20% of the total fire activity per designation. In terms of TF-OUT versus TF-IN, some land designations had relatively high TF-IN (GFM, BLM, DEER), while others had more TF-OUT (OLG, STATE, AQUA) (Table 1 and Fig. 4A). The underlying factors for these findings are discussed below.

The transmission among individual pairs of land designations was used to create a network as shown in Fig. 5, where each land designation was represented as a node, and the linkages (arrows) were populated with pairwise values of TF_{ij}, where i is the ignition designation and j represents the recipient. As described in Section 2.7, nodes consist of multiple polygons for a given land designation, and hence the linkages measured the transmission (ha) per ignition among the polygons. There were 704 non-zero linkages between the nodes in the network, which correspond to a network density of 0.798, meaning that 79.8% of all possible linkages between land designations were present. The network illustrates the connectivity of specific land designations in terms of fire within the study area, and the relative magnitude of the linkages. For instance, the strongest sources of transmitted fire to northern spotted owl nest sites (OWL) were other conservation reserves (OWLCH, WILD, LSR). Aquatic reserves (AQUA) received fire from a relatively large number of weak linkages to most of the other designations. General forest matrix (GFM) had strong incoming linkages from OLG, VIS, and PVT_S designations. Transmission of fire to private lands varied depending on the private parcel's location within the study area, although DEER was a common source among three of the five private designations (PVT_E, PVT_N, PVT_SKY). However, PVT_N received most transmitted fire from other private designations (PVT_PCC and PVT_SKY), and PVT_S received the most fire from STATE and EAGL. By contrast, WUI was threatened by fire primarily from other private designations, and Forest designations AQUA and DEER (Fig. 5). Connectivity, as measured by node degree (number of linkages including both incoming and outgoing) varied from a low of 23 (PVT_E) to a high of 42 (GFM and WUI), the latter two having the maximum possible node degree. High node degree indicated fire transmission among many management designations, but not necessarily large values of transmitted fire.

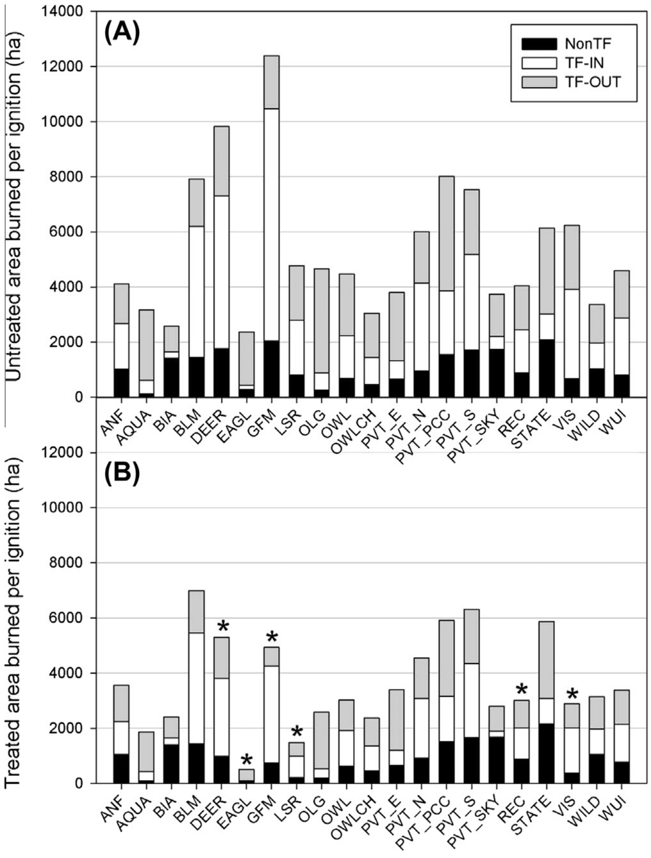

Fig. 4. (A) Incoming (TF-IN), outgoing (TF-OUT), and non-transmitted (NonTF) fire by land designation within the study area. Data represent the area burned per ignition. (B) Same as (A) for the treated landscape. See Table 1 for land designation descriptions. Asterisks denote land designations where treatments were modeled.

We explored three metrics to better understand factors that might explain variation in fire transmission among the land designations: node degree, average polygon size, and shape of the polygon as measured by perimeter to area ratio. Scatterplots of node degree versus percent transmitted fire (Fig. 6A) showed that, with the exception of two private parcels, land designations with higher node degree had more transmitted fire. For instance, over 90% of the area burned associated with AQUA and OLG ignitions was transmitted fire, both of these having node degrees of 39 of a possible 42. Decreasing complexity in parcel geometry (low perimeter to area ratio) was associated with decreasing transmitted fire (Fig. 6B). For instance, the least amount of total transmitted fire was observed for the BIA designation, which consisted of one large polygon of 20,000 ha. Designations with linear geometry such as riparian reserves (AQUA) or bisected irregular geometries (PVT_S) had high values for total fire transmission. In terms of polygon size, designations with an average polygon size less than 2000 ha all had more than 80% transmitted fire (TF_IN + TF_OUT) (Fig. 6C), mostly due to higher TF-OUT values because fires originating on these smaller land designations had little area to burn except onto adjacent designations. Plots of the transmission ratio (TF-IN/TF-OUT) against polygon size (Fig. 6D) showed that as polygon size increased, designations went from being influenced by outside fire to being transmitters of fire, the tipping point at about 4000 ha, roughly the average simulated fire size. Outliers to this overall trend included several designations with polygon sizes less than 2000 ha that transmitted more fire than they received (PVT_E, EAGL, AQUA, lower left Fig. 6D). In the case of EAGL the polygons for this land designation are located predominately on the east and northeast side of several lakes where they were protected from simulated fires burning in a southwest to northwest direction (the dominant fire spread direction). Yet ignitions from the EAGL polygons were capable of generating large fires due to extensive and continuous fuels to the west and northwest. Other outliers (PVT_N, PVT_S and WUI) all had relatively low transmitted fire ratios for their size (Fig. 6D), which can be explained by their location within the project area where fires arrived from the national forest to the west, but ignitions within these areas did not result in large fires due to generally reduced fuel loadings and non-burnable fuel in the urban areas to the east.

3.3. Effect of fuel treatments

Fuel treatments on the study landscape resulted in a reduction in average fire size from 3668 to 2381 ha (−35%) and in average burn probability (BP) from 0.0019 to 0.0013 (−32%) (Fig. 7A). Average conditional flame length (CFL) was reduced from 2.62 to 2.28 m (−13%) on the treated versus the untreated landscape (Fig. 7B). Burn probability was primarily reduced within treated land designations although treatment effects were observed in

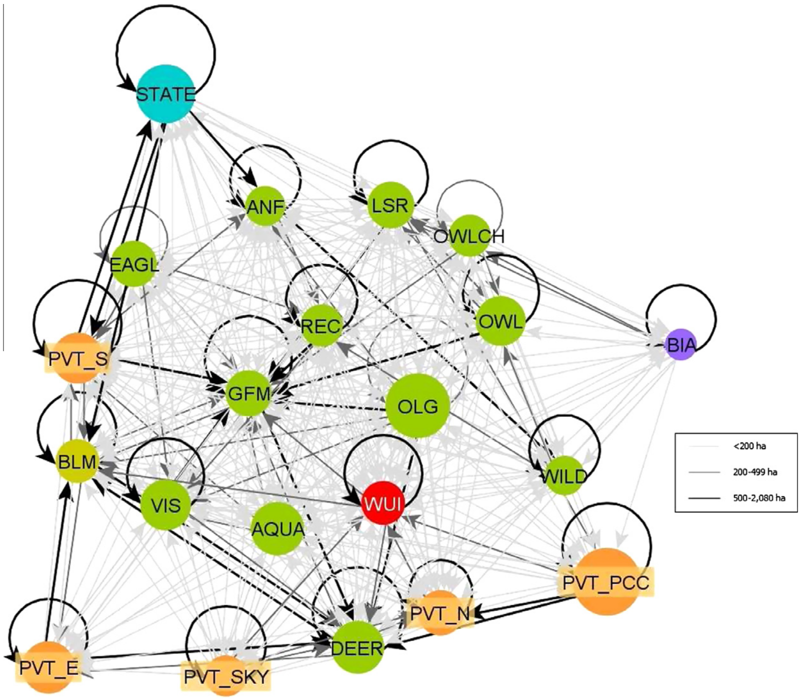

Fig. 5. Network diagram for the Deschutes National Forest and surrounding lands showing the 704 linkages among the 21 land designations. Linkages measure the area burned per ignition, as well as self-burning (circular links). Arrows indicate direction of transmission based on ignition source and resulting fire. Node size is proportional to the transmitted fire (TF-OUT) from that node. Nodes on the Deschutes National Forest are shown in green. See Table 1 for land designation descriptions.

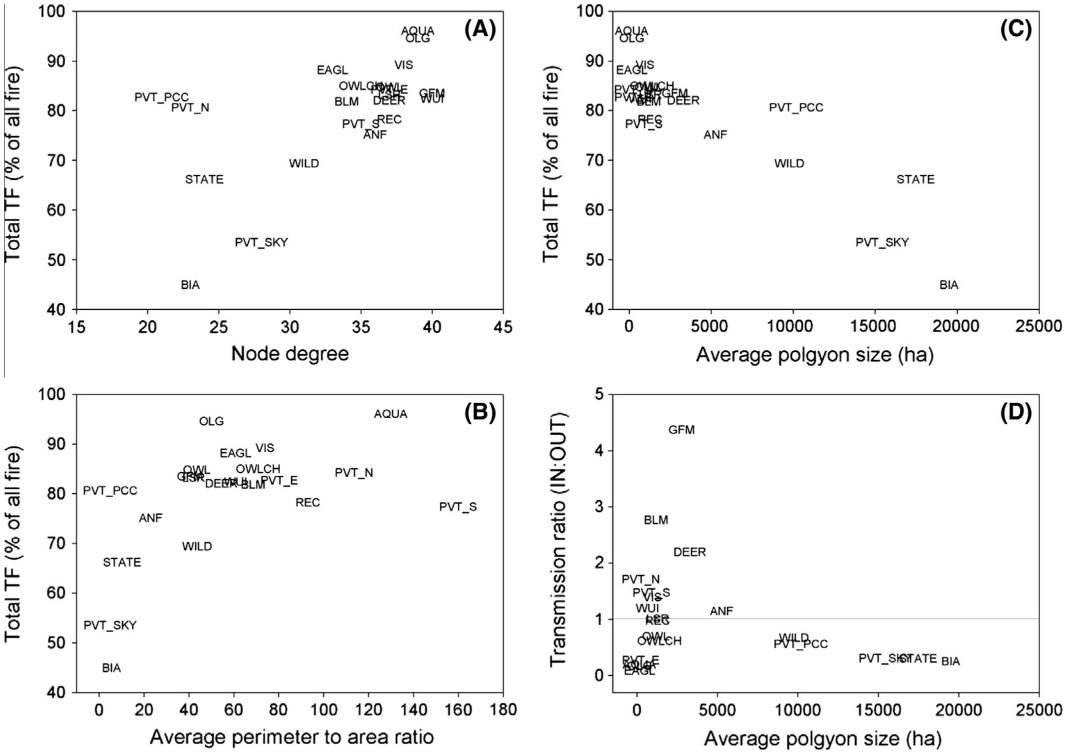

Fig. 6. Scatterplots showing (A) node degree by percentage of transmitted fire, (B) average perimeter to area ratio for land designation polygons by percentage of transmitted fire, (C) average land designation polygon size versus percentage of transmitted fire, (D) average land designation polygon size by the ratio of incoming (TF-IN) versus outgoing (TF-OUT) transmitted fire. Node degree measures the number of linkages for each designation both incoming and outgoing. Transmitted fire is calculated as the percentage of TF-IN + TF-OUT to the total area burned (TF-IN + TF-OUT + NonTF). All values are per ignition. In panel D, designations above the gray receive more fire than they transmit, and below the line transmit more fire than they receive.

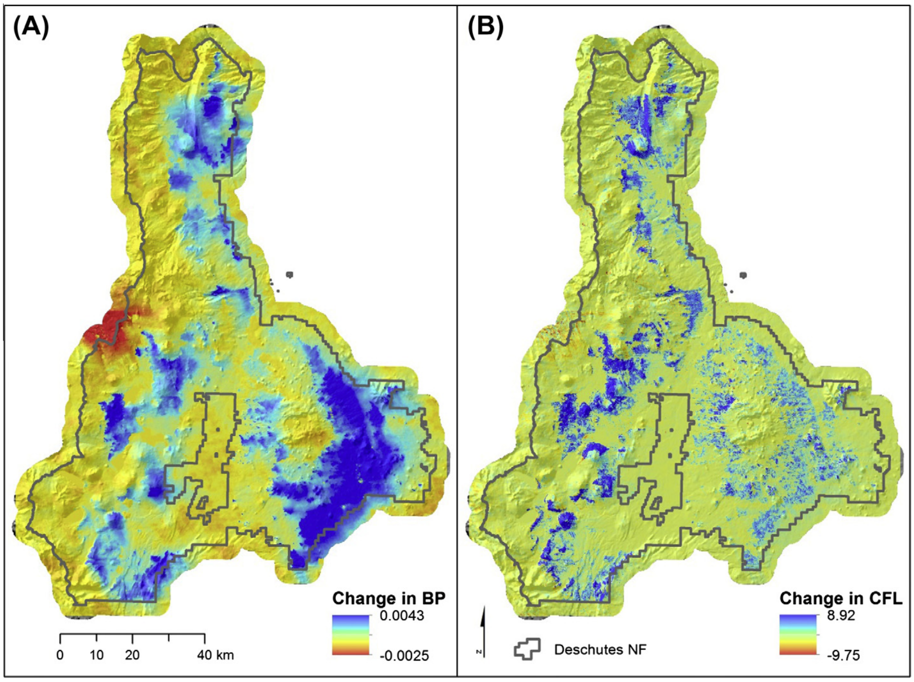

Fig. 7. Map of the Deschutes National Forest and surrounding lands showing the change (untreated minus treated) in (A) overall burn probability (BP) and (B) conditional flame length (CFL, m) as a result of simulating fuel treatments on 20% of the Forest. Fuel treatment parameters are described in Tables 5 and 6. See Fig. 2 for fuel treatment locations.

other designations as well. On the treated landscape, 65% of the simulated fires encountered at least one fuel treatment polygon. The average number of land designations burned in a single fire was reduced on average from 4.2 to 3.4, although there were still simulated fires that burned 12 of the 21 land designations on the treated landscape. The largest reduction for non-transmitted fire (NonTF) was observed for the treated land designations (GFM, DEER and LSR, Table 1, Fig. 4). The effect of the treatments on TF-IN varied among the designations, with reductions averaging 31%. The lowest reduction in TF-IN from treatments was for WILD (2%) and the highest was observed for GFM (4908 ha, 58%) (Table 1). The change in TF-OUT from treatments was also variable among the land designations, and ranged from a high of 1709 ha (45%) for OLG to a low of 113 ha (8%) for ANF.

The effect of fuel treatments on fire transmission can be seen in network diagrams for the untreated and treated landscapes (Fig. 8). Note that for clarity, we only show linkages with >200 ha of transmitted fire (TF-OUT, TF-IN). Much of the treatments effect on the network linkages was observed for GFM where the bulk of the treatments were located. Large reductions in transmitted fire were observed between particular land designation pairs (OLG to GFM, VIS to GFM). The fuel treatments resulted in 10 fewer linkages with transmitted fire >200 ha to the GFM designation. The node degree for the treated landscape had 682 non-zero linkages, a reduction of 22 compared to the untreated landscape. The density of the network for the treated landscape was 0.773, meaning that 77.3% of all possible linkages between land designations were present, a reduction of 3.1% from the treatments. Average node degree for the untreated designations was 33.5 (range 21–40) and 32.5 (range 20–40) for the treated land designations. The land designations with the lowest connectivity as measured by node degree (including both incoming and outgoing linkages) on the treated landscape were PVT_E and PVT_PCC (20), and those with the highest were GFM and WUI (40). Thus the treatments had a small effect on network connectivity as measured by node degree, and a more substantial effect on the connection strength as measured by transmitted fire.

4. Discussion

Risk transmission is arguably a key consideration for the “all lands” approach to managing large fire risk as described in the revised US Cohesive Wildfire Management Strategy (USDA-USDI, 2014). Understanding who owns the risk on landowner mosaics and their respective capacity to manage fuels is important in the design of effective management strategies to protect ecological and social assets, and reduce large fire occurrence. The compartmentalization of all national forests by planning efforts (NFMA, 1976) and subsequent modifications (ESA, 1973; USDA and USDI, 1994; USDC, 1998) were done with little consideration for potential wildfire transmission among land designations, leaving a management mosaic that has inherent vulnerabilities in terms of fire impacts. In particular, identifying zones of risk transmission from public lands to wildland urban interfaces on fire-prone national forests is of growing interest to agency managers tasked with allocating fuels investments to reduce losses from Forest Service ignited fires. Similarly, protecting the many conservation reserves of national forests and other public lands from wildfire losses may well benefit from incorporating wildfire transmission analyses into recovery plans and similar forest planning efforts (USFWS, 2010). The analytical methods in this paper potentially contribute to the mapping of wildfire transmission, and can be readily scaled up and adopted for broader scale assessments.

The simulation results suggested that a large scale fuel management program on a typical western US national forest can potentially reduce overall wildfire exposure as measured by burn probability, flame length, and wildfire transmission. Our study is the first we know of that examined a large scale mosaic of managed and non-managed lands and the potential effect of a widespread forest fuel reduction program, consistent with the federal

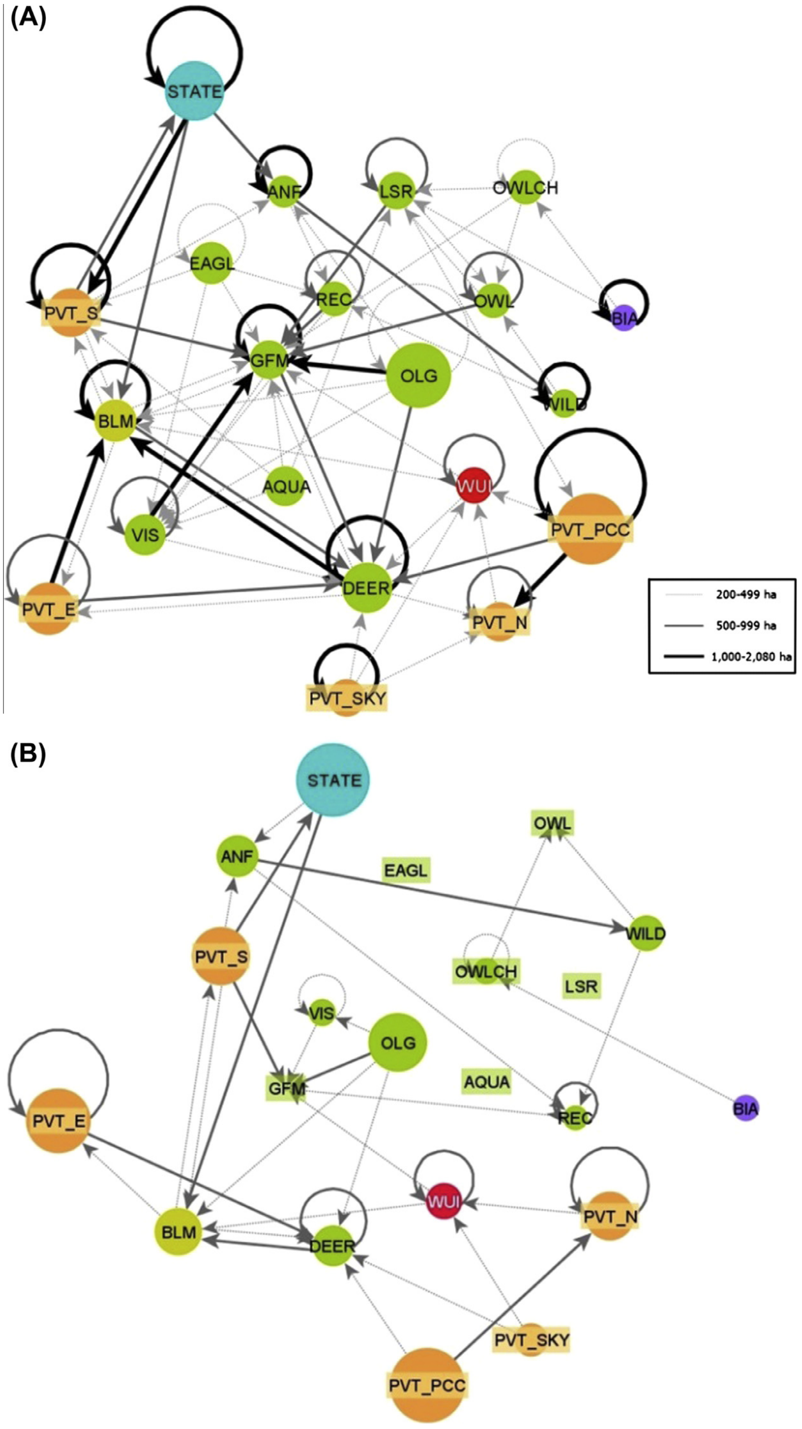

Fig. 8. Network diagrams of fire transmission for the study area showing treatment effects on network connections. (A) untreated landscape; (B) treated landscape. The network was filtered for clarity and only displays linkages with area burned of 200 ha or greater. Node size is proportional to transmitted fire (TF-OUT) from that node. See Table 1 for land designation descriptions.

planning rules and priorities on the Forest. The results suggested that treating 20% of the national forest within the managed land designations could reduce burn probability, mean fire size, and conditional flame length, 32, 35 and 13%, respectively. The fuel management effects were observed both inside and outside of the treated national forest land designations in terms of both local and transmitted fire (Table 1). Treatments also reduced transmitted fire from the national forest to WUI, and to a minor extent, from national forest to private (non-WUI) lands as well.

In terms of specific results in the study area, we make the following observations about some of the key land designations and transmission of wildfire exposure. Overall, the network had a density of 79%, meaning that almost 80% of the designations exchange fire, which we interpret as a relatively high level of connectivity. Area burned by non-local ignitions (TF-IN) averaged 34% (2153 ha), suggesting strong interdependence among the land designations in terms of fire exposure. Wildfire exposure to WUI designations came principally from the other private inholdings

(Fig. 8A), not the national forest. In general, conservation reserves with small polygon size (AQUA, OLG, OWL, OWLCH) had relatively high amounts of transmitted versus non-transmitted fire, and contributed more fire to other designations than they received. The primary managed designation GFM, had the highest node degree and relative amount of incoming (TF-IN) fire. In a previous study, we noted that much of the GFM has high fuels with relatively fast spread rates, either due to past management activities, or their location within the dry forests that support fast-burning surface fuels (Ager et al., 2012b). Thus ignitions from adjacent designations essentially created large fires because of the fuel conditions within. The GFM polygons are slightly larger than the small conservation reserve polygons, but are widely located around the Forest, making them vulnerable to fire from other designations.

The effect of fuel treatments was a slightly lower network density and substantial reduction in transmitted fire for both treated and untreated land designations. For the latter, the major effects were observed for designations that were largely contained within treated (GFM) land designations (e.g., AQUA, OLG, OWL, REC). Incoming fire to the GFM designation was reduced because fires starting elsewhere burned slower within the treated landscape. Fuel treatments reduced transmitted (TF-IN and TF-OUT) fire to the WUI despite not receiving treatments. High transmission to adjacent land designations was observed where the recipient land designation had fuels that are conducive to high spread rates. For instance, PVT_PCC is adjacent to mule deer habitat on the Forest which is typified by dry forests having surface fuels with fast spread rates.

Although we identified a number of factors that influenced both relative and absolute transmission, including fuels, assumed weather for simulated fires, parcel size, geometry, and arrangement (Figs. 6 and 8), it is difficult to quantify the relative importance of the causal factors. High node degree was associated with both relatively high outgoing (AQUA, OLG) and incoming (GFM) fire, and thus was related to overall connectivity of land designations to the larger landscape. However, even large parcels with regular shapes with low node degree (e.g., PVT_PCC, Fig. 6A and B) exhibited high transmission, likely due to high fire spread rates in the adjacent (DEER) land designations. In this case, the balance between incoming and outgoing fire seemed to be related to the relative spread rates of the respective fuels within the designations.

Some of the designations that had linear or irregular geometry also had high rates of transmission both in and out, relative to the amount of self-burning (AQUA, VIS). As polygon size increased, the relative amount of incoming versus outgoing fire decreased, with the change from being a net receiver versus transmitter at about 4000 ha, roughly the average simulated fire size. Exceptions to this trend were designations with relatively small average polygon size (<2000 ha), where more localized effects were observed related to position on the landscape relative to fuel loadings and the potential for large fires incoming versus outgoing. For instance, EAGL polygons were protected from incoming simulated fires owing to their position on the east side of lakes, yet ignitions within them generated relatively large fires that burned through extensive fuels to the east.

There are a number of both broad and specific management implications regarding wildfire risk management that stem from this study. First, most fuel treatment modeling studies (Lehmkuhl et al., 2007; Schmidt et al., 2008; Ager et al., 2010; Collins et al., 2011; Chung et al., 2013), but not all (Parisien et al., 2007), have used small landscapes (5000–20,000 ha) relative to the size of common mega-fires (e.g., >100,000 ha), and thus there may well be a scale mismatch between the size of the disturbance and the landscape used to test the effectiveness of fuel management scenarios. Moreover, previous studies on fuel treatment effectiveness have trimmed study areas to exclude adjacent reserves that cannot be managed with mechanical fuel treatments (e.g., wilderness, roadless, conservation and amenity reserves). Thus the effect of wildfires from non-managed (untreated) reserves within the treated landscape is not considered, potentially inflating the benefits of fuel treatments. This point is made relevant by the fact that the 82 national forests in the western US have on average 42% of the area within wilderness and roadless areas where mechanical fuel management is prohibited.

Second, network methods can inform landscape planning for restoration, conservation and fire protection efforts both on federal lands and adjacent privately owned parcels. Network analyses of risk transmission have been explored for many different problems, particularly the spread of disease (Sander et al., 2002) and within social science (Scherer and Cho, 2003; Muter et al., 2013). Network analysis has more recently been used as a tool in conservation biology and resource management as a way to understand landscape connectivity (Minor and Urban, 2008; Kininmonth et al., 2011; Rayfield et al., 2011; Mills et al., 2013; Foltête et al., 2014). In the current study, network analysis of simulation outputs provided an analytical framework to decompose transmission on a large fragmented landscape and visualize landscape connectivity from a fire perspective. Network methods were also useful to understand factors contributing to transmission and the effects of fuel management (i.e., network intervention, Valente, 2012). Our network characterization was limited to a few key metrics to facilitate testing and development of the analysis process. We used network nodes that represented land strata rather than spatially explicit polygons, an approach that makes the resulting network easier to interpret by forest-scale managers interested in general relationships rather than polygon specific linkages. In addition, limitations in the wildfire simulation methods prevented the explicit identification of transmission paths involving multiple land designations. For instance, we could not discern from the perimeters the temporal sequence with which fires traveled through multiple designations. This limitation prevented us from analyzing network statistics such as betweeness and centrality (Borgatti et al., 2013) that describe a node's overall influence on network properties. Despite these limitations, the metrics and graphics we report in the paper, including node degree, network density, transmission ratios, and transmitted fire, all point to emergent properties of fire transmission on fragmented landscapes that can be used for managing fuels (Collins et al., 2010) and suppression preparedness. For instance, from a fire suppression standpoint, high node degree for a private land designation would indicate a risk liability to other public and private parcels in the network. Similarly, fuels management activities on lands with high values of TF-IN will likely not reduce the likelihood of a fire arriving from another designation, and fuel management activities need to target nodes in the network that are responsible for ignitions. The methods have potential application for WUI protection planning, where transmission networks could be used to provide explicit identification of the sources of wildfire exposure and the responsible landowners. As an example, we used transmission outputs from wildfire simulations to create a “fireshed” around all the SILVIS (Radeloff et al., 2005) WUI communities in the study area. This fireshed encloses ignition locations that transmitted fire to the WUI (Fig. 9) thus identifying the relevant planning area from a biophysical risk standpoint for community protection planning. This approach is in contrast to the current community wildfire protection planning guidelines (CWPP Task Force, 2008) where boundaries are typically based on ownership and administrative borders (Jakes et al., 2011). The lack of a spatial planning framework for CWPP planning led to a wide range of planning scales (e.g., neighborhoods, towns, multiple towns, entire counties) and associated boundary delineations that are potentially unrelated to the spatial extent of fire transmis-

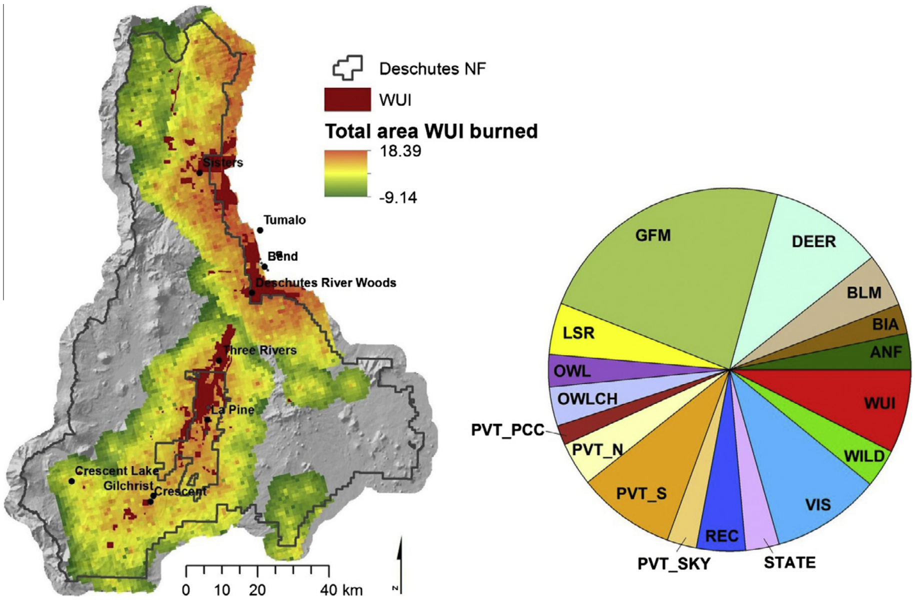

Fig. 9. Application of transmission analysis to delineate areas for community wildfire protection planning. Map shows the spatial extent of ignition locations for simulated fires that burned into SILVIS WUI polygons within the study area. Each ignition was attributed with the area burned within the WUI and the resulting map smoothed with inverse distance weighting, resulting in a "fireshed" map. Legend shows log transformed values for total WUI area burned per year. Dark red polygons show mapped wildland urban interface (WUI). Pie chart contains the percentage contribution of fire from originating land designations (ignition sources), showing that most of the exposure originates from GFM and DEER where fuel treatments are permitted under the Forest Plan.

sion to communities. This type of scale mismatch between planning boundaries and the scale of the ecological pattern or process relevant to the conservation or protection problem has been widely discussed (e.g. Cumming et al., 2006; Sarkar et al., 2006; Guerrero et al., 2013).

Equally important as WUI protection is the conservation of many fire sensitive biodiversity and conservation reserves within national forests. In particular, habitat reserves for the northern spotted owl created under the Northwest Forest Plan have incurred substantial losses due to wildfire over the past decade (Mouer et al., 2005), and these potential losses were not factored into the original reserve design. An analogous situation exists for the aquatic reserves created in the Pacific Northwest (Henderson et al., 2005) which were delineated without respect to long-term impacts of wildfire from the surrounding landscape on riparian vegetation. We identified specific transmission linkages to both reserves and other protected areas that heretofore were not explicitly recognized in existing conservation plans (Figs. 5 and 8).

As in our previous simulation studies, we recognize limitations in the models and input data (Ager et al., 2011), and the necessity of proper calibration and validation (McHugh, 2006; Stratton, 2006). We have reported previously that the LANDFIRE fuels data used in the study are consistent with the major east–west gradient in forest vegetation within the study area (Ager et al., 2012b). Both FlamMap, Randig, and related models (see Methods) employ semi-empirical fire spread algorithms and do not account for fire-atmospheric and fire-fuel interactions, and the crown fire models are not well validated (Cruz and Alexander, 2010). Despite these limitations, the models continue to provide informative simulation outputs to both the research and management community (Finney et al., 2011b; Noonan-Wright et al., 2011; Salis et al., 2012; Ager et al., 2014). Careful calibration and validation with empirical fire data can help minimize modeling errors (e.g., Fig. 3).

Additional case studies may reveal emerging patterns of transmission networks among and within national forests and other federally managed lands, and the potential for strategic fuel treatments to reduce undesirable linkages. The sizes and shapes of many of the designations found in the study area mirror those on other national forests throughout the 166 million ha national forest system, and thus we can generalize some of the findings to other national forests. Integrating risk transmission into local, regional, and national assessments, and into national forest plan revision efforts (http://www.fs.usda.gov/planningrule), could pave the way to reducing wildfire threats to key ecosystems on fire-prone national forests, and reduce losses in the adjacent WUI.

Acknowledgements

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