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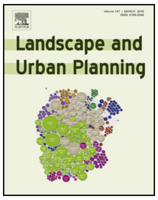

Assessing the impacts of federal forest planning on wildfire risk mitigation in the Pacific Northwest, USA

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HIGHLIGHTS

- We mapped wildfire risk transmission from national forests to the WUI.
- We examined management restrictions on areas with high transmission.
- Most transmission originated from areas where mechanical fuel treatments are permitted.
- Forest restoration with mechanical treatments is compatible with WUI protection.
- Mapping risk transmission facilitates identification of conflicts and opportunities.

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ABSTRACT

We analyzed the impact of amenity and biodiversity protection as mandated in national forest plans on the implementation of hazardous fuel reduction treatments aimed at protecting the wildland urban interface (WUI) and restoring fire resilient forests. We used simulation modeling to delineate areas on national forests that can potentially transmit fires to adjacent WUI. We then intersected these areas with national forest planning maps to determine where mechanical treatments are allowed for restoration and fire protection, versus areas where they are prohibited. We found that a large proportion of the national forest lands (79%) can spawn fires that burn adjacent WUIs. The bulk of the predicted WUI exposure originated from simulated fires ignited outside of conservation and preservation reserves and in dry forests, rather than moist mixed conifer forests. Thus the notion that fuel buildup in reserves on national forests contributes to wildfire risk in the urban interface was only partially supported by the data for the region studied. Most of the national forest lands that contribute wildfires to the WUI are not within the boundaries of community wildfire protection plans, which may undermine the effectiveness of these planning efforts. We used the spatial data themes developed in the study to map conflicts and opportunities for restoration and mitigation of WUI wildfire risk. The analysis disentangles the spatial complexity of managing landscapes for multiple socio-ecological objectives as part of ongoing restoration programs, collaborative planning, and national forest plan revisions on national forests in the US.

1. Introduction

Landscape vegetation patterns in concert with land use, human settlement, weather, and ignitions are all important factors to consider in wildfire mitigation policies aimed at curbing growing wildfire losses in the wildland urban interface (WUI). The global diversity of these conditions under which wildland fires ignite, spread, and affect human values, creates a myriad of complex challenges for local, regional, and national policy planning, requiring markedly different mitigation strategies for protecting communities and people from wildfire, especially under a changing climate. For example, recent work in the Mediterranean region has focused on understanding how the spatial structure (e.g., fragmentation) of urban and rural landscapes in relation to human ignition patterns and dwelling density contributes to risk (Chas-Amil, Touza, & García-Martínez, 2013; Herrero-Corral, Jappiot, Bouillon, & Long-Fournel, 2012; Lampin-Maillet, Jappiot, Long, Morge, & Ferrier,

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2010; Lampin-Maillet, Long-Fournel, Ganteaume, Jappiot, & Ferrier, 2011). By contrast, researchers in Australia and the US have begun focusing on mechanisms by which mega fires from lightning ignitions on large tracts of public land spread to the WUI and intermix (Ager, Day, Finney, Vance-Borland, & Vaillant, 2014a; Haas, Calkin, & Thompson, 2015; Price, Borah, Bradstock, & Penman, 2015). However, a key consideration among these diverse wildland fire systems in terms of mitigation planning is the importance of understanding constraints on fuel management activities that can reduce wildfire spread and intensity, facilitate suppression efforts, and reduce wildfire related damage. For instance, in the western US, a presumed contributing factor to the transmission of fire from national forests to the WUI is that on average about 45% of the land area is within designated conservation reserves where mechanical fuels treatments are either prohibited or highly restricted, potentially marginalizing risk reduction efforts (Agee, 2002; Finney et al., 2007; Kaufman, 2004; North et al., 2015; Williams, 2013). These constraints on managing hazardous fuels have their origins in a long history of legislation and national forest planning including the wilderness act (Wilderness Act, 1964) and subsequent development of land and resource management plans for each national forest to protect local biological diversity and amenity values (Duncan & Thompson, 2006; ESA, 1973; USDA & USDI, 1994; USDC, 1998; Williams, 2013). Specific assessments that quantify how national forest restrictions affect wildfire risk to adjacent WUI do not exist, and thus Community Wildfire Protection Planning (CWPP) (Abrams, Nielsen-Pincus, Paveglio, & Moseley, 2015; Jakes et al., 2007) to design local wildfire protection strategies is potentially compromised, perhaps contributing to continued WUI losses and increased suppression expenditures (Bailey, 2013; Calkin, Cohen, Finney, & Thompson, 2014; Cohen, 2008; Graham et al., 2012).

National forest planning for biodiversity and amenity protection also potentially compromises newer accelerated restoration programs that call for reducing ecological departure from historical fire regimes, improving ecosystem resiliency, and increasing raw wood materials to mills in timber dependent communities (USDA-USDI, 2014; USDA, 2012; USDA Forest Service, 2013). National forest investments in restoration are focused on dry, fire prone ecosystems, and priorities are driven by ecological departure (fire regime and condition class; Rollins & Frame, 2006). The ecological basis and need for restoration from a socio-economic standpoint have been widely described at regional and national scales (Franklin & Johnson, 2012; Franklin et al., 2013; Noss, Franklin, Baker, Schoennagel, & Moyle, 2006; Rasmussen et al., 2012; Rieman, Hessburg, Luce, & Dare, 2010; USDA Forest Service, 2012b, 2013), yet tradeoffs among competing demands between newer restoration initiatives and conservation goals in national forest planning have yet to be analyzed with rigor at the scale of individual national forests (e.g., 500,000 ha) where actual restoration projects are prioritized and implemented. Moreover, overlap between WUI protection and restoration has yet to be quantified and mapped at meaningful scales to understand potential synergies between two distinct federal investment strategies for wildfire mitigation. For instance, restoration of fire-adapted dry forest ecosystems may or may not contribute to wildfire risk to the WUI depending on the location of treatments relative to areas that spawn severe fires. On the other hand, about 560,000 ha of fuels treatments are currently targeted for WUI protection in the 2015 national forest fuels budget (578,700 ha; USDA Forest Service, 2014a), thus diminishing investments on surrounding landscapes.

In this paper, we analyzed the intersection of planning restrictions, ecological restoration goals, and community wildfire protection on national forests and grasslands in Oregon and Washington, USA. We address four questions: (1) to what extent and where do fires ignited on national forests threaten adjacent WUI, (2) do fires that threaten the WUI originate on lands where national forest plans allow mechanical fuel management, (3) what proportion of #2 are in the fire-adapted dry forest type that is the primary target for accelerated restoration efforts, and (4) where do biophysical and socio-ecological conditions create inherent conflicts among policy objectives and how can they be resolved? For the latter, we stratified national forests according to their impact on WUI risk, biophysical fire regime, and national forest plan management goal. We used the resulting management matrix to untangle multiple and conflicting management objectives that exist within national forest restoration policy, and describe spatial themes for specific restoration opportunities and conflicts (Bullock, Aronson, Newton, Pywell, & Rey-Benayas, 2011; Rieman et al., 2010) for achieving federal policy goals of creating fire-adapted communities and fire resilient landscapes (USDA-USDI, 2014).

2. Methods

2.1. Study area

The study area consisted of 16 national forests and grasslands (10.6 million ha) in Oregon and Washington, USA (Fig. 1A) and adjacent WUI (Radeloff et al., 2005) within 10 km of the national forest boundary. The national forests are administered by the Forest Service, a US federal agency. The study area is divided by the Cascade Mountain range into two major ecological types, with primarily dry pine forests to the east, and wetter, mixed conifer forests to the west. About 9.6 million ha of national forest land is classified as burnable according to LANDFIRE data (Rollins, 2009). The national forests experience substantial wildfires, primarily east of the Cascade Mountains, with a total of over 1.4 million ha burned between 1992 and 2014 (annual = 63,800 ha)(FIRESTAT, 2011). This translates to 0.6% per year on an area basis. Investments in fuel reduction in the study area average around $20.5 million per year, treating 71,751 ha and include an array of activities such as mechanical thinning, prescribed burning, mowing, mastication and pile burns (Laura Mayer, USDA Forest Service, pers. comm.). On average 44% of the treated area specifically targets WUI protection. Improving fire resiliency in dry pine-dominated forest areas is the primary focus of fuel management and forest restoration activities and is concentrated in the fire prone forests in the eastern and southwestern portion of the study area.

2.2. Land management designations

To understand the origins of wildfires in relation to management capacity on national forests we compiled a study area-wide national forest planning map using spatial data from the Forest Service GIS library (USDA Forest Service, 2014b). The 16 national forests contained over 800 different land management designations developed as part of national forest planning (NFMA, 1976) and subsequent modifications by the Northwest Forest Plan (USDA & USDI, 1994) and PACFISH/INFISH (Pacific Anadromous Fish Strategy; Henderson, Archer, Bouwes, Coles-Ritchie, & Kershner, 2005). The land designations allocate lands to specialized uses including scenic quality, wildlife habitat, timber production, rare ecological communities, endemic plant populations, municipal watersheds, and recreational values, to name a few. Pre-existing land designations established as wilderness areas (Wilderness Act, 1964), Roadless Area Review and Evaluation (RARE I and II) areas, and wild and scenic river corridors (Wild and Scenic Rivers Act, 1968) were grandfathered into the plans. Land designations were absorbed into conservation reserves established for a number of newly listed threatened and endangered species (i.e., Northwest Forest Plan, USDA & USDI, 1994), including extensive habitat networks for

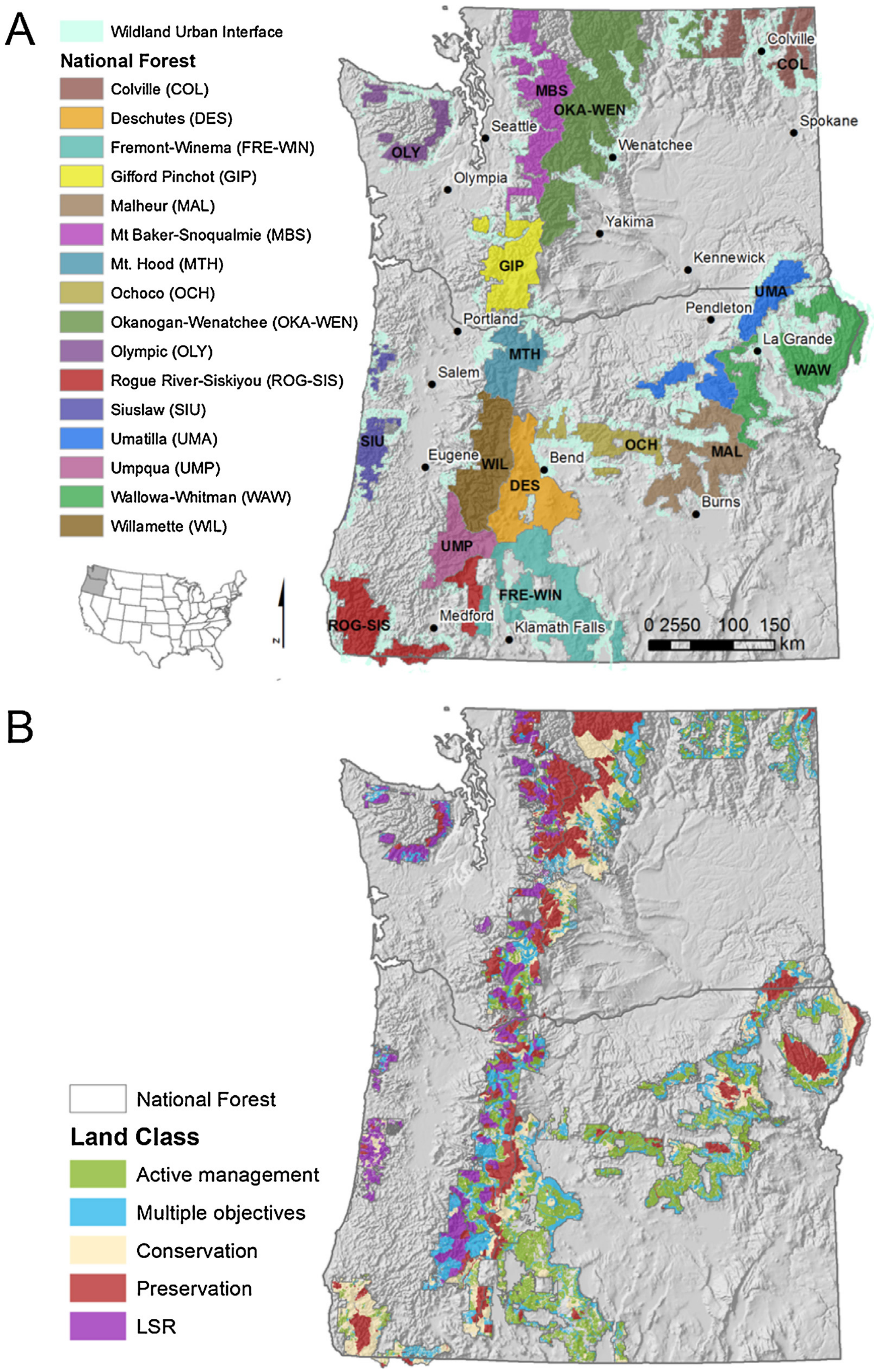

Fig. 1. (A) Map of the national forests in Oregon and Washington. (B) Land designation class defining where mechanical treatments are permitted or restricted. See Table 1 for details.

species such as the northern spotted owl (*Strix occidentalis caurina*), and an array of anadromous fish species including steelhead trout (*Onchorynchus mykiss gairdneri*) and bull trout (*Salvelinus confluentus*).

We grouped land designations into five categories based on restrictions for conducting mechanical fuels treatments (Table 1, Fig. 1B). The least restrictive land designation class (LDC) specified harvest activities to produce forest products (henceforth active

Table 1
Description of the land designation classes created from over 800 national forest plan land management designations in the study area, along with total area and area of transmitted fire to the wildland urban interface (WUI). Land designation classes were created to differentiate areas in terms of restrictions on mechanical treatments. Also shown is the percentage of area in the fireshed, and the number of predicted structures lost from transmitted fire.

Land class	Description	Examples	Total national forest area (ha) (%)	Total fireshed area (% of total national forest area)	Predicted annual WUI area (ha) burned (% of study area total)	Percent of land class in fireshed	Predicted structures affected (% of study area total)
Active management	Mechanical treatments used to meet wood production targets	General forest, suitable timber, timber production	2483,687 (25%)	2082,122 (26%)	57.8 (21.6%)	84%	18.4 (21.4%)
Multiple objectives	Mechanical treatments possible if no adverse effects on other national forest plan objectives	Elk winter range	2192,810 (22%)	1695,530 (22%)	146.9 (55.1%)	77%	46.8 (54.2%)
Conservation	Mechanical treatments possible if needed to protect management objectives	Riparian reserves, managed old growth, visual corridors.	1982,832 (20%)	1657,233 (21%)	43.8 (16.4%)	84%	14.6 (16.9%)
Preservation	Long-term preservation by act of congress or national forest plan allocation; Mechanical treatment not permitted	Wilderness, old growth reserves, critical habitat	2149,752 (21%)	1667,769 (21%)	8.1 (3.0%)	78%	2.9 (3.4%)
Late Successional Reserve (LSR)	Age-dependent management under Northwest Forest Plan; Mechanical treatments possible depending on stand age	Late successional reserves in mesic forest types	1187,853 (12%)	745,033 (10%)	1.6 (0.6%)	63%	0.5 (0.5%)

management). The next least restrictive class included land designations that specified non-timber primary management objectives but were scheduled for harvest activities (multiple objectives). Here treatments must be compatible with primary management objectives, but the rate and/or location of treatment is restricted by the management area objective and/or spatial location. The most prevalent example is the extensive ungulate summer range where management activities can be used to maintain an optimal mix and arrangement of forest cover patches providing that forest cover restrictions remain at or above a critical level. A third category was created for myriad land designations where protection and/or conservation of biological and amenity values are the primary focus (conservation). Examples of these latter designations include scenic areas, botanical reserves, wildlife conservation areas for federally listed species, and aquatic reserves, to name a few. Here, mechanical treatments are permitted on a case by case basis if needed to meet or improve the land designation's primary objective. For instance fuels treatments are permitted when it is determined they are needed to reduce wildfire threats to federally listed species. These designations are not part of the regulated national forest area. The fourth and most restrictive category included wilderness and inventoried roadless areas (preservation). In wilderness areas, management is confined to non-mechanized activities such as trail building and maintenance of undeveloped campsites, and prescribed fire, although the latter practice is rare in the study area. Although roadless areas can receive mechanical treatments if not part of a more restrictive national forest plan designation, projects are rarely proposed in these areas due to management conflicts, and hence they were lumped into the preservation LDC. Lastly, a separate category was created for a relatively small area of late successional reserves created under the Northwest Forest Plan where mechanical treatments are allowed if the stand age is <80 years (LSR, Table 1).

2.3. Wildland urban interface

We identified all lands within 10 km of the national forest boundary (Fig. 1A) that were classified as WUI according to the SILVIS wildland urban interface data (Radeloff et al., 2005). We removed SILVIS polygons that were (1) classified as uninhabited, (2) classified as water, and (3) <0.1 ha in size. The criteria for removing polygons conserved even the lowest density WUI areas and created a layer that reflects the fact that suppression efforts often target even low density areas or even individual structures in remote areas. Each WUI polygon was attributed with population density, housing unit density (hereafter referred to as structures) and area. There were a total of 40,138 WUI polygons covering an area of over 5 million ha.

2.4. Predicted wildfire transmission

We used the 2014 version of the wildfire simulation model FSim and methods described by Finney, McHugh, Grenfell, Riley, and Short (2011b) and summarized elsewhere (Ager et al., 2014d) to generate a library of predicted wildfires and their perimeters in the study area. The FSim program generates wildfire scenarios for a large number (e.g., 50,000) of hypothetical wildfire seasons using relationships between Energy Release Component (ERC) and fire occurrence. The ERC and other weather data are derived from weather records that span between 20 and 30 years and were collected as part of the network of remote automated weather stations (RAWS, Zachariassen, Zeller, Nikolov, & McClelland, 2003). The simulation operated on a daily time step and the daily probability of a fire was predicted by logistic regression of recent fire occurrence and ERC. Once a fire is ignited, daily weather is generated using a time series model developed from RAWS weather data (Finney et al., 2011b). The time series uses estimates of seasonal trends, autocorrelation (dependency of a day's ERC value on previous days), and daily standard deviation to generate synthetic daily weather streams for each day of simulation. Wind data (speed by direction) were also derived from RAWS stations and tabulated by month as a joint probability distribution. The resulting distribution was then randomly sampled to obtain daily wind data. Each fire's growth and behavior were simulated from its ignition day through the remainder of the season, or until containment was achieved as predicted based on recent large fires and their recorded sequence of daily activity (Finney, Grenfell, & McHugh, 2009). The containment model was developed from an analysis of the daily change in fire size to identify intervals of high and low spread for each fire. The containment probability model was found to be positively related to periods of low fire spread (Finney et al., 2009).

Surface and canopy fuel and terrain data were obtained from 2010 LANDFIRE refresh data (LANDFIRE, 2013a; Rollins, 2009) and included elevation (m), slope (degrees), aspect (azimuth), fuel model (Scott & Burgan, 2005), canopy cover (percent), canopy base height (m), canopy height (m), and canopy bulk density ($\mathrm{kg\,m^{-3}}$). The surface fuel data consisted of stylized fuel models as described elsewhere (Scott & Burgan, 2005). LANDFIRE is a standardized fuel dataset available for the US and widely used for wildfire modeling and research on federal and other lands (Krasnow, Schoennagel, & Veblen, 2009; Rollins, 2009). LANDFIRE data are regularly used to model potential fire behavior for fuels treatment projects on national forests.

FSim employs the Minimum Time Travel (MTT) algorithm to calculate fire growth by Huygens' principle where growth and behavior of the fire edge is modeled as a vector or wave front (Finney, 2002; Richards, 1990). Rates of fire spread and crown fire initiation are predicted by appropriate fire behavior equations (Rothermel, 1972; Scott & Reinhardt, 2001). Extensive application has demonstrated that Huygens' principle and the MTT algorithm can be used to replicate large fire distributions and perimeters over a range of fuel types and weather conditions (Ager, Finney, Kerns, & Maffei, 2007; Ager, Vaillant, Finney, & Preisler, 2012; Andrews, Finney, & Fischetti, 2007; Finney et al., 2011b). Validation of fire size distributions from FSim simulations was performed as described in Finney et al. (2011b) including comparison of recent versus predicted fires (Finney et al., 2011a). While technical refinements to FSim have been made since the simulation outputs used in the current study were generated, including refinements to the perimeter algorithm, the outputs used in the current study were deemed adequate for examining broad landscape patterns of fire exposure within the study area. In particular, the simulation outputs predicted high wildfire transmission to the WUI in areas that are surrounded by national forest lands, and have high predicted rates of spread. Moreover, the mapped outputs were reviewed by a number of Forest Service fire specialists and in general found to be consistent with local knowledge concerning the juxtaposition of WUI and national forest land that has high potential for large fires. The simulation outputs included 418,764 final fire perimeters derived from 20,000 to 50,000 simulated fire seasons. The simulations were performed as part of the Fire Program Analysis Project (FPA, 2010) and used a stratification system according to federal interagency fire planning units (FPU) within the study area. National forests were contained within a single FPU, except for the Malheur which spanned two. Each FPU was represented by a RAWS weather station (Zachariassen et al., 2003). The station was selected based on local Forest Service fire staff recommendations. Selected weather stations had a minimum of 20 years of weather data and were judged to best reflect fire weather, and seasonal and daily climatology for the FPU.

We assumed random ignition locations for simulated fires (Finney et al., 2011b). Large fire events within the study area have been primarily caused by lightning, and there are insufficient large fire incidents to detect spatial patterns if they existed. Fire simulations were performed at 270 × 270 m pixel resolution, a scale that permitted relatively fast simulation times and incorporated important spatial variation in fuel data.

FSim outputs a fire perimeter and ignition location for each simulated fire in polygon and point format, respectively. Fire perimeter outputs and ignition locations were intersected with the land designation and SILVIS WUI maps, and the resulting outputs were used to calculate the area of each WUI parcel burned by each ignition (Fig. 2). The structures affected were estimated by multiplying the structure count for each WUI parcel by the proportion of the parcel burned. These values were calculated and assigned to each ignition point, allowing the structure and WUI area burned data to be summarized by land designation category and national forest.

2.5. Identification of WUI firesheds

We delineated the area on national forests that could transmit wildfire to the WUI (Ager et al., 2014d) by creating a continuous smoothed surface fitted to the WUI area burned for each FSim ignition point. The surface was built via universal kriging using a spherical variogram model that was fit to the entire study area using the 'gstat' package in R 3.1.1 (Pebesma, 2004; R Core Team, 2014). Kriging is one of a number of interpolation techniques used to estimate a value at some arbitrary point in space based on a limited set of observations (such as ignitions). Kriging is a geospatial interpolation technique that is preferable to commonly used deterministic approaches (e.g., inverse distance weighting), since it is based on the spatial relationships actually observed within the dataset rather than fixed mathematical formulas (Berman, Breysse, White, Waugh, & Curriero, 2015; Zimmerman, Pavlik, Ruggles, & Armstrong, 1999). The kriging model was applied to a regular grid of 1 $\mathrm{km^2}$ cells with a maximum search distance of 25 km and maximum number of points of 200. Predicted values on non-Forest Service land were manually removed to produce outputs of predicted wildfire transmission specifically from Forest Service land. Transmission from other lands to the WUI was not considered in this study and is the subject of future work (see Fig. 8 in Ager, Day, Finney, Vance-Borland, & Vaillant, 2014b).

To compare WUI fireshed area with the area of national forests within defined CWPPs we obtained spatial layers for the latter from Oregon and Washington state GIS data libraries and intersected these layers with national forest boundaries. The resulting layer was used to determine if the areas delineated for managing wildfire risk in CWPP efforts were similar to the WUI fireshed as determined from simulation modeling.

2.6. Fire regime data

We used fire regimes to identify fire-adapted forest areas within the study area (Fig. 3) where restoration activities could focus on restoring natural and prescribed fire (Noss et al., 2006). We used the map of historical fire regimes created by the LANDFIRE project (LANDFIRE, 2013b) with modifications described by Rollins, Ward, Dillon, Pratt, and Wolf (2007). Historical fire regime is a combination of the expected fire frequency and intensity under pre-settlement conditions (Hessburg & Agee, 2003). Fire regime definitions were: group 1 (0–30 year frequency, low severity), group 2 (0–30 year frequency, high severity), group 3 (35–200 year frequency, low to mixed severity), group 4 (35–200 year frequency, high severity), and group 5 (>200 year frequency, any severity).

2.7. Recent fire transmission

To compare recent and simulated WUI wildfire transmission from national forests in the study area we obtained the former data

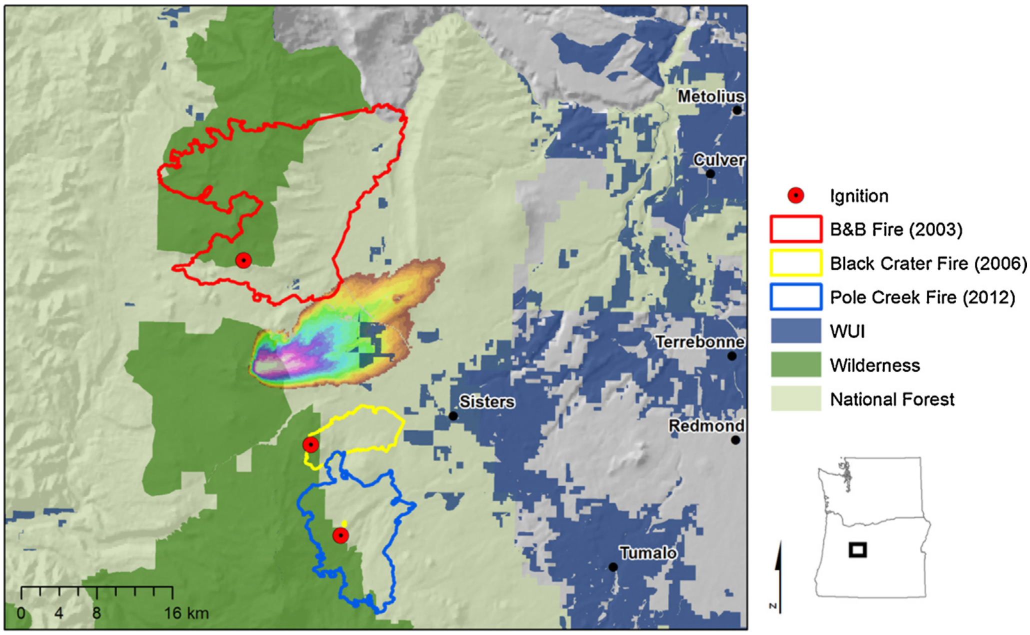

Fig. 2. Methods to calculate wildfire exposure to the wildland urban interface (WUI) from simulation outputs. Each simulated ignition point was classified with respect to its location on lands suitable for fuel management activities and the perimeter was used to determine the potential impact of each fire to the WUI. Simulated fire shown with color ramp. Recent fire perimeters shown for the 32,267 ha B&B fire, the 3,804 ha Black Crater fire and the 10,844 ha Pole Creek fire. Ignition shown above for the 15,843 ha simulated fire is located in the Mt. Washington wilderness, and burned 3,885 ha of SILVIS WUI. The B&B started in the Mt. Jefferson wilderness and the Black Crater fire started in the Three Sisters wilderness. The Pole Creek started adjacent to the Three Sisters wilderness in an area classified as 'Conservation' in Fig. 1. The wilderness area mapped here is classified as 'Preservation' in Fig. 1.

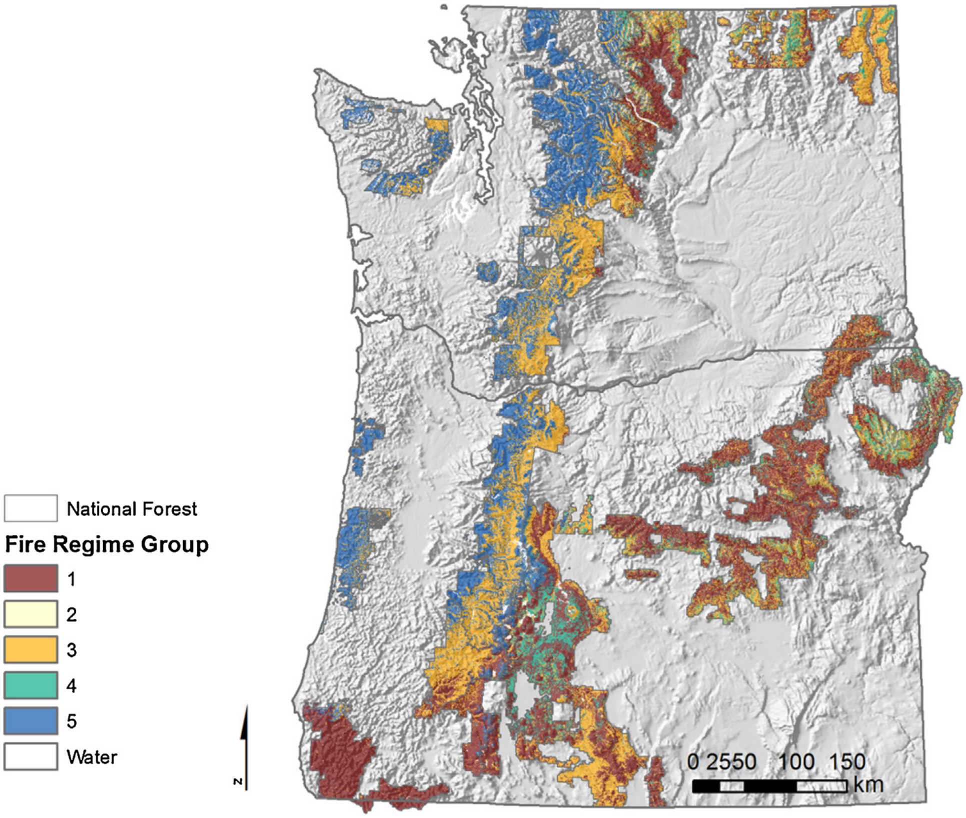

Fig. 3. Fire regimes for the national forests in Oregon and Washington. Group 1 = ≤35 year fire return interval, low and mixed severity; Group 2 = ≤35 year fire return interval, replacement severity; Group 3 = 35–200 year fire return interval, low and mixed severity; Group 4 = 35–200 year fire return interval, replacement severity; Group 5 = >200 year fire return interval, any severity. Data are from LANDFIRE (2013b).

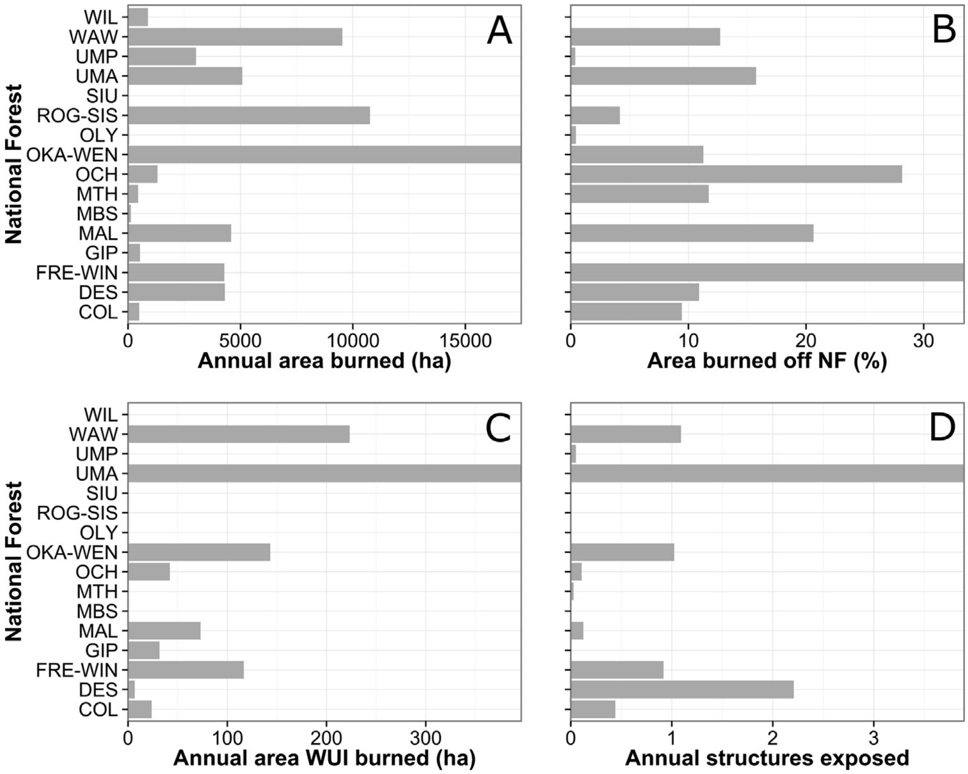

Fig. 4. Recent wildfire exposure on Forest Service (FS) and non-FS lands impacted by wildfires ignited on the national forests (NF) in Oregon and Washington. (A) Annual area burned by fires originating on FS lands, 1992–2012 (Short, 2014); (B) Percent of area burned on non-FS lands for fires ≥405 ha that originated on FS lands, 1990–2011(data are from NIFMID (FIRESTAT, 2011), see methods for details); C) Annual area of SILVIS wildland urban interface (WUI) burned from fires ignited on national forests (1991–2012, $n = 188$); D) Annual number of structures exposed to wildfire based on data in (C) and SILVIS WUI data. See methods for additional details. Data for (D) and (E) obtained from FS spatial data library and SILVIS WUI polygons (Radeloff et al., 2005). See Fig. 1 to reference national forest abbreviations.

from several sources including: (1) recent area burned, as reported in Short (2014) for fires from 1992 to 2012 ($n = 29{,}418$); and (2) recent fire perimeters (1991–2012, $n = 188$) obtained from the Forest Service data library. The latter were intersected with SILVIS WUI to calculate WUI area burned and estimate structures affected. To determine the percent of non-Forest Service land burned by individual wildfires, data not included in the Short (2014) database, we re-queried the National Interagency Fire Management Integrated Database (NFMID) at the National Information Technology Center in Kansas City, Missouri for the time period 1990–2011 for fires >405 ha (FIRESTAT, 2011).

2.8. Analysis

We intersected the fireshed and land designation maps to tabulate the area in firesheds by land designation class. These data were summarized by individual national forests and used to assess the proportion of the fireshed that could be managed with mechanical fuels treatments. We performed similar intersections to analyze the fire regime composition of the fireshed in order to determine the extent to which these areas are targeted for restoration management. We then tabulated the amount of wildfire transmission to WUIs by management capability according to the land designation map. We used the map outputs to develop an integrated social-ecological planning framework where lands were stratified into restoration and fire management themes. The framework consisted of a dichotomous key that classified lands according to: (1) fire adaptation based on fire regime, (2) ability to manage using our land designation classes, and (3) location within a community fireshed (i.e., if ignitions are predicted to transmit fire to the WUI). We then interpreted each of the themes relative to federal restoration policies and the revised federal Cohesive Strategy (USDA-USDI, 2014), to identify specific opportunities for restoration and where conflicts exist between restoring fire-adapted forests and protecting communities from potential wildfire losses.

3. Results

3.1. Recent fire transmission to the WUI

The average annual area burned per national forest by fires ignited on them was 3930 ha during the period 1992–2012 (Fig. 4A). About 10% of the burned area between 1990 and 2011 (≥405 ha) burned outside the national forest boundary (Fig. 4B). The individual national forests contributing the most to total annual area burned were not the same as those transmitting the most fire. The Okanogan-Wenatchee and Rogue River-Siskiyou both burned over 10,000 ha annually, while the Fremont-Winema and the Ochoco transmitted the most area burned to the WUI (>28%, Fig. 4B). Analysis of recent fire perimeters showed that that these fires on average burned 66 ha of WUI per 569 ha burned annually, or an annual transmission of 12%. The total area of SILVIS WUI burned by FS ignitions was 21,156 ha, or 1058 ha per year. The national forest with the highest transmission was the Umatilla, on average burning 396 ha of WUI annually over the period examined, and the lowest transmission occurred on the Willamette, burning <1 ha of WUI annually (Fig. 4C), although nearly all of the coastal and west Cascade national forests had negligible fire transmission to the WUI. The total number of structures exposed to fires ignited on national forests showed a similar pattern although outliers were evident (i.e., Deschutes, Fig. 4D). Breakdown of fire transmission by the land designation class of the ignition (Fig. 5) showed that most of the exposure came from the conservation land designation (38% of total), followed by preservation (26%). Conservation areas

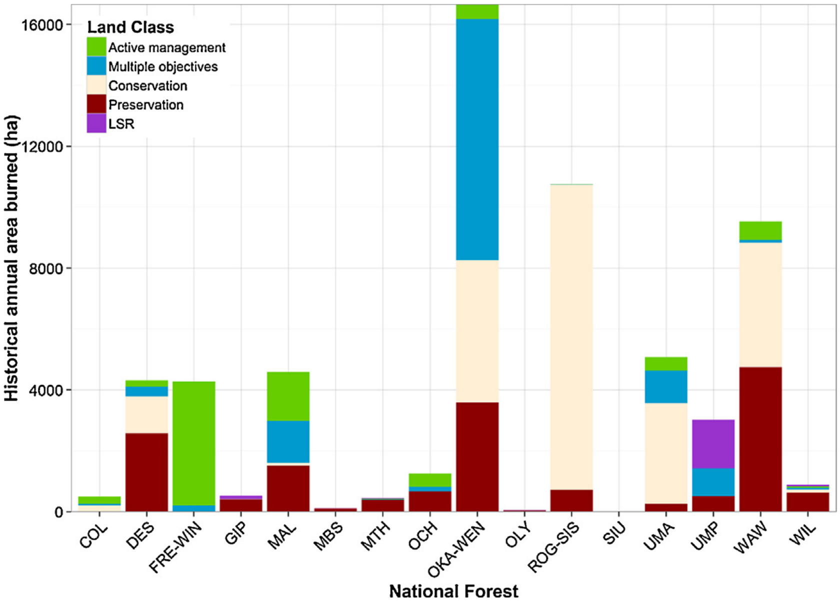

Fig. 5. Recent annual area burned both on and off national forests from ignitions on national forests in the study area partitioned by the land designation class of the ignition. Data from Short (2014). See Fig. 1 to reference national forest abbreviations.

were a particularly large source of exposure on the Rogue River-Siskiyou, as were preservation areas on the Wallowa-Whitman and Okanogan-Wenatchee (Fig. 5).

3.2. *Predicted transmission of fire to the WUI*

The predicted annual area of WUI burned from fires ignited within national forests was estimated at 3328 ha (Fig. 6A). The average annual number of structures predicted to burn from these fires was 106, or 0.0007 percent of the total structures (Fig. 6B). Of the five LDCs, multiple objective management areas were responsible for the majority of the predicted adjacent WUI area burned, followed by the active management designation (Table 1, Fig. 6A). The structures affected by the different LDCs showed a similar distribution as the WUI area burned (Table 1, Fig. 6B), although outliers were evident caused by relatively high or low WUI structure densities (Deschutes, Umatilla, and Wallowa-Whitman).

3.3. *WUI fireshed distribution and management potential*

The WUI fireshed map generated from the simulations (Fig. 7) suggested that extensive areas of national forest can potentially expose adjacent WUI to wildfire (Table 1). Particular hotpots were evident on the Okanogan-Wenatchee, Wallowa-Whitman, Fremont-Winema and parts of the Umatilla (Fig. 7). On a percentage basis, the fireshed area ranged from 63 to 84% of the total area in each LDC (Table 1). The area in firesheds was distributed evenly among the five LDCs except for the Late Successional Reserve (LSR) designation which accounted for only 10% of the total fireshed area regionally (Table 1). Most noteworthy is that 42% of the total fireshed area lies within conservation and preservation areas that are excluded from management (Table 1). However, the total fireshed area and percentage of land within firesheds by LDC varied widely among the individual national forests (Fig. 8). In some areas firesheds were contained mostly within LDCs that allow active management (Colville, Ochoco, Malheur) but not others (Okanogan-Wenatchee, Rogue River-Siskiyou). On the Ochoco, the vast majority of the fireshed area can be managed (83%). Half of the national forests have the potential for mechanical treatments on more than 50% of the fireshed area (Fig. 8B). Six of the national forests had more than 30% of the fireshed area in the active management LDC, where management goals emphasize the production and harvesting of sawlogs and fiber. The three national forests with the highest fireshed area were the Okanogan-Wenatchee, Wallowa-Whitman, and Fremont-Winema. National forests with low management capacity within firesheds were generally west of the Cascade Mountains, are within the domain of the Northwest Forest Plan, and had minimal projected WUI exposure.

Mapping the distribution of fireshed area relative to affected WUIs (Fig. 9) showed how areas of high fire transmission affected WUI polygons outside national forests and provided a method to examine both the sources and sinks of wildfire at the interface. Among the LDCs, some were more efficient than others on an area basis in terms of generating fires that spread to the interface (Fig. 10). For instance, although active management areas account for the greatest proportion of the fireshed, the multiple objectives LDC transmitted the most fire to the WUI on a percentage basis (Fig. 10). Pronounced variation in fire transmission was also evident among the national forests in the study area (Fig. A1, electronic appendix).

The comparison of WUI fireshed area relative to the CWPP boundaries in Oregon and Washington revealed that only 43% of the former is within the latter, meaning that over half of the area that potentially contributes wildfires to the WUI is not analyzed as part of community wildfire mitigation planning in the study area.

3.4. *Fire regime composition of the WUI firesheds*

Partitioning the firesheds according to management capability and fire regime showed that substantial exposure to WUIs originated from fire-adapted forest areas (FRG 1 and 3), however in many cases these areas were not available for mechanical treatments (Table 2, Fig. 11C and D). Seventy-four percent of the fireshed was in fire-adapted forest area (FRG1, FRG3) but of that amount, only 42% was in the actively managed and multiple objectives LDCs, the remaining area was not available for restoration treatments, and thus will continue to expose the WUI. At the national forest scale, these particular areas can be identified. In particular, the Rogue River-Siskiyou, Umatilla, and Wallowa-Whitman all have substantial area in FRG1 and FRG3 in conservation and preservation

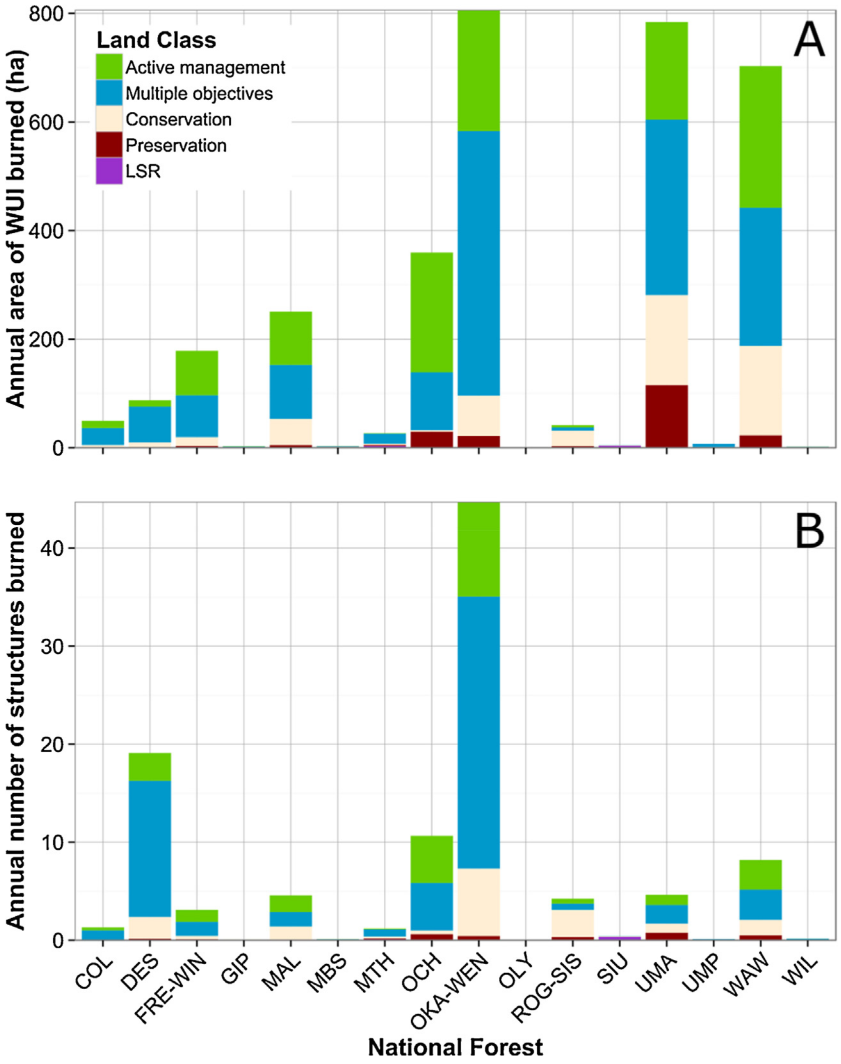

Fig. 6. (A) Predicted annual wildland urban interface (WUI) area burned, and (B) structures affected from simulated wildfires on national forests in the study area partitioned according to the land designation class of the ignition. See Table 2 for description of land classes. See Fig. 1 to reference national forest abbreviations.

LDCs that fall within the mapped fireshed boundary (Fig. 11). Conversely, national forests such as the Fremont-Winema and Malheur have the bulk of the fire-adapted fire regimes in areas that can be managed to restore fire.

3.5. *Identification of restoration and fire management themes*

Using a dichotomous key (Fig. 12A) we identified eight landscape restoration themes (LRTs, Table 3) within the study area. Restoration themes identify opportunities and conflicts for managing wildfire risk and achieving restoration objectives on dry forest areas versus other ecological conditions. The most prevalent restoration theme (LRT1, 34%, Table 3) consisted of low elevation dry forest areas that were predicted to transmit fire to the WUI, and can be managed with mechanical thinning and prescribed fire as provided for in national forest plans. Thus, in 34% of the area in national forests, fuels treatments can be applied to address both restoration and protection themes as part of building fire-adapted communities (USDA-USDI, 2014), and prioritizing landscapes with hazardous fuels, high ecological departure, and high levels of wildfire transmission to the WUI. By contrast, the second most prevalent land strata (LRT3, 25%) consisted of low elevation dry forest areas,

Table 2

Composition of national forests in terms of land designation class and fire regime within wildland urban interface firesheds. Percentage values refer to the composition of each land designation class among the different fire regimes. Group 1 = ≤35 year fire return interval, low and mixed severity; Group 2 = ≤35 year fire return interval, replacement severity; Group 3 = 35–200 year fire return interval, low and mixed severity; Group 4 = 35–200 year fire return interval, replacement severity; Group 5 = >200 year fire return interval, any severity. Data are from LANDFIRE (2013b). See Table 1 for descriptions of land classes.

Land designation class	Fire regime group area (ha)				
	1	2	3	4	5
Active management	1560,496 (63%)	80 (<0.1%)	645,005 (26%)	136,437 (6%)	141,669 (6%)
Multiple objectives	1036,218 (47%)	56 (<0.1%)	757,870 (35%)	92,900 (4%)	305,766 (14%)
Conservation	1082,881 (55%)	1333 (<0.1%)	512,906 (26%)	83,276 (4%)	302,436 (15%)
Preservation	526,815 (25%)	301 (<0.1%)	544,750 (25%)	85,593 (4%)	992,293 (46%)
LSR	9111 (1%)	0 (0%)	434,133 (37%)	37 (<0.1%)	744,572 (63%)

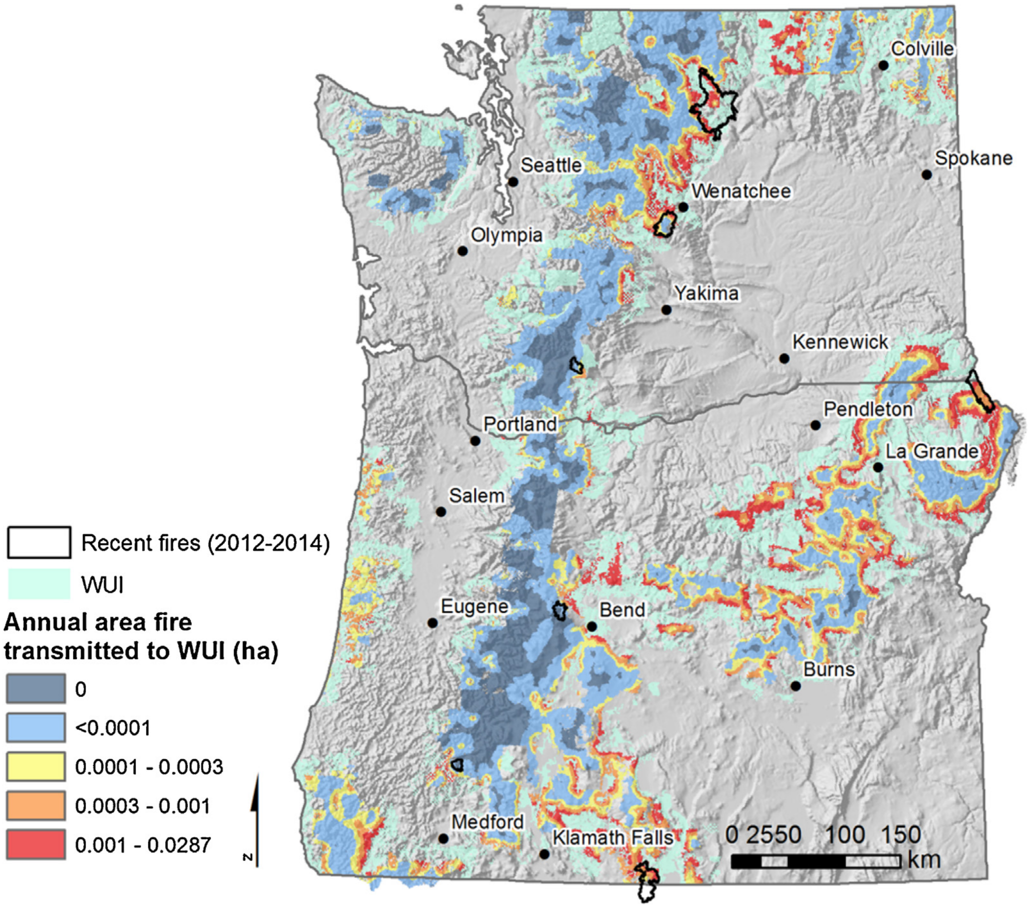

Fig. 7. Map of firesheds on national forests that delineate the areas where ignitions contribute fires that spread to the wildland urban interface (WUI). See methods for details on the estimation methods. Recent large wildfire perimeters are included to highlight areas where conditions are not represented in the modeling and may overestimate wildfire risk.

low severity fire regimes, where management is restricted by national forest plans and wildfires potentially threaten the WUI. Wildfire mitigation planning will need to rely on wildfire response, community wildfire protection planning, and the use of prescribed and natural fire to achieve ecological objectives. The third most prevalent restoration theme (LRT4, 16%) differed from LRT3 with respect to fire ecology, consisting of stand replacing fire regimes where management is not permitted under national forest plans, and there is potential for fire transmission to the WUI. Here, wildfire mitigation planning is limited to wildfire response and community protection activities to build fire-adapted communities. The remaining five landscape restoration themes span a range of

Table 3

Descriptions of example landscape restoration themes (LRT) created with the data layers generated in the analyses. Each theme addresses the intersection of management capability in national forest plans with wildland urban interface (WUI) protection issues and fire management goals related to the fire regime. Additional classes can be derived by adding in specific amenity protection issues (e.g., critical wildlife habitat, municipal watersheds) and economic factors such as thinning volume.

Restoration theme	WUI transmission	Capacity to manage under national forest plan	Fire regime group[a]	Total national forest area (ha) (%)	Landscape treatment strategy[b]	Restoration theme description—Cohesive Strategy
LRT-1	High	High	1 & 3	3366,144 (34)	C	Community protection/restoration for socioeconomic benefit
LRT-2	High	High	2, 4 & 5	471,207 (5)	C	Community protection/restoration for socioeconomic benefit
LRT-3	High	Low	1 & 3	2532,851 (25)	A	Suppression response/prescribed fire
LRT-4	High	Low	2, 4 & 5	1619,090 (16)	none	Suppression response
LRT-5	Low	High	1 & 3	633,445 (6)	A	Ecological departure
LRT-6	Low	High	2, 4 & 5	205,702 (2)	B, F	Ecological departure/restoration for socioeconomic benefit
LRT-7	Low	Low	1 & 3	600,479 (6)	none	Fire for benefit
LRT-8	Low	Low	2, 4 & 5	616,888 (6)	none	Fire for benefit

[a] See descriptions in Table 2.
[b] Landscape treatment strategies are defined in electronic Appendix 1 Fig. A2.

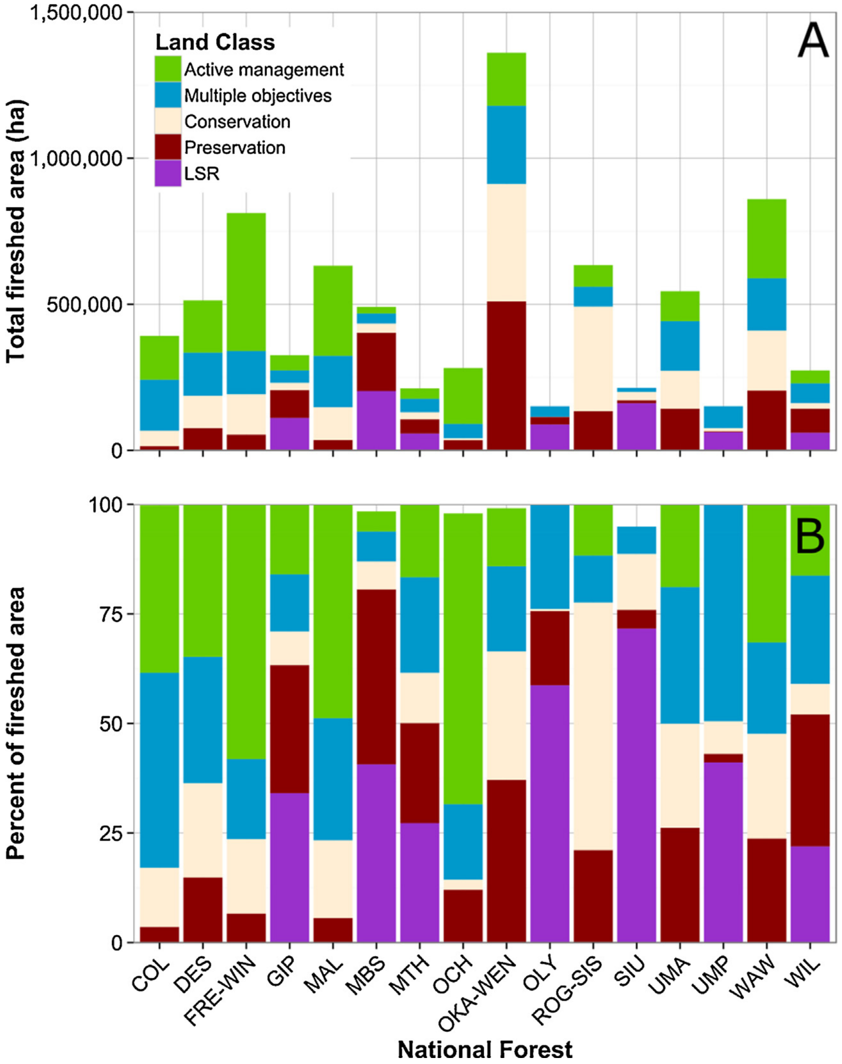

Fig. 8. Partitoning of the fireshed areas on national forests according to the land designation class. See Fig. 7 for the fireshed map and the methods section for the process used to delineate firesheds. See Fig. 1 to reference national forest abbreviations.

socio-ecological settings and each accounted for 2–5% of the study area (Table 3). Only 6% of the study area was classified as dry forest, with low severity fire regimes outside of areas that are predicted to threaten WUI with wildfires, thus areas where ecological fire management goals are devoid of consideration for wildfire WUI protection. Only 5% of the study area was in mixed and stand replacing fire regimes that can be managed and have potential to impact the WUI. Thus relatively minor areas in the study area are devoid of WUI protection concerns in the moist mixed-conifer forest areas.

4. Discussion

The results suggest that much of the wildfire risk to the WUI that originates on national forests in the Pacific Northwest can be mitigated with mechanical fuels treatments assuming that operability and economic factors are not constraints (North et al., 2015). However, we did not examine potential impacts of non-national forest lands on wildfire risk to the WUI, which can be substantial and are the topic of further investigation using network analysis methods (Ager et al., 2014b). The simulation outputs suggested that 78% of the potential wildfire WUI exposure as measured by WUI area burned resulted from ignitions outside of wilderness and roadless reserves, or other conservation or amenity areas created as part of national forest plans. Thus impacts of legislation to create wilderness and other conservation amenity reserves within the Pacific Northwest are in general perhaps less of a constraint to mitigating wildfire risk than discussed in other studies (North et al., 2015; Williams, 2013). We are not, however, suggesting that wilderness areas and other reserves do not contribute to large fire growth. For instance, Keeley, Safford, Fotheringham, Franklin, and Moritz (2009) concluded that suppression activities on the 2007 Zaca fire in southern California were strongly impeded by inaccessibility and the fire's location in wilderness, factors that contributed to the fire's unusual size and duration. The remoteness of the area also resulted in fewer anthropogenic ignitions, and thus 41% of the area had not burned since 1911, and another 46% had not burned since 1950. Narayanaraj and Wimberly (2012) found that in the eastern Cascade Mountains of Washington, larger sized fires tended to be in more remote areas where landscapes are less accessible to humans, in particular wilderness and roadless areas that are not fragmented by roads and have high fuel continuity that impeded suppression effectiveness. Despite these observations, fires outside of wilderness areas and other reserves commonly contribute to WUI disasters (Graham et al., 2012; Morrison, 2014).

The methods in this paper can contribute to improving wildfire mitigation planning in other fire prone countries by providing a process to explicitly identify individual sources of wildfire risk and the capacity to manage them, thereby defining the importance

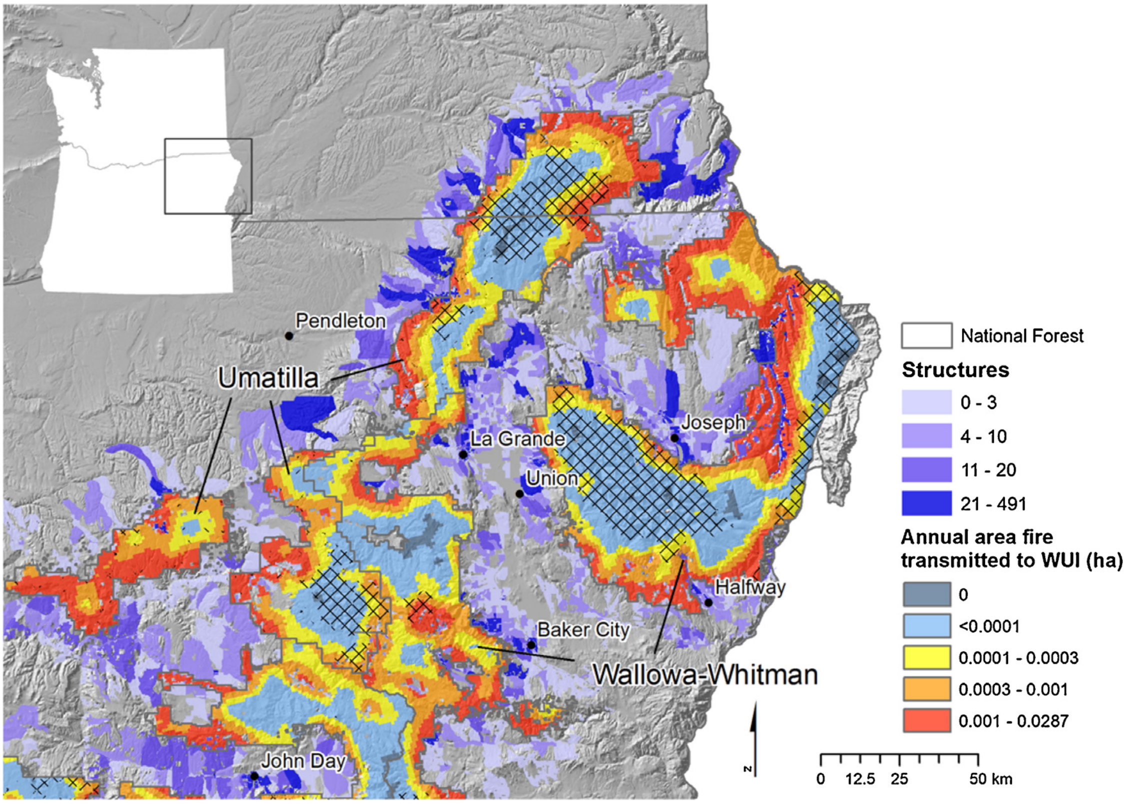

Fig. 9. Expanded view of two national forests in Fig. 7 showing both the location of the fireshed where simulated ignitions burned into SILVIS wildland urban interface (WUI) and the WUIs symbolized by the number of structures. See methods for details on estimation method. Hatched area is the area classified as 'Preservation' in Fig. 1.

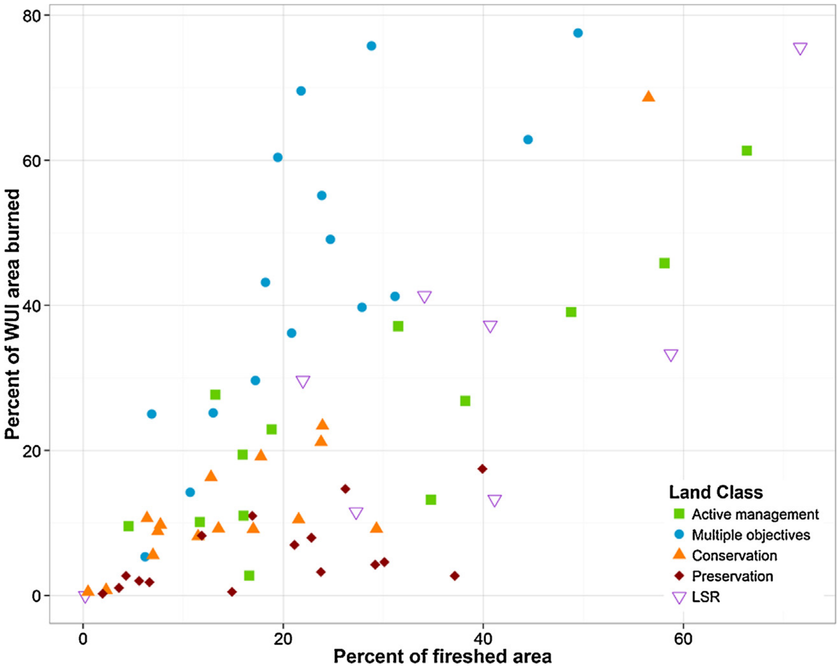

Fig. 10. Percent area of wildland urban interface (WUI) fireshed versus percent WUI area burned by land designation class and national forest. Each data point represents the values for a particular land designation class on an individual national forest.

and role of other risk abatement programs including suppression, reducing vulnerability of dwellings, and prevention programs such as "firewise" activities. Such analysis would partition risk within firesheds among the major land ownerships according to management capability, and identify where wildfire risk transmission and risk mitigation potential coincide, i.e., locations where opportunities exist for reducing wildfire risk. For instance, current direction under the Healthy Forest Restoration Act, unless broadened in local CWPP processes (CWPP Task Force, 2008; SAF, 2004), calls only for defining the WUI as within 1/2 mile from a community boundary

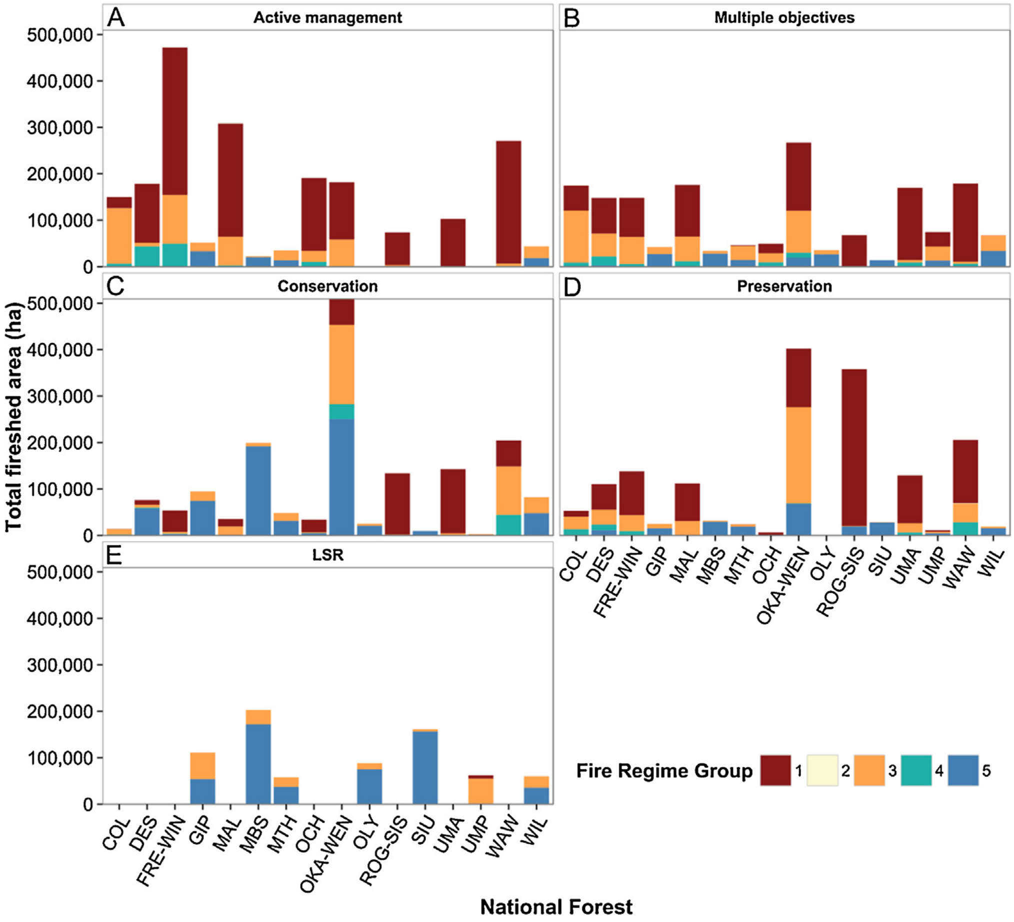

Fig. 11. Partitioning of the fireshed areas on national forests in Oregon and Washington according to land designation class (panels, see Table 1) and fire regime group. See Fig. 7 for the fireshed map, Fig. 3 for the fire regime group map, and the methods section for the process used to delineate firesheds. See Fig. 1 to reference national forest abbreviations. Fire Regime Group 1 = ≤35 year fire return interval, low and mixed severity; Group 2 = ≤35 year fire return interval, replacement severity; Group 3 = 35–200 year fire return interval, low and mixed severity; Group 4 = 35–200 year fire return interval, replacement severity; Group 5 = >200 year fire return interval, any severity. Data are from LANDFIRE (2013b).

and only up to 1.5 miles under mitigating circumstances, which is most likely inadequate to capture landscape scale risk associated with large fires (e.g., 10,000–100,000 ha) that cause most of the losses within and around WUIs (especially in the case of "mega fires," see Attiwill & Binkley, 2013) and can spread 20–50 km before reaching communities. We found that substantial areas of national forests (62%) can influence wildfire risk to the WUI, whereas the sum total of all CWPP boundaries overlapping national forests constitutes only 43% of the fireshed area (3.5 million ha). Although fireshed size will vary with estimation methods, the growing incidence of large fires (Attiwill & Binkley, 2013) and recent WUI losses (e.g., Graham et al., 2012) would support a liberal interpretation of their boundaries. The scale mismatch between wildfire disturbances and the CWPP process (Cumming, Cumming, & Redman, 2006; Folke, Pritchard, Berkes, Colding, & Svedin, 2007) contributes to poor risk perception and undermines the effectiveness of planning efforts.

Previous studies on effects of management restrictions on treating hazardous fuels led to somewhat different results. North et al. (2015) concluded that mechanical fuel reduction is not feasible over sufficient area in the Sierra Nevada national forests to facilitate containment or suppression of wildfires due to economic, administrative, and other constraints. Specifically, 46% of the subwatersheds had restrictions that would prevent projects from treating sufficient area to change potential fire behavior. However, it was suggested that a significant increase in treatment rate was possible if mechanical thinning was used to facilitate more extensive use of non-mechanical fuel reduction strategies (prescribed burns, managed wildfire). Mechanical treatments to specifically protect WUIs were not examined, and it is likely they are distributed in areas where management is possible, as observed in this study (Table 1). Platt, Veblen, and Sherriff (2006) used fire modeling and historic fire frequency to understand where both fire protection and restoration were needed in Boulder County, CO and determined that relatively small areas on national forest lands were in need of both mitigation and restoration treatments, although neither national forest plan restrictions nor transmission to the WUI were considered. Halofsky, Creutzburg, and Hemstrom (2014) generated a large geospatial database for the Pacific Northwest for mid- to broad-scale prioritization of land management actions, but also only considered local hazard metrics (i.e., in situ fire behavior) and thus were unable to measure conflicts between national forest plans, restoration of fire-adapted forest areas, and wildfire threats to the WUI from federal lands.

The finding that the bulk of fire transmission to WUIs from national forests in the Pacific Northwest region is from actively managed areas is in part due to their proximity to "Old West" (Winkler, Field, Luloff, Krannich, & Williams, 2007) timber-dependent communities that were founded at lower elevations on the fringe of forested lands, and were supported by logging on national forests. Areas where timber harvesting occurred in settlement periods were not eligible candidates for wilderness and

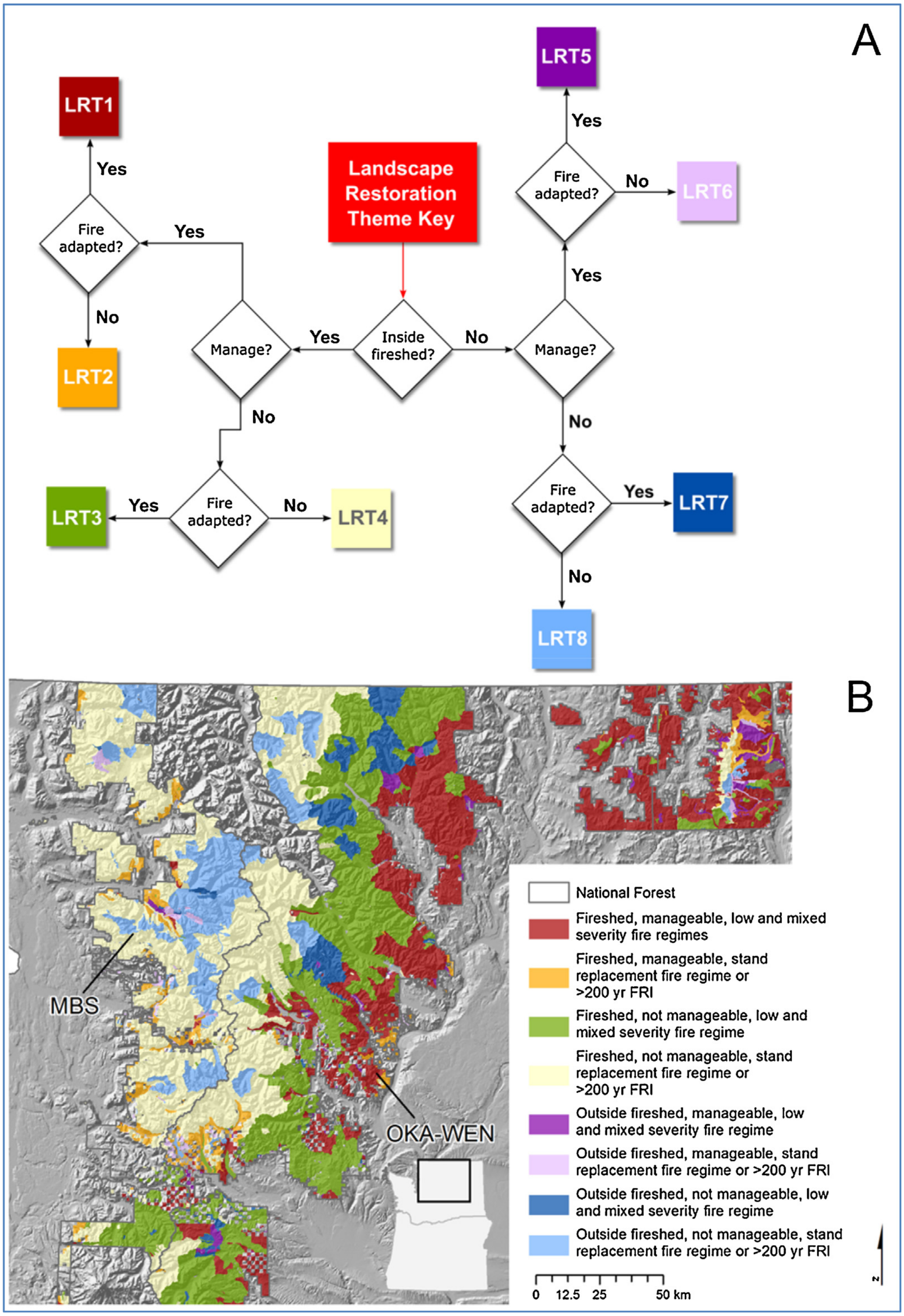

Fig. 12. (A) Dichotomous key that uses data layers developed in the study to stratify lands and identify landscape restoration themes (LRT). See Table 3 for details. (B) Resulting map showing the spatial distribution of the restoration themes for the Mt. Baker-Snoqualmie (MBS) and Okanogan-Wenatchee (OKA-WEN) national forests.

roadless areas, and biodiversity values in terms of rare habitat were probably eliminated by logging activities over the last century. Thus reserve systems are located in remote locations, lessening their potential impacts as a source of wildfire. However, the establishment of "New West" amenity communities (Winkler et al., 2007) and the overall expansion of the WUI (Theobald & Romme, 2007) has probably increased the potential transmission from reserve systems in recent years.

The broad scale mapping of restoration themes (Fig. A2, electronic appendix) can facilitate explicit identification of management conflicts and opportunities (Bullock et al., 2011; Rieman et al., 2010), as well as provide a roadmap to build multi-functional landscapes (Reyers, O'Farrell, Nel, & Wilson, 2012) envisioned in restoration and wildfire policy (USDA-USDI, 2014; USDA Forest Service, 2012a). In contrast to previous studies, we did not render judgements on the specific needs for restoration versus fire protection programs (e.g., Platt et al., 2006), a complex problem given the uncertainty of mega fires under a changing climate, but rather provided a way to organize and prioritize existing programs according to major socio-ecological dimensions of managing wildfire risk on national forests. Our approach (Fig. 12) linked transmission of wildfire risk with federal planning direction and local fire ecology to map restoration themes, thereby revealing spatially explicit management conflicts and opportunities. Existing policy and prioritization frameworks lack the spatial specificity needed by planners to downscale broad management goals (resilient landscapes, fire adapted communities, wildfire response; USDA-USDI, 2014) from county scale data (e.g., Fig. 2.1 in USDA-USDI, 2014) to the scale of planning areas (e.g., 5000–20,000 ha) where treatments are prioritized and implemented. This process can also help national forest planning efforts navigate the nexus between emerging policy initiatives for restoration, fuel management, and fire protection. For instance, we identified areas of conflict where WUI and amenity fire protection objectives may not be achieved due to national forest plan constraints (LRT3, Table 3), or because reference dry forest structure may not adequately address wildfire risk transmission (LRT1, Table 3). Subsequent analyses on the individual restoration themes that include variables describing economics and resource protection can be performed at local scales to prioritize landscapes for restoration using spatial optimization and other prioritization tools (Ager, Vaillant, & McMahan, 2013; Hessburg et al., 2013), as well as perform tradeoff analyses to identify production possibility frontiers for restoration and fire protection (Allan et al., 2013; Maron & Cockfield, 2008; Schroter, Rusch, Barton, Blumentrath, & Norden, 2014).

Collaborative planning groups engaged in forest restoration (Butler, Monroe, & McCaffrey, 2015; Schultz, Jedd, & Beam, 2012) and ongoing national forest plan revision efforts (USDA, 2012) can leverage explicit wildfire risk and transmission patterns intersected with management capability and ecological conditions to improve their understanding of mega fire impacts to WUI (Butler et al., 2015), conservation reserves, and amenity areas. The process can facilitate linking restoration goals and managing landscapes for fire protection, historical range of variability, and socio-economic goals for increasing jobs in timber dependent communities to site-specific treatment strategies and priorities as part of project planning (Ager et al., 2013) (Fig. 12). Compared to current ad hoc prioritization systems that rely on fire regime and condition class, we argue that spatially explicit planning frameworks can untangle competing objectives and prioritize activities based upon a broader context. The juxtaposition of forests, people, and large fires (Spies et al., 2014) should be incorporated in a coupled systems context.

We acknowledge limitations in both the data and modeling. In particular LANDFIRE data on fire regimes probably overestimates the area of fire-adapted forest area on the eastside forests. In retrospect, using potential vegetation maps might have provided better resolution on the location of fire-adapted forest areas, but regional data are inconsistent and incomplete. We also chose to use LANDFIRE since its coverage makes it possible to extend the analyses to other fire prone national forests. Our aggregation of the over 800 national forest plan land designations in the study area in terms of management restrictions was not without error, since local national forest managers can have variable interpretations of national forest plan direction and the acceptability of active management. Some land designations require extensive consultation and approval with regulatory agencies, including Late Successional Reserves and riparian reserves in order to implement active management. However our approach did not require expert opinion as used in previous studies to interpret management capability (North et al., 2015); we identified specific language in national forest plans to assess management restrictions. The wildfire modeling has a number of limitations discussed previously (Cruz & Alexander, 2010) and thus we limited our interpretation to broad patterns of potential fire impacts within the study area. We suggest that modeling methods be refined with local data as part of ongoing national forest plan revisions, collaborative planning, and accelerated restoration programs on the national forests (USDA Forest Service, 2015). For instance, local downscaling of the methods by planning teams could provide more refined analyses that lead to identification of locations where fuels treatments are constrained by national forest plans and ignitions have a high potential to impact the WUI.

5. Conclusions

We demonstrated the integration of broad-scale and diverse geospatial data to identify and map conflicts and opportunities for restoring fire-adapted forests and fire protection programs aimed at reducing wildfire impacts to the WUI in the Pacific Northwest, US. The results showed that most of the wildfire impacts to adjacent WUI emanate from lands where mechanical fuels treatments and underburning are allowed under national forest plans. Heretofore, the lack of spatial data and models to map management conflicts at strategic scales undoubtedly contributes to ongoing debates about the effectiveness of restoration, biodiversity conservation, and fire protection policy (DellaSala et al., 2013; Franklin & Johnson, 2012). We envision local application of the methods and results at the scale of individual national forests to improve the effectiveness of landscape planning efforts and address "all lands" federal policies regarding restoration, resiliency, and wildfire protection.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.landurbplan.2015.11.007.

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