

Wildfire exposure to the wildland urban interface in the western US

Alan A. Ager^{a,*}, Palaiologos Palaiologou^b, Cody R. Evers^c, Michelle A. Day^b, Chris Ringo^d, Karen Short^a

^a USDA Forest Service, Rocky Mountain Research Station, Missoula Fire Sciences Laboratory, 5775 US Highway 10W, Missoula, MT, 59808, USA

^b Oregon State University, Department of Forest Engineering, Resources and Management, 280 Peavy Hall, Corvallis, OR, 97331, USA

^c Portland State University, Department of Environmental Sciences and Management, PO Box 751, Portland, OR, 97207, USA

^d Oregon State University, Department of Crop and Soil Science, 109 Crop Science Building, Corvallis, OR, 97331, USA

ARTICLE INFO

Keywords:

Firesheds
Wildland urban interface
Community wildfire risk
Wildland fuel management
Wildfire transmission

ABSTRACT

Predicting wildfire disasters presents a major challenge to the field of risk science, especially when fires propagate long distances through diverse fuel types and complex terrain. A good example is in the western US where large tracts of public lands routinely experience large fires that spread from remote wildlands into developed areas and cause structure loss and fatalities. In this paper we provide the first comprehensive assessment of where public wildlands potentially contribute wildfire exposure to communities in the 11 western US states. We used simulation modeling to map and characterize the composition of the source landscapes (firesheds) and recipient communities in terms of fuels, fire behavior and forest management suitability. The information was used to build a prototype investment prioritization framework that targets highly exposed communities where forest and fuel management activities are feasible. We found that simulated wildfires ignited on national forests can potentially affect about half of the communities in the western US (2560 out of 5118), with 90% of exposure affecting the top 20% of the communities ($n = 516$). Firesheds within national forests, defined as areas that have the potential to expose communities to fire, were estimated at 35 million ha (62% of the total national forest area), and were almost three times larger than the affected community lands. Large contiguous areas of wildfire transmission were evident on a number of national forests. Only 22% of the fireshed area is forested, fire-adapted, and lies within land management designations that allow mechanical fuels management. The methods demonstrate how cross-boundary exposure can be factored into prioritizing federal investments in hazardous fuels reduction on national forests in concert with community protection measures. The results can also help scale wildfire governance systems to match the geography of risk from large wildfire events, which augments existing assessments that do not explicitly identify the source of risk to communities.

1. Introduction

Wildfire losses to developed areas continue to grow globally and are driven by a number of factors including warming climate (Abatzoglou & Williams, 2016; Littell, McKenzie, Wan, & Cushman, 2018; McKenzie & Littell, 2017), expanding wildland urban interface (WUI, Radeloff, et al., 2018), suppression policies (Calkin, Cohen, Finney, & Thompson, 2014), and increasing fire occurrence from human ignitions (Nagy, Fusco, Bradley, Abatzoglou, & Balch, 2018). In the western US, the buildup of forest fuels on public wildlands coupled with regional droughts (Littell, Peterson, Riley, Liu, & Luce, 2016) and high-wind events (Abatzoglou, Balch, Bradley, & Kolden, 2018) are catalyzing plume-driven fires that spread to developed areas, and are capable of consuming entire housing subdivisions (e.g., 2018 Carr Fire). These fire

events challenge risk governance systems on a global basis owing to the diversity of fire regimes, fragmented institutional fire policy, and landowner behavior with respect to managing fire and the fuels they consume (Fischer et al., 2016; Steelman, 2016). As losses grow, so do efforts to better understand the WUI problem from both a social and biophysical perspective, and to develop community mitigation planning systems to adapt to the increasing incidence of large fires. Most of the recent research has emphasized *in situ* WUI characterization and conditions that contribute to loss. For instance, researchers have developed various schemata to define and map WUI (Lampin-Maillet et al., 2010; Modugno, Balzter, Cole, & Borrelli, 2016; Radeloff et al., 2005), assess *in situ* fire hazard in relation to social vulnerability (Wigtill et al., 2016), create community typologies (Carroll & Paveglio, 2016), characterize social diversity (Paveglio et al., 2015), measure recent WUI expansion

* Corresponding author.

E-mail address: alan.ager@usda.gov (A.A. Ager).

(Radeloff et al., 2018; Strader, 2018), examine the equity of fuel management investments (Adams & Charnley, 2018), and predict structure loss (Kramer, Mockrin, Alexandre, Stewart, & Radeloff, 2018). At the same time, numerous large-scale assessments in the US have been used to map fire hazard and risk around the WUI (Dillon, Menakis, & Fay, 2015; WWWRA, 2013) to target investments in hazardous fuel reduction projects (Butler, Monroe, & McCaffrey, 2015; USDA Forest Service, 2015). These investments are focused on western US national forest lands, which account for some 30–50% of the total burned area in the western US, and result in the treatment of about 1.2 million hectares per year with 81% allocated to protect adjacent developed areas identified in Community Wildfire Protection Plans (CWPP) (USDA Forest Service, 2017a). Several studies have examined how these investments are allocated relative to the geography of the WUI (Adams & Charnley, 2018; Schoennagel, Nelson, Theobald, Carnwath, & Chapman, 2009), high fire hazard locations (Vaillant & Reinhardt, 2017), and demography of affected populations (Adams & Charnley, 2018; Palaologou, Ager, Nielsen-Pincus, Evers, & Day, 2019).

Despite advancements in risk science, assessment methods, and a myriad of state, federal, and local fire protection activities and programs (Jakes & Sturtevant, 2013), it is widely recognized that further improvements in community wildfire protection strategies are needed to curb escalating losses and make progress towards the goals of the federal wildland cohesive strategy (USDA-USDI, 2013). In terms of large scale assessments, more effort has been expended on mapping and characterizing the WUI than assessing its exposure to wildfire, owing to the fact that the former is a relatively simple problem compared to the latter. Initial identification of "at risk" communities published in the federal register (USDA and USDI, 2001) was based on qualitative ad hoc assessments. While *in situ* fire hazard (Dillon et al., 2015) has been mapped for the US and incorporated into social assessments (Wigtil et al., 2016), these and other assessments focus on fuel conditions in the WUI and do not consider how large fires ignited in distant locations spread to the WUI and shower them with embers that cause widespread structure ignitions.

Contributing to the problem is the fact that current CWPP programs (Jakes et al., 2007) allow for arbitrary definitions of community planning area, rather than defining them based on risk from large fire events (Healthy Forests Restoration Act). Thus delineations of planning areas for community protection planning (USDA & USDI, 2001) do not account for the geography of wildfire risk to communities (Ager, Kline, & Fischer, 2015). When these assessments are used for prioritizing federal assistance under the CWPP program (Jakes et al., 2011), the resulting investments may or may not target the lands that are a primary driver of WUI risk. Moreover, several studies that evaluated how well federal hazardous fuels programs address community protection also omitted the connection between landscape fuels, large fires and risk to the WUI (Adams & Charnley, 2018; Schoennagel et al., 2009). Clearly, existing large scale assessments (Dillon et al., 2015; WWWRA, 2013) that focus on *in situ* risk need to be revised to explicitly identify the source of large fires that often ignite in distant wildlands and spread to developed areas (Haas, Calkin, & Thompson, 2013). In this way, Firewise and other homeowner mitigation activities implemented as part of CWPP (Williams et al., 2012) could be better synchronized with landscape fuel management efforts on the wildlands from which fires originate. Although there have been assessments to prioritize communities based on risk transmission from surrounding lands, these have been few in number and small in scale.

In this paper we combine simulation modeling with geospatial analyses to provide a comprehensive assessment of where public wildlands in the 11 western US states potentially contribute wildfire exposure to communities. The goal of this work is to measure the scale of wildfire risk to communities and describe patterns of geographic variation in relation to fire exposure metrics. The study uses a spatial framework that recognizes the multiple scales and processes by which wildfire risk is transmitted from wildlands to developed areas (Fig. 1).

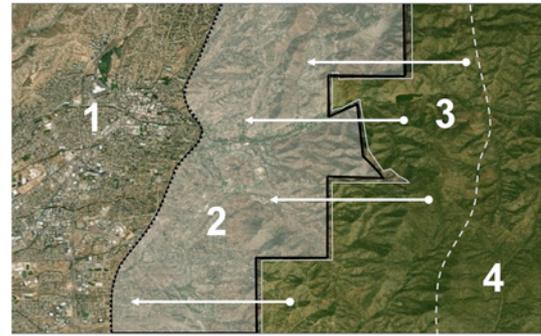


Fig. 1. Conceptual framework to organize geographic attributes for assessing community exposure from wildfire and capacity to respond. Arrows indicate wildfire ignition and spread into the wildland urban interface (WUI). Zones are as follows: 1) Community core not exposed to wildfire; 2) WUI predicted to be exposed to fire; 3) federal firehazard where ignitions are likely to expose communities to fire; and 4) federal land where ignitions are unlikely to generate community-exposing wildfires.

The study contributes methods and information that can be used at a range of scales to improve and prioritize community wildfire protection planning.

2. Methods

2.1. Study area

The study area included the 76 national forests (NF) of the 11 western US states (Fig. 2), and the adjacent WUI as mapped by the SILVIS project (Radeloff et al., 2005). We excluded the Dakota Prairie Grasslands, and the Black Hills and Nebraska National Forests because they were outside our study area (even though they belong to USFS Regions 1 and 2). National forest land within our study area covers over 56 million ha and contains a diverse array of forest and rangeland ecosystems. About 36 million ha are fire-adapted forests (LANDFIRE fire regime groups 1 and 3), 27 million ha are available for treatment and 30.5 million ha are classified with forested fuel models (Timber-litter, Timber understory and Slash-blowdown) from 2014 LANDFIRE data (Rollins, 2009). Lands available for treatment, hereafter manageable, exclude protected areas such as wilderness, roadless and nationally designated protected areas (see section 2.4). Fire-adapted forests include forested areas with fire return intervals < 35 years or 35–200 years and low or mixed severity fire regimes. This group excludes areas with historical high severity fire, or > 200 year fire return intervals. The national forest network is bisected by many mountain ranges including the Rockies, Sierra Nevada, Cascades, and numerous sub-ranges, which creates pronounced gradients in vegetation, climate, and fire regimes.

2.2. Wildfire simulation modeling

Wildfire simulation data from the large-fire simulator, FSim, were used to quantify current wildfire exposure within and among the national forests. The simulation methods are reported in detail elsewhere (Finney, McHugh, Grenfell, Riley, & Short, 2011; Short, Finney, Scott, Gilbertson-Day, & Grenfell, 2016), and results have been used in several other studies (Ager, Buonopane, Reger, & Finney, 2013; Thompson, Calkin, Finney, Ager, & Gilbertson-Day, 2011). In general, FSim simulates weather, fire occurrence, growth and suppression on large landscapes over thousands of simulations or fire seasons to estimate average burn probabilities (BP) and fire size distributions, in order to produce BP and flame length intensity grids, ignition points, and fire perimeters. FSim generates daily wildfire scenarios for a large number of wildfire seasons using relationships between historical Energy Release

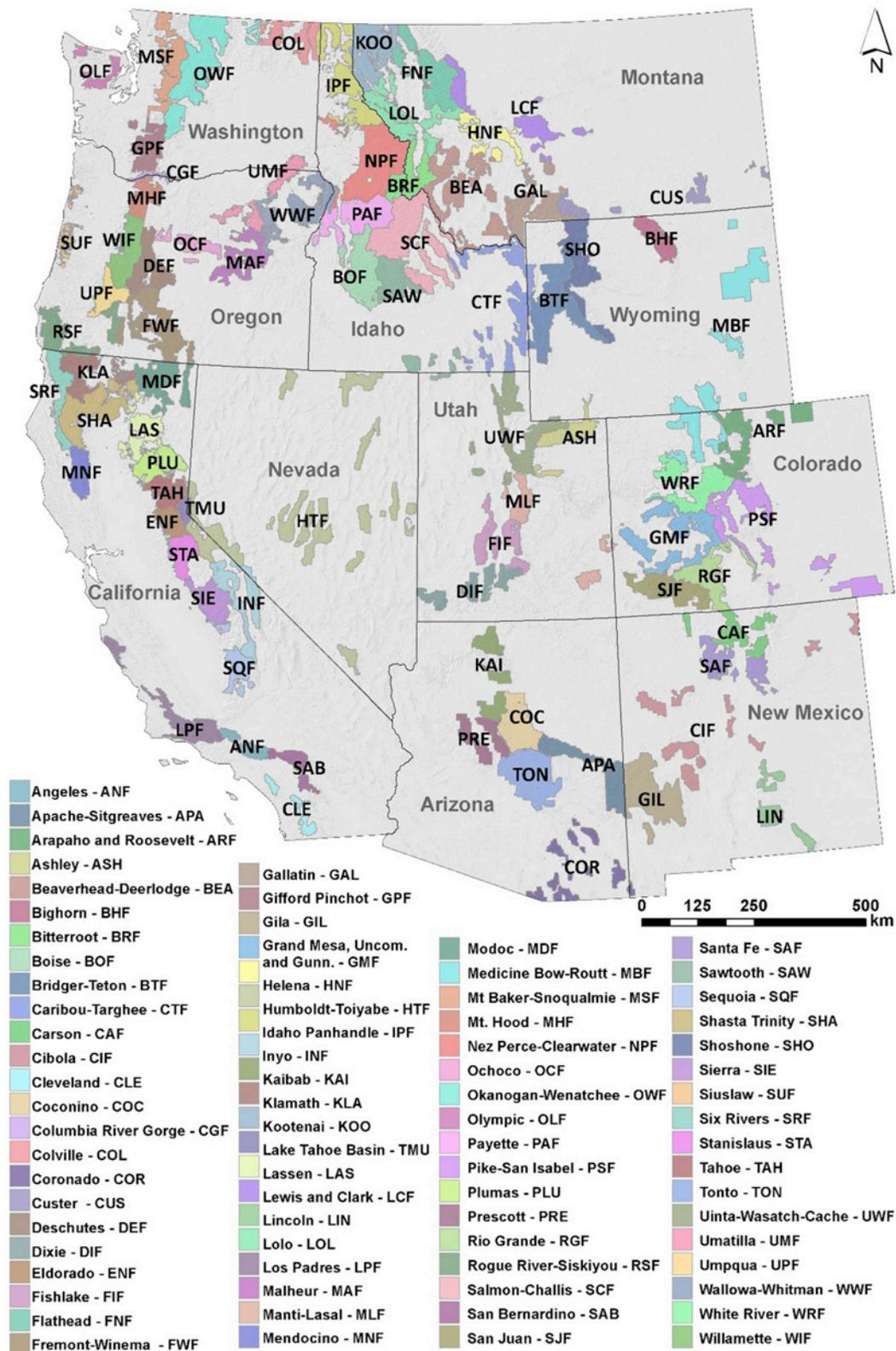


Fig. 2. The 11 western US states with the 76 national forests we analyzed for transmission and exposure to the ~5000 communities in the study area.

Component (ERC; Bradshaw, Deeming, Burgan, & Cohen, 1983) and historical fire occurrence. Wildfires are simulated with the minimum travel time (MTT, Finney, 2002) algorithm under weather conditions derived from time series analysis of historical weather. Weather data are derived from the network of remote automated weather stations located throughout the US (Zachariassen, Zeller, Nikolov, &

McClelland, 2003). FSim outputs include the ignition location of each fire, fire perimeters, and grids of BP and conditional probabilities by flame length category. The data used consist of 3.5 million ignitions (262,368 causing structure exposure) simulated inside US Forest Service lands, representing between 20,000 and 50,000 fire season replicates depending on the region (see Finney et al., 2011).

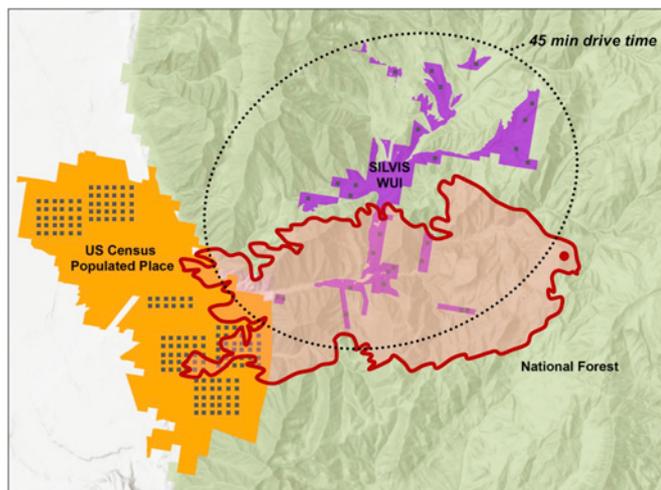


Fig. 3. Schematic diagram of the transmission assessment process to measure community exposure for a single community. Communities are defined using US Census populated places (US Census Bureau, 2016), including surrounding wildland urban interface (WUI) (Radeloff et al., 2005) within a 45-min drive time. Wildfire exposure was calculated using the structure density of those areas that intersect a given wildfire perimeter. The total exposure for a community represents the sum of all exposure events. Red dot represents wildfire ignition location.

2.3. Community exposure

We identified 5118 core communities in the US Census data (US Census Bureau, 2016), representing 65 million people and 25 million structures. We attached SILVIS WUI polygons (SILVIS Lab, 2012) to the core communities (US Census Bureau, 2016) using road networks and minimum travel time from the community's core to each WUI polygon. We use the term “community” to describe the combined core community defined by the census and the adjacent WUI (Fig. 3). Travel speed was used to create a cost raster that was input into the Cost Allocation ArcGIS tool with a maximum distance equal to 45 min driving time. We used the relatively long driving time to capture and organize 98.3% of the WUI into communities. We removed SILVIS WUI polygons that were classified as uninhabited, water, were smaller than 0.1 ha or had structure density less than 2 structures per km², thus our definition of WUI includes lower density census blocks than Radeloff et al. (2005) and includes no thresholds for wildland vegetation. Each community polygon was characterized in terms of fire hazard and fuel model composition using wildfire simulation modeling output layers and 2014 LANDFIRE data (Table 1). We combined the area characterized as high or very high wildfire hazard potential (classes 4 and 5) (Dillon, 2015),

to estimate the percentage of each community with high fire hazard (henceforth termed fire hazard).

We then intersected simulated fire perimeters with the community layer to estimate the annual number of structures exposed to wildfire, creating a set of intersected fire/community polygons. For a single fire f intersecting a single community c , the structure exposure e_{fc} is calculated as

$$e_{fc} = \sum_{i=1}^N A_{fc} D_{fc}$$

where A_{fc} is the area and D_{fc} the structure density (structures ha⁻¹) of the intersected polygon, summed over all community polygons that intersect fire f as shown in Fig. 3. The combined exposure across multiple fires and thousands of fire seasons for the entire community c represents the sum of exposures for all fires that intersect that community. The annualized exposure E_c (structures yr⁻¹) for a given community c is

$$E_c = \frac{1}{s} \sum_{i=1}^M e_{ic}$$

where M is the number fires intersecting community c throughout the entire simulation period, and s is the number of fire seasons or years simulated. We also estimate the normalized exposure for the entire community (\hat{E}_c), which is the number of structures affected per year per hectare of exposed community, as

$$\hat{E}_c = \frac{E_c}{\bar{A}_c}$$

where annualized community exposure is divided by \bar{A}_c , the area of the community exposed to wildfire.

2.4. Characterizing national forests

We partitioned national forests into 680,000 hexcells and attributed each with the same fire behavior and fuel information variables as described above for communities (Table 1). Irregular boundaries resulted in variable hexcell sizes from 10 to 135 ha (mean 80 ha). Attribute information added to each hexcell included majority wildfire hazard potential class (Dillon, 2015), fire regime and fuel model (Scott & Burgan, 2005) from 2014 LANDFIRE databases, annual transmitted structure exposure (derived as above in equation (1) but for all fires across all communities) and management status, defined by combining three datasets. The National Gap Analysis Project, Protected Areas Database (PAD) was used to set as non-manageable those hexcells with the majority of their area in codes 1 and 2 (management for conservation; which includes wilderness). In addition, roadless areas (2001 rule) (USDA Forest Service, 2017b) and National Designated areas were

Table 1
Attributes and data sources used in analysis of wildfire exposure analysis.

Variable	Description	Data download	Citations
Fuel model (class)	Fuel models grouped into grass-shrub (FM100 – FM140), shrub (FM140 - FM150), forest (FM160 – FM189) and non-burnable (FM90 - FM99)	LANDFIRE (2016)	Scott and Burgan (2005)
Structure exposure (structures yr ⁻¹)	Estimated from intersecting simulated fire perimeters with communities and deriving the number of affected structures out of the total number of structures, by the overlap fraction	SILVIS Lab (2012)	Ager et al. (2014); Ager et al. (2018)
Structure exposure density (structures ha ⁻¹ yr ⁻¹)	Estimated by dividing structure exposure by the area of community exposure by wildfires ignited on national forests	SILVIS Lab (2012)	
Fire regime (binary)	Fire- versus non-fire-adapted forests as defined by fire regime (fire regime groups 1 and 3: fire-adapted; fire regime groups 2, 4 and 5: non-fire-adapted)	LANDFIRE (2013)	
Management capability (binary)	Managed lands are USGS GAP Status codes 3 and 4, and excluding roadless areas and designated wilderness	USDA Forest Service (2017b, 2017c); USGS (2016)	
Wildfire hazard potential (binary)	Lands classified as at high hazard as defined by the ‘very high’ and ‘high’ wildfire hazard potential classes	Dillon (2015)	Dillon et al. (2015)

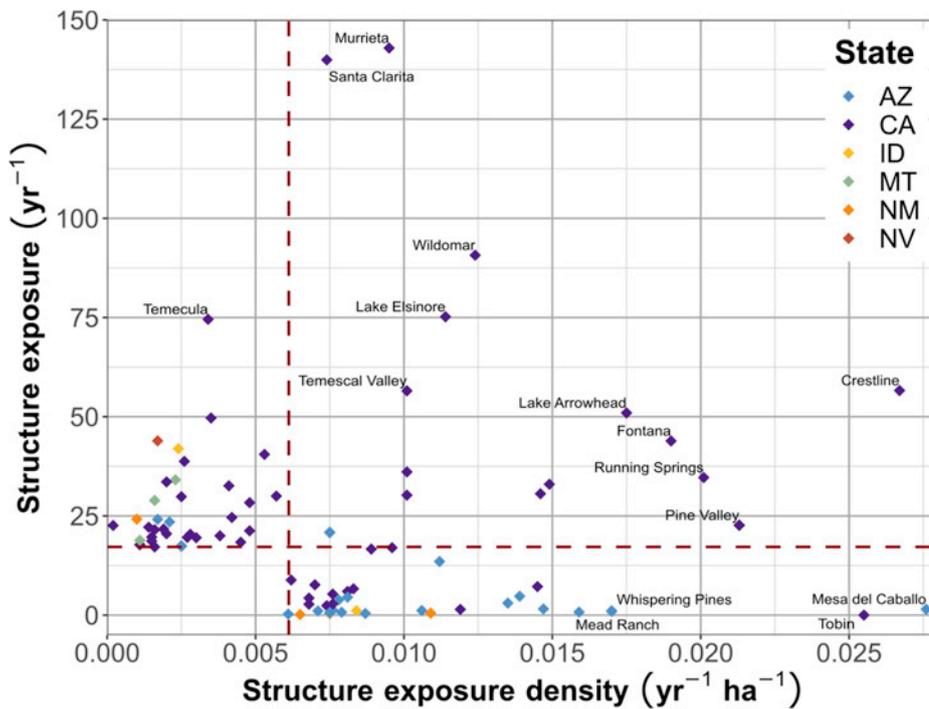


Fig. 4. Structure exposure of the top 50 communities in the western US to wildfire ignited on national forest land by state based on number of structures exposed and structure density. The top 50 communities for both metrics are indicated by the dashed red lines. Structure exposure is measured as the annual predicted structures affected using simulation outputs. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 2
Wildfire exposure to communities from national forest (NF) land for the 11 western US states.

State	Area burned from wildfires ignited on NF land and transmitted to communities		Total area burned		Structure exposure		Structure exposure density	
	ha yr ⁻¹	% of total	ha yr ⁻¹	% of total	n yr ⁻¹	% of total	n ha ⁻¹ yr ⁻¹	% of total
California	5031	47.3	40,823	24.4	2390	61.3	0.637	46.8
Montana	1334	12.5	14,903	8.9	255	6.5	0.048	3.6
Idaho	1042	9.8	39,881	23.9	190	4.8	0.047	3.4
Arizona	927	8.7	17,877	10.7	500	12.7	0.364	26.7
Utah	619	5.8	13,490	8.1	200	5.0	0.107	7.9
New Mexico	464	4.4	13,139	7.9	125	3.1	0.087	6.4
Washington	439	4.1	2977	1.8	50	1.2	0.006	0.5
Oregon	284	2.7	10,282	6.2	60	1.3	0.014	1.0
Wyoming	200	1.9	4252	2.5	35	0.8	0.011	0.8
Nevada	156	1.5	7490	4.5	110	2.6	0.030	2.2
Colorado	134	1.3	1984	1.2	30	0.7	0.009	0.7
Total	10,630	100	167,098	100	3945	100	1.36	100

excluded from manageable lands (USDA Forest Service, 2017c).

Annual transmitted structure exposure for each hexcell was estimated by creating a continuous smoothed surface of predicted structure exposure from all FSim ignitions that were predicted to cause some structure exposure, using empirical Bayesian kriging (EBK) geostatistical interpolation, implemented through the ArcGIS geostatistical analyst module (ESRI 2018). EBK accounts for the error introduced by estimating the underlying semivariogram, with accurate predictions of nonstationary data (i.e., wildfire ignitions). EBK kriging was based on the estimation of a series of semi-variograms for overlapping subsets of a specified size (100 points) that capture observed spatial dependence between points (Berman, Breyse, White, Waugh, & Curriero, 2015; Pilz & Spöck, 2008; Zimmerman, Pavlik, Ruggles, & Armstrong, 1999). We applied a log-empirical transformation on the data, and included up to 10 neighbors at a radius of 1.6 km. Then, using the EBK raster layer (100 m cell size), we estimated the maximum exposure value of all cells that intersected each hexcell, and standardized values so that total exposure of all fireshed hexcells equaled the total simulated exposure of all ignitions on NFs (3945 structures yr⁻¹).

2.5. Community fireshed and prioritization

We defined community firesheds as the area on national forests that is likely to transmit wildfire to communities based on simulation modeling (Ager et al., 2014). We mapped the linkage between each national forest hexcell and community polygon based on the simulated ignition location and perimeter, to enable the characterization of the landscape conditions of the ignition source for all the affected community polygons. For each community, we had the unique dataset of hexcells that were predicted to cause structure exposure. These unique datasets were used to assess community prioritization by ranking communities by both structure exposure and structure density and assessing hazard on both the source (Forest Service) and sink (community) sides of the transmission problem including the following metrics: structure exposure or density (sink), percentage of ignition source as manageable forest (source), percentage of ignition source as fire-adapted (source), percentage of community with high or very high wildfire hazard potential (sink) and percentage of ignition source with high or very high wildfire hazard potential (source).

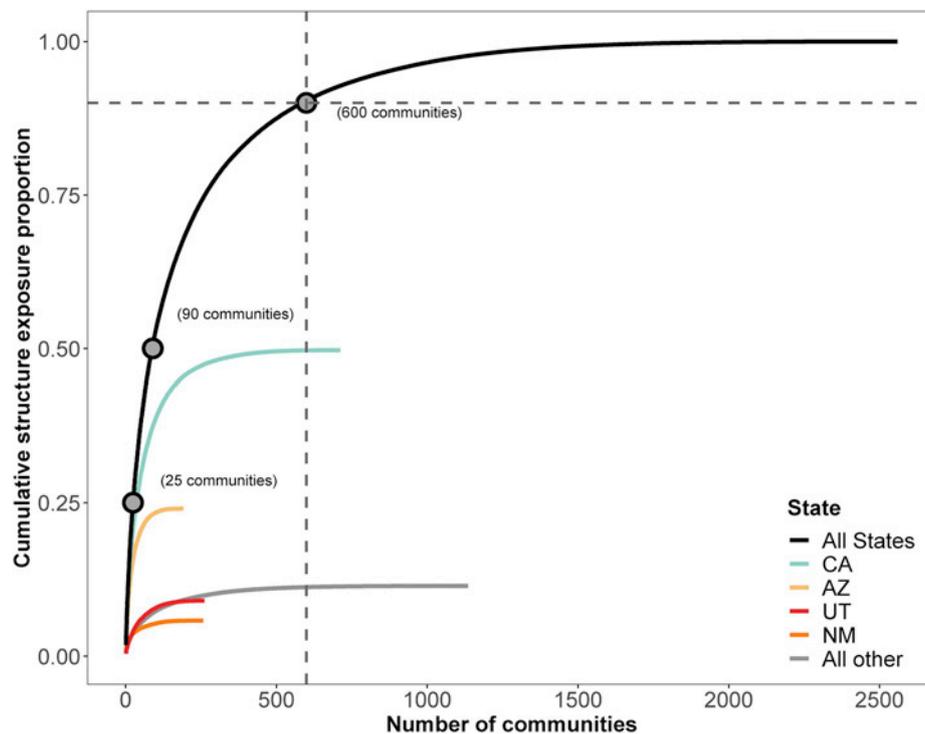


Fig. 5. Cumulative structure exposure from wildfires ignited on US national forests for the 11 western US states predicted from simulation modeling.

3. Results

3.1. Community exposure

Structures in 2560 out of 5118 communities were exposed from wildfires ignited on national forests, with 10,630 ha burned per year and 3945 structures exposed per year. The majority of the exposed communities were located in CA (712), followed by UT (262) and NM (258). Structures exposed to simulated wildfire for the top 50 communities ranged from a low of 17.2 (Boulevard, CA) to a high of 143 structures per year (Murrieta, CA) (Fig. 4). The amount of fire received also varied by community with a maximum of 262 ha yr⁻¹ (Salmon, ID). Of the top 50 exposed communities (communities above the dashed horizontal line, Fig. 4), 80% were located in CA. Half of all area burned in communities from NF ignitions was located in California, while area burned in communities in the least exposed five states accounted for only 11.5% (Table 2).

When exposure was adjusted by the exposed area of each community (structures yr⁻¹ ha⁻¹), emphasizing structure density, a different suite of communities was ranked in the top 50 for exposure (communities to the right of the dashed vertical line, Fig. 4). Only 15 communities were ranked on both lists (above the dashed horizontal line and to the right of the vertical dashed line), with three communities in the top 10 based on both metrics (Crestline, Lake Arrowhead, Fontana), thus there was not a strong relationship in structure exposure between raw and area weighted values (Fig. 4). While communities in CA still had the highest percentage of adjusted exposure (46.8%), communities in AZ (26.7%), UT (7.9%) and NM (6.4%) also showed high exposed structure density (Table 2).

In terms of cumulative structure exposure (Fig. 5), 90% of all structure exposure was received by 23% of the exposed communities (600) (black curve), while the top 90 communities contained 50% of all structure exposure in the western US (yet representing only 3.5% of exposed communities). Across the study area or within an individual state, community exposure was concentrated in a small proportion of the communities, however the slope of the curve was much steeper for CA and AZ (Fig. 5).

Half of all area burned within communities came from seven NFs (Cleveland, San Bernardino and Angeles in CA; Bitterroot in MT; Okanogan-Wenatchee in WA; Salmon-Challis in ID and Lolo in MT) (Fig. 6B), while 30 NFs cumulatively accounted for less than 5% of all area burned within communities. Half of the structure exposure originated from three NFs in CA (Cleveland, San Bernardino and Angeles) (Fig. 6A), while six other NFs caused exposure greater than 100 structures yr⁻¹, accounting for 19% of total exposure. Structure exposure and annual area of communities burned were generally correlated; however, there were NFs that contributed large amounts of total area burned where fires rarely exposed communities, such as the Salmon-Challis in ID (13,000 ha yr⁻¹, 1.4% of structures affected), the Gila in NM (10,000 ha yr⁻¹, 0.8% of structures affected), and the Sawtooth in ID (8100 ha yr⁻¹, 0.6% of structures affected).

The number of communities affected by wildfire ignited on each national forest and population exposed were weakly correlated and revealed several outlier NFs in California (Fig. 7). In addition to California's NFs, Tonto and Coronado (AZ), Uinta-Wasatch-Cache (UT) and Humboldt-Toiyabe (NV) each had the potential to affect more than a million people, while 35 NFs each affected less than 100,000 people and 1.5 million people in total. The number of communities affected by a single NF ranged from a low of six (Umpqua, OR) to a high of 150 for Uinta-Wasatch-Cache NF, with a median number of 35 communities.

3.2. Characterization of national forest lands

Simulations revealed that 35 million ha, or 62% of the total NF area, potentially contributed wildfire to communities, 19 million ha of which are manageable (14 million ha are both manageable and fire-adapted) (Fig. 8). This is also reflected in a map of firesheds that delineates areas where wildfires ignited and caused structure exposure to communities (Fig. 9). Only 7.6 million ha (14% of the total NF area; 22% of the total fireshed area) are manageable, fire-adapted and forested, limiting the area on national forest that can be treated to reduce risk (~700 structures yr⁻¹, 17.5% of total exposure). One quarter of the total fireshed was predicted to have very low exposure to communities (9 million ha with only 1% of total exposure). Approximately 6.5% of the total area

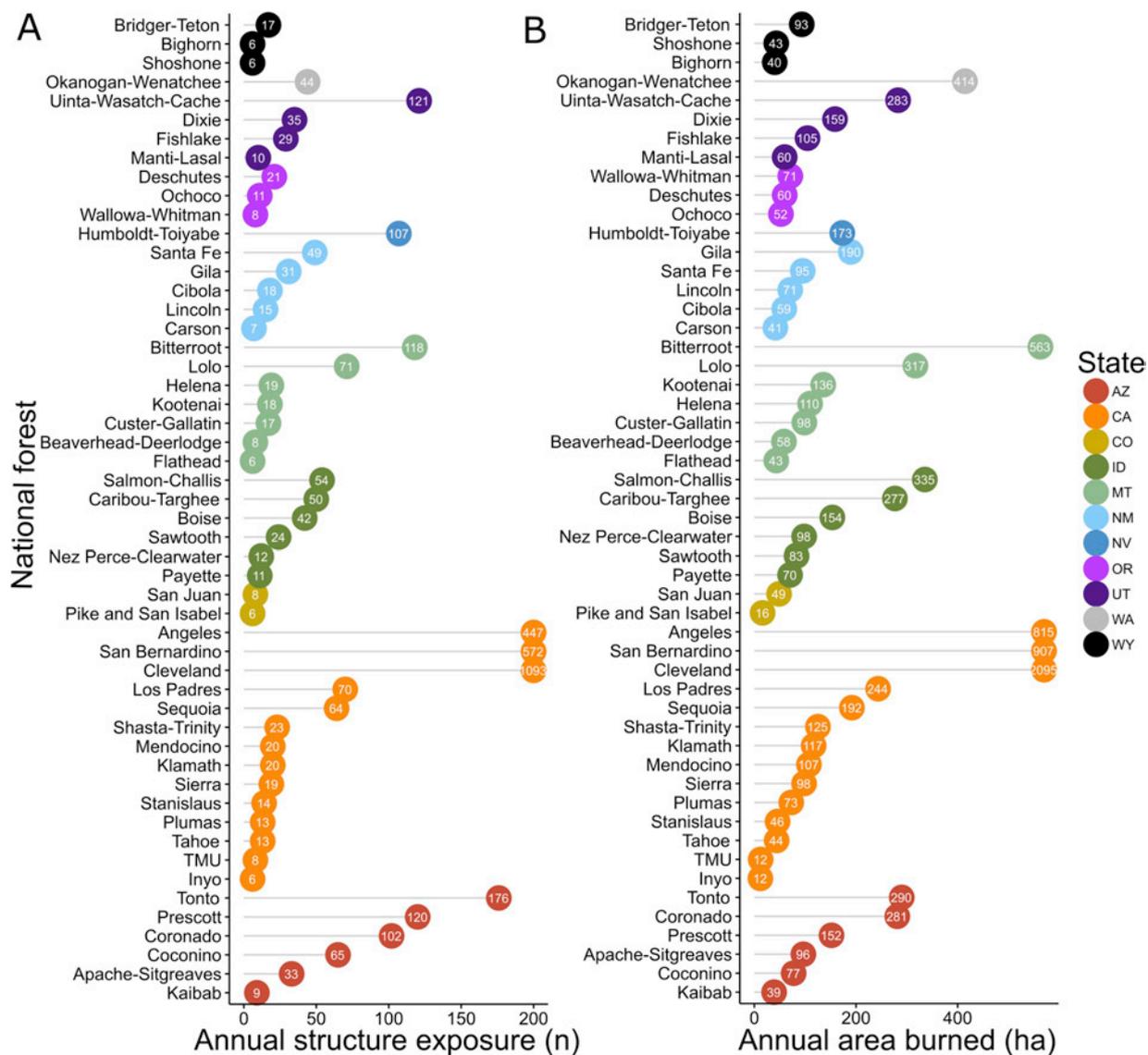


Fig. 6. Wildfire exposure to communities from simulated ignitions on national forests as measured by (A) annual structures exposed, and (B) annual area of community burned. National forests with < 5 structures exposed were removed from the plot. Note order of national forests within state changes based on exposure metric and maximum value is truncated for outlier forests (exposure value indicated by dot value).

burned by fires ignited inside NFs was transmitted to the community core and/or WUI polygons (Table 2), with state-level values ranging from ~1% (CO, NV) to 47% (CA). These numbers are substantially smaller than we have previously reported (Ager et al., 2014) but are limited to area burned from fires ignited within national forests that intersected community polygons (simulated fires not reaching communities were excluded from the analysis). The total amount of fire generated was 167,100 ha per year (Table 2), most of which burned in CA (24.4%), ID (23.9%) and AZ (10.7%). However, while structure exposure was highest in California (Figs. 4 and 6), the fireshed analysis shows very little (6%) of that exposure can be mitigated by hazardous fuel treatments (Fig. 8–10). The states with highest exposure mitigation potential were Washington (47%), Colorado (46%), Montana (38%), Oregon (30%) and Idaho (20%) (Fig. 10).

3.3. Community ranking

Ranking of communities and assessing the hazard profile on both sides of the transmission boundary revealed high variability across communities, especially in terms of structure density (Fig. 11). Eighty

percent of the top 50 communities in terms of raw structure exposure were in California where management is limited at the ignition source despite high wildfire hazard potential (38 out of 50 were in southern California; Fig. S1). Much more variability was seen in terms of the percentage of area that is fire-adapted. When comparing the number of communities in the top 50 ranking for structure exposure versus the area weighted structure exposure density, Arizona had only 8% of the top 50 communities (versus 36% for structure exposure density), while California had 80% (versus 56% for structure exposure density). High variability existed across communities for both source and sink metrics.

4. Discussion

Our work provides the first large-scale characterization of wildfire exposure from western US national forests to adjacent communities and WUI. The assessment linked fire behavior, management potential, and fuels conditions for both the source of fire exposure and the affected locations. We estimate that in the western US, 12.5 million ha of the 22.4 million ha WUI were exposed to wildfire from about 35 million ha of national forest lands. These community firesheds represent about

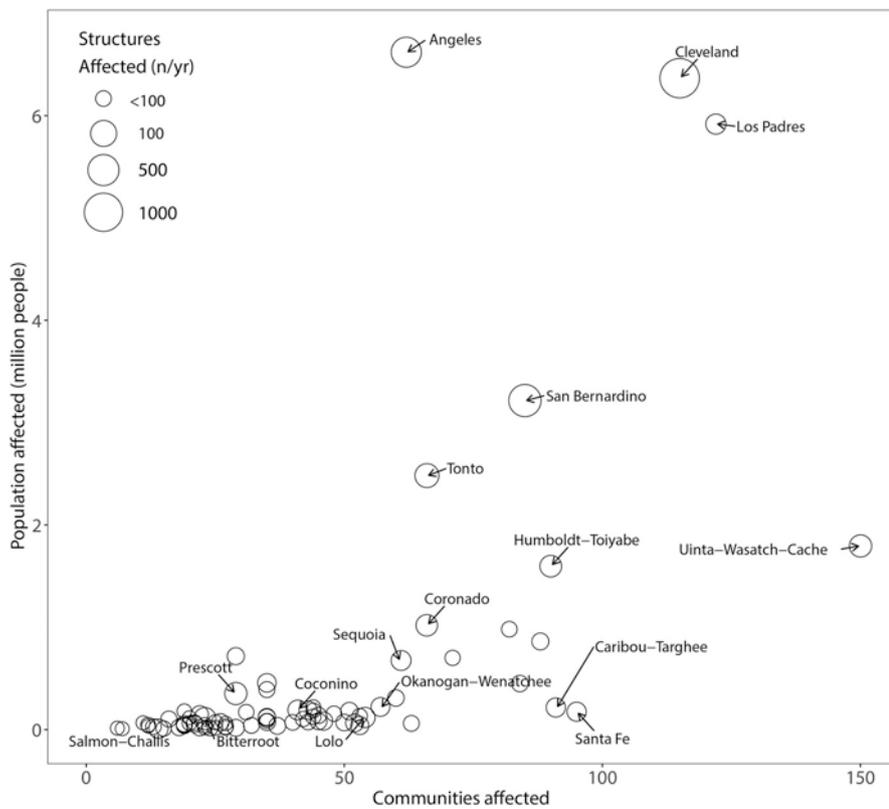


Fig. 7. Scatterplot of the 76 national forests in the western US with the estimated number of communities and population affected from wildfire simulations. Population is the sum of 2010 census records of all communities affected by ignitions on each national forest. Dot size denotes the annual number of structures affected. Names appear for the national forests with values of structures affected higher than the mean.

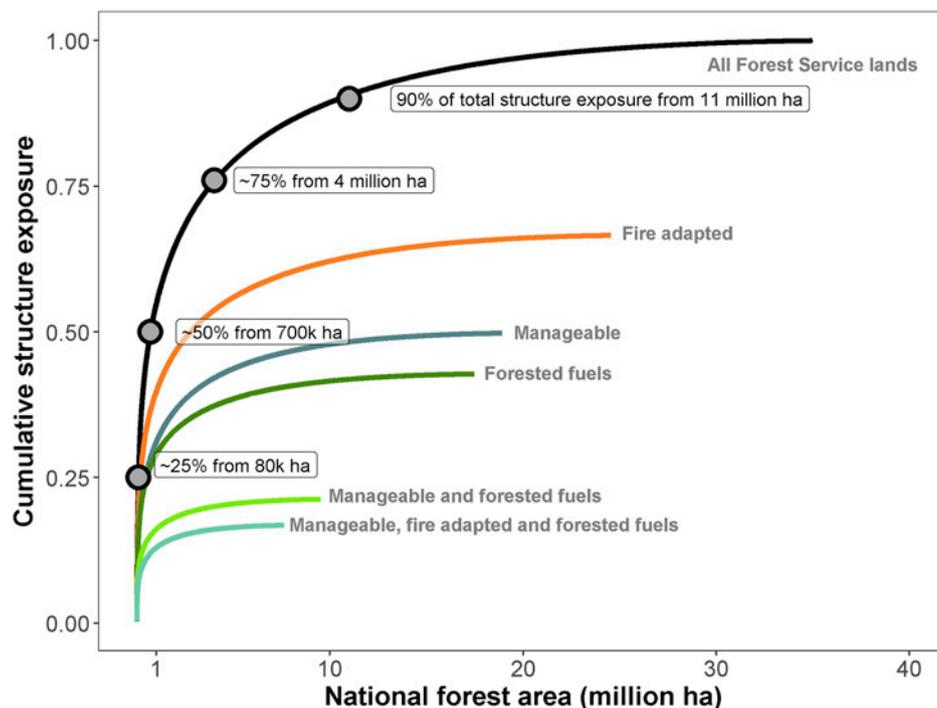


Fig. 8. Cumulative structure exposure from wildfires ignited on western US national forests predicted from simulation modeling. Colored lines are Forest Service lands by management capacity and fuel model.

45% of the national forest lands in the western US, almost three times that of the exposed wildland urban interface, and ten times larger than the 2560 community cores assessed. Most national forest wildfire source areas are fire-adapted, yet less than half are forested. Further, more than half of these lands have restrictions in place that limit mechanical treatments. In total, only 22% of the firesheds on national

forest lands are forested, fire-adapted, and can be managed with mechanical treatments under current land management resource plans.

The problem of wildfire exposure to developed areas is manifested at both landscape and community scales (Finney & Cohen, 2003). We connected these scales by characterizing exposure in terms of the frequency and intensity of wildfire burning from wildlands to WUI parcels

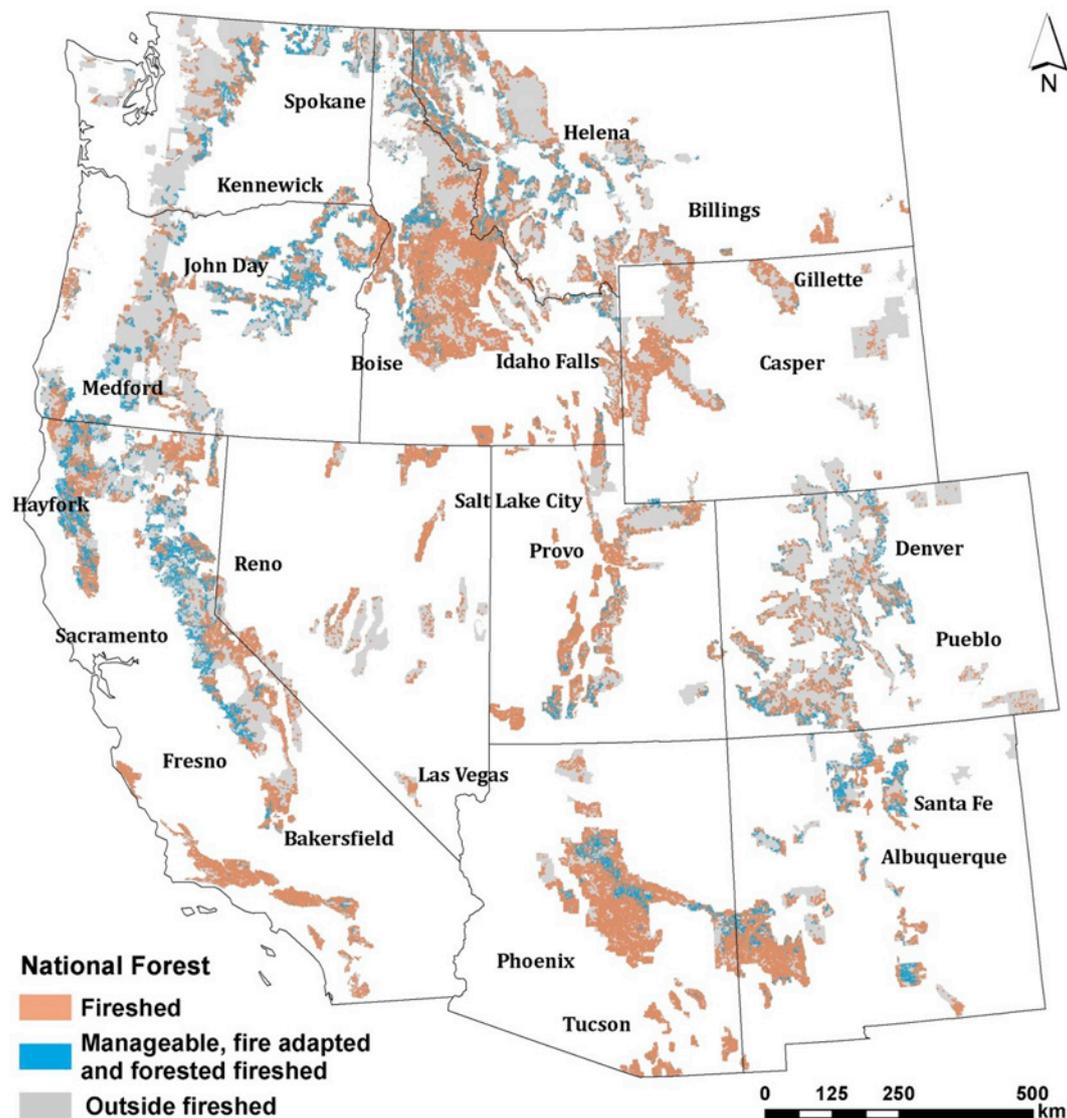


Fig. 9. Firesheds in the western US delineating national forest areas where ignitions have the potential to cause structure exposure to nearby communities, as estimated by empirical Bayesian kriging geostatistical interpolation on all simulated ignitions that reached community polygons. The parts of the fireshed that are manageable, fire-adapted and with forested fuel models are highlighted with blue. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

and communities. Prior studies have focused on the community scale to identify factors that explain structure susceptibility (or loss), including topography, spatial arrangement of structures (intermix versus interface), development patterns, density, building materials, and fuels in the immediate vicinity (Chas-Amil, Touza, & García-Martínez, 2013; Collins, Penman, & Price, 2016; Penman, Nicholson, Bradstock, Collins, & Price, 2015; Price & Bradstock, 2013; Syphard, Brennan, & Keeley, 2017). While prior post-fire studies on structure loss have pointed to specific contributing factors (e.g., structure location relative to other structures) (e.g., Alexandre et al., 2016), structure loss in these analyses was conditional on a fire spreading to the community, which ultimately might be a more important driver of loss than within-WUI conditions. Detailed structure loss models need to be integrated into fire transmission studies to fully assess the relative importance of *in situ* community versus landscape factors in prevention of structure loss.

We did not model specialized suppression resources that are deployed in and around communities during wildfire events, nor did we model long distance ember showers (i.e., firebrands) and structure ignition from approaching fire (Koo, P.J., Weise, & Woycheese, 2010; Penman et al., 2015). The simulated wildfires burned according to

historical suppression as predicted by energy release component (Finney et al., 2011) and burned only where there were combustible wildland fuels as indicated by LANDFIRE data. Thus, in general community cores (US Census Bureau, 2016) and high density WUI did not burn in our modeling, whereas these areas can be and often are exposed from ember showers that ignite structures and initiate structure-to-structure events (e.g., 2014 Carlton Complex fire, WA; 2018 Carr Fire, CA). Ember showers in particular are a major factor driving WUI losses and with recent improvements to the FSim wildfire model it will be possible in the future to model ember production and transport into WUI parcels. While empirical models (e.g., Syphard, et al., 2017) could be coupled with our fire exposure outputs to predict structure level loss and damage, we currently lack the required structure-level input data at large scales, although recent machine-learning techniques show promise to acquire detailed structure information (Microsoft, 2013).

Despite these limitations, the outputs from this work have useful application to prioritize federal, state, and local investments into community wildfire protection programs based on the level of exposure, source, and potential for forest management activities. The sheer number of communities exposed to wildfires from national forests

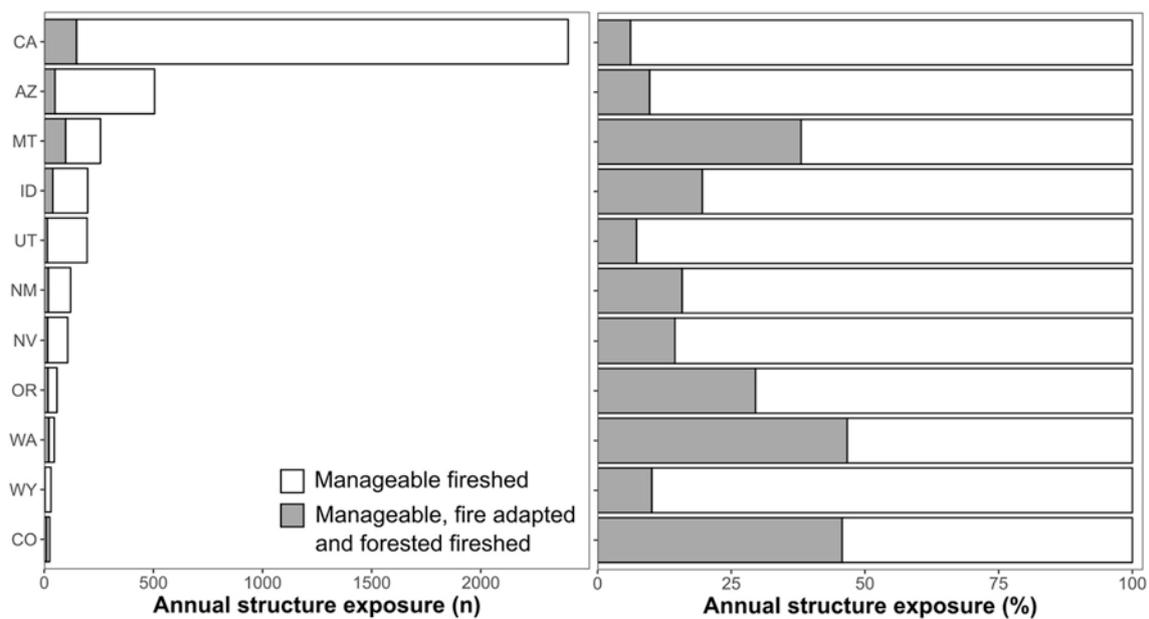


Fig. 10. Structure exposure from wildfires ignited on national forest land based on management capacity of the ignition source by state.

makes a community-by-community approach to investment in fireshed fuel management programs on national forests difficult. Our results show how relatively few hotspots account for the majority of the exposure to multiple communities (Fig. 4), suggesting substantial efficiencies can be gained by focusing investments in these areas, especially when compared to investments to address widespread problems identified in other agency assessments of overall wildfire hazard and terrestrial restoration (Cleland et al., 2017; Dillon et al., 2015). Scaling up wildfire planning boundaries to encompass the wildlands that potentially expose communities to large “surprise” fires will reveal connections among communities in term of common sources of exposure, and the potential to create multi-community planning areas that are sufficient in scale to consider fuel management that includes prescribed and natural fire.

Definitions of communities-at-risk to wildfire are increasingly blurred as the WUI expands to create continuous intermix between previously distinct communities. Recent assessments show over 40% of structures threatened by wildfire are not being included in current definitions of WUI or identified within a community (Kramer et al., 2018). Our geospatial methods organized close to 1.5 million WUI parcels (98.3%) into distinct communities that can be collectively recognized as discrete units in risk assessment and investment prioritization. Our definition of communities was an aggregate of geographic place names (US Census Bureau, 2016) and the surrounding WUI parcels (Radeloff et al., 2005) as defined by the minimum travel time process using a 45 min drive time. The bulk of the WUI (> 80%) was within 15 min, and the longer driving time was used as a means to assign remaining WUI to particular communities. The methods provide a more transparent framework to understand the geography of WUI wildfire risk and can potentially improve federal funding systems that currently allocate assistance to communities that are frequently based on fixed boundaries (Jakes et al., 2011) that exclude lands that are the source of risk. For example, comparing fireshed maps surrounding a typical at risk community Ager et al. (2015; Fig. 3) show that CWPP boundaries based on ownership and administrative borders (Jakes et al., 2011) are substantially smaller than the spatial scale of wildfire risk.

The global scale of the wildfire WUI problem (Buxton, Haynes, Mercer, & Butt, 2011; Lampin-Maillet et al., 2010; Modugno et al., 2016; van Wilgen, Forsyth, & Prins, 2012) and the potential for future growth (Gude, Rasker, & Van den Noort, 2008; Radeloff et al., 2018;

Theobald & Romme, 2007) underscores the need for expanding and improving existing planning systems and wildfire risk governance (Palaiologou, Ager, Nielsen-Pincus, Evers, & Kalabokidis, 2018). The rapid increase in housing units and developed land area in the western US has resulted in a 1150% increase in the total number of exposed structures and 256% increase in exposed developed land area between 1940 and 2010 (Strader, 2018). At the same time, fuels buildup, drought and extreme weather (Abatzoglou, Kolden, Williams, Lutz, & Smith, 2017) have substantially increased the size of community fire-sheds. In other words, the substantial growth in area burned alone would translate into larger WUI losses even without the WUI expansion reported by Radeloff et al. (2018) and Strader (2018). Moreover, WUI expansion leads to cascading effects on WUI fire exposure since it increases both the probability of ignitions from human activities (Nagy et al., 2018) and the potential loss of value.

Communities with high wildfire connectivity and large firesheds have a higher potential for scale mismatches in community planning, stemming from poor perception of risk transmission (Ager et al., 2015; Fleming, McCartha, & Steelman, 2015; Ivery, 2008). Reducing scale mismatches in the CWPP process can be facilitated by bridging linkages across organizations within collaborative planning groups (Abrams, Nielsen-Pincus, Paveglio, & Moseley, 2016; Brummel, Nelson, Souter, Jakes, & Williams, 2010; Hamilton, Fischer, & Ager, 2019; Steelman, 2008) that share risk. As reported by Steelman (2016) current wildfire risk governance is highly fragmented along institutional, jurisdictional, and other boundaries, and poorly designed to respond specifically to transboundary wildfire risk. Our analytical framework provides several improvements over various ad hoc methods to define spatial boundaries around the WUI as part of assessing social factors, fire hazard, and the relevance of mitigation activities (Adams & Charnley, 2018; Schoennagel et al., 2009; Wigtil et al., 2016).

Future characterization of community exposure coupled with fire-shed assessments can contribute fireshed typologies where populations of communities can be organized based on amount of exposure, fire intensity, fire likelihood, contributing land tenures, and fuel types (Evers, Ager, Nielsen-Pincus, Palaiologou, & Bunzel, 2019). Prior archetype discussions either focused exclusively on social (Carroll & Paveglio, 2016) or biophysical (Lampin-Maillet et al., 2010) variables. For instance Galiana-Martin, Herrero, and Solana (2011) built a WUI typology for fire prone areas in Europe but it lacked consideration of the scale of exposure to communities. Archetypes can be designed based

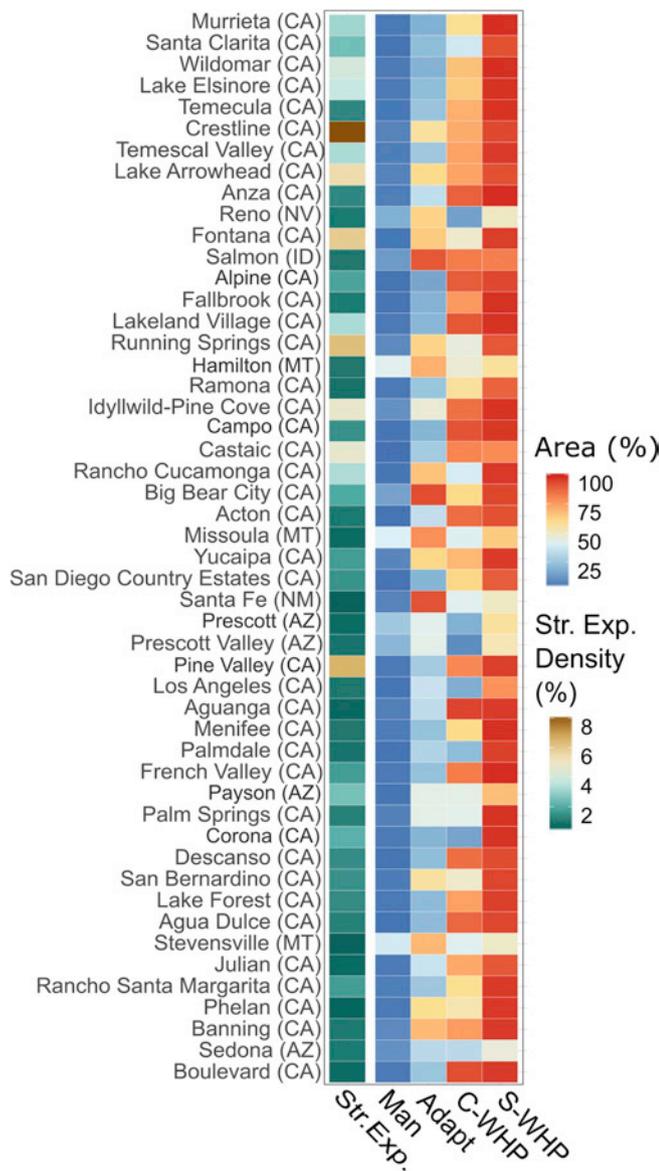


Fig. 11. Top 50 communities ranked by raw structure exposure. Communities at the top of the list were the most exposed to wildfire from national forest ignitions (in terms of raw structure exposure); those at the bottom the least exposed. Individual color ramps depict the percentage contribution to total structure density (Str. Exp.); the percentage of the ignition source area that is manageable (Man), fire-adapted (Adapt), or with high wildfire hazard (S-WHP); and the percentage of the community area that has high wildfire hazard (C-WHP).

on socioeconomic factors (Carroll & Paveglio, 2016; Paveglio et al., 2015) combined with land ownership patterns, capacity to manage fuels, and public versus private sources of risk, and diversity of land tenures.

Our analysis was specifically motivated by the spatial patterns of WUI and national forest lands in the western US which are characterized by large tracts of public lands surrounded by interfaces of private developed lands and communities (Fig. 1). Our methods are applicable in other fire-prone regions such as Mediterranean areas, with a high incidence of wildfire transmission between wildlands and communities, and with fragmented risk governance (Alcasena, Salis, Ager, Castell, & Vega-Garcia, 2017; Palaologou et al., 2018). Lacking a complete understanding of the scale and geography of risk will hinder risk abatement programs that address the changing geography of risk.

Transboundary wildfire exposure has been examined in previous

studies in the western US (Ager et al., 2014; Ager et al., 2018; Haas, Calkin, & Thompson, 2015; Scott, Thompson, & Gilbertson-Day, 2016) and elsewhere (Alcasena et al., 2017; Argañaraz et al., 2017; Palaologou et al., 2018) but other prior studies are limited in geographic scope, and/or omitted characterization of conditions of both the source and affected area. Existing US federal and state risk assessment frameworks do not assess fire exchange among different landowners and jurisdictions (e.g., Dillon, 2015; Scott, Thompson, & Calkin, 2013; WWWRA, 2013) but rather conform to the two-dimensional definition of risk (probability and consequences) compared to the three dimensions proposed by Gardoni and Murphy (2014) that also consider the source of the risk. As pointed out here and elsewhere (van Asselt & Renn, 2011), two dimensional assessments of risk fail to reveal the process by which risk is created or sustained, thereby compromising strategies to reduce it.

Declarations of interest

None.

Acknowledgements

Funding was provided by the USDA Forest Service National Fire Decision Support Center. We thank Ken Bunzel for help with GIS processing, and Ana M.G. Barros, Rachel M. Houtman and two anonymous reviewers for helpful comments on this manuscript.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.apgeog.2019.102059>.

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