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Cross-Boundary Wildfire and Community Exposure: A Framework and Application in the Western U.S.

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Abstract

In this report we provide a framework for assessing cross-boundary wildfire exposure and a case study application in the western U.S. The case study provides detailed mapping and tabular decision support materials for prioritizing fuel management investments aimed at reducing wildfire exposure to communities located proximal to national forests. The work was motivated by a number of factors, including a request from U.S. Department of Agriculture Undersecretary James Hubbard (Natural Resources and Environment) to assess community wildfire risk specifically from Forest Service lands, language in the 2018 omnibus bill (Public Law 115-141) calling for a national assessment of wildfire risk to communities, and newer shared stewardship initiatives (Clavet 2018). We used national FSim simulation outputs to (1) estimate cross-boundary wildfire among major land types (Federal, State, private); (2) quantify structure exposure to all western communities; (3) map sources of community wildfire exposure (firesheds); (4) characterize firesheds in terms of management opportunity and fuels; and (5) prioritize communities based on integration of exposure and fireshed characteristics. The study revealed that 1,812 communities in the western U.S. could potentially be significantly impacted by future wildfires (more than 1 structure per year on average). Ignitions on national forest lands will most likely affect 516 of these 1,812 communities (more than one structure per year on average). Of the total exposure, ignitions on national forest lands will expose an estimated 4,000 structures (21 percent of total) in the western U.S. per year on average. Due to administrative restrictions on national forest lands, only about half of the total exposure from national forest lands (2,200 structures) originates on lands where mechanical treatments and prescribed fire are either allowed or ecologically appropriate. The framework can guide future efforts aimed at quantifying community and other cross-boundary exposure situations, and the outputs can be used to help identify shared stewardship projects, and prioritize fuel and other management activities within public land management agencies.

Keywords: firesheds, wildland urban interface, community wildfire risk, wildland fuel management, wildfire transmission

Front cover: A DC10 Air Tanker is seen over the Woolsey Fire in California. (Photo courtesy of Peter Buschmann)

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Contents

Introduction

The cause of recent wildfire catastrophes can be traced to multiple factors including the expanding urban footprint (Radeloff et al. 2018), increasing human ignitions (Nagy et al. 2018), droughts (Littell et al. 2016), and high-wind events (Abatzoglou et al. 2018). Plume-driven fires shower developed areas with embers causing a chain reaction of mass structure ignitions, burning urban subdivisions (e.g., Carr and Camp Fires of 2018). The expanding scale of wildfire risk to communities in the U.S. and elsewhere is recognized in several new federal forest management authorities and initiatives that aim to motivate larger-scale management activities spanning jurisdictional and landowner boundaries (USDA Forest Service 2018). This includes the Good Neighbor Authority (2014), the 2014 Farm Bill, and the recent Shared Stewardship Strategy (USDA Forest Service 2018).

Emphasis on cross-boundary management of wildfire issues can benefit from new assessment frameworks that are fine-tuned to meet the information needs found in new cross-boundary authorizing legislation (Ager et al. in press; Ager et al. 2018; Evers et al. 2019). For instance, existing risk assessment technologies and frameworks do not explicitly examine the cross-boundary problem intrinsic to community wildfire risk from large areas of public wildlands (Dillon et al. 2015; WWWRA 2013) because they measure in situ risk without specifying a linkage to ignition origin or fire-spread path through parcels to developed areas. As fires get larger and larger, linking human and natural values to the wildlands that propagate fires becomes increasingly important. In particular, the risk assessment process used by State agencies and implemented in Wildfire Risk Assessment Portals (WRAPs) for each of the 17 western States (WWWRA 2013) could be enhanced with newer methods to consider cross-boundary risk and exposure metrics. These risk assessments use pixel-level indices to measure community exposure to wildfire, ignoring large fire spread in the surrounding wildlands. By contrast, the newer assessment methods developed by Forest Service researchers use large fire simulations (Dillon et al. 2015; Scott et al. 2013), but lack frameworks to explicitly measure and map cross-boundary and wildland-community wildfire transmission. Neither ad hoc nor published definitions of community wildfire protection areas (USDA and USDI 2001) account for the geography and scale of risk to communities (Ager et al. 2015). Science reviews (Miller and Ager 2013) also lack discussion of cross-boundary fire and measurement of community wildfire risk. Clearly, in an era where the scale of risk is rapidly expanding with larger and larger fires, it is important to understand the topological properties of cross-boundary fire on landscapes in the U.S. and elsewhere that are fragmented by ownership type, management intent (Charnley et al. 2017), and fire management jurisdictions.

In this report, we first summarize methods and findings from a series of prior research studies on cross-boundary wildfire exposure in the western U.S. with the aim of providing a framework for assessing cross-boundary wildfire issues. We then provide a detailed assessment of community cross-boundary wildfire exposure in the western U.S., both among major land ownerships (private, public, State, Federal) and from those land types to communities. The results can be used to refine a wide spectrum of fire protection and management activities, including efforts to prioritize fuel management programs on public lands surrounding populated areas, as well as cross-boundary projects as part of the shared stewardship initiative. The results from this study are available in ArcGIS online (Palaiologou and Aiello, 2019).

Cross-Boundary and Community Assessment Framework

Cross-boundary or transboundary risk (sensu Lidskog et al. (2010)) has been described and documented for a wide range of global environmental problems, especially water and air pollution (Lidskog et al. 2010; Lidskog et al. 2011; Linnerooth-Bayer et al. 2001). A number of wildfire studies have examined cross-boundary wildfire issues, but typically do not frame the problem in a cross-boundary governance context. The assessment framework described here can be applied to fire exchange across social, jurisdictional, legal, administrative, and ecological boundaries. The cross-boundary framework includes methods and metrics that quantify numerous aspects of fire exchange and community exposure, including metrics that measure scale of risk, diversity of landowners that contribute risk to communities, and other measures that describe mitigation opportunities. In the first section of this report, we describe core metrics for measuring cross-boundary exposure and community risk. This material is followed by a case study that assesses cross-boundary fire in the western U.S.

Wildfire Risk and Exposure

Risk concerns the prediction of expected loss, calculated as the product of the likelihood of a fire at a given intensity and the consequence(s). A formal definition of risk consistent with the Society for Risk Analysis was first formulated by Finney (2005). It was first applied by Ager et al. (2007) in studies of the northern spotted owl, followed by application to study risk to old growth and carbon storage (Miller and Ager 2013). Risk is composed of three components: (1) ignition likelihood, (2) expected fire intensity, and (3) effects related to expected fire intensity. Fire can be beneficial or result in loss to social and ecological values (Miller and Ager 2013). Early risk studies used the site-specific response functions developed using the Forest Vegetation Simulator (Miller and Ager 2013). Large-scale risk assessments with multiple values were first conducted by the Cohesive Strategy Science Team, (Calkin et al. 2011) where four category response functions were developed using expert judgment. A geospatial risk assessment system was integrated into ArcMap via the ArcFuels landscape planning system (Ager et al. 2011; Vaillant et al. 2013). This latter system provided a robust framework for integrating response functions with burn probability outputs from models like FlamMap and FSim for building wildfire risk maps. Scott (2006) summarized risk calculations in a technical guide.

Wildfire exposure, by contrast, only concerns the juxtaposition of threatened values in relation to predicted fire occurrence and intensity without estimating potential loss (SRA 2006). The framework in this document focuses on wildfire exposure for the following reasons. First, it is not possible to estimate structure loss from large fire simulations because the variables necessary to perform such estimates are not used in large landscape simulation studies (Mell et al. 2010). Second, many other factors besides landscape fuels ultimately influence whether or not structures ignite after fire arrives in the vicinity. Third, exposure formulation reduces the complexity associated with multiple resource risk estimates, which require some form of decomposition to understand the driving factors causing risk in the first place, e.g., fire likelihood, fire intensity, or susceptibility. Understanding the relative influence of these risk drivers is key to the socialization of risk assessments and their adoption by landowners, communities, and other affected entities.

Measuring Cross-Boundary Fire

From a cross-boundary wildfire perspective, there are three possible sources of exposure on a given parcel: (1) self-burning, (2) incoming, and (3) outgoing (fig. 1). Again, the parcel boundary can be ecological (e.g. fire regime), jurisdictional (fire suppression), administrative (forest plan allocation), ownership (private versus public), or aggregates thereof (e.g. a community). Self-burning fire originates within the parcel. Incoming fire arrives from other distinct parcels in the landscape. Outgoing fire is fire that originates on a given parcel and burns into adjacent parcels. In general, land parcels with similar conditions (e.g., fire spread rate, spatial ignition density, and wind direction) will have equal amounts of incoming versus outgoing fire. Experiments with real landscapes show dramatically different ratios of incoming to outgoing fire (Ager et al. 2014a; fig. 4). A number of factors influenced both relative and absolute transmission including fuels, assumed weather for simulated fires, parcel size, geometry, and arrangement, but it is difficult to quantify the relative importance of the causal factors (Ager et al. 2014a). In general, the ratio of fire exchange (incoming + outgoing) to self-burning generally decreases with increasing parcel size and decreasing edge to area ratio (Ager et al. 2018).

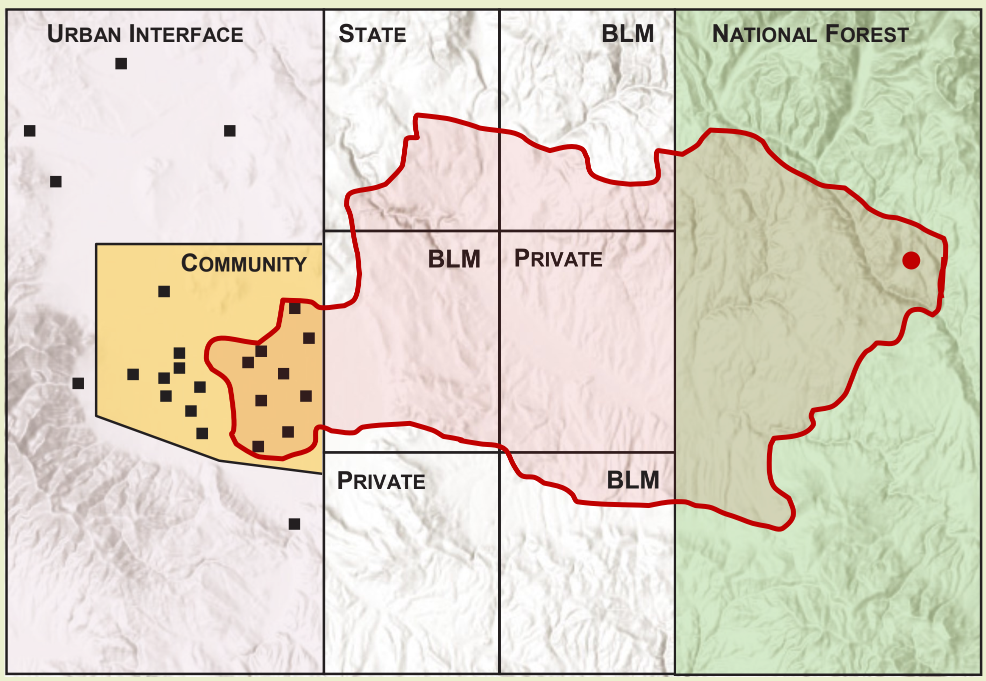


__Figure 1__—For each parcel, cross-boundary fire components include self-burning, incoming, and outgoing. In this example an ignition on a national forest (red dot at right) spreads to adjacent landowners and into a community where structures are exposed to the fire. Within the national forest the fire is considered self-burning, while it is incoming for the other land parcels. Over many fires, incoming and outgoing area burned may differ due to ignition density, spread rates, parcel geometry, and other factors. In the present study, wildfire exposure to communities was determined by intersecting the fire perimeter with the developed area (red boundary within the orange community parcel). Exposure to structures was then calculated by multiplying the proportion of the community or wildland urban interface polygon that was burned by the count of the structures in the parcel.

Quantifying cross-boundary fire requires an ignition location, the fire perimeter, and a spatial definition of parcels. These can be estimated from both empirical and simulated fires, although the empirical data are typically too sparse to obtain robust estimates of cross-boundary fire, the exception being large (e.g., 10^6 hectares) study areas (Ager et al. 2014b; fig. 8). There are many ways cross-boundary fire can be expressed using nonstandardized or standardized measures that correct for size differences among the parcels or communities. For instance, fire transmitted from a parcel can be expressed as total area of fire transmitted or standardized to the area of the source parcel to measure transmission efficiency or expressed as a per fire basis. In the simplest case of estimating the amount of outgoing fire (TF) for a fire ignited in land designation *i* that burned across a boundary into *j*, the calculations can be expressed as:

$$\mathrm{TF}_{ij} = \mathrm{AB}_j / \mathrm{N}_i \qquad (1)$$

The sum of TF_{ij} for designation *i* (ignition source) over *j* parcels yields the total amount of transmitted fire to other parcels (TF-OUT). The sum of area burned across all ignition sources *i* for a particular designation *j* estimates the total incoming fire per ignition outside the designation (TF-IN). TF_{ij} measures the average area burned in an adjacent parcel *j* given an ignition in *i*. The area of fire per ignition where $i=j$ is nontransmitted, or self-burning (NonTF).

Risk Transmission

Cross-boundary fire can be viewed as transmission of risk when the recipient of a fire event from another parcel incurs loss or benefits. The science of risk transmission has many important applications, such as calculating the spread of disease in humans, plants, and animal populations (Sander et al. 2002). As with disease transmission, many elements or circumstances influence or affect the causal factors and the eventual outcome. Wildfire risk transmission is dependent on spatial heterogeneity in landowner-specific vegetation management, wind direction, responsibility for fire suppression, parcel size, management practices, and ignition probability.

We defined risk transmission as occurring when the conditions in one parcel result in an amplified expected loss (SRA 2006) in the other. For instance, consider two adjacent land parcels, A and B, of similar size, shape, and conditions with respect to fire spread rate, intensity, ignition probability, suppression capacity, and potential loss (ecological, financial, or other). When wind direction is random, the net expected transmission of risk between the two parcels will be equal. A change in these factors creates the potential for risk transmission among the parcels. Some of these factors are natural (e.g., wind direction), ecological (e.g., fire regime), or anthropogenic (e.g., fuel management, urban development, or parcel geometry). Transmitted risk can be quantitatively defined and measured with the following formula, modified from Finney (2005), where we include both the source parcel (ignition) and the affected parcel where losses occur:

$$E(L) = \sum_{j/\in A} \sum_{i=1}^{n} \mathrm{RF}_{ij}\left(P_{ij}\right) \qquad (2)$$

where: E(L) is the expected loss (risk), RF_{ij} is the loss from fire intensity class *i* in pixel *j*, *A* is the set of all pixels of a given land parcel, P_{ij} is the probability of a fire of intensity *i* from an ignition in pixel *j* located outside *A*. Local risk (i.e., fires ignited within the parcel) versus transmitted risk can be calculated by substituting $j \in A$ into the first term. Removing the response term RF_{ij} leads to a measure of wildfire exposure. The key difference between risk and exposure is that the former requires intensity information for each pixel, while the latter does not.

Existing simulation methods in models such as FlamMap, Randig, and FSim store perimeter footprints and ignition locations for each fire, but pixel-specific intensity values are not retained for both computational and storage space reasons. Processing fire intensity outputs for more than 100,000 fire perimeters would overwhelm the typical geo-processing capabilities of desktop computers. It is possible to obtain estimates of intensity by modeling static fire conditions (wind speed, wind direction) for every pixel in a landscape (Finney 2006). The marginal benefits of this, over quantifying exposure from fire, as in the current study, would be small in our opinion. This approach would only be warranted when robust response functions can be developed for particularly high value infrastructure or natural resources.

Fireshed Mapping

The first mention of "firesheds" was in the Pacific Southwest Region in the early 2000s (Bahro et al. 2007). It was introduced as a concept to advance an integrated interdisciplinary approach to evaluating fuel treatment effectiveness at reducing fire spread across landscapes (GAO 2004). The evaluation process recognized the scale of the fire problem and was most useful on landscapes where forest land and resource management plans resulted in fragmented management opportunity and fire management goals. Thus collaborative and integrated solutions were developed for fuel management programs that respected parcel level (i.e., forest plan allocation) management goals and restrictions while recognizing that all parcels were potentially exposed to the same fire event. The fireshed concept was forgotten by the fire community for almost two decades and eventually resurfaced as spatial fire planning.

Many years later, the fireshed concept was redefined as a process for identifying the scale of risk, or risk container, around communities or other values. It proved particularly useful in developing Community Wildfire Protection Plans because the Healthy Forest Restoration Act only specified arbitrary buffers around communities (1-½ miles) (HFRA 2003), whereas fire simulation outputs provided a way to estimate the actual risk container (fireshed) around communities. The latter proved to be substantially larger (10–50 times) than the planning boundaries based on the fixed buffer (Ager et al. 2016), except in the few cases where entire counties were used as the boundary.

Methods for mapping firesheds using wildfire simulation outputs have become widely used, but lack consistent methodology (table 1). Recent attempts (Ager et al. in press; Ager et al. 2016; Ager et al. 2018; Evers et al. 2019; Palaiologou et al. 2019; Scott et al. 2015) have used a variety of approaches. Scott et al. (2015), for example, describe a convex hull that circumscribes all ignition points. Concave hulls are similar to convex hull firesheds, but allow more flexibility in defining the fireshed perimeter (see Park and Oh 2012). Both approaches tend to create large firesheds that are defined by the most distant ignition point. While these distant ignitions are notable for the size of the

Table 1—Geospatial techniques available for describing firesheds.

Technique	Description
Convex hull	Envelope drawn around all ignition points
Concave hull	Similar to convex hulls, but able to capture more nuanced firesheds due to concave indents in the hull
IDW	Inverse distance weighting (IDW) is a simple deterministic interpolation technique based on surrounding points that assumes that each measured point has a local influence that diminishes with distance
Kriging	Kriging is an advanced geostatistical interpolation technique based on a fitted spatial model (variogram) that allows for more flexibility compared to IDW
KDE	Kernel density estimation (KDE) is a point process analysis that calculates the density of point features around each output cell using a Gaussian bandwidth

resulting fire, they also tend to be extremely rare, which means that hull-based firesheds tend to be defined by outlier events.

Another set of geospatial techniques relies on interpolation that results in firesheds as surfaces. These techniques include inverse-distance weighting, spatial kriging, and kernel density estimates. Kriging functions are similar to a logistic regression model, and therefore require both ignition points that reached community areas and ignition points that did not. Kernel-density estimation applies a Gaussian bandwidth to interpolate point density estimates across an entire region.

Firesheds can be mapped for any feature of interest to define the scale of risk and examine fuel and forest management opportunities. Most fireshed applications to date are focused on communities and the surrounding wildland-urban interface (WUI), but other examples include sensitive habitat (Ager et al. 2007) and historical monuments (Palaiologou et al. 2018). If interpolation techniques are used to create the fireshed, individual ignition points can be weighted by the degree of exposure. For example, some community firesheds are highly skewed in a single geographic direction due to a combination of fuels, topography, and development patterns. Weighting can reveal these asymmetries. For firesheds in the shape of a hull, the fireshed represents the space within which ignitions can reach communities.

Integrated Prioritization

Once defined, firesheds can be characterized with respect to forest conditions, fuels, ownership, fire regimes, fire hazard, and many other variables to shape management strategies and priorities (Evers et al. 2019). For instance, the landowner composition of the fireshed represents the relative contribution of exposure to communities by different owners and creates a clear picture of who owns the risk. Some communities will receive the majority of their exposure from surrounding national forests, while in other communities, exposure may be spread across a dozen different land tenure classes. Information on fire hazard (e.g., fire regime and forest conditions) within the fireshed can be used to prioritize forest management activities. Areas available for treatment as determined from forest land and resource management plans can be examined to understand what role fuel management can play. Firesheds can also be decomposed into individual exposure vectors that connect potential ignition points to specific community parcels. These vectors connect source conditions with those where exposure occurs. In similar fashion, the fireshed can be decomposed into individual exposure pathways, which allows for analysis of conditions along the entire exposure continuum.

All of this information contributes to integrated prioritization schemes that measure conditions in both the fireshed and community. A multitude of variables, both social and biophysical, can be combined to rank communities and evaluate the type and amount of exposure. These variables can combine community characteristics such as fuels, fire intensity, and the properties of the fireshed (Evers et al. 2019). Exposure conditions are further examined both in terms of how the variables co-vary, but also in terms of the primary dimensions of risk management. For instance, Evers et al. (2019) reported three biophysical dimensions and five management dimensions of community exposure in the western U.S. At the community scale, they found that WUI class varied independently of dominant canopy and fuels.

Statistical clustering is one method used to sort the different types of firesheds or archetypes. Using a combination of eighteen variables, Evers et al. (2019) identified five community exposure archetypes (table 2). Each archetype was used to classify communities, both to prioritize them and consider treatment options within the fireshed. In this process a workflow was used to identify meaningful clusters that differentiated types of community exposure. These variables are scaled and decomposed into individual components using factor analysis or principal component analysis. Biplots can be used to examine correlation among individual exposure variables in addition to identifying how exposure variables for individual communities vary in relation to these components. Once values are scaled and compressed, a variety of different clustering approaches can be applied to identify distinct groups of communities.

A key problem in the practical application of firesheds is determining the number of archetypes supported by the data. Dendrograms can help reveal where large branches in the data begin to splinter into individual leaves. Another technique is to examine the amount of variation within each cluster, since ideally, clusters will minimize within-cluster variance while maximizing between-cluster variance. A complete discussion about determining the correct cluster number is beyond the scope of this report (see Evers et al. 2019).

Table 2—Variables used to distinguish nature of wildfire exposure among threatened communities in the western U.S. Variables reflect conditions found within the national forest source area (NF), exposed areas of the community (C), or both (NF/C). Table from Evers et al. (2019).

Variable	Zone	Description
Canopy cover (%)	NF/C	Canopy cover can limit spread but also lead to crowning and spotting. Source: LANDFIRE
Flame length (m)	NF/C	Conditional flame length describes the intensity of the fire and can limit suppression. Source: FSIM
Forested fuel types (%)	NF/C	Fuel models 161–189 contain timber-understory and timber-litter fuels. Source: LANDFIRE
Shrub fuel types (%)	NF/C	Fuel models 141–149 contain woody shrubs and foliage with limited herbaceous fuels. Source: LANDFIRE
Grass/shrub fuel types (%)	NF/C	Fuel models 101–129 contain mixture of grasses and shrubs, including chaparral fuels in SE California. Source: LANDFIRE
Nonburnable fuel types (%)	NF/C	Fuel models <100 include urban/developed, agricultural, and bare lands. Source: LANDFIRE
Slope (%)	NF/C	Slope amplifies fire spread, influences local winds, and limits access. Source: LANDFIRE
Manageable (%)	NF	Portion of forest that is manageable, i.e., not a protected status where mechanical thinning might be limited or prohibited. Source: PAD
Vegetation departure (%)	NF	Percent difference in successional class from historical reference conditions. Suppression in fire-adapted forest increases departure. Source: LANDFIRE
Low-severity fire (%)	NF	Fire regime group 1. Fire occurred at <35-year fire return interval, low and mixed severity. Vegetation often fire adapted. Source: LANDFIRE
Mixed-severity fire (%)	NF	Fire regime group 3. Fire historically occurred at 35–200 year fire return interval, resulted in low and mixed severity. Vegetation often fire adapted. Source: LANDFIRE
High-severity fire (%)	NF	Fire regime group 4. Fire historically occurred at 35–200 year fire return interval, replacement severity. Source: LANDFIRE
Infrequent fire (%)	NF	Fire regime group 5. Fire historically occurred at >200-year fire return interval, any severity. Source: LANDFIRE
Agricultural lands (%)	C	Percent of WUI classified as agriculture or pasture. Agricultural lands are much less likely to carry fire due to intensive management. Source: NLCD
Intermixed WUI (%)	C	Development (density > 1 hu/6.17 km^2) that intersects with wildland vegetation (> 50% cover). Source: SILVIS
Interface WUI (%)	C	Development where wildland vegetation cover <50% but located <2.4 km from heavily vegetated area (> 75% wildland vegetation, >5km^2). Source: SILVIS
Non-WUI (%)	C	Development not classified as either interface or intermix due to lack of structure density, lack of wildland vegetation, or lack of proximity to wildland vegetation. Source: SILVIS
Percent high, medium, or low density (%)	C	Percent of community exposure from areas with structure density > 741 hu/km^2, density > 49.5 hu/km^2 and 6.17 hu/km^2 respectively. Source: SILVIS

Case Study

Assessment Overview

We demonstrate the assessment process described above with a case study in the western U.S. The case study synthesizes and condenses several earlier papers; additional details can be found in these reports (Ager et al. in press; Evers et al. 2019; Palaiologou et al. in press). In the following sections we report: (1) estimates of cross-boundary wildfire among major land types (Federal, State, private), (2) structure exposure from wildfire to communities, (3) community fireshed maps, (4) fireshed characteristics in terms of management opportunity and fuels, and (5) an example of ranking communities based on integration of exposure and fireshed characteristics.

Methods

Study Area

The primary study area included all lands in the 11 western U.S states (fig. 2) and the adjacent wildland urban interface as mapped by the SILVIS project (Radeloff et al. 2005). The secondary study area is comprised of the western national forests, covering 56 million ha. The Dakota Prairie Grasslands and the Black Hills and Nebraska National Forests were excluded from the secondary study area. About 36 million ha of national forests (64 percent) are fire-adapted (fire regimes 1 and 3) (LANDFIRE 2009), 27 million ha are managed (48 percent), and 30.5 million ha are classified as forested fuel (Timber-litter, Timber understory and Slash-blowdown; 56 percent) based on 2014 LANDFIRE data (Rollins 2009).

Land Tenures

Land tenures were derived from the Protected Areas Database of the United States (PADUS) (USGS 2016). We considered protected areas as lands coded with PAD designations 1 and 2. In addition, roadless areas (2001 rule; 36 CFR Part 294) (USDA Forest Service 2017a) and wilderness, wild and scenic rivers, and other designated or protected areas were excluded from manageable lands (USDA Forest Service 2017b). Although management activities can take place in specific roadless areas, we excluded them from consideration based on the fact that few are actually managed. The listing of land tenures is included in table 3.

Mapping WUI and Communities

To delineate discrete communities, we attached SILVIS WUI with the U.S. Census Bureau populated places (U.S. Census Bureau 2016) using a travel time estimated with the Cost Allocation ArcGIS tool. We used a maximum distance equal to 45 minutes driving time (Ager et al. 2018). Using this approach, we organized 98.3 percent of WUI polygons into 5,118 communities, representing 65 million people and 25 million structures. We removed SILVIS WUI polygons that were smaller than 0.1 ha or had a structure density less than two structures per km^2. The SILVIS WUI defines WUI as the area where houses meet or intermingle with undeveloped wildland vegetation, classified according to four density categories, structure density (one structure per 16 ha minimum), and distance to wildland vegetation, with further classifications into intermix

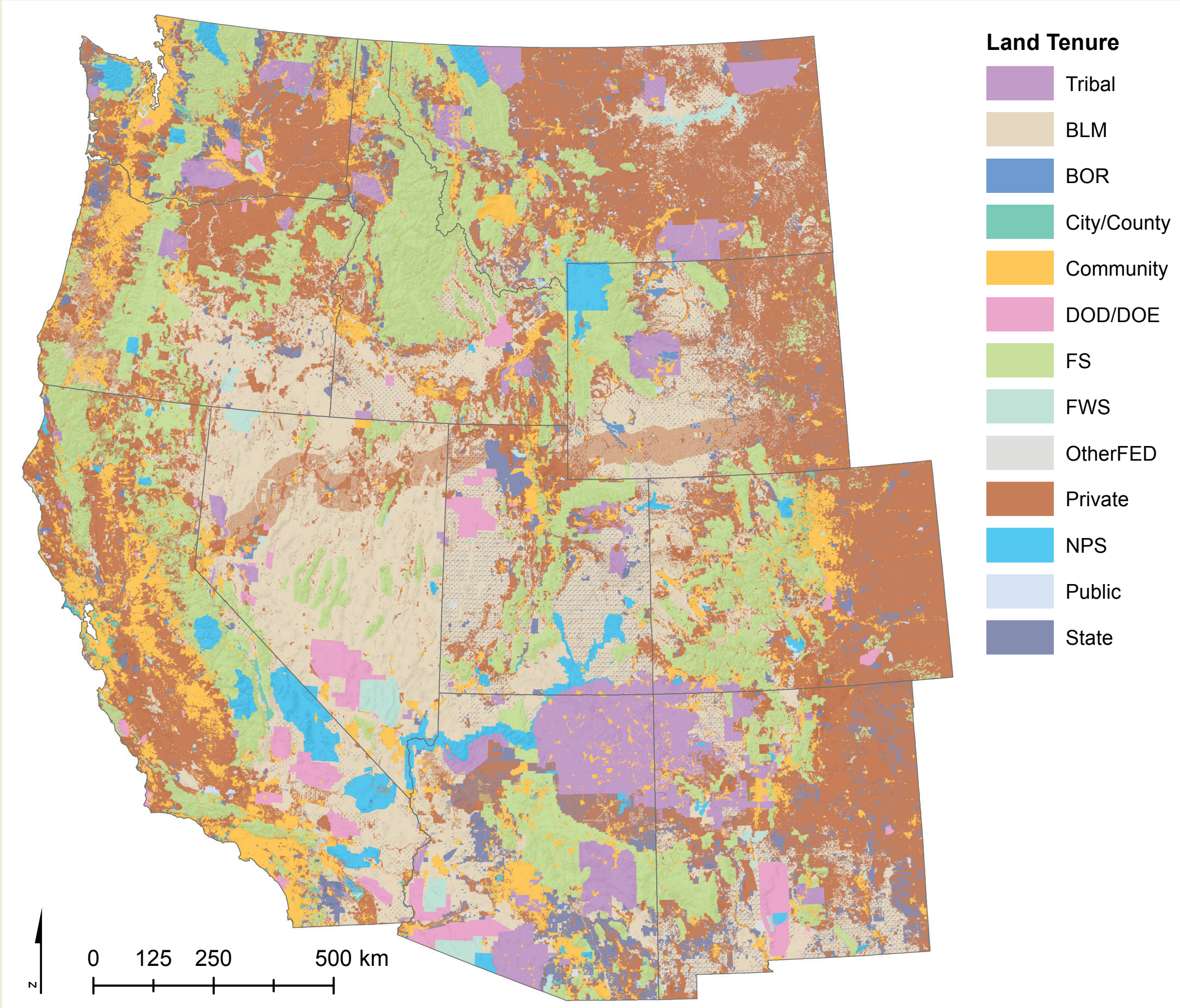


Figure 2—*Map of the major land tenures included in the assessment. The majority of the land is privately owned, and found in the States along the eastern edge of the 11 State area, followed by BLM, Forest Service, and Community lands. See table 3 for land tenure descriptions.*

(housing and vegetation intermingle) and interface (housing in the vicinity of contiguous vegetation) (Radeloff et al. 2005).

Fire Simulation

Wildfire simulation data from FSim (Finney et al. 2011) were used to predict wildfire exposure within and among the national forests and adjacent land tenures. FSim generates daily wildfire scenarios for a large number of wildfire seasons based on observed relationships between historical Energy Release Component (ERC) (Bradshaw et al. 1983) and large 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. Fires can burn over several days if ERC remains high. Weather data were derived from the network of remote automated weather stations located throughout the US (Zachariassen et al. 2003). FSim outputs include the ignition location of each fire, fire perimeters, and grids of burn probability and conditional probabilities by flame length category. The data used consisted of 262,368 ignitions simulated

Table 3—Land tenures used in the assessment of cross-boundary wildfire transmission in the western U.S.

Land tenure	Code	Comment
Bureau of Land Management	BLM	Extensive land tenure in the west composed of a variety of shrub and forest systems. Often checker-boarded.
Bureau of Reclamation	BOR	Lands typically adjacent to reservoirs or large water bodies.
City and County	City/County	Municipal and county lands.
Community	Community	U.S. Census populated places and wildland urban interface within 45-minute drive time
U.S. Department of Defense	DOD	Large land-holdings uses for training and weapons testing. Often includes large undeveloped landscapes.
U.S. Department of Energy	DOE	Land operated for energy production and transmission.
U.S. Forest Service	FS	The national forest systems tend towards forested systems at higher elevation, but also includes extensive grasslands. Multiple demands lead to gridwork of managed and protected areas
U.S. Fish and Wildfire Service	FWS	Land primary managed for habitat values. Often located in or near riparian or wetlands.
National Park Service	NPS	Recreation and conservation locations that often operate under strict management constraints.
Other federal	OtherFED	Other federal land not described above.
Private	Private	Private lands include large holdings such as industrial forestry and large-acreage grazing operations in addition to smaller family forests, rural residential lots, and denser urban development.
Public	Public	Nongovernmental organizations and public trusts
State	State	The extent of State lands varies drastically by State. In many States, State land occurs adjacent to national forests and forms a buffer between federal and private lands.
Tribal	Tribal	Tribal lands can exhibit drastically different fire regimes and vegetation patterns than neighboring lands.

inside USFS administered lands, representing between 20,000 and 50,000 fire season replicates depending on the region (Finney et al. 2011).

Modeling Human Versus Natural Ignitions

Simulated fires were partitioned post hoc into human or natural caused ignitions using historic wildfire occurrence data for the 11 western U.S. States for the 1992-2013 period (Short 2015). The cause of ignition (natural vs human) was modelled by fire size (acres), longitude and latitude (decimal degrees), Geographic Area Coordination Centers (GACC), and day of ignition as a General Additive Model (GAM) with a logit link function and a binomial error distribution:

$$\text{resp} \sim \text{te}(\text{lon},\text{lat}) + \text{te}(\text{jday},\text{bs} = \text{“cc”},\text{by} = \text{gac}) + \text{te}(\text{lsize},\text{k} = 4) \quad (3)$$

where:

- resp is the probability of lightning ignition (i.e., 1 minus resp is the probability of a human-caused ignition),
- lon is longitude, lat is latitude, jday is the day-of-year of fire ignition,
- gac is the GACC,
- bs = “cc” specifies a cyclic cubic regression spline, lsize is the fire size,
- the ‘te’ function is a full tensor product smooth, and
- k = 4 is the dimension of the basis used to represent the smooth term.

The simulated ignition dataset was then partitioned into either natural or human-caused ignitions using the rbinom function in the Binomial stats package in R (Kachitvichyanukul and Schmeiser 1988).

Cross-Boundary Fire Transmission Among Ownerships

Cross-boundary wildfire was quantified by intersecting wildfire perimeters with major land tenures and communities of the western U.S. Polygons were dissolved by the major land tenure to avoid a false fragmentation within the same agency/landowner, while all polygons and slivers < 1 ha were merged with their largest neighbor. Second, all fire perimeters were partitioned into non-transmitting areas (i.e., burned areas within the same land tenure as the ignition). The origin of each wildfire was assigned based on the point of ignition. Third, total burn area within each land tenure was aggregated by incoming fire (TFin, the sum of all fire ignited on another land tenure and entering each particular polygon) or outgoing fire (TFout, the sum of all fire ignited in a land tenure or community that escapes its boundaries) (fig. 1).

Community Exposure

We intersected simulated fire perimeters with the community layer to estimate the annual number of structures exposed to wildfire. Structure exposure estimates were calculated as the product of the proportion of each community polygon burned and the number of structures within a polygon. We also estimated the normalized structure exposure for the entire community, which is the number of structures affected per year, per hectare of the exposed polygon. We assumed that structures reported in U.S. census data for each WUI polygon are spatially distributed equally, and the percentage of burned area from each simulated fire within each polygon was translated into the annualized number of structures affected. For each ignition, we summed all the predicted structures affected based on the intersection of the associated fire perimeter with the different WUI polygons (for more details see Evers et al. 2019).

Fireshed Mapping

We mapped community firesheds by creating a continuous smoothed surface of predicted structure exposure from all FSim ignitions that resulted in fires that intersected SILVIS community polygons. In this instance, we used Empirical Bayesian Kriging (EBK) geostatistical interpolation, implemented through the ArcGIS geostatistical analyst module (ESRI 2018). Kriging accounts for the error introduced by estimating the underlying semi-variogram, with accurate predictions of nonstationary data (i.e. wildfire ignitions). EBK was based on the estimation of a series of semi-variograms for overlapping subsets of specified size (100 points) that capture observed spatial dependence between points (Berman et al. 2015; Pilz and Spöck 2008; Zimmerman et al. 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 intersect each parcel, and standardized values so that total exposure of all fireshed parcel equaled the total simulated exposure of all ignitions in NFs (3,945 structures yr^{-1}).

Fireshed Characterization

We used spatial data on fuels (LANDFIRE 2016) and manageability (USGS 2016) to characterize conditions in the fireshed. Fireshed composition was summarized at the State level and by national forest. The purpose was to determine the composition of fuels and suitability for fuel management. Each community fireshed was characterized in terms of fire hazard and fuel model composition using wildfire simulation modeling output layers and 2014 LANDFIRE data. 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 fireshed with high fire hazard (henceforth termed fire hazard).

Integrated Prioritization

We experimented with several approaches for identifying high priority communities in terms of fuel treatment investments in the fireshed and community investments in terms of Firewise and other preparation and planning processes. There are many methods that work for this process based on multi-criteria plots that integrated both exposure in the WUI and characteristics of the fireshed. The concept of archetypes can also be used to organize variability in exposure and capacity to respond In our example case study, we present several approaches for plotting exposure data to obtain integrated measures that can be used for ranking and prioritizing communities.

Assessment Results

Cross-Boundary Fire Among Ownerships

The amount of incoming versus outgoing fire averaged for all major land tenures was nearly equal (fig. 3). However, ownerships varied substantially by amount of self-burning and by the relative amounts in human versus natural ignitions. Forest Service, National Park Service (NPS), and tribal lands had the lowest amount of fire exchange as a proportion of total transmission. State lands had substantially higher rates of fire exchange with surrounding lands.

Examining the relative amount of incoming versus self-burning shows locations where the majority of area burned is from fires that originate on other land ownerships (fig. 4a). Variability among States shows that Nevada had the highest rate of self-burning. The areas of highest incoming area burned were in central Arizona and western New Mexico, southern California, and south-central Wyoming (fig. 4a). Areas of the western U.S. with large homogenous polygons with one owner, such as the tribal lands in northern Arizona, national forest lands in central Idaho, BLM lands in southern Nevada, and private lands in eastern Colorado, had low (<20 percent) and homogenous areas of incoming area burned. When summarized by State (fig. 4b), the differences are much less pronounced. Summarized by land tenure (fig. 4c), the percentage of area burned by high values of incoming fire varied among land tenures with the highest values for transmitted fire observed for the Bureau of Reclamation (BOR), city/county, and minor public lands (Public).

Filtering the data to just show where more than 50 percent of the fire is incoming highlights transmission zones (fig. 5). For clarity the map is limited to NFS, BLM, and private lands (fig. 5), and shows that the majority of national forest boundaries receive a high percentage of incoming fire (red), with the exception of some enclaves where land

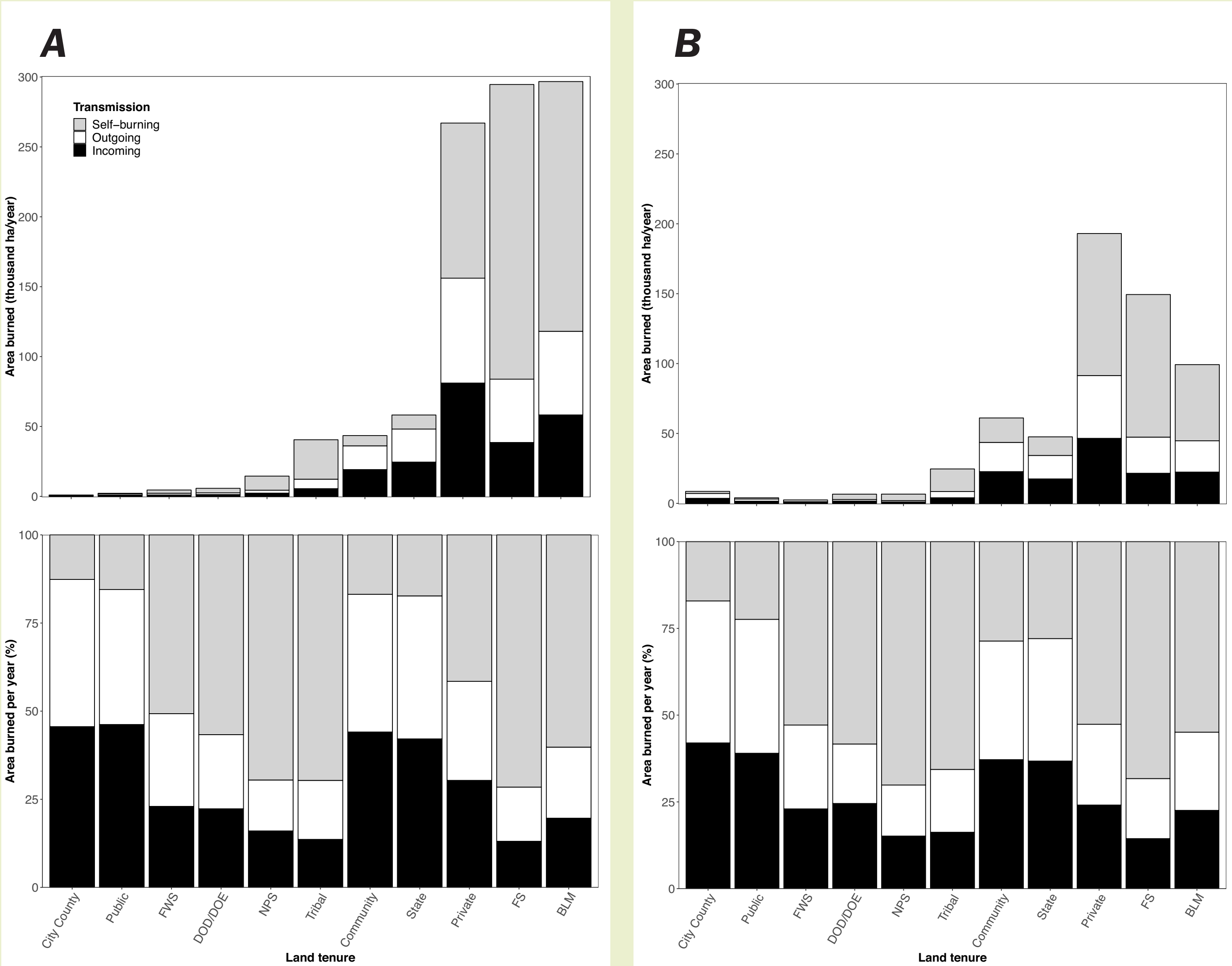


Figure 3—*Wildfire transmission (incoming, outgoing, non-transmitted) among major land tenures of 11 western U.S. States estimated for (a) natural ignitions; and (b) human ignitions. The amount of incoming versus outgoing fire for all land tenures was nearly equal. The amount of self-burning and relative amounts of human versus natural ignitions varied widely by ownership. Figure modified from Palaiologou et al. in press.*

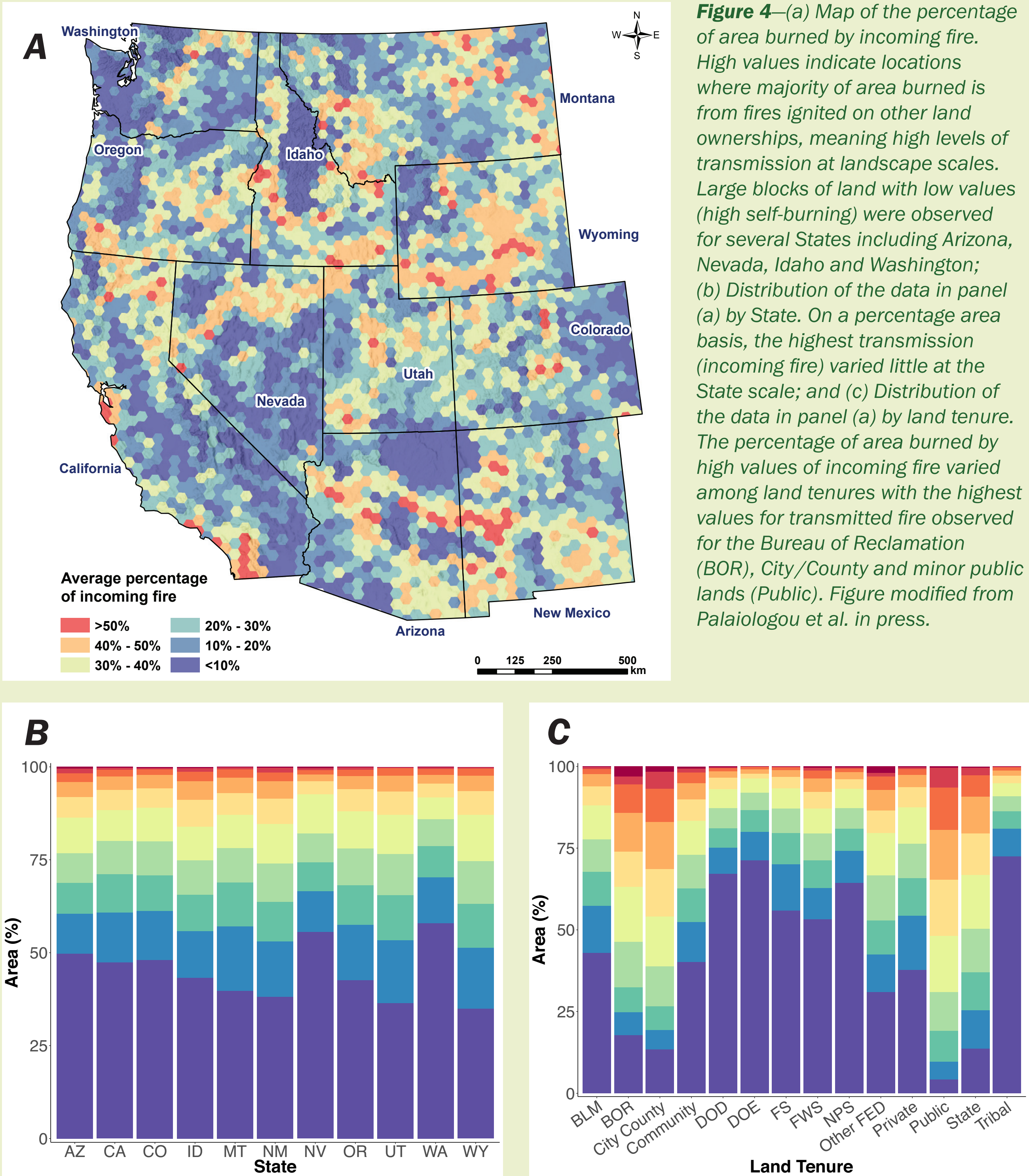


***Figure 4**—(a) Map of the percentage of area burned by incoming fire. High values indicate locations where majority of area burned is from fires ignited on other land ownerships, meaning high levels of transmission at landscape scales. Large blocks of land with low values (high self-burning) were observed for several States including Arizona, Nevada, Idaho and Washington; (b) Distribution of the data in panel (a) by State. On a percentage area basis, the highest transmission (incoming fire) varied little at the State scale; and (c) Distribution of the data in panel (a) by land tenure. The percentage of area burned by high values of incoming fire varied among land tenures with the highest values for transmitted fire observed for the Bureau of Reclamation (BOR), City/County and minor public lands (Public). Figure modified from Palaiologou et al. in press.*

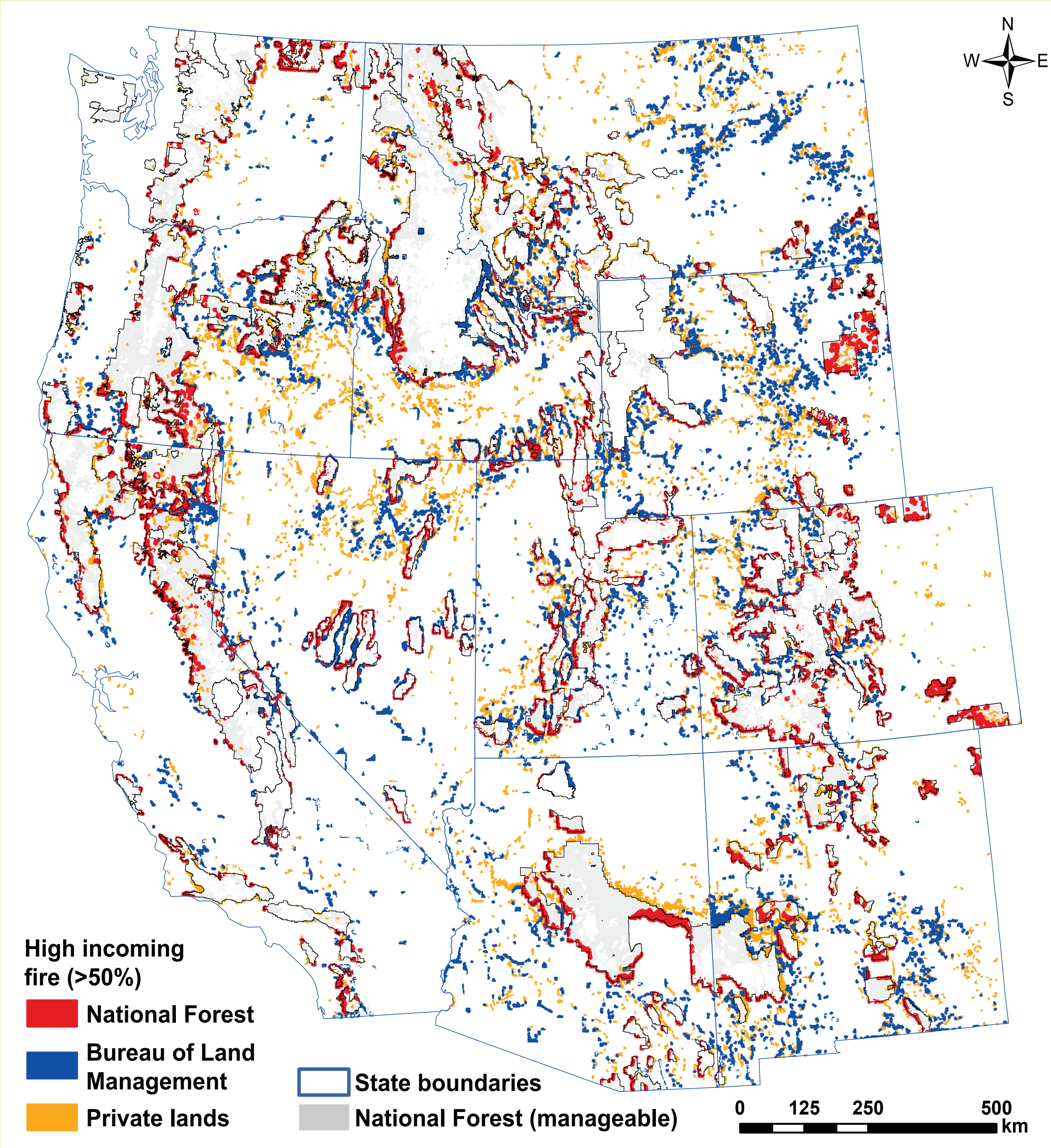


Figure 5—*Locations where incoming fire exceeds 50 percent on the three highest fire transmission land tenures (National Forest System, NFS; BLM, Bureau of Land Management and private). The majority of national forest boundaries received a high percentage of incoming fire. Figure modified from Palaiologou et al. in press.*

tenures are intermixed. Sinks of private and BLM land adjacent to national forest land are also evident, showing clear hot spots for collaborative planning to reduce risk.

Community Exposure

We estimated that a total of 1,812 communities in the western U.S. could be significantly impacted by future wildfires ignited on any land tenures ("significant" is defined as more than 1 structure per year on average) (figs. 6 and 7 show the top 100 communities by source of exposure). Ignitions on national forest lands will likely affect 516 out of the 1,812 communities—more than 1 structure per year on average. We estimated that ignitions on all land tenures will expose 19,400 structures to wildfire per year on average. Note that these estimates do not predict structure loss, but rather exposure to wildfire on a portion or all of the SILVIS parcel where structures are located. The modeling estimates account for structure exposure from wildland fires, not structure to structure fire within communities. Of the total exposure, ignitions on national forest lands will expose an estimated 4,000 structures (21 percent of total)

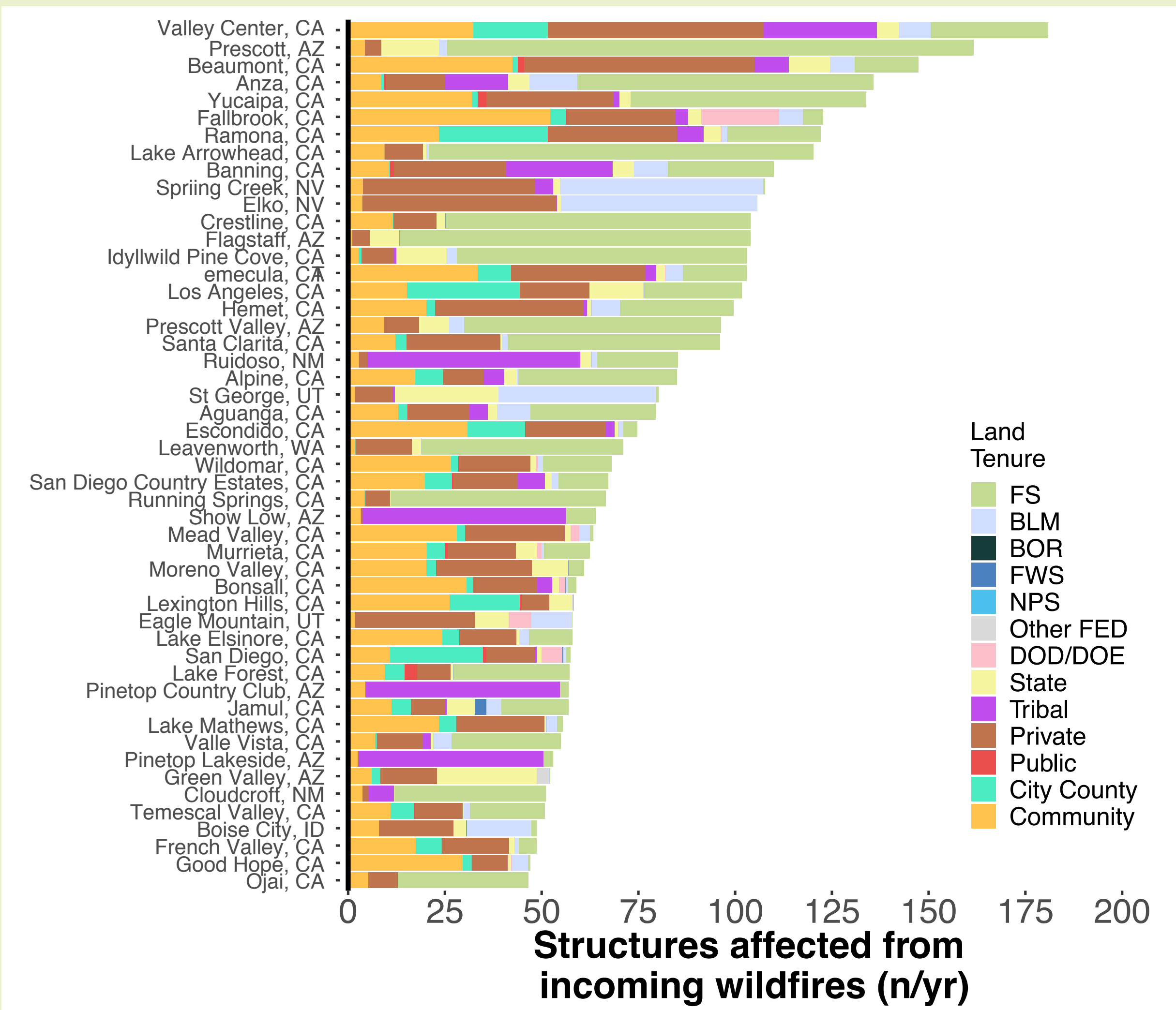


Figure 6—Top 50 communities exposed to wildfire in the western U.S. by ignition source. The different colors indicate the magnitude of exposure to each community from different land ownerships/agencies. In general Forest Service, private, and community lands were the largest ignition sources. Note that the distribution changes substantially among the different communities.

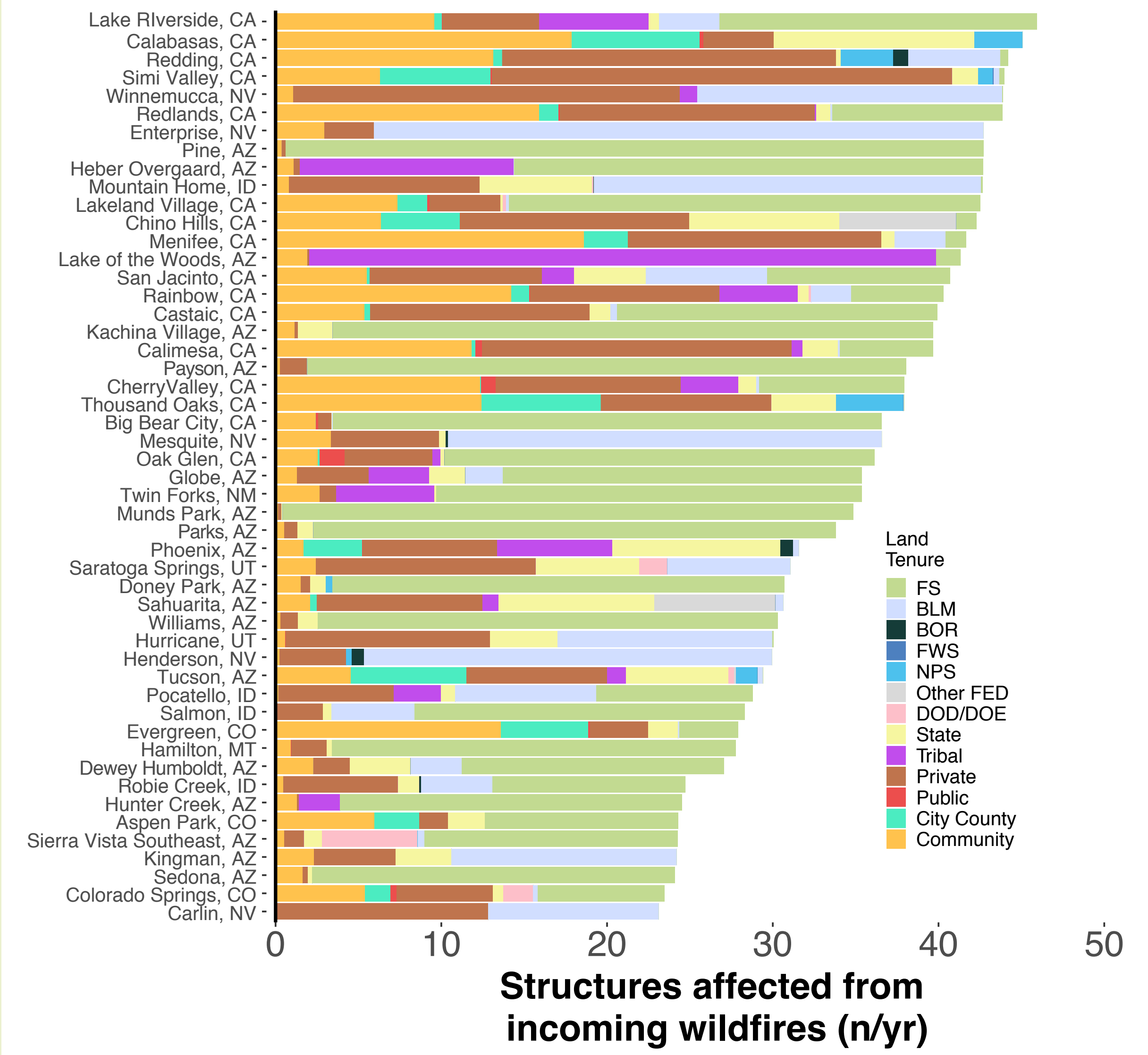


***Figure 7**—The top 51–100 communities exposed to wildfire in the western U.S. by ignition source. The different colors indicate the magnitude of exposure to each community from different land ownerships/agencies. Note x-axis scale differs from figure 6. In general, Forest Service, private, and community lands were the largest ignition sources. Note exceptions to this, for example Henderson, NV and Lake of the Woods, AZ.*

in the western U.S. per year on average. Larger communities experienced higher exposure due to their larger populations. However, when exposure was adjusted by the exposed area of each community (str. yr^{-1} ha^{-1}), emphasizing structure density, a different suite of communities was ranked in the top 50 for exposure (dashed vertical line, fig. 8). Only 15 communities were ranked on both lists, with three communities in the top 10 based on both metrics (Crestline, CA; Lake Arrowhead, CA; Fontana, CA). Thus, there was not a strong relationship in structure exposure between raw and area weighted values (fig. 8). While communities in California still had the highest percentage of adjusted exposure (46.8 percent), communities in Arizona (26.7 percent), Utah (7.9 percent), and New Mexico (6.4 percent) also showed highly exposed structure density.

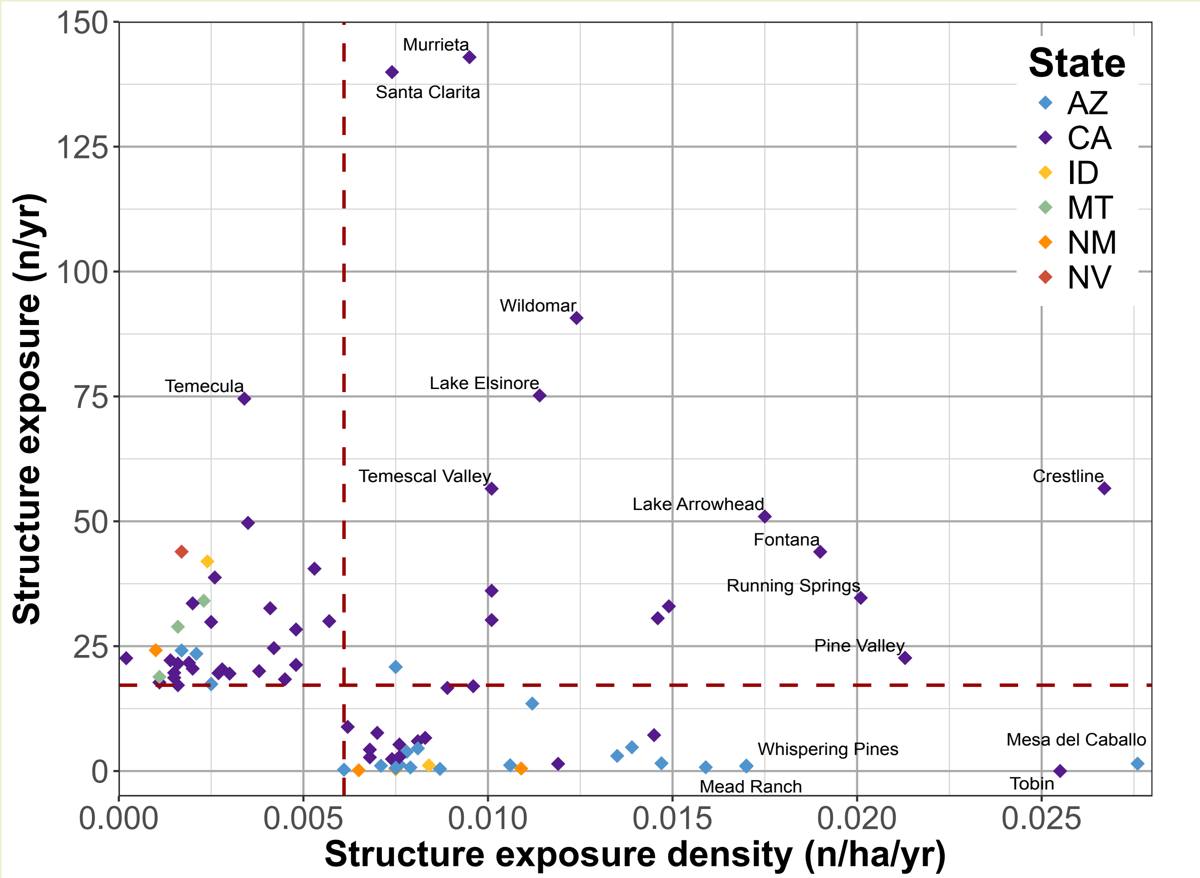
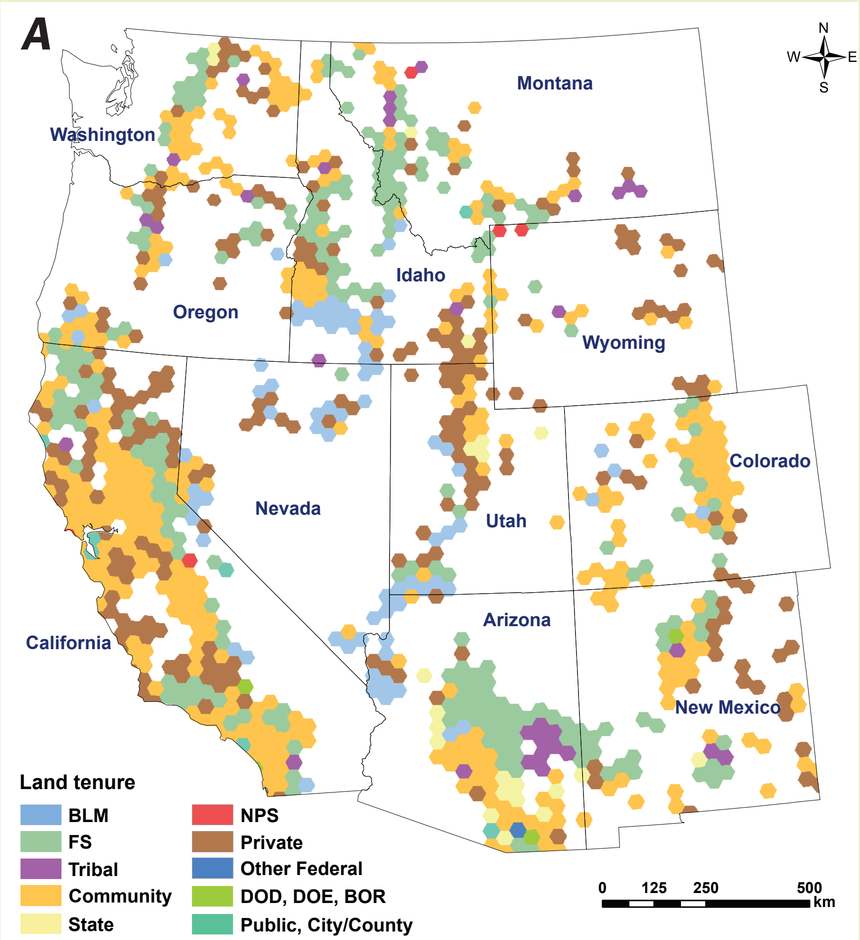


Figure 8—*Structure exposure of the top 50 communities in the western U.S. to wildfires ignited on national forest land by State, based on number of structures exposed and structure density. The top 50 communities for both metrics are indicated by the dashed horizontal and vertical red lines. Structure exposure is measured as the annual predicted structures affected using simulation outputs. Communities in California had the highest percentage of exposure. Figure modified from Ager et al. in press.*

For each land tenure, we estimated the area burned by ignitions and transmitted to communities, and color coded them by the land tenure causing the highest structure exposure (fig. 9a). The southern parts of Idaho and Utah, and northwestern Arizona and northwestern Nevada are mostly affected by fires ignited on BLM lands, while in northern Utah, southwest and northern California, northern Nevada and eastern New Mexico, structure exposure fires are mostly a problem caused by private land ignitions. National forest ignitions are responsible for most of the community exposure in parts of northern and southern California, central Idaho and western Montana, north-central Washington, central Arizona, and southwest New Mexico. State land fires are dominant in southern Arizona and central Utah, while WUI ignitions prevail in coastal California and across the Sierras, north-central Colorado, and northeast and southern Washington. Tribal land fires mostly expose communities to fire in central Arizona, but have a lower influence in Montana, Washington, and central Oregon.

When fire transmission is expressed in terms of annual structure exposure (fig. 9b), we see big differences between California and Arizona and the majority of other States. More than 11,000 and 2,500 structures per year were predicted to be exposed in California (59 percent of total exposed structures) and Arizona (14 percent) respectively.



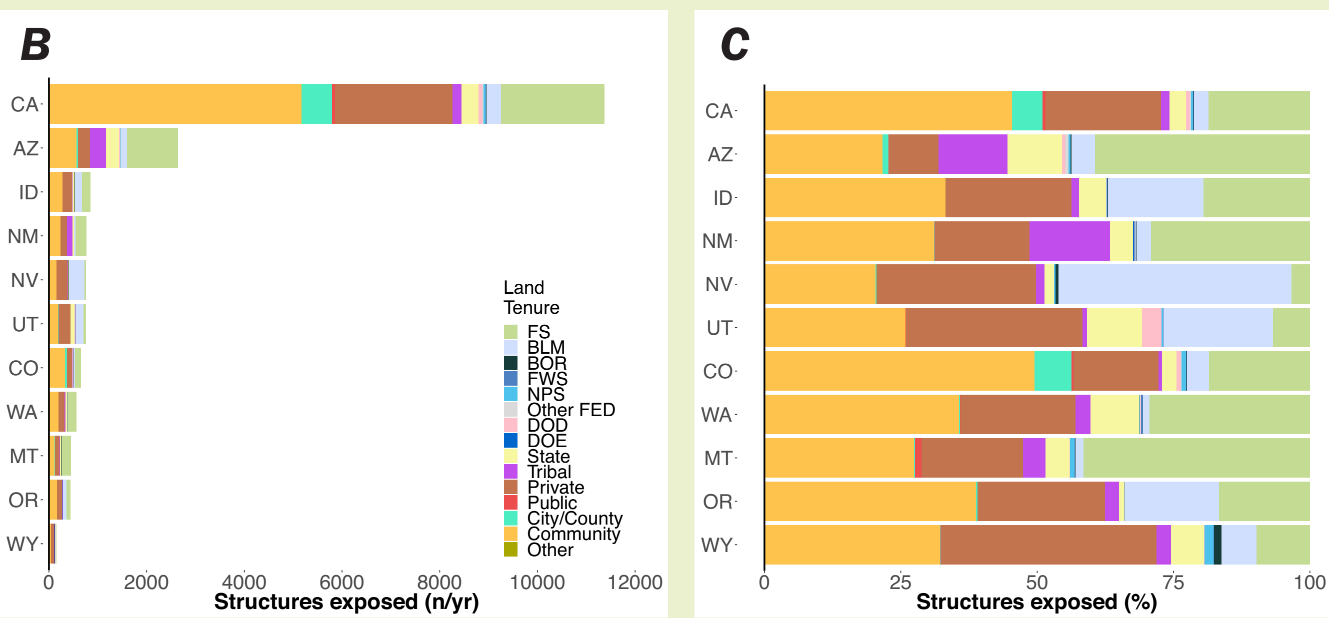


Figure 9—*(a) Land tenures causing the highest structure exposure to communities in the 11 western U.S. States. Data are filtered to show exposure greater than or equal to 1 structure per year as defines the fireshed, (b) total annual structure exposure, and (c) percentage exposure by land tenure where the wildfire was ignited. California and Arizona were the only States with more than 1,000 structures exposed. Half of the predicted structure exposure came from ignitions on private and community lands. Figure modified from Palaiologou et al. in press.*

Although total fire activity in Idaho and California was similar, we observed huge differences in terms of structure exposure. All other States had fewer than 1,000 structures exposed per year, ranging from a low of 150 in Wyoming (1 percent) to a high of 850 in Idaho (4.5 percent). In conjunction with our previous findings, half of the predicted structure exposure is coming from ignitions on private and community lands, followed by national forest (21.5 percent), BLM (6 percent), State (4.5 percent), city/county and tribal lands (3.6 percent each) (fig. 9c).

Fireshed Mapping

We estimate that within the western 11 U.S. States, 86 million acres, or 62 percent of the total national forest area, have the potential to contribute wildfire to communities (fig. 10). When including all landowners, firesheds comprise approximately 173 million acres across the 11 western U.S. States, or 24 percent of all burnable lands

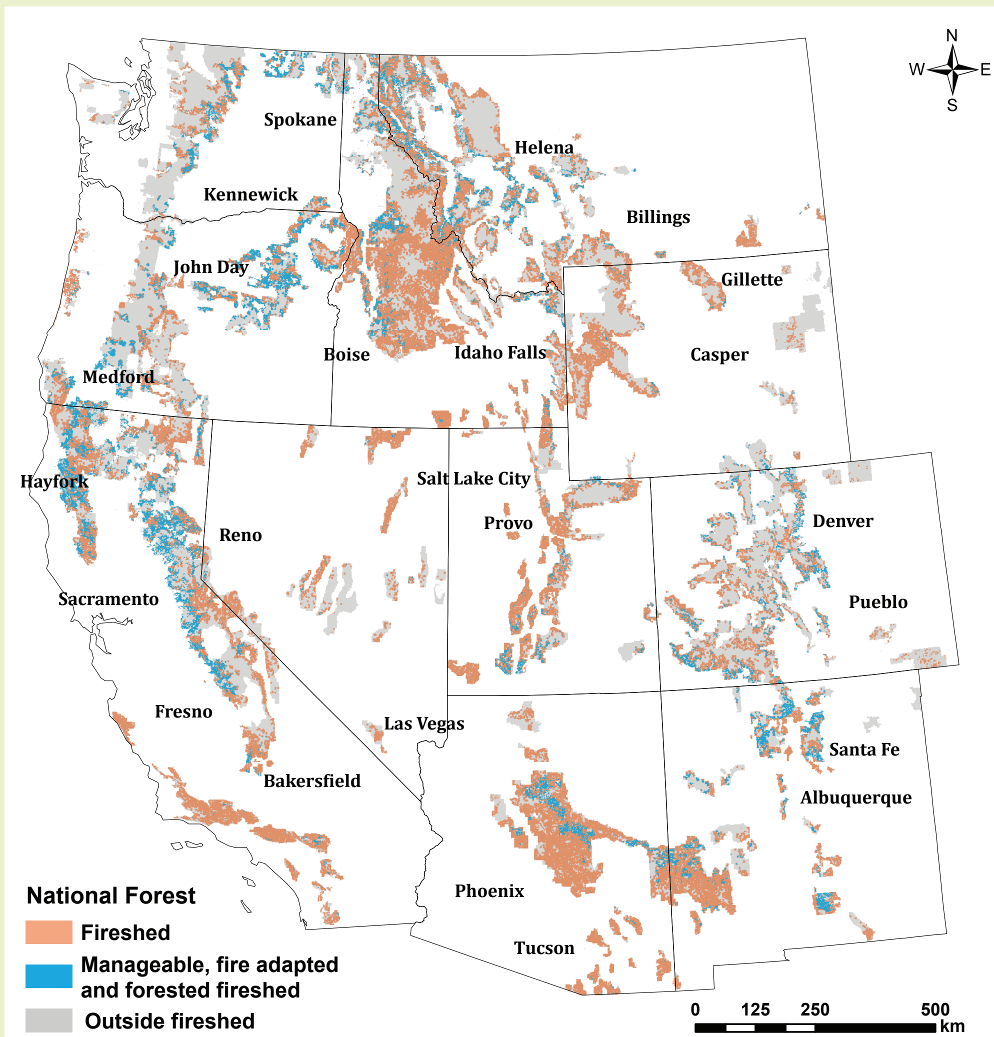


Figure 10—*National forest firesheds in the western U.S. showing where ignitions have the potential to cause structure exposure to nearby communities. Eighty-six million acres (62 percent) of the total national forest area have the potential to contribute wildfire to communities. Areas in blue (19 million acres; 14 percent) are firesheds that are manageable according to the PADUS data and have fire-adapted conifer forests. Figure modified from Ager et al. in press.*

(NLCD 2011). California has the greatest total area contained in firesheds, followed by Arizona, Montana, Colorado, and New Mexico (fig. 11). Firesheds are found in distinct geographic clusters, which in turn form regional wildfire risk hot spots. In total, we identified approximately twenty hot spots. These hot spots define the regional scale at which fire management operates.

Fireshed Characterization

Five land tenures own or manage 92 percent of the area within community firesheds. Half of these lands are under private and community ownership, followed by national forest (25 percent), BLM (10 percent) and State (6 percent) (fig. 11a). The distribution of land tenure throughout the States shows that percentages of ownerships are relatively consistent throughout the western U.S., with the exception of increased tribal ownership in Arizona, Montana, and New Mexico, and a higher proportion of BLM lands in

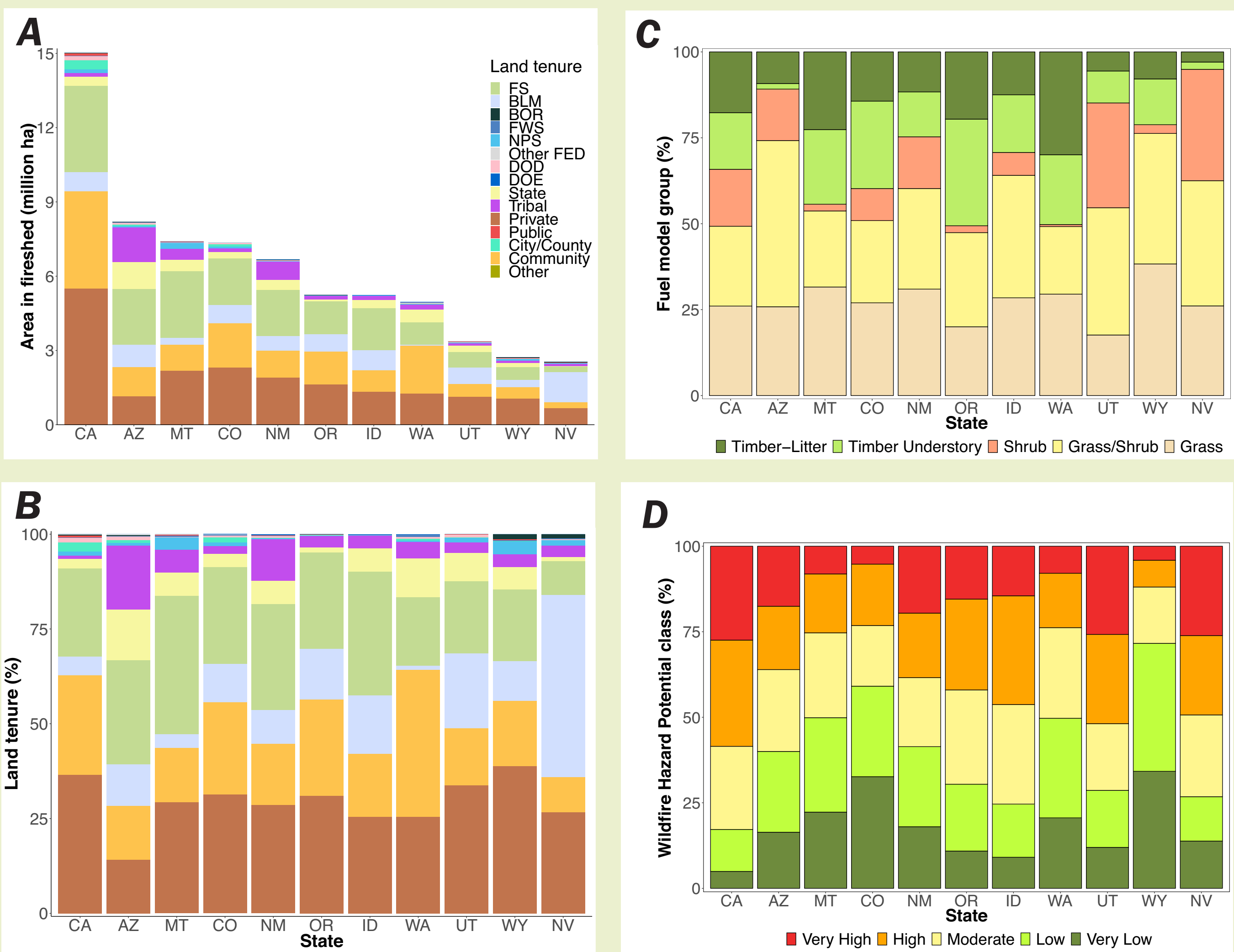


Figure 11*—State level breakdown for (a) land tenure area, (b) percentage area, (c) fuel model composition class percentage, and (d) wildfire hazard potential (Dillon 2015) for firesheds in the western U.S. Five land tenures own or manage 92 percent of the fireshed area; ownership percentages are fairly consistent across States. Grass and grass/shrub fuel models combined composed more than half of all firesheds. Wildfire hazard potential was very low or low on more than 50 percent of Wyoming, Washington, and Colorado firesheds. California, Idaho, Utah, Nevada, and Oregon firesheds had high or very high hazard potential on at least 40 percent of the fireshed area. Figure modified from Palaiologou et al. in press.*

Nevada (fig. 11b). The distribution of surface fuel models within firesheds shows that grass and grass/shrub fuel models combined composed more than half of all firesheds, although there was variation among the States (fig. 11c). Forested fuel models (timber understory and timber-litter) have the lowest share in Nevada (10 percent) and the highest in Oregon and Washington (~50 percent) (fig. 11c). The distribution of wildfire hazard potential is vital to understanding where community firesheds and high hazard converge. Wildfire hazard potential was low or very low on more than 50 percent of Wyoming, Washington, and Colorado firesheds, while California, Idaho, Utah, Nevada, and Oregon firesheds had high or very high hazard potential in at least 40 percent of the fireshed area (fig. 11d).

Contribution of National Forests to Community Wildfire Exposure

Examining structure exposure in terms of where risk on national forest lands can be mitigated, only 7.6 million ha (14 percent of the total NF area) were manageable, fire-adapted, and forested, thus limiting the area on national forest land that can be treated to reduce risk (~700 structures yr^{-1}, 17.5 percent of total exposure) (fig. 12). One-quarter of the total national forest fireshed was predicted to have very low exposure to communities (9 million ha with only 1 percent of total exposure). Approximately 6 percent of the total area burned by fires ignited inside the national forests was transmitted to the community core and/or WUI polygons, with

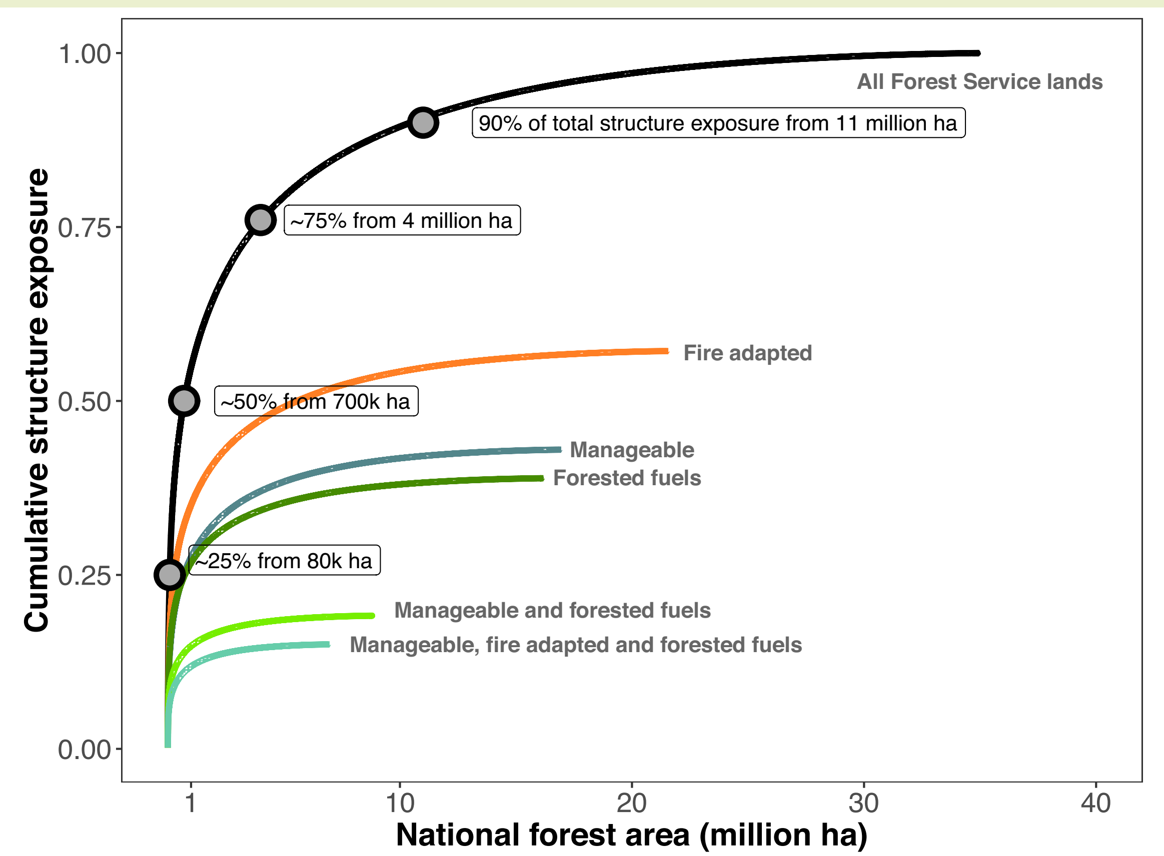


***Figure 12**—Cumulative structure exposure from wildfires ignited on western U.S. national forests as predicted by simulation modeling. The lines represent Forest Service lands by management capacity and fuel models. Only 14 percent of the national forest area is manageable, fire-adapted, and forested land, limiting the area that can be treated to reduce risk. Figure from Ager et al. in press.*

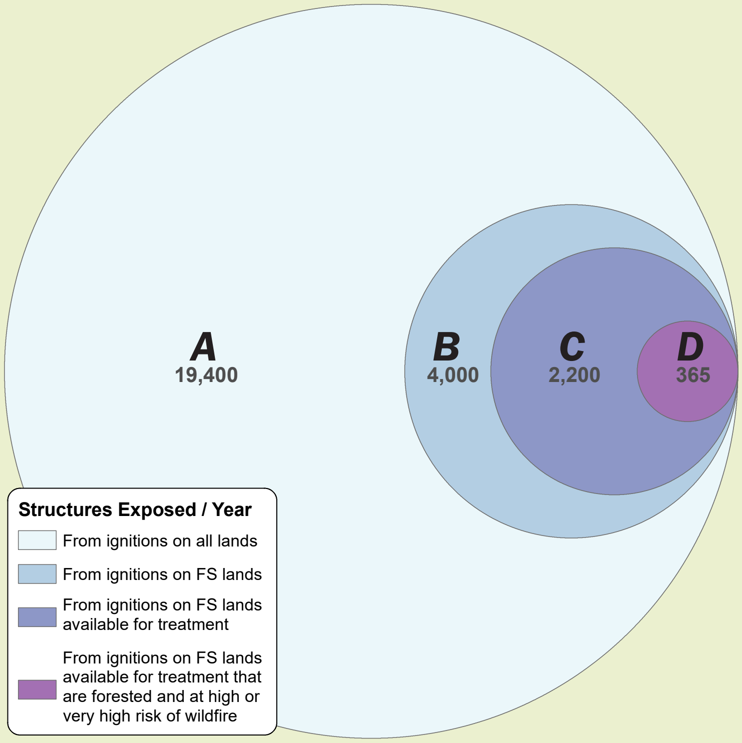


Figure 13*—The number of structures exposed to wildfire by land base. Concentric circles indicate relative exposure by A) all lands, B) national forest land, C) national forest land available for treatment, and D) national forest land available for treatment and forested in areas of high or very high wildfire potential.*

State-level values ranging from about 1 percent (Colorado, Nevada) to 47 percent (California). These numbers are substantially smaller than we have previously reported (Ager, et al. 2014b), but are limited to the area burned from fires ignited within national forests that intersected with community polygons (simulated fires not reaching communities were excluded from the analysis). In terms of structure exposure, of the 19,400 structures yr^{-1} exposed from all lands, 20 percent were exposed from national forest lands only (fig. 13). Due to administrative restrictions on national forest lands, 11 percent of structure exposure originated on NFS lands where mechanical treatments can be conducted, and 2 percent originated on NFS lands available for treatment and in areas of high or very high wildfire potential (fig. 13).

Integrated Prioritization

A heat diagram (fig. 14) shows an example of integrated prioritization of both community and ignition source wildfire hazard for the top 50 communities ranked by structure exposure from wildfires ignited on national forest land and percentage contribution to total structure density (HU). The diagram also shows the percentage of the ignition source area that is manageable, fire-adapted, and located in areas of high wildfire hazard (S-WHP), as well as the percentage of the community area that is located in areas of high wildfire hazard (C-WHP). Communities are ranked from top to bottom; those at the top of the list were the most exposed to wildfire, those at the bottom, the least exposed. The darker brown color indicates communities that also had the highest exposure when weighed by community area. Warmer colors indicate a higher percentage in high hazard areas or with higher percentages of area available for mechanical treatments (Man) and that are fire-adapted (Adapt).

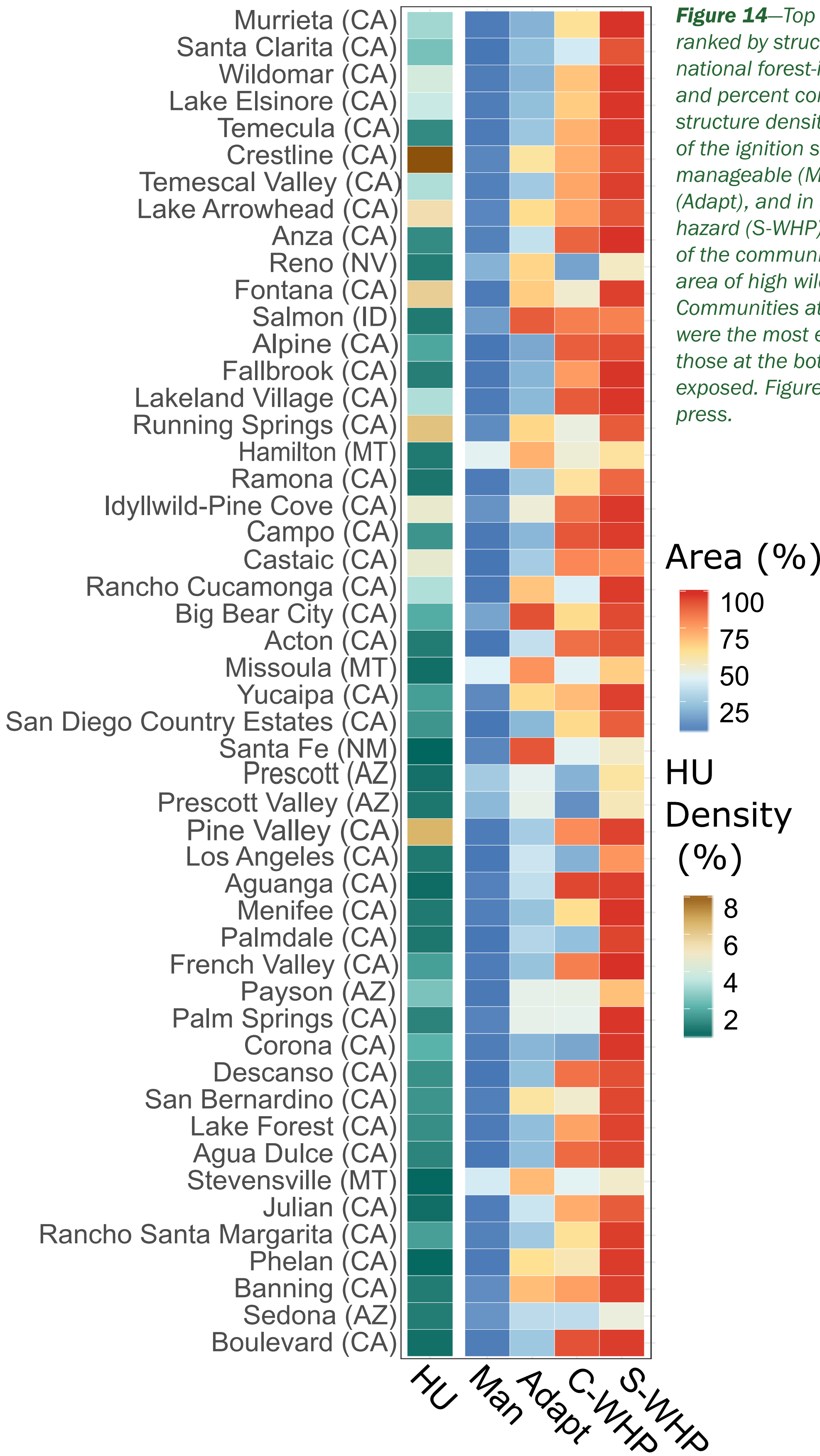


Figure 14—*Top 50 communities ranked by structure exposure from national forest-ignited wildfires and percent contribution to total structure density (HU); percentage of the ignition source area that is manageable (Man), fire-adapted (Adapt), and in areas of high wildfire hazard (S-WHP); and the percentage of the community area that is in area of high wildfire hazard (C-WHP). Communities at the top of the list were the most exposed to wildfire; those at the bottom, the least exposed. Figure from Ager et al. in press.*

Community Archetypes

We selected the top 20 percent of the communities most exposed to wildfire from western U.S. national forest lands and identified five primary exposure archetypes within this group. Each exposure archetype reflects a common set of management opportunities and constraints based on biophysical and social conditions on both sides of the national forest boundary. The five community exposure archetypes are (1) infrequent exposure, (2) open-interface, (3) mixed-interface, (4) forested-intermix, and (5) shrub-interface. While this classification schema is related to common WUI descriptors, such as the SILVIS WUI, it differs in that these archetypes are process-based because they consider the pathway of exposure from ignition to household. Further, because this definition is process-based, this schema describes the proportional mix of WUI-type threats westwide. For instance, the two most common exposure types are open-interface and forested-intermix, which roughly correspond to interface and intermixed WUI. Other exposure categories are less recognized, including the communities where exposure can be extreme, but is highly unlikely, such as the shrub-based interface found along much of the Wasatch region of Utah. This area shares many of the characteristics of southern California chaparral, yet has received much less attention in terms of management and planning.

Discussion

Our multiscale quantitative framework and case study for measuring both cross-boundary wildfire exposure for large landowners and structures within communities, directly addresses the specific initiatives that stimulated the development of cross-boundary assessment methods and the assessment itself. This assessment of communities in the western U.S. that are potentially exposed to wildfires originating on national forest lands has underscored the need for Federal agencies to understand their role in community risk relative to other public and private land organizations and administrative units. As noted in the Introduction of this report, there have been several calls for community assessments and cross-boundary planning to help integrate management among State, private, and Federal land management agencies. Assessment methods will always improve over time with new data and technologies. This assessment provides a wealth of information to guide investments by the Forest Service, communities, and other public land management agencies to enact a wide spectrum of fire management activities aimed at reducing wildfire losses. These activities include management mapping activities, such as identifying areas where unplanned ignitions can be used to manage fuels as part of spatial community fire planning.

The methods and data presented here were synthesized from a number of prior papers by the authors (Ager et al. in press; Evers et al. 2019; Palaiologou et al. 2019). The methods can contribute to improving wildfire mitigation planning by providing a process to explicitly measure the scale of risk and identify individual sources of wildfire risk to parcels and communities. This type of information is key to providing a quantitative foundation for community risk mitigation programs, including the Community Wildfire Protection Plan (CWPP) process (Jakes et al. 2012). As a result, the framework has a potentially important role for prioritizing shared stewardship projects aimed at reducing community risk. Realizing the diversity of conditions that lead to exposure, integrated prioritization provides a decision tree to aid in allocating resources among risk abatement efforts, including suppression, fuel management, reducing vulnerability of dwellings, and ignition prevention programs. For instance, we partition risk within firesheds among the major land ownerships according to management capability, and then identify locations where opportunities exist for reducing wildfire risk. The methods summarized here have been used in several studies outside the U.S. including Greece (Palaiologou et al. 2018), Spain (Alcasena et al. 2017), and Argentina (Argañaraz et al. 2017).

The assessment process used an array of metrics to describe the scale of fire exposure to communities and properties within the firesheds in relation to opportunities for forest and fuel management. Some of the broad metrics we presented are relatively insensitive to the underlying variability in wildfire activities. For example, large areas of fuels with high spread rates and intensity are more fire prone and contribute to the observed spatial patterns. Land ownership patterns and the degree to which landscapes are fragmented contribute significantly to the exchange of fire.

The least robust of the metrics we are reporting, however, are probably those that describe community exposure. There are multiple reasons for this, including the fact that many WUI disasters result from structure to structure ignitions. Further, fuel mapping within urban interface and intermix around communities is prone to error, especially where dryland and irrigated agriculture create fuels that vary substantially within a fire season in terms of loadings and flammability. Thus, the community rankings should be viewed as groups of communities with high, medium, or low overall structure exposure. Another consideration is that larger communities have higher exposure just because they have more people. We did not present statistics showing per area or per capita exposure, which would dramatically change the rankings (Ager et al. in press). Our future work will consider bootstrap estimates of community rankings to better understand inherent variability in fire simulation outputs.

The evaluation of fuel treatment strategies for cross-boundary risk has been largely ignored in several recent reviews (Kalies and Yocom Kent 2016; Vaillant and Reinhardt 2017). The fact that most new initiatives and legislative authorities are attuned to cross-boundaries suggests a change in the scale of management investments needed to counter the dual effects of urban expansion into wildlands and climate change, both of which are increasing the scale of risk. The degree to which risk is in situ versus ex situ has substantial bearing on formulating fire protection and restoration goals in areas fragmented by jurisdictions, ownerships, and fire regimes. For instance, fire-adapted lands near land tenure boundaries where transmission risk is generally high will not be maintained with natural ignitions; thus, mechanical treatments and prescribed fire must be emphasized in these areas. To get the most out of the combined effect of mechanical treatments and restoration wildfires at the landscape scale to meet socioeconomic and ecological goals of federal forest restoration programs will require mapping protection from versus restoration of wildfire, while also considering the juxtaposition of patch size, fire regimes, and socioecological values.

In the western U.S., about 45 percent of the land area is within designated conservation reserves where 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). We found that about 40 percent of national forest land in community firesheds is either not available or not suitable for treatments, even with the coarse filter we used for operability. Management restrictions are particularly prominent in some regions. For instance, 90 percent of the national forest land in the Wasatch region of northern Utah lies in wilderness, roadless, or source-water protection areas. Additional economic and operational constraints on lands that can be managed will further reduce the area of opportunity.

Our cross-boundary assessment methods have multiple applications for WUI protection planning. By classifying WUI both in terms of the surrounding landscape and community structure, we have provided a functional definition of the WUI that is necessary in order to link the biophysical and social processes that together define this space (Moritz et al. 2014; Spies et al. 2014). From the perspective of Federal land management agencies, this functional definition of the WUI provides guidance on where to spend Federal dollars effectively and provides opportunities for drafting agreements with communities and private landowners that better leverage these expenditures.

A framework that better accounts for the scale and geography of WUI wildfire risk would most likely improve federal funding systems that currently allocate assistance to communities based on boundaries (Jakes et al. 2011) that do not include the major sources of risk. Thus, identification of community transmission hot spots could dramatically increase the efficiency of building fire-adapted communities and fire-resilient landscapes (USDA-USDI 2013). Incorporation of social factors would also help and is part of ongoing efforts (Palaiologou et al. 2019).

The scale of the risk to communities as defined by firesheds vastly exceeds the scale of planning as defined in the CWPP process. Ager et al. (2016) found that over half the area that contributes wildfire exposure to CWPPs fell outside CWPP boundaries, and was not analyzed as part of the planning process. As a result, Firewise and other homeowner mitigation activities implemented as part of CWPP planning (Williams et al. 2012) can potentially be ineffective without matching mitigation efforts on the adjacent wildlands and forests in which fires originate. Transmission networks can be used to provide explicit identification of the sources of wildfire exposure and the responsible landowners. This approach differs from current community wildfire protection CWPP guidelines (Jakes et al. 2007) where perimeters are typically based on administrative boundaries (Williams et al. 2012). The lack of a spatial planning framework for the CWPP process has led to a wide range of planning scales (e.g., neighborhoods, towns, multiple towns, entire counties) and subsequent boundary delineations that may not incorporate the spatial extent of fire transmission to communities.

This type of scale mismatch between planning boundaries and biophysical disturbances has been widely discussed in the literature. Our analysis inherently connects landscapes and represents exposure as a process among land parcels rather than being a property of the parcel. Since landscape fragmentation within public lands and on private lands is at a fraction of the scale of large wildfire events, the importance of the landscape overshadows the properties of individual parcels in terms of risk. While this is incorporated in risk assessments that use burn probability, it is not possible to disentangle the spatial scale of risk and the relative contributors of different parcels.

Our work contributes to building community archetypes that can help organize federal wildland fire policy at the community scale in terms of blending goals for promoting fire-adapted communities, restoring fire-resilient landscapes, and ensuring safe and effective wildfire response. There is not enough guidance regarding translating these policy goals into specific strategies appropriate to each local context. Community exposure archetypes aid in tailoring national risk mitigation policies to local conditions. Differences among these communities suggest implementing strategies that emphasize mitigation along a spectrum of management options. These strategies may target anything from the source of ignitions to the area of fire exposure and potential structure loss. For instance, projects may include actions such as restricting development in wildlands (Schoennagel et al. 2009), expanding and improving hazardous fuel treatments and prescribed burns (North et al. 2015; OIG 2016), reducing flammable vegetation surrounding homes (Gibbons et al. 2012), and improving community-based disaster planning and response (Calkin et al. 2014; Paveglio et al. 2016).

This work has several applications and implications for the shared stewardship initiative. The data in this assessment can be integrated into cross-boundary planning efforts to prioritize management investments in areas of high fire transmission. Specifically, combining transmission data with existing State and Forest Service assessments provides a spatial planning container within which the respective landowners share wildfire issues that will only be solved with collaborative planning efforts.

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