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Natural Hazards and Earth System Sciences
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Discussions

Fine scale assessment of cross boundary wildfire events in the Western US

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Abstract. We report a fine scale assessment of cross-boundary wildfire events for the western US. We used simulation modeling to quantify the extent of fire exchange among major federal, state, and private land tenures and mapped locations where fire ignitions can potentially affect populated places. We examined how parcel size effects the wildfire transmission and partitioned the relative amounts of transmitted fire between human and natural ignitions. We estimated that almost 90% of the total predicted wildfire activity as measured by area burned originates from four land tenures (Forest Service, Bureau of Land Management, private and State lands) and 63% of the total amount results from natural versus human ignitions. On average, one third of the area burned by predicted wildfires was non-local, meaning that the source ignition was on a different land tenure. Land tenures with smaller parcels tended to receive more incoming fire on a proportional basis, while the largest fires were generated from ignitions in national parks, national forests, public and tribal lands. Among the 11 western States, the amount and pattern of cross-boundary fire varied substantially in terms of which land tenures were mostly exposed, by whom and to what fire sizes. We also found spatial variability in terms of community exposure among States, and more than half of the predicted structure exposure was caused by ignitions on private lands or within the wildland-urban interface areas. This study addressed gaps in existing wildfire risk assessments, that do not explicitly consider cross-boundary fire transmission and do not identify the sources of fire. The results can be used by State, Federal, and local fire planning organizations to help improve risk mitigation programs.

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1 Introduction

Most environmental hazard issues span multiple social, ecological, and political boundaries, especially atmospheric and water pollution (Lyons, 2016;Mitchell, 1994;Brack, 2017;Zeitoun and Warner, 2006;Van Eerd et al., 2015;Uitto and Duda, 2002;Hills et al., 1998), habitat conservation (Liu et al., 2017) watershed restoration (Sayles and Baggio, 2017), water supply (Lara, 2015;Bark et al., 2014), and numerous natural disturbances. Thus the effectiveness of mitigation programs for these hazards depends on effective engagement of multiple governments, regulatory and land management agencies, and administrators within them to negotiate solutions to render cross-boundary issues governable (Lidskog et al., 2011;Linnerooth-Bayer et al., 2001;Lidskog et al., 2010). Perhaps one of the most transparent examples is the case of large destructive wildfires in the western US, where fires burn through multiple land tenures across a mosaic of land ownerships and jurisdictional boundaries, destroying communities on private lands and highly valued natural resources on public tracts. The cross-boundary nature of the problem has stimulated multiple new authorities, regulations, and executive orders that specifically address coordinated management across social and political boundaries (USDA Forest Service, 2015b, a, 2018; US Congress, 2014). Implementation of these authorities to perform risk reduction on mixed ownership planning areas have helped demonstrate how cross-boundary collaboration can amplify the scale of risk reduction activities by leveraging the economies of scale, i.e. expand the scale of fuel management (Ager et al., 2011;Graham et al., 2010) and community protection programs (Sexton, 2006;Abrams et al., 2016) commensurate with the scale of wildfire events (Charnley et al., 2016;Fischer et al., 2018;Markus et al., 2018).

Despite new legislation and a growing number of fuel management and restoration cross-boundary projects, there has not been a systematic large-scale assessment of the extent to which fire is exchanged among the major land owners in the western US or elsewhere. Yet, several recent studies have stressed the need to map potential cross-boundary wildfire as a means to better target areas where cross-boundary planning is needed to solve wildfire issues (Hamilton et al., In press;Fischer et al., 2018;Ager et al., 2018;Ager et al., 2014;Evers et al., 2019). For instance, where are zones of high fire transmission between large tracts of US Federal and private lands, and are the former priorities for investment in hazardous fuels treatments?

In this study we address this gap by using fire simulation modelling to predict future levels of cross-boundary fire exchange among major land tenures on 310 million ha of public and private lands in the 11 western US States, owned or managed by 14 major entities. We ask the following questions: 1) where do the cross-boundary fire problem is greater and how it varies among different land tenures and among the western US states? (2) What are the community fire exposure patterns and the extent of fireshed? (3) How does the relative parcel size and ignition

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type (human versus natural) affect fire transmission across boundaries? Results were used to understand how anthropogenic actions influence the different scales and complexity of fire transmission, notably parcel geometry, landownership composition and landscape fragmentation, e.g. checkerboard vs. large boundary lines between two land tenures. This work expands the scale of our earlier investigations that assessed cross boundary fire transmission for individual national forests and the State of Arizona (Ager et al., 2014;Ager et al., 2018).

2 Methods

2.1 Study area and land tenures

Our study area covers the 11 western US States (Arizona, AZ; California, CA; Colorado, CO; Idaho, ID; Nevada, NV; New Mexico, NM; Montana, MT; Oregon, OR; Utah, UT; Washington, WA; and Wyoming, WY), encompassing 76 national forests. Since 1970s, the annual average number of large fires has tripled and the average fire size increased by at least six times (Kenward et al., 2016). A checkerboard of different landownerships exists in the western US (USGS, 2016). For analysis purposes, we grouped the 26 detailed land ownership classes found in the Protected Areas Database (PAD) into 14 major land tenures (USGS, 2016). Federal agencies manage approximately half of the landscape (145.5 million ha, 48% of all lands), which primarily include the Bureau of Land Management (BLM, 71 million ha) and the US Forest Service (USFS, 57.5 million ha). The Other Federal land tenure class covers 300,000 ha and is mostly comprised by the following agencies: Agricultural Research Service, Natural Resources Conservation Service and the Army Corps of Engineers. Private lands cover an area of 96 million ha, followed by tribal (20 million ha), State (19 million ha) and city/county with other public lands (2 million ha) (Table 1). The extent of wildland-urban interface (WUI) is 22 million ha (Evers et al., 2019;Radeloff et al., 2005). Shrublands cover the 27% of the study area, followed by herbaceous-grasslands (25%), open (18%) and closed (11%) tree canopy forests (83% of which are conifers) (LANDFIRE, 2014). Approximately 115 million ha are fire adapted (fire regimes 1 and 3), with differences among States and land tenures (see Table B1). More than 65 million ha are of high or very high fire risk (Dillon et al., 2015), and USFS estimated that on the National Forest System (NFS) lands at high to very high fire risk and/or above-normal levels of insect and disease mortality, we can potentially treat seven million ha through traditional timber sales and 14 million ha through prescribed fire and/or another fuels treatment (USDA Forest Service, 2018).

==========Insert Table 1 about here==========

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2.2 Wildfire simulations

Wildfire simulations were generated by the USFS Missoula Fire Science Laboratory (Short et al., 2016), creating a library with millions of simulated ignitions for each US State. FSim attempts to model the ignition and growth with the Minimum Travel Time algorithm (Finney, 2002) of only those wildfires with a propensity to spread, focusing on relatively large and generally fast-moving fires that contribute the greatest to the probability of a wildland fire burning a given parcel of land. Our analysis relied on the 2016 dataset, which used inputs from the 2012 version of LANDFIRE data describing topography, fuels and vegetation structure (Rollins, 2009). Simulated fire represents between 10,000 to 100,000 potential annual weather scenarios based on observed fire-weather relationships recorded since 1984 (Abatzoglou, 2013;Hall et al., 2003). We omit additional details on the modelling approach since they are covered extensively elsewhere (Finney et al., 2011a;Finney et al., 2011b;Scott et al., 2012).

Fires were partitioned post-hoc into human or natural caused fires using historic wildfire occurrence data of the western US for the 1992-2013 period (Short, 2015). The cause of ignition (natural vs human) was modelled by fire size (acres), longitude/ latitude (decimal degrees), Geographic Area Coordination Centers (GACC) and day of ignition as a General Additive Models (GAM) with a logit link function and a binomial error distribution with Eq. (1):

$$resp \sim te(lon, lat) + te(jday, bs = "cc", by = gac) + te(lsize, k = 4) \quad (1)$$

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).

2.3 Fire exchange

Wildfire perimeters were intersected with major land tenures and communities of the western US. Private lands were partitioned into community and non-community areas based on housing density estimates derived from SILVIS WUI data (Radeloff et al., 2005). Second, all fire perimeters were partitioned into self-burning (i.e., burned areas within the same land tenure as the ignition) and outgoing parts (i.e., burned areas different from

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ignition land tenure). The origin of each wildfire was assigned based on the location of ignition. Third, total burned area within each land tenure was aggregated into three fire exchange classes: incoming fire (TFin, the sum of all fire ignited on another land tenure and entering each particular polygon), outgoing fire (TFout, the sum of all fire ignited in a land tenure or community that escapes its boundaries), and self-burning fire (TFself, the sum of those predicted fire perimeter parts from fires ignited in a polygon and burn within its boundary or to another polygon with the same landownership) (Figure 1).

==========Insert figure 1 about here==========

2.4 Parcel geometry and cross-boundary transmission zones

We used the PAD layer to estimate parcel characteristics, including the number of parcels, average parcel area and perimeter for each land tenure. All polygons were dissolved by the major land tenure and then converted from multipart to single part to ensure that there are no neighbouring parcels with the same owner, while slivers and parcels smaller than 1 ha were merged with the polygon sharing the largest common boundary. We spatially defined the cross-boundary fire transmission zones between national forests and the three largest land tenures: private, BLM and State lands. Since for each ignition we added information regarding the land tenure where it occurred, we queried the FSim ignitions database and selected certain pairs of ignitions (e.g. from NFS to BLM and the opposite) to estimate the amounts of transmitted fire to the other land tenure (e.g. the area of the fire perimeter of a BLM ignition that burned into National forests). On the selected ignition pairs, we applied a kernel function to fit a smoothly tapered surface to each ignition to calculate the magnitude per km^2 of the fire send from that ignition to the other land tenure, using a 6 km search radius. Finally, we estimated the self-burning fire spatial index (NTFI) to map the percentage of self-burning versus incoming fire, averaged across all fires. Pixels with values <50% in the NTFI define those zones with high incoming fire (>50%).

2.5 Fireshed mapping and community exposure

To estimate predicted structure exposure to fires we assumed that structures reported in US 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 from all intersections with the different WUI polygons, while for each WUI polygon, we summed all predicted structure exposure from all ignitions that intersected it, similar to our previous studies (Evers et al., 2019;Ager et al., 2018). We also used simulated fires to predict the area around communities

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where large fires are likely to ignite and spread into them (community fireshed), allowing us to identify sources of risk in terms of ownerships, wildfire hazard, management capabilities and fuel models (Scott and Burgan, 2005). Fireshed was derived from the conditional total housing units affected, assuming a fire occurred at the location. We applied the ArcGIS IDW process on all ignitions, interpolating the predicted total structure exposure of each simulated fire, and subsequent smoothing using a Focal Mean process. The resulting raster layer define as fireshed all pixels where ignitions are causing on average at least one exposed structure.

3 Results

3.1 Patterns of fire transmission

Statistical modelling of the ignition cause for simulated fires show that 63% of all predicted burned area was generated from natural ignitions (Figure 2a), mostly originating on NFS (31% of total area burned by natural ignitions on any land tenure), BLM (30%), private (24%), State and tribal lands (4% each). Human caused ignitions (37% of total area burned) were predicted to generate in private (32%), NFS (27%), BLM (17%), WUI (9%) and State lands (7%) (Figure 2b). We noticed that FWS lands are mostly affected by natural ignitions, while City/County lands from human ignitions. For natural ignitions, community, State and Public lands received more incoming compared to self-burning fire, while in human ignitions we see a balance of fire exchange for the abovementioned land tenures. Compared to the historic ignitions for 1992-2015 (Short, 2017), most verified lightning-caused area burned started on NFS (38%), BLM (35%) private (16%) and tribal lands (4%).

==========Insert figure 2 about here==========

Across all States, 30% of predicted burned lands (sum of incoming and self-burning fire) are within national forests, followed by private (27%), BLM (25%) and WUI and State lands (5%) each. The highest predicted ignition rate was recorded for private lands (34% of all simulated ignitions), followed by BLM (24%), FS (19%) and State and WUI (7% each). When we examined where the major land tenures received most of their incoming fire (Table 2), we see that BLM lands were more exposed to incoming fire ignited on private, NFS and State lands. Exposure to national forests is highest from private (46% of total NFS exposure) and community WUI (18%), and less from BLM (15%) and State (10%) lands. More than half of fire exposure in State lands came from private and WUI lands, a quarter from BLM lands and 17% from national forests. A detailed breakdown of the predicted average fire size for each State and land tenure is presented in appendix Table B2. The percentages of incoming fire from the sum of burned areas (incoming + self-burning) inside each land tenure (Figure 3) revealed how

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diverse the problem is across the western US, with each State having different amounts and shares of incoming fire for different land tenures. State, city/county lands and community WUI had more than 50% of their burned areas transmitted from other land tenures. In most cases, FS, Tribal and private lands had most of their burned areas from self-burning fires. More variability across the States was found for NPS, Other Federal and BLM lands.

==========Insert figure 3 about here==========

==========Insert Table 2 about here==========

In Figure 4, we show the location where we expect the largest cross-boundary fire, as well as the amount of incoming fire by each state or land tenure in ten intervals, from a low of <10% (colder colours) and a high of >90% (warmer colours). For mapping clarity, we used a hexnet with a cell size of 162,500 ha with average percentage estimates of incoming fire. The most important areas (warmer colours) were in central AZ and western NM, southern and northern CA, northern NV, southern OR, south-central WY, southern ID and south-western MT (Figure 4a). We also noticed that lands with large homogenous polygons with one owner, such as northern AZ (tribal lands), central ID (NFS), southern NV (BLM) and eastern CO (private), have low amounts (<20%) of incoming fire. Except for NV and WA, where we see more lands with lower incoming fire, all other States had similar trends (Figure 4b). We also noticed that the land tenures city/county, State, public, and Bureau of Reclamation (BOR) had larger share of area that received higher amounts of incoming fire compared to DOE, DOD, Tribal, NFS and NPS lands (Figure 4c), indicating a reverse trend of higher incoming fire when the average parcel size and perimeter were reduced.

==========Insert figure 4 about here==========

We spatially defined the places where >50% of fire is incoming, from ignitions that burned each of the three major land tenures in terms of burned area (NFS, BLM and private lands) (Figure 5). Across most national forests, we noticed that their boundaries received the bulk of the incoming fire (red), with the exception of some enclaves where land tenures were intermixed. Most BLM lands were in proximity to national forests in southern and eastern OR, northern CA, southwestern NM, western CO, across NV, and in south-central ID. Smaller BLM land parcels away from national forests were exposed in southern AZ, northeaster MT, and across UT and WY, from fires ignited in other land tenures. Incoming fire to private lands (orange) was greater across the northern parts of the national forests in central AZ, on the western parts of Sierras in central CA, in northern CA and south-central OR, in southern ID and in the north-eastern parts of MT. Finally, when we compared the increasing parcel size of all

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land tenures with the average percentage of incoming fire (Figure 6), estimated with the NTF index, a decreasing trend is evident (larger parcels – less incoming fire).

==========Insert figure 5 about here==========

==========Insert figure 6 about here==========

3.2 Mapping cross-boundary wildfire transmission

We estimated the cross-boundary wildfire between national forests and three important stakeholders that already participate in existing or had the potential to engage in future shared-stewardship projects: State, private and BLM. These areas define where predicted fires from national forests burn outside their boundaries, or where ignitions from each of the other three land tenures escape their boundaries and burned into national forests (Figure 7). Again, we used the hexnet to estimate the average values of cross boundary fire for hexcell and for each couple of land tenures.

Private lands received the 46% (33,000 ha yr^{-1}) of the total outgoing fire from national forests, while national forests received the 23% (28,000 ha yr^{-1}) of the total outgoing fire from private lands (120,000 ha yr^{-1}) (Table 3). The estimated fire exchange area between the two land tenures in lands with no management restrictions was 53 million ha, with 23 million ha inside private lands. The national forests with fire transmission to private lands were more expanded compared to BLM and State lands, with large interface areas between them (Figure 7a). The cross-boundary zones with highest transmission were in the national forests of central Sierras, southern and north-western CA, eastern OR, north-central WA, southwestern and southern ID, western MT, eastern WY, central and south-eastern CO, western parts of UT, central AZ and southwestern NM.

State lands received the 10% (i.e. 7,000 ha yr^{-1}) of the total outgoing fire from national forests (71,000 ha yr^{-1}), while national forests received the 15% (i.e. 6,000 ha yr^{-1}) of the total outgoing fire from State lands (40,000 ha yr^{-1}) (Table 3). The estimated fire exchange area between the two land tenures in lands with no management restrictions (e.g. roadless in national forests or protected in both land tenures) was 19 million ha, with approximately 3 million ha inside State lands. The national forests with highest fire exchange with State lands (Appendix Figure A1a) were across the boundaries of the national forests in central AZ and southern NM, at the south-western parts of CA, at the south-western parts of national forest in ID, in western MT and eastern OR, and across the eastern front of north-central WA.

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BLM lands received the 15% (10,500 ha yr^{-1}) of the total outgoing fire from national forests, while national forests received the 11% (9,000 ha yr^{-1}) of the total outgoing fire from BLM lands (82,000 ha yr^{-1}) (Table 3). The estimated fire exchange area between the two land tenures in lands with no management restrictions was 23 million ha, with 7 million ha inside BLM lands. Although in spatial proximity, BLM share small amounts of fire with national forests and State lands, while more than two thirds of the total BLM fires were shared with private lands. BLM lands are by 40% smaller than private lands but send 70% less fire (compared to private lands) to national forests. The highest transmission zones from NFS to BLM lands (appendix Figure A1b) were in the national forests of northern NV, in southern and central ID, in southwestern NM and southern AZ, in central and southwestern UT, in southern and eastern OR, in parts of north-central WA, in Grand Mesa, in western CO, and in southern, north-western and central CA.

==========Insert Table 3 about here==========

As a showcase, the right panels of Figure 7 focused at the southwestern US (California, Arizona and New Mexico) where the differences between the three zones were large (NFS – State zones (a); NFS – BLM zones (b); NFS – Private zones (c)). Areas with no or low cross-boundary transmission are shown with light grey for national forests and white hillshade for the other land tenures. There were parts in the landscape where we found large values for all three land tenure couples, e.g. in southwestern NM, whereas in other parts of the landscape only one out of three couples had large values. When we merged the overlapping areas across the three couples, about 60 million ha of manageable land could be allocated for potential shared stewardship projects, including any of the combinations of the four land tenures studied (national forests, private, BLM and State lands), one third of which was inside national forests. Approximately 20 million ha were available for shared projects for fire risk reduction in three land tenures (8.5 million ha of which were inside national forests), and approximately 7.5 million ha available for four land tenures (3.5 million ha of which were inside national forests).

==========Insert figure 7 about here==========

3.3 Community exposure

Community fireshed covered an area of approximately 70 million ha across the western US. For each hexcell we estimated the amounts of fire that each land tenure generates and transmitted to communities, and colour coded them with the land tenure producing the highest exposure (Figure 8a). The southern parts of ID and UT, the northwest AZ and NV were mostly affected by fires ignited on BLM lands, while in northern UT, southwest and northern CA, northern NV and eastern NM structure exposure fires were mostly a problem caused by private land

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ignitions. National forest ignitions caused most community exposure in parts of northern and southern CA, central ID and western MT, north-central WA, central AZ and southwest NM. State land fires were dominant in the southern AZ and central UT, while WUI ignitions prevail in coastal CA and across the Sierras, at the north-central CO, and at the northeast and southern WA. Tribal land fires mostly exposed communities at the central AZ, with lower influence in MT, WA and the central parts of OR.

When fire transmission was expressed in terms of annual structure exposure (Figure 8b), large differences are revealed between CA and AZ with the other States. More than 11,000 structures per year were predicted to be exposed in CA (59% of total exposed structures) and 2,500 in AZ (14%). Although the total burned area in ID and CA was similar, they had large differences in terms of structure exposure. All other States had less than 1,000 structures exposed per year, ranging from a low of 150 in WY (1% of the total structure exposure) and a high of 850 in ID (4.5%). In conjunction with our previous findings, half of the predicted structure exposure came from ignitions on private and WUI lands, followed by national forests (21.5%), BLM lands (6%), State lands (4.5%), city/county and tribal lands (3.6% each) (Figure 8c). Appendix Figure A2 shows the top ten communities of each State in terms of annual structure exposure, with grey representing the amount of structure exposure caused by incoming fire and black the exposure caused by fires ignited within each community's WUI. Appendix Table B3 shows the list of the top 100 communities, regardless of State, ranked by the total of annual structure exposure (sum of incoming and self-burning fires).

==========Insert figure 8 about here==========

Finally, five land tenures own or manage the 92% of fireshed, with private and community together owning half of lands, followed by national forests (25%), BLM lands (10%) and State lands (6%) (Figure 9a,b). More than half of the fireshed lands were covered with grass or grass/shrub fuel models (Figure 9c), and when combined with shrub fuel models the make up to three quarters of fuels in some States (NV, AZ, UT, WY, NM and ID). Forested fuel models (timber understory and timber-litter) had the lowest share in NV (10%) and the highest in OR and WA (~50%), also covering large parts of MT, CO and CA. Wildfire hazard potential was low on more than 50% of WY, WA and CO firesheds (Figure 9d), while CA, ID, UT, NV and OR had more than 40% of their fireshed with high or very high fire hazard.

==========Insert figure 9 about here==========

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4 Discussion

Fire transmission and exchange among land tenures across the western US shows complex patterns related to the source of risk and parcel geometry. Previous studies covering the western US assessed fire risk (AMF, 2018;WWWRA, 2013;Parks et al., 2018;Dillon et al., 2015), but did not consider where the fires are coming from and how they are transmitted from one land tenure to another, which has only been studied locally or for a single State (Ager et al., 2017;Ager et al., 2018). We focused on the four largest land tenures (USFS, BLM, private and State) that create 85% of the total outgoing fire and are important entities in terms of fuel management capacity. Most predicted ignitions originated on private and BLM lands. Results revealed that US national forests have the highest predicted burned area (sum of incoming and self-burning fires), while the highest outgoing fire originates from private landownerships.

Wildfire risk management and planning need also to consider landscape fragmentation, either caused by the different vegetation, fuel or landownerships types, since it creates different scales and complexity in fire transmission, e.g. checkerboard vs. heavy solid lines of interface boundaries. In addition, highly fragmented wildland-urban interface areas among private landowners increase fire suppression complexity and population risk (Chas-Amil et al., 2013;Busby et al., 2012). Effective and cost-efficient cross-boundary fuel management projects could consider the parcel size and the extent of common boundaries, in addition to the sources and the amounts of incoming fire to each land tenure. We found that the large fire exchange between private lands and national forests is due to mixed ownerships inside the national forests' administrative boundary, causing the checkerboard effect of small mixed land parcels. State lands had fire connectivity primarily with private, and secondary with BLM lands, with limited fire exchange zones with national forests. We also found that small landownership parcels tended to receive higher amounts of incoming fire, like public, state, BOR and city/county lands, while larger parcels (e.g. NFS, NPS, DOD) tended to have less transmitted fire.

Estimating the amounts of fire generated by human or natural causes (Balch et al., 2017) can also define where there is potential to let some natural ignitions burn naturally under condition that they are not threatening to communities or other values at risk (Barnett et al., 2016). The majority of unplanned ignitions in wilderness in the US are still suppressed, despite that there is legislation that allows them to burn, but human caused fires have to be suppressed (Fusco et al., 2016;Miller, 2012).Human ignitions are largely preventable and occur at times of the year and in locations that historically did not happen (Balch et al., 2017;Nagy et al., 2018). Although we have sufficient data on where historic natural ignitions occurred since 1992 (Short, 2017), we needed probabilistic estimations of the spatial likelihood for potential natural ignitions. In this study we created a model that can

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separate simulated ignitions into natural and human caused. The statistical model we created allows for modelling of the ignition cause of every simulated fire and can be applied to produce ignition-cause probability maps of higher spatial resolution for the scale of western US. We found that natural ignitions are the major source of fire transmission and caused the two-thirds of the total fire activity in terms of burned area. Despite that large difference, communities were more exposed to human-caused ignitions (60% vs. 40% from natural ignitions), and the same applied for city/county and public lands.

The implications of our results for community wildfire protection planning are several. Community protection planning could benefit from recognizing , i.e. the area that encloses ignition locations that transmitted fire to communities (Ager et al., 2015). Results revealed that the structure exposure problem of the western US communities originated mostly from ignitions in either WUI or private lands, and less from Federal lands (national forests and BLM), and collaboration is required among four major entities (Federal, private, State and Tribal lands). California, Arizona, Idaho and Montana were the States where more than 90% of the predicted structure exposure occurred. The extend, land tenure and fuel model composition of the fireshed differed among the western States, mostly comprised by a combination of private/community lands, national forests, BLM, tribal and State lands, characterized by the dominance of shrub and grass fuel models. Large amounts of burned lands were not directly linked with high structure exposure, since in cases like Idaho and California with similar amounts of burned area, Idaho had 90% less structure exposure. We also provided for a first time a community prioritization assessment (see Appendix A2) based on the predicted structure exposure of each community, separating burned areas from incoming fires from those that were self-burning (ignited and burned within the community).

Results can help towards prioritizing fuel treatment projects that will consider both the anthropogenic and biophysical context of the wildfire problem, which is increasingly drawing the attention of the research community (Evers et al., 2019;Hamilton et al., In press;Palaiologou et al., Under revision;Bodin and Tengö, 2012). Establishing cross-boundary fuel management projects with other major landowners has become a necessity when land managers want to achieve multiple treatment and ecological objectives (improve forest conditions and reduce the wildfire risk to communities) on larger landscapes. This can be accomplished through sharing decision making with partners and implementing projects in an accelerated pace on areas where the cost of service work exceeds product value or with limited markets.

For the western US, ideal planning should be made at the scale of States with increased collaboration between the major Federal agencies (e.g. USFS, BLM) with state foresters and partners that can better identify where are the lands that these projects can make the difference, in particular inside the community fireshed. Several States

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through the development of State Action Plans (SAP) have already set their priority issues (objectives to be achieved) and identified priority areas, like Idaho, Montana, Ohio and Utah. Since designing cross-boundary projects does not have specific implementation standards and nationally directed tools and documents, there is flexibility on how candidate planning areas can be selected and what types of projects can be applied in each landscape. The State Wildfire Risk Assessment Portals (WWWRA, 2013;Arizona Department of Forestry and Fire Management, 2016) moved towards that direction, but they produced pixel level outputs that were not at the appropriate scale and could not be considered as the ideal spatial units of change since we need large planning areas inside the cross-boundary zones that can reduce fire risk or achieve ecological objectives (e.g. spanning from 5 to 20 thousand ha). Developing cross-boundary collaborative fuel management projects requires the assessment of several different aspects, that we addressed in this study.

This study is the first comprehensive and systematic approach of estimating cross-boundary risk transmission over large areas and for all the major land tenures of a study area, applying an assessment framework that can be implemented across different regions of the world to inform fire management agencies decisions on the locations of future fuel management projects. Our methods and concepts were also applied at different scales in Europe (Alcasena et al., 2019;Salis et al., 2018;Palaiologou et al., 2018), but they are not yet considered in the official wildfire risk assessments at the pan-European level (San-Miguel-Ayanz et al., 2018). We anticipate that our study's results, which covered an extended and diverse landscape of the western US, can inform fire management agencies and guide how existing wildfire risk assessments can be improved in regions like the Mediterranean Europe, Australia, southern Africa and Russia. This framework can also be used for any combination of land tenures to map and assess the risk to communities and other assets originating from their cross-boundary fire transmission zones or achieve various management and restoration goals (WUI protection, timber production, restoration of areas affected by insects and disease, watershed management and reduction of fire deficit). This included the assessment of both elements of cross-boundary fire risk, i.e. sources (where fires are coming from) and sinks (where fires do burn), since effective shared-stewardship projects must deal with both elements to achieve change. Finally, perhaps the most important instance of cross-boundary wildfire transmission relates to communities and the lands surrounding a community where wildfire risk might originate, since it is the most burning issue after the recent high death toll, structure loss and economic costs from fires in the western US (California 2017-18), and elsewhere (Greece 2018, Portugal 2017).

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5 Conclusions

We expect that this study can help towards improved planning of cross-boundary fuel management projects by providing a better understanding to a wider audience about the fire related patterns in the western US. We highlighted the importance of collaboration among different land owners to achieve the desired ecological and community protection outcomes and provided an assessment framework that can be used across all lands and all landownerships. Our approach was designed for assessments regarding the current ecological and site conditions, targeting in potential shared stewardship management activities for the short-term future (1-5 years) on the 60 million ha of manageable lands with potential for shared stewardship projects. Future work will combine three or more land tenures to identify larger areas with high fuel treatment potential, with private lands be the core node of this shared-stewardship approach since they produce the highest amounts of outgoing fire. In addition, we will create a typology of how each area is receiving fire transmission, grouping similar regions based on common characteristics such as fuel mode, fire regime, management history and land tenure composition.

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References

Abatzoglou, J. T.: Development of gridded surface meteorological data for ecological applications and modelling, International Journal of Climatology, 33, 121-131, 2013.

Abrams, J., Nielsen-Pincus, M., Paveglio, T., and Moseley, C.: Community wildfire protection planning in the American West: homogeneity within diversity?, Journal of Environmental Planning and Management, 59, 557-572, 10.1080/09640568.2015.1030498, 2016.

Ager, A. A., Day, M. A., McHugh, C. W., Short, K., Gilbertson-Day, J., Finney, M. A., and Calkin, D. E.: Wildfire exposure and fuel management on western US national forests, Journal of Environmental Management, 145, 54-70, 2014.

Ager, A. A., Kline, J., and Fischer, A. P.: Coupling the biophysical and social dimensions of wildfire risk to improve wildfire mitigation planning, Risk Analysis, 35, 1393–1406, 10.1111/risa.12373, 2015.

Ager, A. A., Palaiologou, P., Evers, C. R., Day, M. A., and Barros, A. M. G.: Assessing transboundary wildfire exposure in the southwestern United States, Risk Analysis, 38, 2105-2127, 10.1111/risa.12999, 2018.

Alcasena, F. J., Ager, A. A., Bailey, J. D., Pineda, N., and Vega-Garcia, C.: Towards a comprehensive wildfire management strategy for Mediterranean areas: Framework development and implementation in Catalonia, Spain, Journal of Environmental Management, 231, 303-320, 10.1016/j.jenvman.2018.10.027, 2019.

AMF: Western Water Threatened by Wildfire: it's not just a public lands issue, American Forest Foundation, Washington, DC, 2018.

Arizona Wildfire Risk Assessment Portal (WRAP) - Technical Information: https://forestryandfire.az.gov/AZWRAP-Support, access: 28 November 2016, 2016.

Balch, J. K., Bradley, B. A., Abatzoglou, J. T., Nagy, R. C., Fusco, E. J., and Mahood, A. L.: Human-started wildfires expand the fire niche across the United States, Proceedings of the National Academy of Sciences, 114, 2946-2951, 2017.

Bark, R. H., Frisvold, G., and Flessa, K. W.: The role of economics in transboundary restoration water management in the Colorado River Delta, Water Resources and Economics, 8, 43-56, https://doi.org/10.1016/j.wre.2014.10.006, 2014.

Barnett, K., Miller, C., and Venn, T. J.: Using risk analysis to reveal opportunities for the management of unplanned ignitions in wilderness, Journal of Forestry, 114, 10.5849/jof.15-111, 2016.

Bodin, Ö., and Tengö, M.: Disentangling intangible social-ecological systems, Global Environmental Change, 22, 430-439, 2012.

Brack, D.: International trade and the Montreal Protocol, Routledge, 2017.

Busby, G. M., Albers, H. J., and Montgomery, C. A.: Wildfire Risk Management in a Landscape with Fragmented Ownership and Spatial Interactions, Land Economics, 88, 496-517, 2012.

© Author(s) 2019. CC BY 4.0 License.

Charnley, S., Kelly, E. C., and Wendel, K. L.: All lands approaches to fire management in the Pacific West: A typology, Journal of Forestry, 115, 16-25, 2016.

Chas-Amil, M., Touza, J., and García-Martínez, E.: Forest fires in the wildland–urban interface: a spatial analysis of forest fragmentation and human impacts, Applied Geography, 43, 127-137, 2013.

Dillon, G. K., Menakis, J., and Fay, F.: Wildland fire potential: a tool for assessing wildfire risk and fuel management needs, Proceedings of the large wildland fire conference. Proceedings RMRS-P-73, Missoula, MT, 2015, 60-76,

Evers, C., Ager, A. A., Nielsen-Pincus, M., Palaiologou, P., and Bunzel, K.: Archetypes of community wildfire exposure from national forests in the western US, Landscape and Urban Planning, 182, 55-66, 10.1016/j.landurbplan.2018.10.004, 2019.

Finney, M. A.: Fire growth using minimum travel time methods, Canadian Journal of Forest Research, 32, 1420-1424, 10.1139/x02-068, 2002.

Finney, M. A., Grenfell, I. C., McHugh, C. W., Seli, R. C., Trethewey, D., Stratton, R. D., and Brittain, S.: A method for ensemble wildland fire simulation, Environmental Modeling and Assessment, 16, 153-167, 2011a.

Finney, M. A., McHugh, C. W., Grenfell, I. C., Riley, K. L., and Short, K. C.: A simulation of probabilistic wildfire risk components for the continental United States, Stochastic Environmental Research and Risk Assessment, 25, 973–1000, 10.1007/s00477-011-0462-z, 2011b.

Fischer, A. P., Klooster, A., and Cirhigiri, L.: Cross-boundary cooperation for landscape management: Collective action and social exchange among individual private forest landowners, Landscape and Urban Planning, 2018.

Fusco, E. J., Abatzoglou, J. T., Balch, J. K., Finn, J. T., and Bradley, B. A.: Quantifying the human influence on fire ignition across the western USA, Ecological Applications, 26, 2390-2401, doi:10.1002/eap.1395, 2016.

Graham, R. T., Jain, T. B., and Matthews, S.: Fuel management in forests of the Inland West, in: Cumulative watershed effects of fuel management in the western United States, edited by: Elliot, W. J., Miller, I. S., and Audin, L., Gen. Tech. Rep. RMRS-GTR-231, USDA Forest Service, Rocky Mountain Research Station, Fort Collins, CO, 19-68, 2010.

Hall, B., Brown, T., Bradshaw, L., Jolly, W., and Nemani, R. R.: National standardized energy release component (ERC) forecasts, 2nd International Wildland Fire Ecology and Fire Management Congress and 5th Symposium on Fire and Forest Meteorology, Orlando, FL, 2003, 3,

Hamilton, M., Fischer, A. P., and Ager, A. A.: Using social-ecological networks to assess institutional fit in wildfire risk governance, Global Environmental Change, In press.

Hills, P., Zhang, L., and Liu, J.: Transboundary Pollution between Guangdong Province and Hong Kong: Threats to Water Quality in the Pearl River Estuary and Their Implications for Environmental Policy and Planning, Journal of Environmental Planning and Management, 41, 375-396, 10.1080/09640569811641, 1998.

Kachitvichyanukul, V., and Schmeiser, B. W.: Binomial random variate generation, Communications of the ACM, 31, 216-222, 10.1145/42372.42381, 1988.

© Author(s) 2019. CC BY 4.0 License.

Kenward, A., Sanford, T., and Bronzan, J.: WESTERN WILDFIRES: A Fiery Future, Climate Central, Princeton, NJ, 42, 2016.

Lara, A. A. C.: Transboundary water conflicts in the Lower Colorado River Basin: Mexicali and the salinity and the all American Canal Lining, El Colegio de la Frontera Norte, 2015.

Lidskog, R., Soneryd, L., and Uggla, Y.: Transboundary risk governance, Earthscan, London, 2010.

Lidskog, R., Uggla, Y., and Soneryd, L.: Making transboundary risks governable: Reducing complexity, constructing spatial identity, and ascribing capabilities, Ambio, 40, 111-120, 2011.

Liu, S., Yin, Y., Li, J., Cheng, F., Dong, S., and Zhang, Y.: Using cross-scale landscape connectivity indices to identify key habitat resource patches for Asian elephants in Xishuangbanna, China, Landscape and Urban Planning, 2017.

Lyons, Y.: Transboundary pollution from offshore oil and gas activities in the seas of Southeast Asia, in: Transboundary Environmental Governance, Routledge, 183-218, 2016.

Markus, A., Leavell, D., Bienz Craig , Carlsen Kellie, Davis Emily Jane, Douglas Michael , Ferguson David, Fledderjohann Lee , Johnson Kasey , Livingston Ned , Pettigrew Jason , Rogers Gene , Schreder Marci, Shoun Dan , and Ann, V. L.: Planning and Implementing Cross-boundary, Landscape-scale Restoration and Wildfire Risk Reduction Projects. A Guide to Achieving the Goals of the National Cohesive Wildland Fire Management Strategy, Oregon State University, University of Idaho, Washington State University, Corvallis, Oregon, 117, 2018.

Miller, C.: The hidden consequences of fire suppression, Park Science, 28, 75-80, 2012.

Mitchell, R. B.: Intentional oil pollution at sea: environmental policy and treaty compliance, mit Press, 1994.

Palaiologou, P., Ager, A. A., Nielsen-Pincus, M., Evers, C., and Kalabokidis, K.: Using transboundary wildfire exposure assessments to improve fire management programs: a case study in Greece, International Journal of Wildland Fire, 27, 501-513, 10.1071/WF17119, 2018.

Palaiologou, P., Ager, A. A., Nielsen-Pincus, M., Evers, C., and Day, M.: Social vulnerability to large wildfires in the western USA, Landscape and Urban Planning., Under revision.

Parks, S. A., Holsinger, L. M., Panunto, M. H., Jolly, W. M., Dobrowski, S. Z., and Dillon, G. K.: High-severity fire: evaluating its key drivers and mapping its probability across western US forests, Environmental Research Letters, 13, 044037, 10.1088/1748-9326/aab791, 2018.

Radeloff, V. C., Hammer, R. B., Stewart, S. I., Fried, J. S., Holcomb, S. S., and McKeefry, J. F.: The wildland-urban interface in the United States, Ecological Applications, 15, 799-805, 2005.

Salis, M., Del Guiudice, L., Arca, B., Ager, A. A., Alcasena, F., Lozano, O., Bacciu, V., Spano, D., and Duce, P.: Modeling the effects of different fuel treatment mosaics on wildfire spread and behavior in a Mediterranean agro-pastoral area, Journal of Environmental Management, 212, 490-505, 10.1016/j.jenvman.2018.02.020, 2018.

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San-Miguel-Ayanz, J., Costa, H., De Rigo, D., Liberta, G., Artes V, T., Durrant H., T., Nuijten, D., Loffler, P., and Moore, P.: Basic criteria to assess wildfire risk at the pan-European level, European Union, 26, 2018.

Scott, J. H., and Burgan, R. E.: Standard fire behavior fuel models: a comprehensive set for use with Rothermel's surface fire spread model, USDA Forest Service, Rocky Mountain Research Station, Fort Collins, CO, Gen. Tech. Rep. RMRS-GTR-153, 72, 2005.

Scott, J. H., Helmbrecht, D. J., Parks, S. A., and Miller, C.: Quantifying the threat of unsuppressed wildfires reaching the adjacent wildland-urban interface on the Bridger-Teton National Forest, Wyoming, USA, Fire Ecology, 8, 125-142, 10.4996/fireecology.0802125, 2012.

Sexton, T.: U.S. Federal fuel management programs: reducing risk to communities and increasing ecosystem resilience and sustainability, Fuels Management—How to Measure Success: Conference Proceedings, Portland, OR, March 28–30, 2006, pp. 9–12; Proceedings RMRS-P-41, USDA Forest Service, Rocky Mountain Research Station, Fort Collins, CO, 809 p, 2006,

Uitto, J. I., and Duda, A. M.: Management of Transboundary Water Resources: Lessons from International Cooperation for Conflict Prevention, The Geographical Journal, 168, 365-378, 2002.

National Cohesive Wildland Fire Management Strategy: http://www.forestsandrangelands.gov/strategy/index.shtml, access: 25 March 2015, 2015a.

U.S. Congress, 2014.Agricultural Act of 2014, 7 February 2014,8598,H.R. 2642 113-79

USDA Forest Service: Collaborative Forest Landscape Restoration Program 5-Year Report, USDA Forest Service, Washington, DCFS-1047, 2015b.

USDA Forest Service: Towards shared stewardship across landscapes: An outcome-based investment strategy, USDA Forest Service, Washington, DCFS-118, 2018.

Van Eerd, M. C., Wiering, M. A., and Dieperink, C.: Solidarity in transboundary flood risk management: A view from the Dutch North Rhine–Westphalian catchment area, Climate Policy, 1-19, 2015.

WWWRA: West Wide Wildfire Risk Assessment - Final Report, Oregon Department of Forestry, Council of Western State Foresters and the Western Forestry Leadership CoalitionFinal Report, 2013.

Zeitoun, M., and Warner, J.: Hydro-hegemony – a framework for analysis of trans-boundary water conflicts, Water Policy, 8, 435-460, 10.2166/wp.2006.054, 2006.

Nat. Hazards Earth Syst. Sci. Discuss., https://doi.org/10.5194/nhess-2019-56
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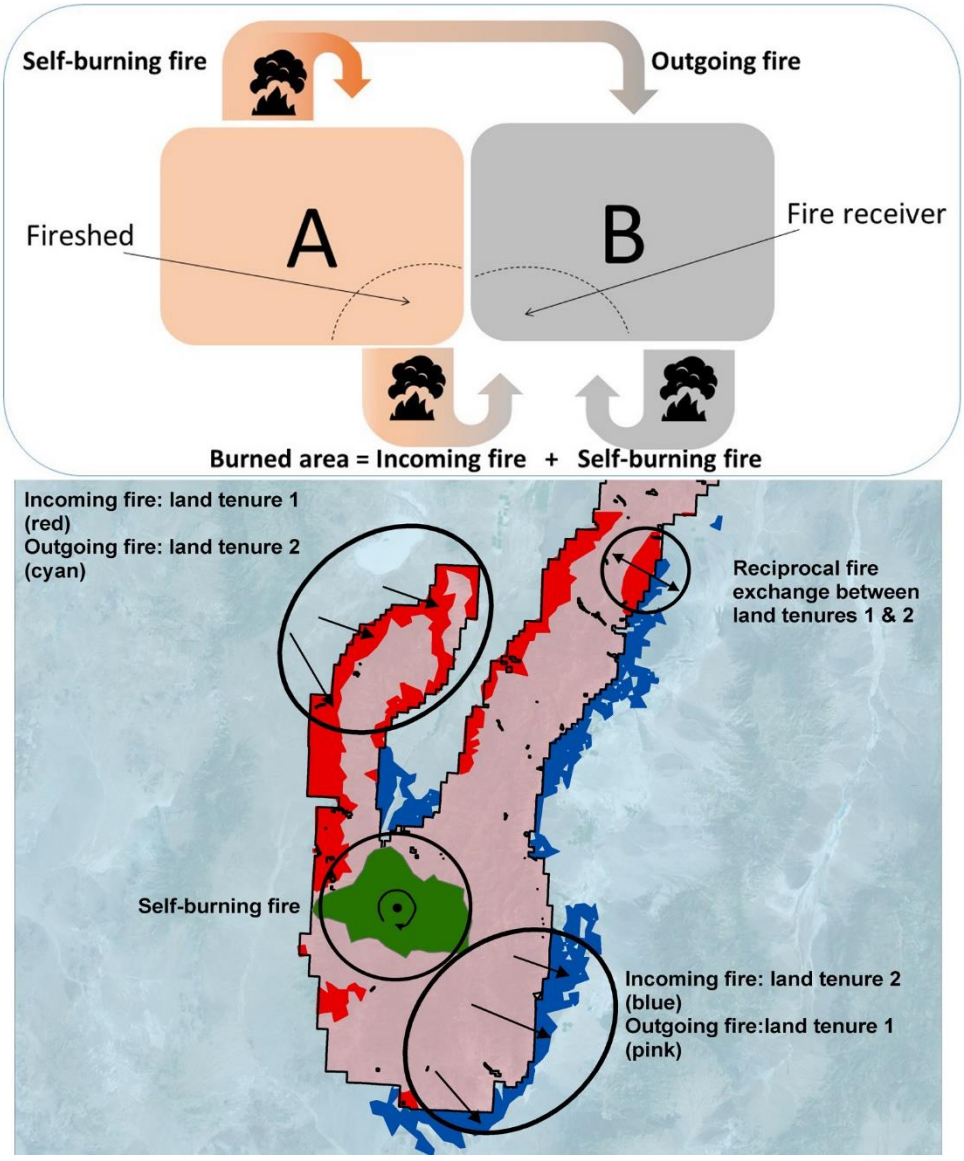

Figure 1: Conceptual map showing the cross-boundary fire exchange (incoming, outgoing, self-burning) between two land tenures.

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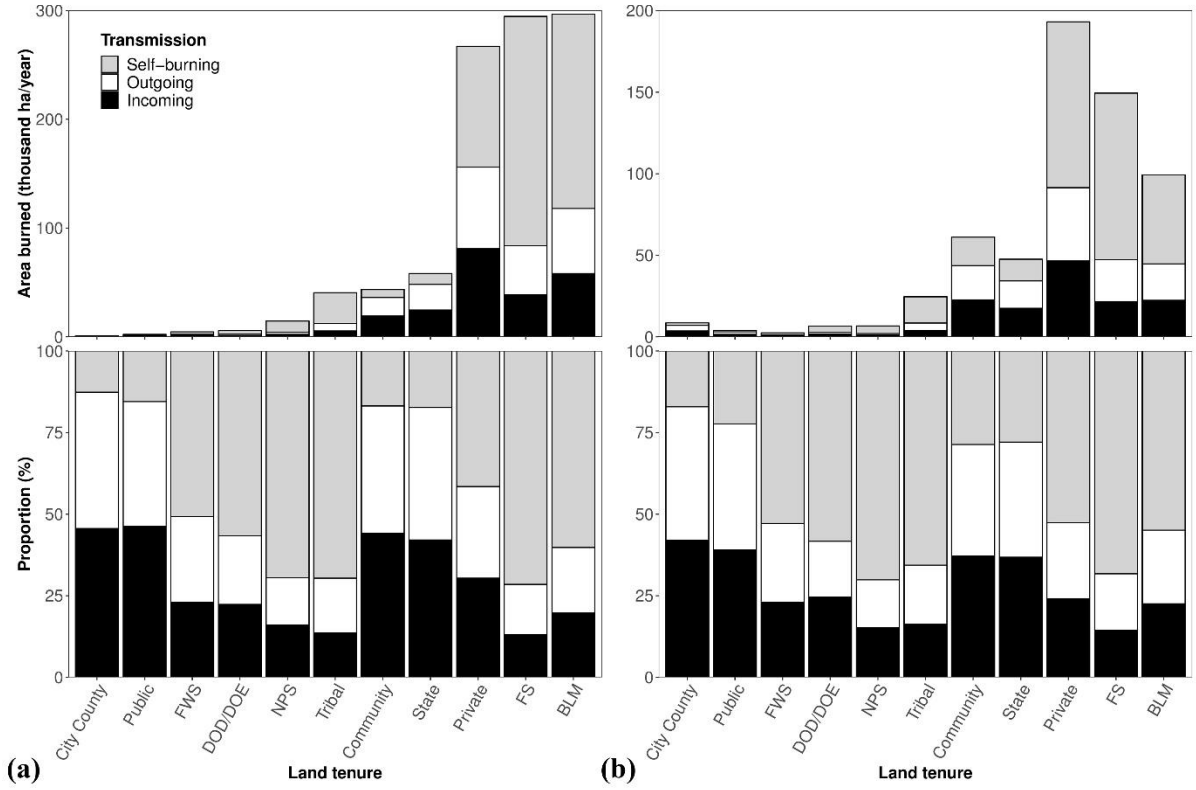

Figure 2: Fire exchange for the major land tenures of the 11 western US States estimated for: a) natural ignitions; and b) human ignitions.

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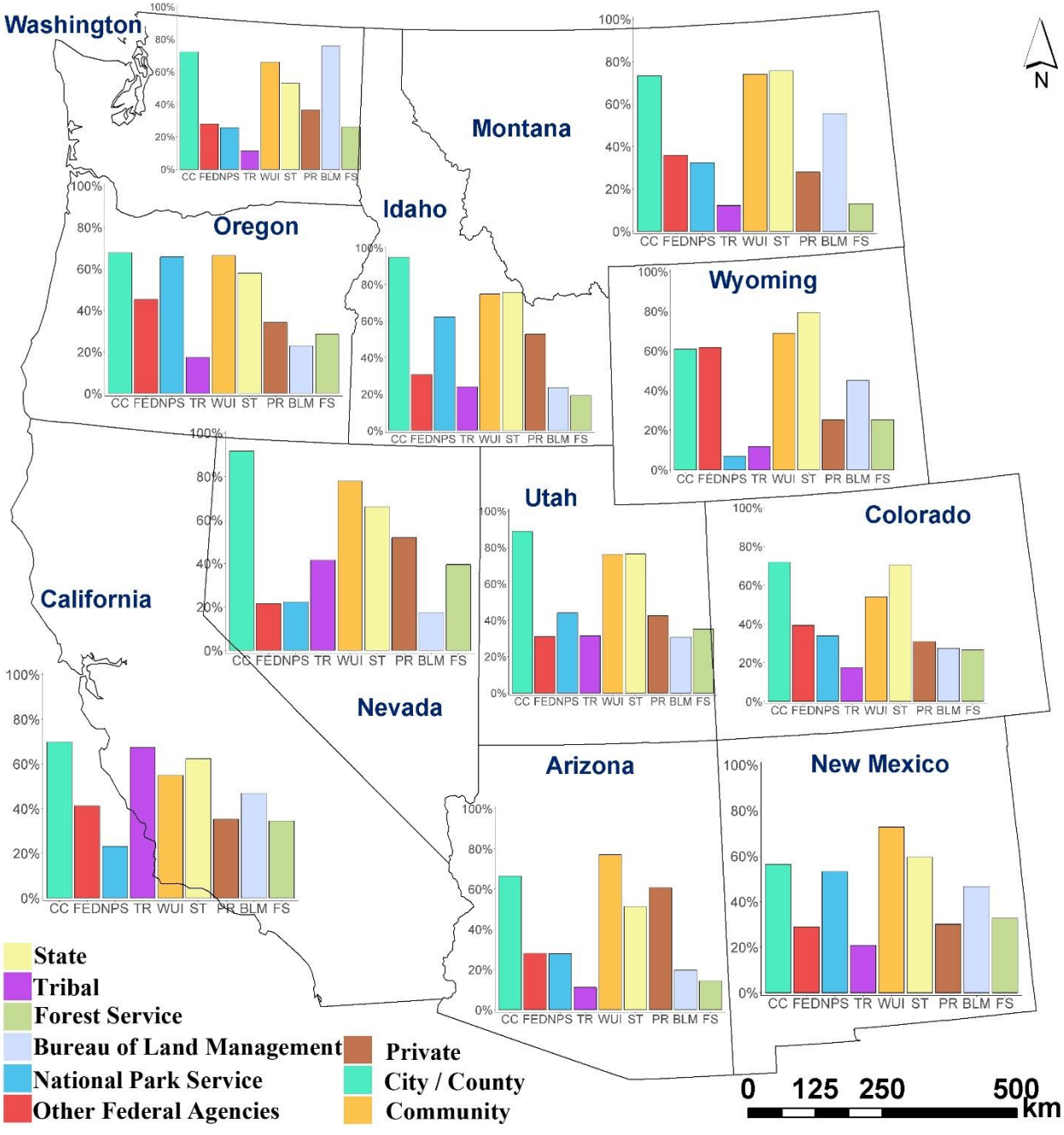

Figure 3: Proportion of incoming fire to the total fire (incoming / (incoming + self-burning) * 100) for each western US State.

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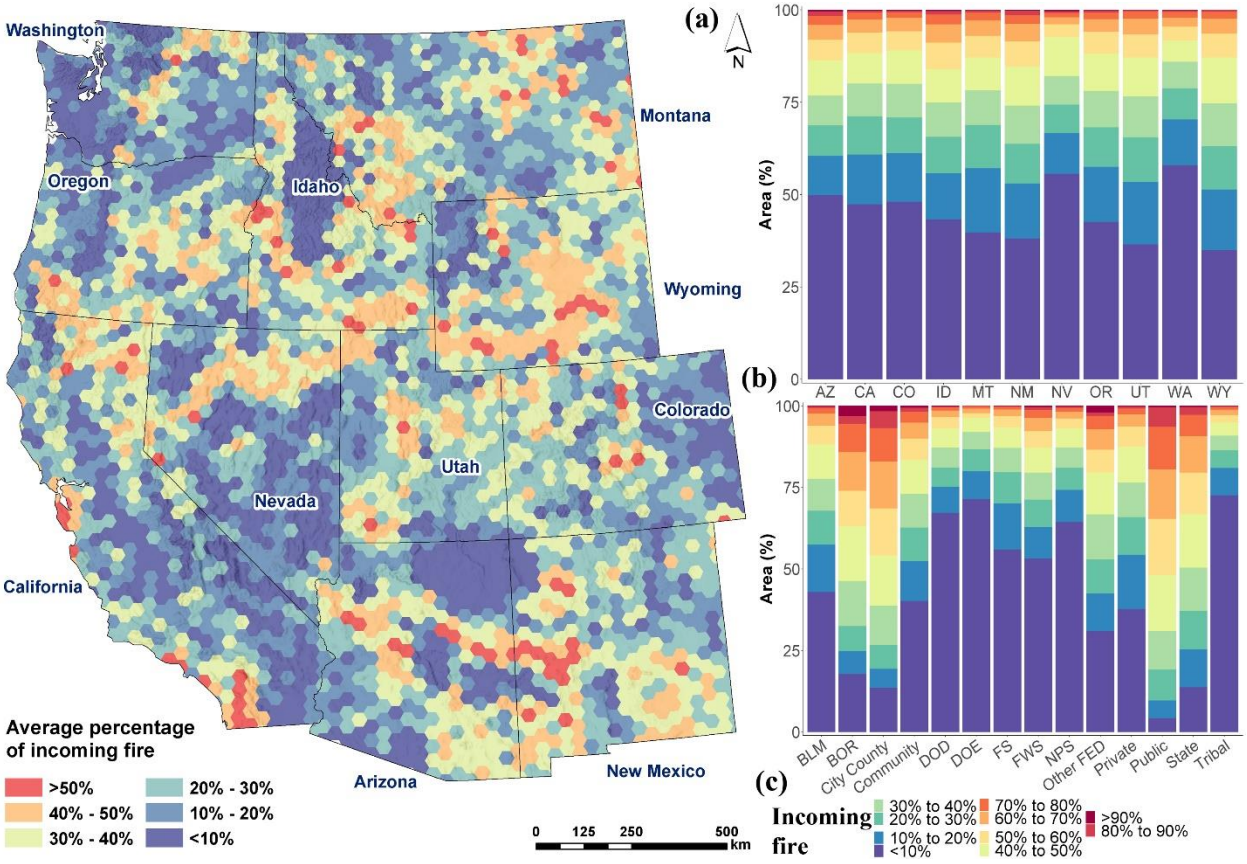

Figure 4: (a) Average percentage of incoming fire across the western US. By state, calculated for its entire area and for all land tenures (b); and land tenure (c).

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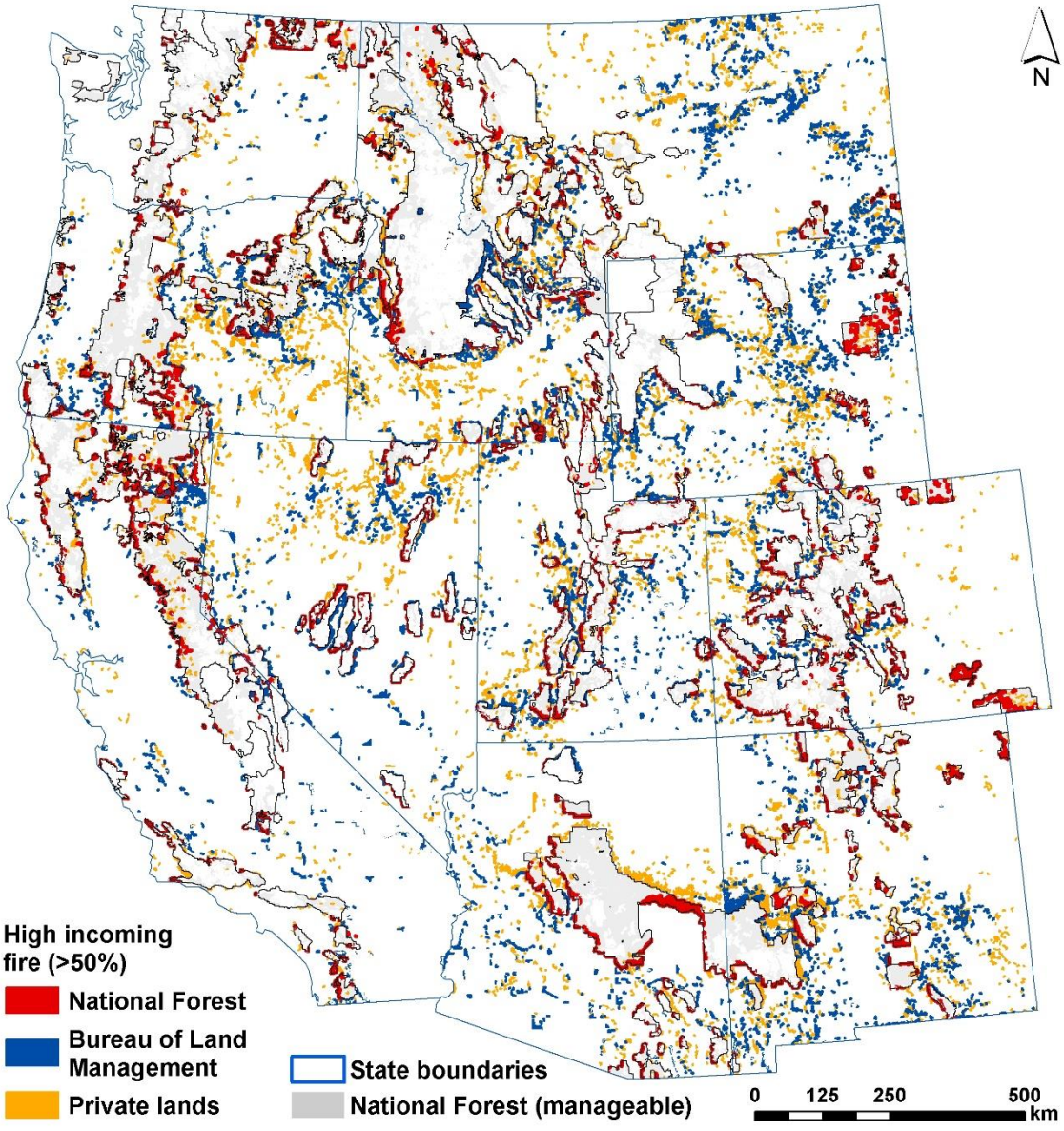

Figure 5: Locations where incoming fire exceeds >50% of the total fire (incoming +self-burning) on the three larger land tenures of the western US.

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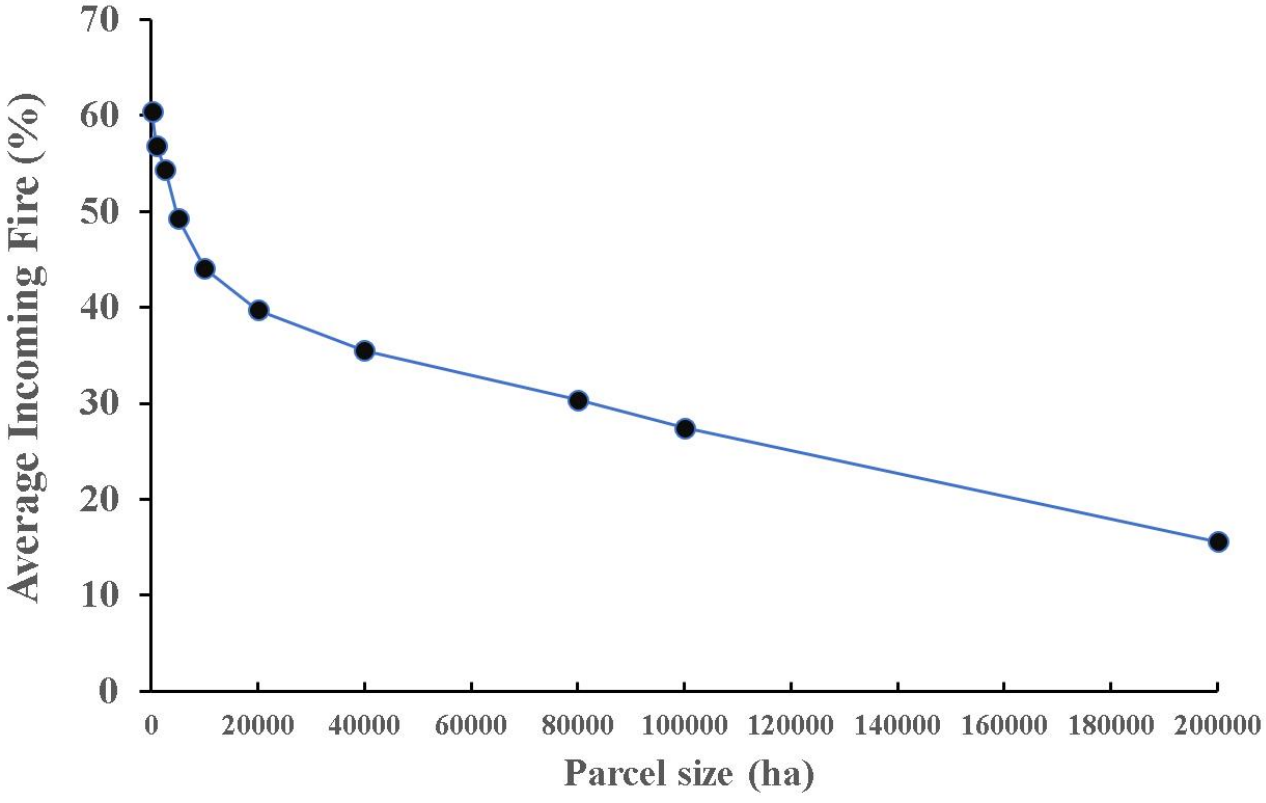

Figure 6: Relationship between parcel size and average percentage of incoming fire.

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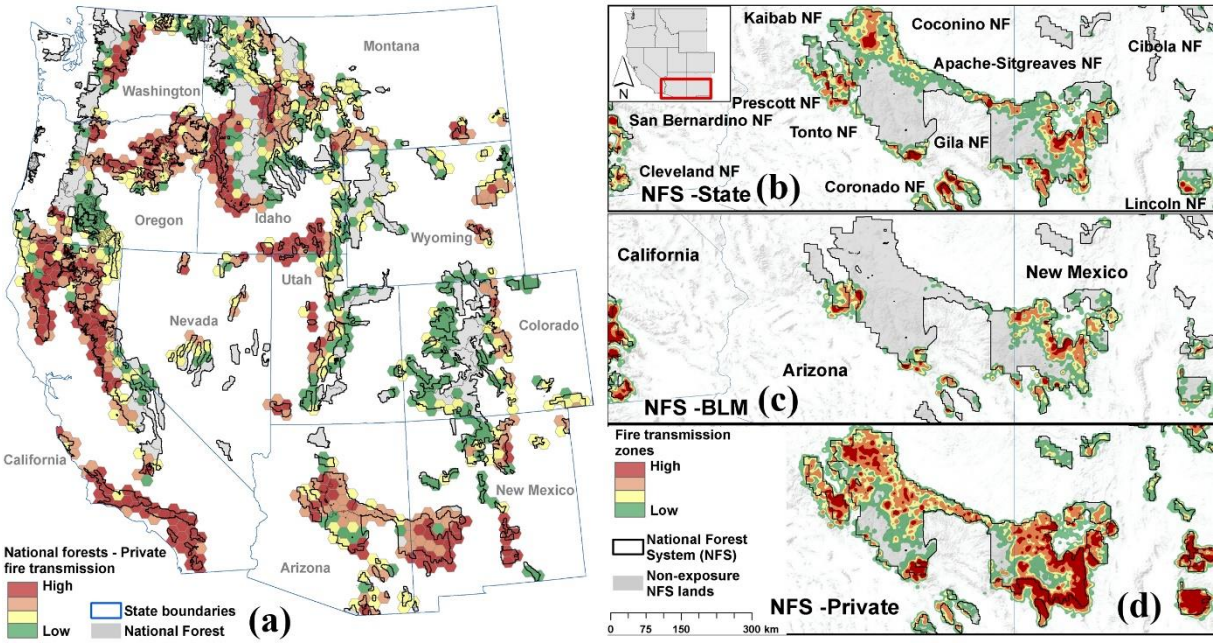

Figure 7: Cross boundary wildfire from national forests (NFS) to private lands (a). Grey areas indicate national forest lands where transmission to other land tenures is very low (high percent of self-burning fire). Panels to the right zoom in the southern part of the study area to show the detailed cross-boundary fire transmission zones and highlight the differences among the three couples of the largest land tenures of the western US: (a) NFS-State; (b) NFS-BLM; (c) NFS-Private.

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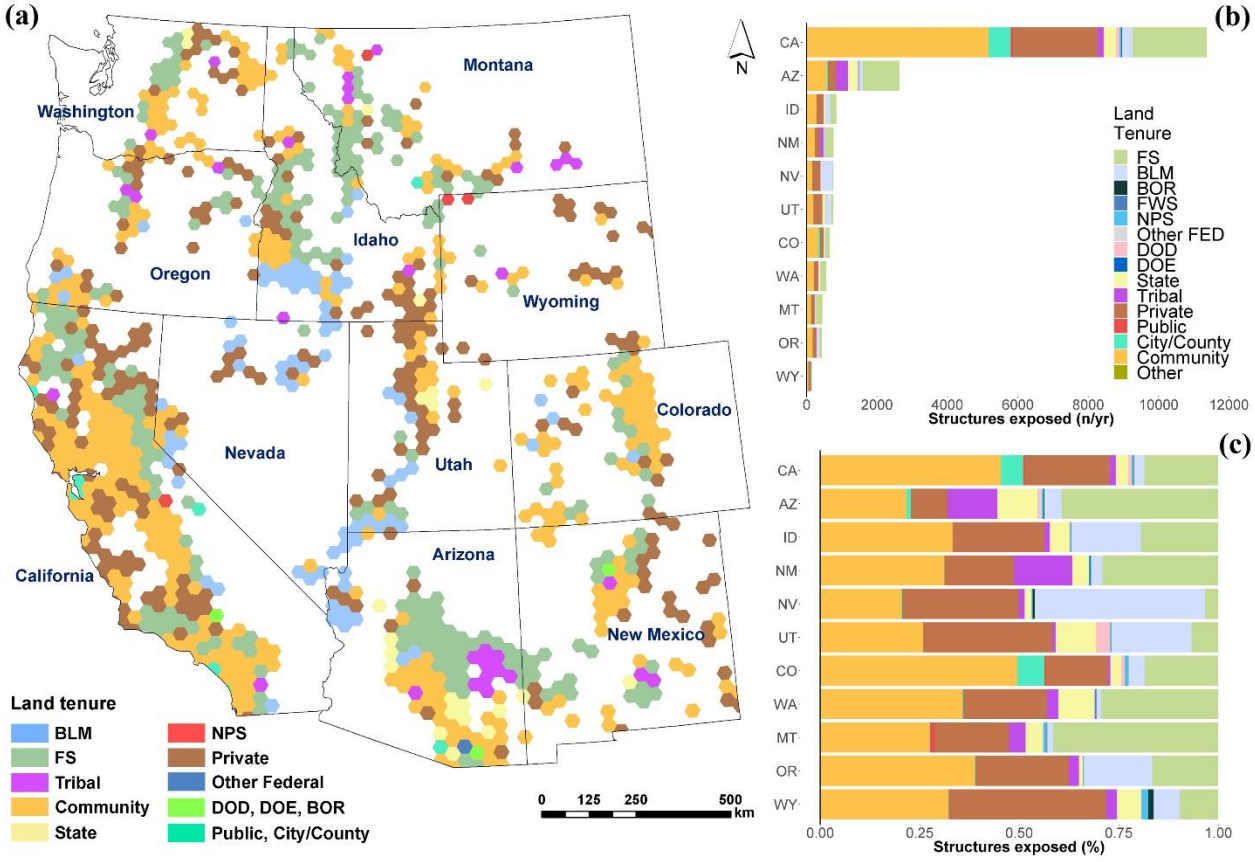

Figure 8: (a) Land tenures contributing the highest structure exposure to communities in the western US. (b) Total annual structure exposure by State; (c) Percent exposure for each State by the land tenure where the fire was ignited.

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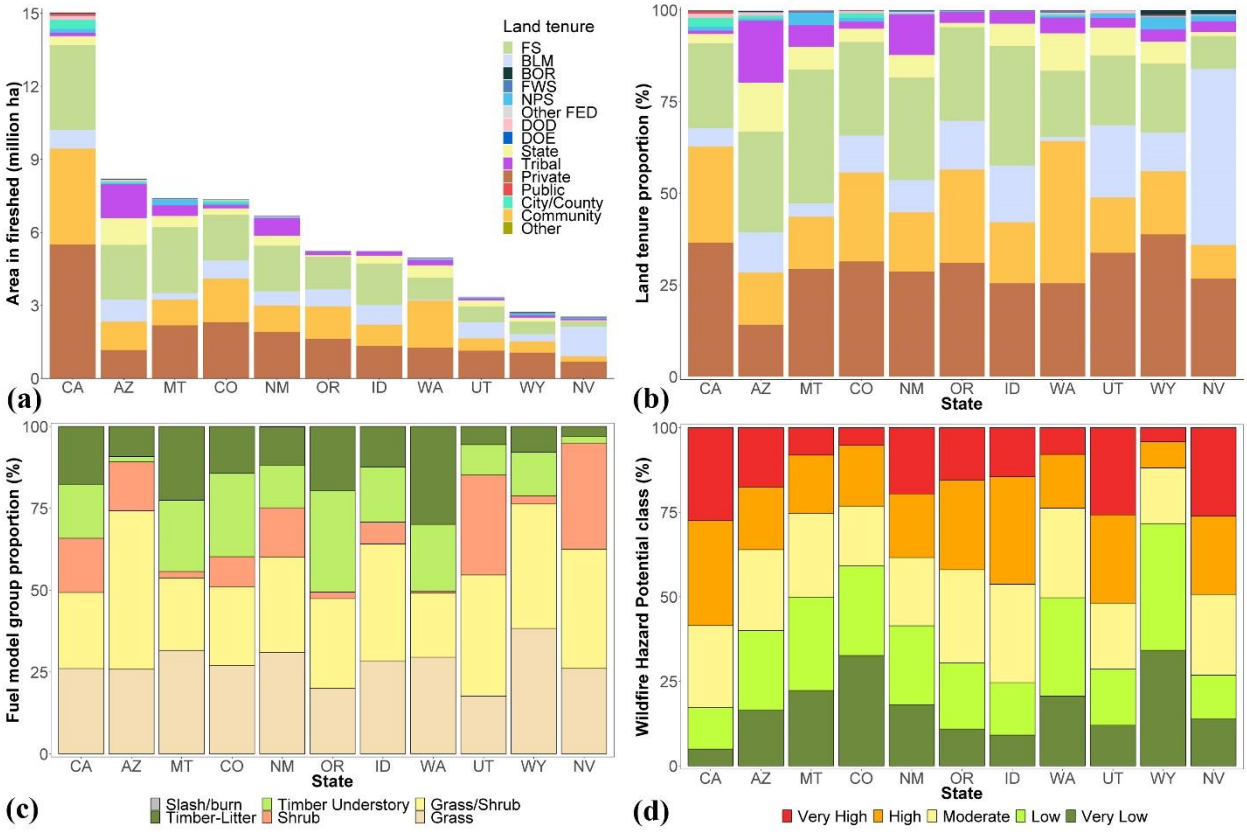

Figure 9: Characteristics of the western states in the study area in terms of State level breakdown for: (a) land tenure area; (b) land tenure percentages area; (c) fuel model composition percentage; (d) average wildfire hazard potential (Dillon et al., 2015); for the western US.

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Tables

Table 1: Average parcel area and perimeter, total number of parcels, and total area for each land tenure across the western US. See text for definition of the "other federal" category.

Land Tenure	Number of Parcels	Average Parcel Size (ha)	Average Parcel Perimeter (km)	Total Area (ha)
DOE	31	19,545	30.8	606,543
NPS	557	14,528	36.7	8,124,284
DOD	513	11,271	21.0	5,808,883
FS	7,164	8,009	29.9	57,538,442
Tribal	4,674	4,074	13.5	20,218,201
FWS	1,359	2,213	11.1	3,013,824
BLM	51,740	1,369	10.7	71,081,410
Other Federal	269	1,073	22.9	290,392
Private	134,611	731	8.4	96,161,657
BOR	981	591	10.6	611,394
WUI	49,715	448	10.0	22,391,746
State	48,321	397	7.5	19,360,591
Public	2,659	346	6.9	1,030,294
City County	13,605	75	2.8	1,162,538

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Table 2: Percentages of the total incoming fire to each land tenure (rows) from other land tenures (columns).

	BLM	BOR	City County	Comm.	DOD /DOE	USFS	FWS	NPS	Other Fed.	Priv.	Public	State	Tribal	Total fire (ha/yr.)
BLM	n/a	0.2	0.2	5.6	1.2	13.1	1.1	1.1	0.1	62.6	0.3	12.8	1.8	80,661
BOR	21.2	n/a	0.2	14.0	0.1	7.1	0.1	2.0	0.0	45.5	0.1	8.0	1.9	697
City/County	4.1	0.0	n/a	35.9	0.5	18.2	0.2	0.4	0.1	28.0	1.3	6.9	4.5	4,037
Community	11.4	0.2	3.6	n/a	0.6	32.5	0.1	0.4	0.1	38.0	0.6	7.1	5.3	41,888
DOE/DOE	35.5	0.0	1.2	12.3	n/a	17.5	1.2	0.3	0.0	24.1	0.5	7.2	0.2	2,900
USFS	14.7	0.1	0.9	18.0	0.3	n/a	0.2	2.3	0.0	46.2	0.7	10.0	6.5	60,092
FWS	44.3	0.1	0.5	4.6	1.1	8.4	n/a	0.3	0.7	28.3	0.6	10.0	1.1	1,613
NPS	22.2	0.5	0.6	5.4	0.3	51.8	0.1	n/a	0.0	13.2	0.1	3.6	2.3	3,328
Other Federal	12.1	0.2	2.1	13.7	0.2	4.4	5.5	0.1	n/a	43.9	0.4	16.6	0.8	184
Private	41.4	0.2	0.9	12.3	0.4	25.9	0.4	0.3	0.1	n/a	0.9	15.2	2.0	127,600
Public	8.4	0.0	2.0	9.7	0.3	23.9	0.5	0.1	0.1	46.6	n/a	7.1	1.2	2,579
State	26.5	0.1	0.7	6.6	0.6	16.8	0.5	0.2	0.1	45.7	0.4	n/a	1.9	42,021
Tribal	16.9	0.1	1.1	17.6	0.1	33.1	0.1	0.7	0.0	22.9	0.2	7.1	n/a	9,518

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Table 3: Percentages of the total outgoing fire from each land tenure (rows) to the other land tenures (columns).

	BLM	BOR	City County	Comm.	DOD /DOE	USFS	FWS	NPS	Other Fed.	Priv.	Public	State	Tribal	Total fire (ha/yr.)
BLM	n/a	0.2	0.2	5.8	1.3	10.7	0.9	0.9	0.0	64.3	0.3	13.5	2.0	82,160
BOR	25.7	n/a	0.1	13.1	0.1	5.7	0.2	2.4	0.0	43.3	0.2	8.1	1.0	655
City/County	4.1	0.0	n/a	38.1	0.9	14.3	0.2	0.5	0.1	30.1	1.3	7.5	2.7	3,906
Community	11.9	0.3	3.8	n/a	0.9	28.6	0.2	0.5	0.1	41.4	0.7	7.3	4.4	37,867
DOE/DOE	42.6	0.0	0.8	11.5	n/a	8.6	0.8	0.4	0.0	24.3	0.3	10.1	0.4	2,339
USFS	14.8	0.1	1.0	19.2	0.7	n/a	0.2	2.4	0.0	46.4	0.9	9.9	4.4	71,133
FWS	47.6	0.0	0.4	3.1	2.0	5.4	n/a	0.2	0.6	28.5	0.6	10.7	0.8	1,793
NPS	29.0	0.5	0.5	6.0	0.2	45.7	0.2	n/a	0.0	12.8	0.1	2.9	2.2	3,069
Other Federal	16.7	0.1	0.8	13.8	0.3	10.4	4.2	0.0	n/a	39.5	0.8	12.3	1.1	250
Private	42.1	0.3	0.9	13.3	0.6	23.1	0.4	0.4	0.1	n/a	1.0	16.0	1.8	119,923
Public	11.1	0.0	2.1	10.3	0.6	18.7	0.4	0.1	0.0	48.0	n/a	7.6	0.8	2,387
State	25.6	0.1	0.7	7.3	0.5	14.8	0.4	0.3	0.1	48.0	0.5	n/a	1.7	40,403
Tribal	12.7	0.1	1.6	19.8	0.0	34.9	0.2	0.7	0.0	22.6	0.3	7.0	n/a	11,235

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Appendix A

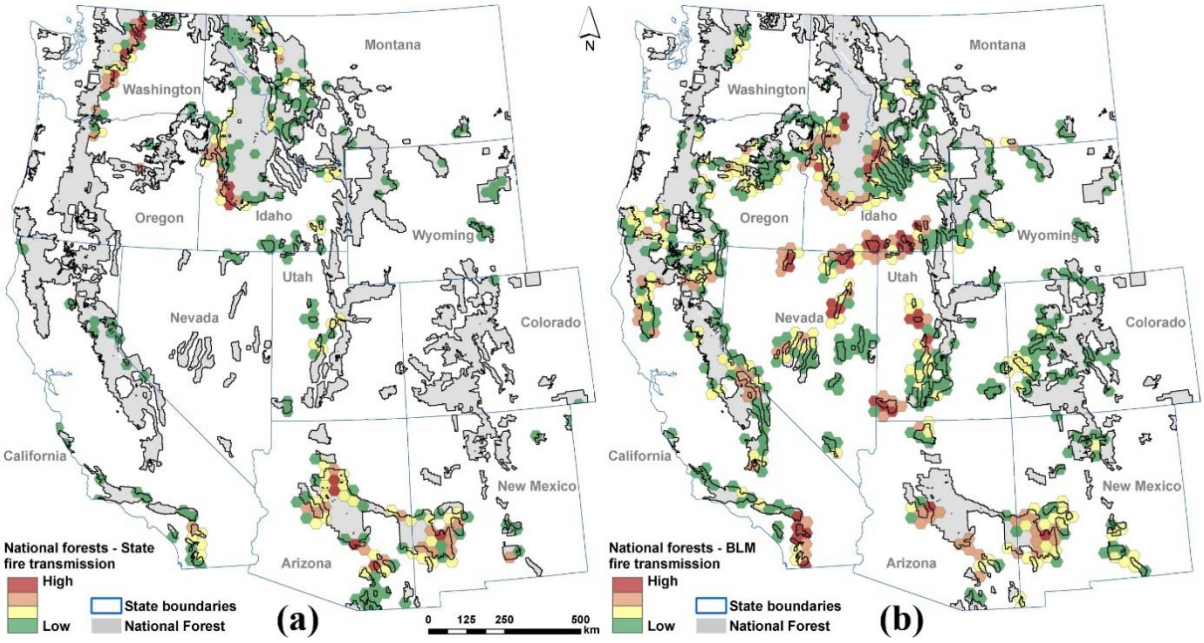

Figure A1: Cross-boundary wildfire transmission zones from national forests to (a) state and (b) BLM lands. Grey areas indicate national forest lands where transmission to other land tenures is very low (high percent of self-burning fire).

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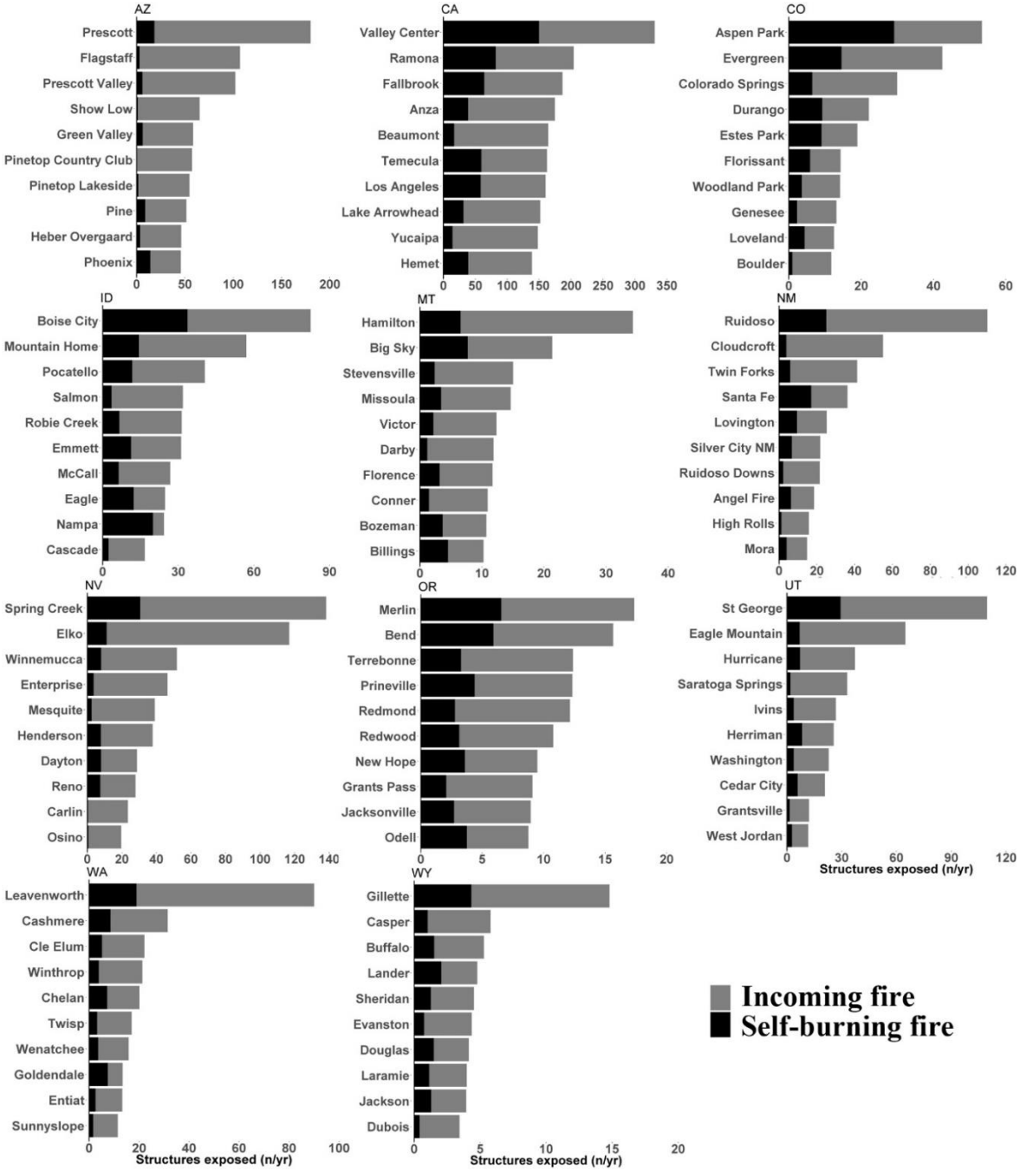

Figure A2: The top-10 communities for each state with the highest predicted fire exposure.

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Appendix B

Table B1: Percentage of fire adapted area (fire regimes 1 or 3) (source: LANDFIRE 2014) for each land tenure and State.

	AZ	CA	CO	ID	MT	NM	NV	OR	UT	WA	WY
BLM	16.5	15.3	59.7	34.6	19.5	34.9	32.6	70.9	36.2	20.4	3.9
BOR	3.9	26.0	13.7	5.0	10.5	6.7	0.2	21.6	n/a	1.9	5.1
City/County	3.5	34.7	50.6	n/a	22.5	47.6	38.6	66.3	26.0	9.4	21.4
DOD	1.1	7.2	13.2	0.0	37.7	37.2	14.9	34.8	2.8	20.6	6.9
DOE	n/a	n/a	34.4	7.9	n/a	96.9	15.8	n/a	n/a	13.0	n/a
USFS	61.4	78.6	40.7	68.3	54.3	84.8	64.7	74.6	64.9	53.8	22.0
FWS	2.4	16.9	31.0	14.3	14.1	38.9	25.8	45.3	4.5	35.3	14.5
Other Federal	29.3	23.2	17.0	3.0	10.9	4.3	n/a	3.3	50.4	0.5	n/a
Private	27.7	47.8	21.4	34.7	18.7	31.6	21.5	51.0	32.1	24.7	9.8
NPS	32.3	18.1	47.7	13.1	25.6	40.3	10.2	47.0	36.5	18.0	13.2
Public	8.7	57.5	38.2	73.5	38.5	24.5	27.4	52.2	40.7	7.8	32.4
State	22.5	33.3	22.9	56.3	29.7	30.9	19.9	47.2	27.0	33.5	9.9
Tribal	33.9	53.6	77.3	50.9	22.1	64.5	24.9	67.8	40.2	55.9	13.8
Community	19.2	44.8	44.7	36.9	57.1	51.0	14.3	70.8	26.4	33.1	21.0

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Table B2: Predicted average fire size from all the ignitions of each land tenure and State, expressed as hectares burned per year.

Land tenure	AZ	CA	CO	ID	MT	NM	NV	OR	UT	WA	WY	Average
BLM	695	649	559	968	474	330	1308	865	738	437	333	669
BOR	628	451	405	393	298	186	1085	425	0	163	234	388
City/County	401	908	464	525	378	134	226	638	104	168	931	443
DOD	429	493	371	1231	1914	254	359	228	413	405	263	578
DOE	0	0	14	565	0	1083	745	0	0	99	0	228
USFS	1676	997	543	1171	1427	2378	1091	1012	582	938	926	1158
FWS	444	310	282	555	488	219	582	654	204	233	257	384
Other Federal	744	408	152	450	807	267	0	51	139	143	0	287
Private	494	641	379	890	478	443	1351	634	743	356	420	621
NPS	614	301	478	4096	2994	283	1232	172	474	223	2547	1219
Public	514	610	554	1710	398	445	4687	677	824	355	647	1038
State	462	589	424	953	534	435	1827	795	619	639	415	699
Tribal	927	1096	482	1075	421	577	895	1027	461	531	463	723
Community	652	559	480	434	578	544	791	369	494	366	393	515

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Table B3: List of the top-100 most exposed communities, ranked by the total amount of annual structure exposure (sum of incoming and self-burning fires).

Rank	Community	State	County	Predicted Structures exposed from incoming fires (n/yr)	Structures exposed from self-burning fires (n/yr)	Total structure exposure (n/yr)
1	Valley Center	CA	San Diego	180.9	150.0	330.9
2	Ramona	CA	San Diego	122.1	82.0	204.1
3	Fallbrook	CA	San Diego	122.7	63.9	186.6
4	Prescott	AZ	Yavapai	161.6	18.4	180.0
5	Anza	CA	Riverside	135.7	38.8	174.5
6	Beaumont	CA	Riverside	147.4	16.7	164.1
7	Temecula	CA	Riverside	102.9	59.4	162.4
8	Los Angeles	CA	Los Angeles	101.7	58.4	160.1
9	Lake Arrowhead	CA	San Bernardino	120.2	31.4	151.7
10	Yucaipa	CA	San Bernardino	133.8	14.1	147.9
11	Hemet	CA	Riverside	99.6	39.1	138.6
12	Spring Creek	NV	Elko	107.6	30.6	138.2
13	Banning	CA	Riverside	110.0	19.2	129.2
14	Santa Clarita	CA	Los Angeles	96.1	30.8	126.9
15	Crestline	CA	San Bernardino	104.0	22.2	126.2
16	Idyllwild Pine Cove	CA	Riverside	103.0	23.1	126.1
17	Elko	NV	Elko	105.7	11.2	116.9
18	Alpine	CA	San Diego	85.0	25.9	110.9
19	Ruidoso	NM	Lincoln	85.2	25.0	110.2
20	St George	UT	Washington	80.2	29.4	109.6
21	Flagstaff	AZ	Coconino	103.9	3.1	107.0
22	Mead Valley	CA	Riverside	63.4	41.6	104.9
23	Aguanga	CA	Riverside	79.5	24.2	103.6
24	Prescott Valley	AZ	Yavapai	96.3	5.9	102.2
25	Wildomar	CA	Riverside	68.0	27.0	95.1
26	Murrieta	CA	Riverside	62.5	29.5	92.0
27	Bonsall	CA	San Diego	59.0	32.4	91.3
28	Leavenworth	WA	Chelan	71.0	19.0	90.0
29	Escondido	CA	San Diego	74.7	15.1	89.8
30	Redding	CA	Shasta	44.2	43.6	87.8
31	Jamul	CA	San Diego	57.0	26.7	83.6

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Rank	Community	State	County	Predicted Structures exposed from incoming fires (n/yr)	Structures exposed from self-burning fires (n/yr)	Total structure exposure (n/yr)
32	Lexington Hills	CA	Santa Clara	58.3	24.5	82.8
33	Boise City	ID	Ada	48.8	33.7	82.5
34	San Diego	CA	San Diego	57.4	24.1	81.5
35	Lake Mathews	CA	Riverside	55.4	25.5	80.9
36	San Diego Country Estates	CA	San Diego	67.2	12.3	79.5
37	Moreno Valley	CA	Riverside	60.9	16.8	77.8
38	Running Springs	CA	San Bernardino	66.6	4.7	71.3
39	Lake Forest	CA	Orange	57.2	12.8	70.0
40	Good Hope	CA	Riverside	47.0	20.0	67.1
41	Lake Elsinore	CA	Riverside	57.9	8.9	66.9
42	Menifee	CA	Riverside	41.7	23.9	65.6
43	Show Low	AZ	Navajo	63.9	1.3	65.2
44	Eagle Mountain	UT	Utah	58.0	6.9	64.9
45	Redlands	CA	San Bernardino	43.9	17.9	61.7
46	Valle Vista	CA	Riverside	55.0	6.1	61.0
47	Temescal Valley	CA	Riverside	50.8	8.2	59.1
48	Green Valley	AZ	Pima	52.2	6.2	58.4
49	Pinetop Country Club	AZ	Navajo	57.0	0.4	57.4
50	Mountain Home	ID	Elmore	42.7	14.3	57.0
51	Lake Riverside	CA	Riverside	45.9	10.9	56.9
52	Chino Hills	CA	San Bernardino	42.3	13.7	55.9
53	French Valley	CA	Riverside	48.7	7.1	55.9
54	Cloudcroft	NM	Otero	51.1	3.8	55.0
55	Pinetop Lakeside	AZ	Navajo	53.0	1.7	54.7
56	Calabasas	CA	Los Angeles	45.1	9.2	54.3
57	Calimesa	CA	Riverside	39.7	14.3	54.0
58	Aspen Park	CO	Jefferson	24.3	29.1	53.4
59	Rainbow	CA	San Diego	40.3	12.8	53.1
60	Simi Valley	CA	Ventura	44.0	8.5	52.4
61	Ojai	CA	Ventura	46.5	5.5	52.1
62	Thousand Oaks	CA	Ventura	37.9	14.1	52.1
63	Winnemucca	NV	Humboldt	43.9	8.0	51.9
64	Pine	AZ	Gila	42.7	8.7	51.4

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Rank	Community	State	County	Predicted Structures exposed from incoming fires (n/yr)	Structures exposed from self-burning fires (n/yr)	Total structure exposure (n/yr)
65	San Jacinto	CA	Riverside	40.7	8.7	49.4
66	Lakeland Village	CA	Riverside	42.5	5.9	48.4
67	Nevada City	CA	Nevada	21.6	25.0	46.6
68	Enterprise	NV	Clark	42.7	3.6	46.3
69	Heber Overgaard	AZ	Navajo	42.7	3.5	46.2
70	Boulder Creek	CA	Santa Cruz	33.0	12.8	45.8
71	Phoenix	AZ	Maricopa	31.6	14.1	45.7
72	Hidden Meadows	CA	San Diego	35.6	9.3	44.9
73	Cherry Valley	CA	Riverside	37.9	6.9	44.9
74	Castaic	CA	Los Angeles	39.9	4.4	44.3
75	Tucson	AZ	Pima	29.4	14.7	44.1
76	Big Bear City	CA	San Bernardino	36.6	7.1	43.6
77	Poway	CA	San Diego	32.3	11.0	43.3
78	Julian	CA	San Diego	29.6	13.5	43.1
79	San Jose	CA	Santa Clara	35.3	7.7	43.0
80	Oak Glen	CA	San Bernardino	36.1	6.7	42.8
81	Evergreen	CO	Jefferson	27.9	14.5	42.5
82	Scottsdale	AZ	Maricopa	20.9	21.2	42.1
83	Lake of the Woods	AZ	Navajo	41.3	0.7	42.1
84	Yosemite Lakes	CA	Madera	25.8	15.6	41.4
85	Twin Forks	NM	Otero	35.4	5.9	41.3
86	Payson	AZ	Gila	38.0	2.9	41.0
87	Pocatello	ID	Bannock	28.8	11.7	40.5
88	Kachina Village	AZ	Coconino	39.7	0.6	40.3
89	Coarsegold	CA	Madera	23.2	16.8	40.0
90	Atascadero	CA	San Luis Obispo	24.8	14.9	39.8
91	Santa Rosa	CA	Sonoma	24.0	15.5	39.6
92	Mesquite	NV	Clark	36.6	2.5	39.1
93	Topanga	CA	Los Angeles	27.1	11.5	38.7
94	Santa Paula	CA	Ventura	32.7	5.8	38.5
95	Harbison Canyon	CA	San Diego	32.1	6.3	38.4
96	Henderson	NV	Clark	30.0	7.9	37.8
97	Coto de Caza	CA	Orange	35.7	2.1	37.8

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Rank	Community	State	County	Predicted Structures exposed from incoming fires (n/yr)	Structures exposed from self-burning fires (n/yr)	Total structure exposure (n/yr)
98	Corona	CA	Riverside	31.8	5.8	37.6
99	Auberry	CA	Fresno	16.2	21.4	37.5
100	Campo	CA	San Diego	29.0	8.5	37.5