Interactive comment on "Fine scale assessment of cross boundary wildfire events in the Western US" by Palaiologos Palaiologou et al.

Anonymous Referee #1

Received and published: 21 March 2019

The manuscript entitled "Fine scale assessment of cross boundary wildfire events in the Western US" aims to analyze cross-boundary wildfire exchange among major land tenures on public and private lands in western US by using fire simulation modeling.

The authors also evaluated how ignition types and land tenure characteristics affect wildfire transmission and exposure patterns, and estimated wildfire exposure in terms of incoming or self-burning fires at the community level.

Overall, the work is interesting and the subject addressed in this manuscript is worthy of investigation. The manuscript provides an interesting methodology to inform wildfire risk assessment and to prioritize fuel management in areas at high-risk. The manuscript is well written and clear. Methods and results are adequately described and presented, and the discussion and conclusions are justified by the data presented.

A few points should be better addressed or improved by the authors and can improve the quality of the manuscript.

I recommend a minor revision before publication.

Reply: Many thanks for the comments. We have revised the manuscript carefully to address all your comments/suggestions.

Specific Comments

Pag. 2 – L3-4 (and others): Please order the references following chronological and alphabetical order

Reply: Corrected throughout the manuscript. References have been listed alphabetically at the end of the manuscript under the first author's name. In-text citations were ordered chronologically and for the cases of same year, alphabetically.

Pag. 2 – L26: I suggest replacing "to predict future levels" with "to analyze"

Reply: Corrected as suggested by the reviewer.

Pag. 3 – L22: Please define the meaning of "fire regimes 1 and 3"

Reply: We rephrased the sentence as “Approximately 115 million ha are fire adapted with low and mixed severity fires, as defined by fire regimes 1 (≤35-year fire return interval) and 3 (>35 - 200 year fire return interval)…”

Pag. 4 – L9-11: Even if the FSim modeling approach proposed in this work was covered in previous works, I recommend to provide more information (e.g.: resolution of input and output data; settings of the simulated spot fires; etc.)

Reply: We edited the whole section to provide more information on FSim fire behavior modelling, including details on the evaluation process, resolution, and crown/spotting.

Pag. 6 – L5: Please replace “define” with “defines”

Reply: Corrected as suggested by the reviewer.

Pag. 11 – L27: Please add space between “2012)” and “Human”

Reply: Corrected as suggested by the reviewer.

Pag. 12 – L13: Do the author mean “extent”?

Reply: Corrected to “extent”.

Pag. 14 – L12: Do the authors mean “fuel model”?

Reply: Corrected to “fuel model”.

Figure 2b: In the upper graph, please modify the y-axis adopting the same scale (0- 300) used in Figure 2a.

Reply: Corrected as suggested by the reviewer.

Figure 3: Please specify the acronyms of the land tenures in the Figure legend. In addition, make uniform the size of the graphs (for example, OR graph is larger than WA graph size), so that the graph size will not be different depending on the State

Reply: Acronyms were added, and graph size has been standardized across all states.

Figure 4: Please replace “By” with “by”

Reply: Rephrased as: “(a) Average percentage of incoming fire across the western US; (b) by state, calculated for its entire area and for all land tenures; (c) by land tenure, across all the 11 western US states.”

Figure 5: The color used for National Forests (grey) is too light and does not help readers: please use a darker grey.

Reply: Corrected.

Figure 6: In the x-axis, please use thousand ha, rather than ha

Reply: Corrected.

Figure 7: Again, the grey is too light. Moreover, please replace “to show” with “show”

Reply: Corrected.

Figure 8: Please specify the acronyms of the land tenures in the Figure legend.

Reply: Acronyms were added as suggested by the reviewer.

Figure 9c: Considering that the percentage area covered by slash/burn seems very limited, the authors could remove it from both Figure and legend.

Reply: We removed the fuel model class “slash/burn” as suggested by the reviewer.

Table 1: Please explicit the full name of each land tenure, before or after the acronym

Reply: We added the full names of each land tenure before each acronym.

Table B1: This supplementary table is not mentioned in the text.

Reply: It was mentioned on Page 3, Line 23, in the part where we explain the extent of fire adapted lands, mentioning that the differences among States and land tenures can be found in Table B1.

Table B2: Please consider to replace “0” with “N/A.”, as you did in Table B1

Reply: Zeros were replaced with “n/a” as suggested by the reviewer.

Interactive comment on “Fine scale assessment of cross boundary wildfire events in the Western US” by Palaiologos Palaiologou et al.

Anonymous Referee #2

Received and published: 5 May 2019

This work extends previous fire transmission works to a larger spatial scale, using methods developed by some of the same authors.

The paper is well written, and most of it is very clear. The design of the research is well done, the methods are suited for the purpose, and the major findings are well supported by the results and other studies referenced by the authors.

Reply: Many thanks for the comments. We have revised the manuscript carefully to address all your comments/suggestions.

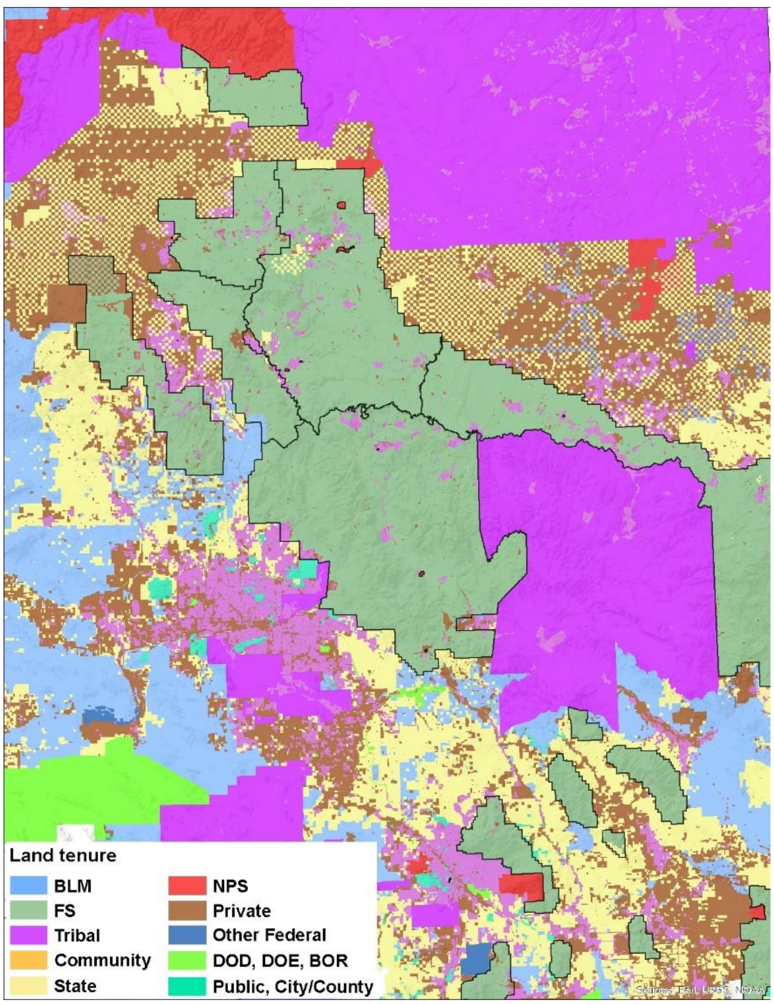
General comments:

1. I understand that the same simulation methods described here have been used in other works and you want to avoid unnecessary repetitions. Nevertheless, as you mentioned, the spatial scale of the simulations presented in this work is unprecedented, and researchers working on similar topics\tools will surely want to understand how they were done. For example: what was the total number of simulations, and what was the spatial resolution of the data used? Adding to this comment, I think it is important to mention that multiple fire seasons are simulated (and not only individual wildfires).
Reply: The FSim simulation section has been substantially edited and expanded, considering the reviewer’s suggestions.

2. At the end of the Introduction you depict three very clear specific questions that you want to address in this work. Then you add that “the results were used to understand how anthropogenic actions influence (...) fire transmission, notably parcel geometry, landownership composition and landscape fragmentation (…).” Where is this shown in the results? For example, the analysis of “checkerboard vs. large boundary lines between two land tenures”. Additionally, in what sense is “parcel geometry” a “anthropogenic action”? Regardless, if this analysis is\was really performed my suggestion is that you add it to a 4th question.
Reply: We followed the reviewer’s suggestion and added this part as a 4th question.

Previous research efforts revealed that parcel geometry and relative size of different ownerships set the stage for fire transmission across boundaries (Ager et al., 2014, 2017, 2018) and is defined by anthropogenic actions. Landscape is full of artificial boundaries, and human actions define not only ownership boundaries and shape, but also what management and land use is occurring in each parcel. At the scale of public land parcels in the United States, transboundary fire risk is primarily an artifact of landscape fragmentation with respect to ownership and administrative fire management jurisdictional boundaries (Ager et al., 2017). In terms of the 'firescape", inside ownership parcels new boundaries are created especially by vegetation management practices (half parcel was treated/half not) or other activities (half grazed/half not).

The most prominent results are in Figure 6, where we show how the percentage of incoming fire is reduced with increasing parcel size across all land tenures. In Figure 2 we show how landownership composition defines the amounts of incoming, self-burning and outgoing fire. In Figure 5 we demonstrate the effect of checkerboard vs. large boundary lines between two land tenures on fire transmission. For example, the large red area in southeastern part of Arizona inside the Apache-Sitgreaves National Forest share a large common boundary with Tribal lands (purple) covered with grass and shrub fuel models (please see example figure 1). North of this area, the checkerboard effect between private and state lands create the high incoming fire on private lands (orange, Figure 5).



Example figure 1: Land tenures in Arizona

References:

Ager, A.A., Day, M.A., Finney, M.A., Vance-Borland, K., and Vaillant, N.M. **2014**. Analyzing the transmission of wildfire exposure on a fire-prone landscape in Oregon, USA, Forest Ecology and Management, 334, 377-390.

Ager, A.A., Evers, C.R., Day, M.A., Preisler, H.K., Barros, A.M., & Nielsen-Pincus, M. **2017**. Network analysis of wildfire transmission and implications for risk governance. PloS one, 12(3), e0172867.

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

3. The statistical model of human\natural ignitions needs to be clarified. This is an important part of your work because part of your results (and conclusions) depend on the predicted cause of ignitions. How well does this model work? Did you calculate performance statistics? Did you use a set to calibrate the model and another to validate? A complex model is not synonymous of a good model. Please provide a clear(er) equation of the model so that all interested readers can understand and replicate if necessary.
Reply: We substantially revised the section and we added a new figure in the appendix (reliability diagram). A clearer equation has been added. We also explain how the goodness of fit of the model was assessed.

4. What is the difference between a “fireshed” and “community fireshed”? Did you use both?
Reply: Technically, it can be show different values when we examine each community separately vs. all communities. This means that the fireshed as a whole include all lands that expose all communities, with structure exposure values for the entire analysis domain, while a single community fireshed values of structure exposure for that particular community. But this is not the case in our paper. We standardized our terminology and we refer to it as “fireshed”, removing the word “community” for the three cases found in the manuscript.

5. Using simulations is an interesting and powerful approach for issues such as the ones studied in this work. However, in my opinion, this should be accompanied whenever possible, by an analysis of the observed patterns. In a general sense, this work disregards much of that “connection to reality”. For example, a calibration exercise is not even mentioned. Another example: the patterns of fire transmission reported in 3.1 could be accompanied by an historical analysis to understand how well did the model predict historical fire transmission.
Reply: As we mention in the manuscript, the dataset of simulated fires was retrieved by the FireLab of the Rocky Mountain Research Station. Finney et al. 2011 did an extensive and complete accuracy assessment of the modelled fire perimeters we used in this work with historical data for the period 1992-2008. In that study, they used two metrics for comparing the simulations with observations (1) average burn probability for each FPU (pyrome), and (2) the fire size frequency distributions for each Geographic Area.

FSim could generate outputs that corresponded well to the patterns and trends evident from historical fire records. Conditions which contributed to the historic fires (ignition sources, land cover types and fire spread patterns) appear to be generalizable beyond that time period (1992-2008) and specific landscape pattern, proving that dry and windy conditions overwhelm the sensitivity of fire behavior to fine scale departures from model assumptions experienced under moderate conditions. Also, the range of modeled and historical burn probabilities estimated is generally consistent with those from other North American studies (Martell and Sun, 2008; Littell et al. 2009; Parisien and Moritz 2009). The close correspondence between simulated and observed fire size distributions was similar to that reported by Moritz et al. (2005).

In our paper, in addition to the comparison of the historic lightning-caused ignitions with simulated ignitions that we provide in the manuscript, using the 24 years of historic data (1992-2015) from the historic ignition database (Short 2017), we found that the historic annual burned area across the western US was 1,268,412 ha yr^{-1}, while the simulated dataset predicted 1,257,182 ha yr^{-1}. Moreover, a per state comparison between historic and predicted annual burned area is provided in a new appendix table. Largest annual differences between historic and predicted annual burned area were found for Oregon (+40,000 ha yr^{-1}), Washington (+29,000 ha yr^{-1}) and Idaho (+16,000 ha yr^{-1}), and Arizona (-23,000 ha yr^{-1}), Wyoming (-20,000 ha yr^{-1}) and New Mexico (-19,000 ha yr^{-1}).

Part of the response was incorporated in the revised manuscript.

References:

Finney, M.A., McHugh, C.W., Grenfell, I. C., Riley, K.L., and Short, K.C. **2011**. A simulation of probabilistic wildfire risk components for the continental United States, Stochastic Environmental Research and Risk Assessment, 25, 973–1000.

Littell J.S., McKenzie D., Peterson D.L., Westerling A.L., **2009**. Climate and wildfire area burned in western U.S. ecoprovinces, 1916–2003. Ecol Appl 19(4):1003–1021.

Martell D.L. and Sun H. **2008**. The impact of fire suppression, vegetation, and weather on the area burned by lightning-caused forest fires in Ontario. Can J For Res 38:1547–1563.

Moritz M.A., Morais M.E., Summerell L.A., Carlson J.M., Doyle J., **2005**. Wildfires, complexity, and highly optimized tolerance. Proc Natl Acad Sci 102(50):17912–17917.

Parisien M.A. and Moritz M.A., **2009**. Environmental controls on the distribution of wildfire at multiple spatial scales. Ecol Monogr 79(1):127–154.

6. After reading the 1st paragraph of the Discussion: it would be interesting to look at the results in terms of normalized incidence instead of total area (i.e. burned area / total area of a given type of cover). For example, national forests have highest predicted burned area because there is a large incidence or because they have the highest cover area?
Reply: We added two new columns in table 2 showing the total burned area (incoming + self-burning) for each land tenure and the normalized burned area by land tenure area. FS still ranks first in terms of normalized burned area, but followed by city/county, BLM, Public and Private. We also added a new column in table 3 where we show the normalized outgoing fire per land tenure. We added additional explanation both in results and on the first paragraph of the Discussion.

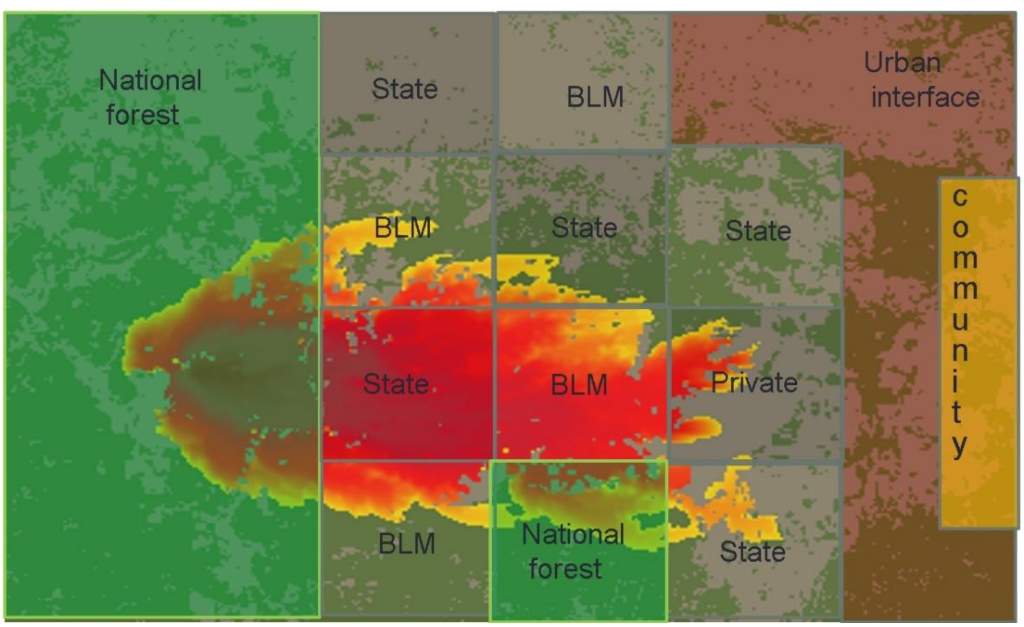
7. Why do you think small parcels tend to receive higher amounts of incoming fire?
Reply: Previous research have shown that decreasing complexity in parcel geometry (low perimeter to area ratio) was associated with decreasing transmitted fire (see Ager et al., 2014).

Consider two adjacent land parcels, A and B, of equal size and shape and conditions with respect to fire spread rate, intensity, ignition probability, suppression capacity, and potential loss (ecological, financial or other), and a random direction of wind. The net expected transmission of risk between the two parcels will be equal, despite ignitions in A burning parcel B and vice versa. Changing any one of the factors listed above creates the potential for unequal risk transmission among the parcels. Some of these factors are natural (e.g., wind direction) while others are ecological (e.g., fire regime), or anthropogenic (e.g., fuel management, urban development, or parcel geometry). The challenge at hand is to determine the magnitude of transmission among land parcels defined by administrative or ownership boundaries and identify the relative importance of the contributing factors.

The reason small parcels tend to receive higher amounts of incoming fire (given all other variables above are constant) is that interior of small parcels are burned more often due to their relatively small distance from the parcel edge. The magnitude of this effect depends on the ratio of fire size to parcel size. When the former is very large relative to the latter, there is a relatively high proportion of incoming fire. However, parcel edge complexity can also influence the incoming fire ratio.

Another factor that contributes to higher incoming fire for smaller parcels has to do with fire growth. Fires spreading as elliptical shapes cross out of the origin parcel with relatively small area burned because of the shape of the perimeter. However, when a small parcel is consumed by a fire that has spread some distance, the ellipse is now rounded and is spreading as a long flaming front. The simulated fire in Figure 2 is an outgoing National Forest fire, which becomes incoming to the smaller state parcel. On a percentage basis, not that much of the National Forest is burned, but state parcel is consumed.

Part of the response was incorporated in the revised manuscript.



Example figure 2: Fire transmission originated on a larger parcel (National forest) to smaller parcels (e.g., state, BLM).

Ager, A.A., Day, M.A., Finney, M.A., Vance-Borland, K., and Vaillant, N.M. 2014. Analyzing the transmission of wildfire exposure on a fire-prone landscape in Oregon, USA, Forest Ecology and Management, 334, 377-390.

Specific comments:

P2, L30: the fireshed
Reply: we added "the" as suggested by the reviewer.

P3, Study Area and land tenures: please mention here the size of your study area.
Reply: we added the size of the study area (307 million ha)

P3, L23-26: don't understand the sentence.
Reply: The information on this sentence was retrieved from:

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

We split the sentence in two parts and rephrased as:

"More than 65 million ha are of high or very high fire risk (Dillon et al., 2015) across all land tenures. On high or very high fire risk and low natural mortality National Forest System lands we can potentially treat seven million ha through traditional timber harvest methods and 14 million ha through prescribed fire and/or another fuels treatment (USDA Forest Service, 2018)."

P4, L6: maybe here it would be good to indicate what is the proportion of the total burned area comprised by these fires that you characterize.
Reply: We added this information in the revised section.

P5. In 2.4, what is the purpose of applying a kernel function to fit (…see the rest in Lines 17-19)?
Reply: The original dataset of cross-boundary transmission zones was comprised of two sets of ignitions: those ignited on land tenure 1 and burned into land tenure 2 (attributed with only the amount of fire that they send to land tenure 2); and the opposite (from land tenure 2 to land tenure 1). To convert ignitions into transmission zones we had to use an interpolation technique to project the values of fire transmission from all neighboring ignitions into a continuous surface that cover also the parts of the landscape without ignitions. Results can be seen in Figure 7 (b-d). We modified the whole sections 2.3 and 2.4 to clarify their meaning to the readers.

P5, L19: how was the NTFI calculated? What is the reference?
Reply: Members of our team have created a toolbox named XFire that can do all the necessary processing. It hasn't been released or published yet. We provided additional explanation of how the self-burning index was calculated – to simply put, it required spatial GIS calculations of the simulated fire perimeters with land tenure data and ignition points. Please refer to the revised section 2.3.

P6, L2: I don't understand the purpose of Scott and Burgan's reference.
Reply: The input data for the production of Figure 9c were the fuel model classes of Scott and Burgan (LANDFIRE data). We moved the reference in the caption of Figure 9.

P7, L21: remove "spatially". Redundant.

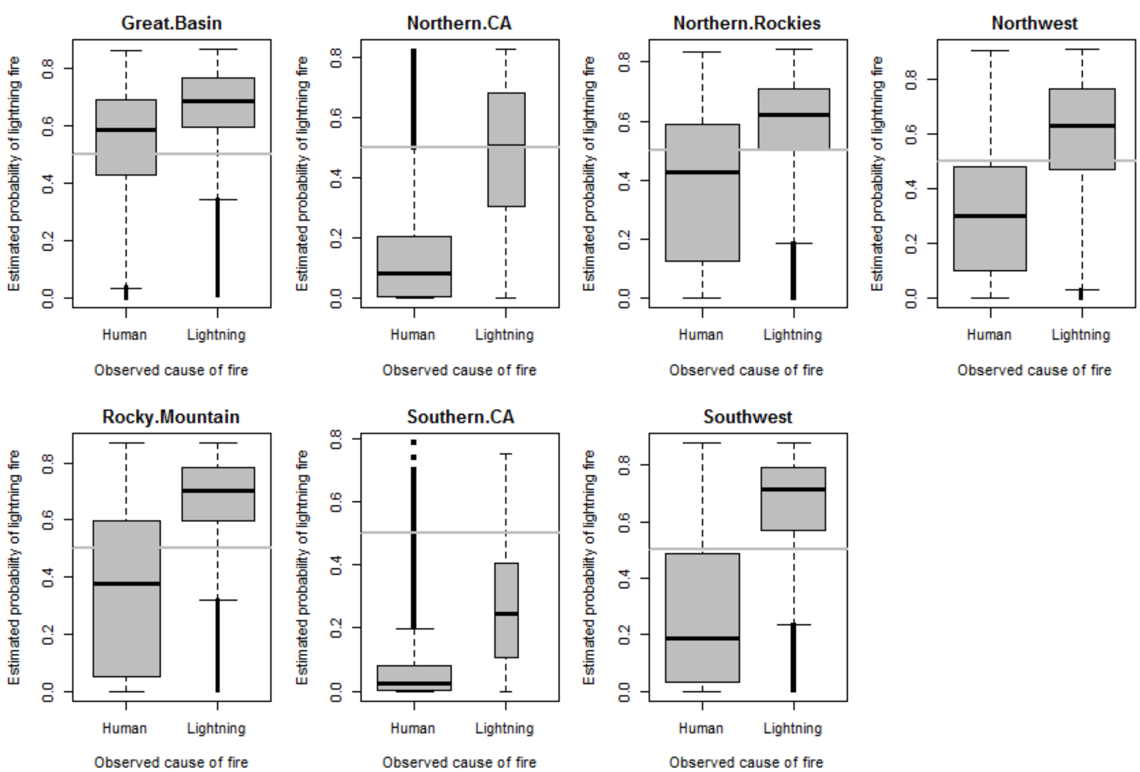
Reply: The word “spatially” has been removed.

P8, L1: don’t understand, probably because NTF index was not explained in the manuscript.
Reply: We added a detailed explanation in part 2.4 on how we estimated the self-burning index

P10, L6: if you use “was”, follow it by “large differences were”.
Reply: Corrected.

P10, L23: I believe it is “shrub fuels account for three quarter of the fuel models in some states”.
Reply: Corrected.

P11, L29: Why do you need probabilistic estimations? No reason provided to the reader.
Reply: The question was that given a hypothetical fire at a given location/day-in-year and size, is it a lightning or human fire? The answer is we can’t know for sure. However, given the historical info, we have seen historically that such fires are 60% of the time lightning caused. So, we can pick a random Bernoulli number with this probability to ascertain whether to assign lightning cause to this fire or not. At any given point and time (day-in-year) an ignition could be lightning with probability p and human with probability 1-p. So given a simulated ignition, this ignition is going to be lightning caused p% of the time. Notice, we are not simulating ignitions, but rather given an ignition we are deciding whether what was the most likely cause of that fire. In figure 3, the boxplots show the observed (human or lightning) fires vs the estimated probability for every GACC. We rephrased the sentence to provide additional info to the readers, including an additional figure in the Appendix.



Example figure 3: Boxplots showing observed (human or lightning) fires vs the estimated probability for every GACC.

P12, L7-9: something wrong with the sentence.
Reply: Rephrased.

P12, L13: extend?
Reply: Corrected to “extent”.

P12, L15-18: something wrong with the sentence.
Reply: Rephrased

P13, L23: what does “reduction of fire deficit” mean?
Reply: It was redundant and out of scope of the paper. It is now removed.

Figure 9: need to mention that the figure concerns fireshed characteristics, otherwise revise the location of the Figure in the document.
Reply: The paneled figures represent fireshed characteristics of each state. We revised the figure caption.

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 modelling 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 wildfire transmission and partitioned the relative amounts of transmitted fire between human and natural ignitions. We estimated that 85% 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 extent. 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 source 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 (Mitchell, 1994; Hills et al., 1998; Uitto and Duda, 2002; Zeitoun and Warner, 2006; Van Eerd et al., 2015; Lyons, 2016; Brack, 2017), habitat conservation (Liu et al., 2017), watershed restoration (Sayles and Baggio, 2017), water supply (Bark et al., 2014; Lara, 2015), 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 (Linnerooth-Bayer et al., 2001; Lidskog et al., 2010; Lidskog et al., 2011). 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 (US Congress, 2014; USDA Forest Service, 2015b, a, 2018). Implementation of these authorities to perform risk reduction on mixed ownership planning areas has helped demonstrate how cross-boundary collaboration can amplify the capacity of risk reduction activities by leveraging the economies of scale, i.e. expand the scale of fuel management (Graham et al., 2010; Ager et al., 2011) 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 landowners 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 (Ager et al., 2014b; Ager et al., 2018; Fischer et al., 2018; Evers et al., 2019; Hamilton et al., In press). For instance, where are zones of high fire transmission between large tracts of US federal and private lands, and are the former areas priorities for investment in hazardous fuels treatments?

In this study we address this gap by using fire simulation modelling to analyse cross-boundary fire exchange among major land tenures on 307 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 is the cross-boundary fire problem greatest and how does it vary among different land tenures and among the western US states? (2) What are the community fire exposure patterns and the extent of the fireshed, i.e., the area that encloses ignition locations that

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transmit fire to communities (Ager et al., 2015)? (3) How does ignition cause (human versus natural) affect fire transmission across boundaries? (4) How do anthropogenic actions influence the different scales and complexity of fire transmission, notably parcel geometry, ownership composition and landscape fragmentation (e.g., checkerboard vs. large boundary lines between two land tenures)?

2 Methods

2.1 Study area and land tenures

Our study area (307 million ha) 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 the 1970s, the average annual number of large fires has tripled and the average fire size has increased six fold (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). Community boundaries were based on SILVIS wildland-urban interface (WUI) layer (Radeloff et al., 2005), excluding polygons that were classified as uninhabited, water, were smaller than 0.1 ha or had structure density less than two structures per km^2. We used the PAD layer to estimate land tenure characteristics, including the number of parcels, average parcel area and perimeter for each land tenure.

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 (FS, 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 public lands (public trust and non-government organizations) with city/county (2 million ha) (Table 1). The extent of communities, including the WUI, is 22 million ha (Radeloff et al., 2005; Evers et al., 2019). Shrublands cover 27% of the study area, followed by herbaceous-grasslands (25%), and open (18%) and closed (11%) tree canopy forests (83% of which are conifers) (LANDFIRE, 2014). Approximately 115 million ha are fire adapted with low and mixed severity fires, as defined by fire regimes 1 (<35-year fire return interval) and 3 (>35 - 200 year fire return interval), with differences among States and land tenures (see Table B1). More than 65 million ha are high or very high fire risk (Dillon et al., 2014) across all land tenures. On high or very high fire risk National Forest

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2.2 Wildfire simulations

Wildfire simulations were generated by the FS Missoula Fire Science Laboratory (Short et al., 2016) with the Large Fire Simulator (FSim) and included a library with millions of simulated ignitions for each US State (19 million simulated fire perimeters in total, 3 million of which were predicted to burn inside community boundaries). 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. The term "large" is used for fires that escape initial attack, irrespective of their actual size (Finney et al., 2011b). These fires are the largest ~3-5% for each simulation region (67 "pyromes" in the western US) and account for the majority (~80-97%) of total area burned. FSim generates a historical relationship between these large fires and a fire danger rating index known as Energy Release Component (ERC), restricting fire growth to days on which ERC reaches or exceeds the 80th percentile condition.

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Our analysis relied on the 2016 dataset, which used inputs from the 2012 version of LANDFIRE data describing topography, fuels and vegetation structure at 30 m resolution (Rollins, 2009), resampled to 270 m to achieve practical simulation times. Simulated fires are not only based on different ignition locations, but also on multiple fire seasons. These fire seasons represent between 10,000 to 100,000 potential annual weather scenarios based on observed fire-weather relationships recorded since 1984 (Hall et al., 2003; Abatzoglou, 2013), generating hypothetical contemporary fire seasons from statistical characterizations of the past, without projecting future weather scenarios. To overcome the possible source of error in the location of ignition points, FSim uses an Ignition Density Grid to allocate ignitions proportionally across the landscape, created from the fire history record of each pyrome (Short, 2015). These fire behaviour calculations (Finney, 2006) yield the spread and intensity of surface fire (Rothermel, 1972), crown fire (Van Wagner, 1977; Rothermel, 1991), and spotting distances from torching trees (Albini, 1979) based on a spotting probability value. Model results (270 m resolution) are objectively evaluated for each simulation unit through comparison with historical fire patterns and statistics (mean annual burn probability and fire size distribution) (Finney et al., 2011b). This evaluation is part of the FSim calibration process, whereby simulation inputs are adjusted until the slopes of the historical and modelled fire size

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distributions are similar, and the modelled average burn probability falls within an acceptable range of the historical reference value (i.e., the 95% confidence interval for the mean) (Thompson et al., 2016). The system was capable of generating output that corresponded well to the patterns and trends evident from historical fire records (Finney et al., 2011b). 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 historical wildfire occurrence data of the western US for the 1992-2013 period (Short, 2015). Given the location (longitude/ latitude in decimal degrees), Geographic Area Coordination Centers (GACC, which are nine federally established regions in the continental US with the same fire administration), day of ignition (Julian day) and the size of a fire (acres), the probability (p) of the fire being natural caused was modelled using a logistic regression model with the logit line, θ, given by Eq. (1):

$$\theta = \log[p/(1-p)] = \mu + s_1(lon, lat) + s_2(jday, gacc) + s_3(lsize) \quad (1)$$

where μ is the intercept of the regression line, *lon* is longitude, *lat* is latitude, *jday* is the day-of-year when the fire occurred, *gacc* is the GACC, *lsize* is the logarithm of fire size, s_1 a two dimensional spline function, and s_2, s_3 are a cyclic and a regular cubic spline function respectively. The spline functions were estimated from the data using Generalized Additive Models (GAM) within the R MGCV package (Wood, 2006; R Core Team, 2016).

The goodness of fit of the model was assessed by first fitting the model to the data with a random sample of 20% of the records being kept for validation. Next, the probability of a given fire being natural caused was estimated for each fire in the validation group and compared with the actual observed fire cause by producing a reliability diagram (Appendix Figure A1). The reliability diagram was produced by binning the estimated probabilities into ~30 classes and plotting the relative frequency of the observed responses against the predicted mean probabilities in each class. Note that the probability of a fire being human caused is 1-p.

2.3 Fire exchange

FSim perimeters were intersected with the PAD land tenure layer and community boundaries. The resulting perimeter fragments were partitioned into self-burning (i.e., burned areas within the same land tenure as the ignition) and outgoing parts (i.e., burned areas outside of the ignition land tenure). The origin of each simulated wildfire (i.e., source land tenure) was assigned based on the location of ignition. The area of these fragments were summed into three fire exchange values per land tenure class (see Figures 2 & 3): (1) self-burning fire (TFself),

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Διέγραψε: *resp* is the probability of lightning ignition (i.e., 1 minus resp is the probability of a human-caused ignition),
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Διέγραψε: *bs* = *"cc"* specifies a cyclic cubic regression spline,
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Διέγραψε: The 'te' function is a full tensor product smooth and 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 th Binomial stats package in R (Kachitvichyanukul and Schmeiser, 1988).…
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Διέγραψε: Private lands were partitioned into community and non-community areas based on housing density estimates derived from SILVIS WUI data (Radeloff et al., 2005).
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the total area burned from fires that ignited within the same tenure class; (2) incoming fire (TFin), the total area burned from fires that ignited on adjacent tenures, and; (3) outgoing fire (TFout), the total area burned from fires that ignited within one land tenure class and burned into another land tenure (Figure 1). The total area burned for a given land tenure equals the sum of TFin and TFself. We used these same metrics to map (see Figures 4 & 5) the percentage of self-burning across the entire landscape (self-burning fire index - SBFI). To do so, we first created a regular lattice of points over the entire domain at a resolution of 500 m. We then tallied the amount of annual burned area for TFin and TFself for all fire perimeter fragments that intersected each point in the lattice. These points were converted to pixels, and pixels with values <50% were classified as areas of high incoming fire (>50%).

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

2.4 Cross-boundary transmission zones and community exposure

We used wildfire ignitions and associated transmission data to estimate several cross-boundary transmission zones: (1) those zones of cross-boundary transmission between national forests and the three largest land tenures: private, BLM and State lands, and; (2) those zones of wildfire transmitted into communities (i.e., firesheds). We queried ignitions to identify specific cross-boundary transmission events (e.g., all fires that ignited on FS and burned into BLM). For ignitions selected for each cross-boundary transmission pair (e.g., FS ignitions that burned into BLM lands), we estimated the amounts of transmitted fire to the other land tenure (e.g., the outgoing parts of an FS ignition that burned into BLM lands). Using the selected ignitions, we applied a kernel function to fit a smoothly tapered surface representing the magnitude of cross-boundary fire transmission per km^2 (see Figure 7).

We used the ignition points of FSim fires where exposure occurred to map the area around communities where fires leading to structure exposure are likely to originate – i.e., the fireshed. Firesheds were generated using the ArcGIS inverse distance weighting tool with the predicted structure exposure from all ignitions. We define the fireshed as those locations surrounding a community where exposure is greater than one structure per year (described in greater detail below). These firesheds were used to classify sources of risk in terms of ownership, wildfire hazard, management capability and fuel model (see Figures 8 & 9).

We estimated structure exposure based on the intersection of fire perimeters and developed SILVIS WUI polygons. We assumed that structures reported in US Census data for each SILVIS WUI polygon are spatially distributed equally inside the polygon, and therefore the magnitude of structure exposure can be calculated based on the area of the fire-WUI intersection. For each ignition, we summed the predicted structures affected from all

Διέγραψε: incoming fire (TFin, the sum of all fire area burned from fire ignited on another land tenure and entering each particu polygon), outgoing fire (TFout, the sum of all area burned from f 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 landownershipland tenure) …

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intersections, while for each WUI polygon, we summed all predicted structure exposure from all ignitions that intersected it, similar to our previous studies (Ager et al., 2018; Evers et al., 2019). Because FSim simulates potential fire seasons, we report exposure as an annualized value, or the total structure exposure divided by the number of fire seasons simulated.

3 Results

3.1 Patterns of fire transmission

Statistical modelling of the ignition cause for simulated fires showed that 63% of all predicted burned area was generated from natural ignitions (Figure 2a), mostly originating on FS (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 on private (32%), FS (27%), BLM (17%), WUI (9%) and State lands (7%) (Figure 2b). FWS lands were 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 for human ignitions we observed equal fire exchange. Compared to the 24 years of historical ignitions for 1992-2015 (Short, 2017), most lightning-caused area burned started on FS (38%), BLM (35%) private (16%) and tribal lands (4%).

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

We found that the amount of historical annual burned area across the western US was 1,268,412 ha yr^{-1} within 1% of the predicted annual burned area (1,257,182 ha yr^{-1}) from FSim simulations (a per state comparison is provided in Appendix Table B2). Across all States, 30% of predicted burned lands (sum of incoming and self-burning fire) were within national forests, followed by private (27%), BLM (25%) and WUI and State lands (5%). When the predicted burned area was normalized by each land tenure's area (Table 2), FS retains the highest rank followed by city/county, BLM, Public and Private lands. 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), BLM lands were more exposed to incoming fire ignited on private, FS and State lands. Exposure to national forests was highest from private (46% of total FS exposure) and community WUI (18%), and less from BLM (15%) and State (10%) lands. More than half of fire exposure on 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

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Διέγραψε: predict the area around communities where large fir are likely to ignite and spread into them (community fireshed), allowing us to identify sources of risk in terms of ownerships, wildfire hazard, management capabilitiesy and fuel models (Scot and Burgan, 2005). Fireshed was derived from the conditional tot housing units affected, assuming a fire occurred at the location. V applied used the ArcGIS IDW inverse distance weighting process toolon all ignitions, interpolating the predicted total structure exposure from all ignitionsof each simulated fire, and subsequent smoothing using a Focal Mean process. The resulting raster layer define athes fireshed as all pixels where ignitions are causinon average expose at least one exposed structure.

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tenure is presented in appendix Table B3. The percentages of incoming fire from the sum of burned areas (incoming + self-burning) inside each land tenure (Figure 3) revealed how 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 area transmitted from other land tenures. In most cases, the majority of burned area on FS, Tribal and private lands resulted from self-burning fires. More variability across the States was found for NPS, Other Federal and BLM lands.

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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). Lands with large homogenous polygons with one owner, such as northern AZ (tribal lands), central ID (FS), southern NV (BLM) and eastern CO (private), had low amounts (<20%) of incoming fire. Except for NV and WA, which had more lands with lower incoming fire, all other States had similar trends (Figure 4b). In addition, city/county, State, public, and Bureau of Reclamation (BOR) land tenures had a larger share of area that received higher amounts of incoming fire compared to DOE, DOD, Tribal, FS and NPS lands (Figure 4c), indicating a reverse trend of higher incoming fire when the average parcel size and perimeter were reduced.

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We defined the places where >50% of area burned is incoming (using SBFI), from ignitions that burned each of the three major land tenures (FS, 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, north eastern 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 (checkerboard ownerships), on the western parts of the 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

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

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3.2 Mapping cross-boundary wildfire transmission

We estimated cross-boundary wildfire between national forests and three important stakeholders that already participate in existing, or have 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 fires from ignitions on each of the other three land tenures escape their boundaries and burned onto national forests (Figure 7). Again, we used the hexnet to estimate the average values of cross-boundary fire for each hexcell and for each paire of land tenures.

Private lands received 46% (33,000 ha yr^{-1}) of the total outgoing fire from national forests (71,000 ha yr^{-1}), while national forests received 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 the central Sierras, southern and north-western CA, eastern OR, north-central WA, and southwestern and southern ID.

State lands received 10% (i.e. 7,000 ha yr^{-1}) of the total outgoing fire from national forests, while national forests received 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 the highest fire exchange with State lands (Appendix Figure A2-a) were in central AZ and southern NM, in the south-western parts of CA as well as ID, in western MT and eastern OR, and across the eastern front of north-central WA.

BLM lands received 15% (10,500 ha yr^{-1}) of the total outgoing fire from national forests, while national forests received 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

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7 million ha inside BLM lands. Although in spatial proximity, BLM lands share small amounts of fire with national forests and State lands, while more than two thirds of the total BLM area burned were shared with private lands. BLM lands encompass 40% less area than private lands but send 70% less fire (compared to private lands) to national forests. The highest transmission zones from FS to BLM lands (appendix Figure A2-b) were on the national forests of northern NV, southern and central ID, southwestern NM and southern AZ, central and southwestern UT, and southern and eastern OR.

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

As an example, the right panels of Figure 7 focused on the southwestern US (California, Arizona and New Mexico) where the differences between the three zones were large. 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 of the landscape with high values of fire transmission for all three land tenure pairs, e.g., in southwestern NM, whereas in other parts of the landscape only one out of three pairs had large values. When we merged the overlapping areas across the three land tenures pairs for the western US, 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 national forest land). 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

The fireshed covered an area of approximately 70 million ha across the western US. For each hexcell we estimated the area burned 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 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 prevailed in coastal CA and across the Sierras, in north-central CO, and

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northeast and southern WA. Tribal land fires mostly exposed communities in 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 were 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 A3 shows the top ten communities of each State in terms of annual structure exposure. Appendix Table B4 shows the list of the top 100 communities, regardless of State, ranked by the total annual structure exposure (sum of incoming and self-burning fires).

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

Finally, five land tenures own or manage 92% of fireshed, with private and community together owning half the land base, 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 fuels account for three quarter of the fuel models 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==================================

4 Discussion

Fire transmission and exchange among land tenures and communities 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 (WWWRA, 2013; Dillon et al., 2014; AMF, 2018; Parks et al., 2018), but did not consider where the fires are coming from and how they are transmitted from one land tenure to another. This work expands the scale of

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our earlier investigations that assessed cross-boundary fire transmission for individual national forests and the State of Arizona (Ager et al., 2014b; Ager et al., 2017; Ager et al., 2018).

We focused on the four largest land tenures (FS, BLM, private and State) that generated 85% of the total outgoing fire. 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. When burned area inside each land tenure was normalized by its area, FS was ranked first but city/county and public lands were among the highest ranked land tenures (Table 2). For normalized outgoing fire, city/county and public lands were ranked highest, followed by State and FS lands, a completely different ranking from the raw outgoing fire values i.e., Private, FS and BLM were ranked higher (Table 3). These findings revealed that smaller land tenures can have increased significance in the fire transmission patterns and were affected by large fire incidents.

Landscape fragmentation needs to be considered in wildfire risk management and planning, whether caused by different vegetation, fuel or landownerships types, since it creates different scales and complexity of fire transmission, e.g., checkerboard vs. linear interface boundaries. In addition, highly fragmented wildland-urban interface areas among private landowners increase fire suppression complexity and population risk (Busby et al., 2012; Chas-Amil et al., 2013). Previous simulation studies have shown that both size and parcel complexity (perimeter to area ratio) affects the proportion of transmitted fire. In general, smaller parcels tend to receive higher amounts of incoming fire since their interior is burned more often from incoming fire due to their relatively small distance from the edge. The proportion of incoming fire is a function of the ratio of fire size to parcel size. When the former is very large relative to the latter, the higher the proportion of incoming fire. However, parcel edge complexity can also influence the proportion of incoming fire relative to the total fire transmission. Complex edge reduces the distance to the interior regions of a parcel and thus increases the proportion of incoming fire (Ager et al., 2014a). 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 secondarily 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., FS, NPS, DOD) tended to have less transmitted fire.

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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 conditions 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 legislation that allows them to burn, but human caused fires have to be suppressed (Miller, 2012; Fusco et al., 2016). 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 historical natural ignitions occurred since 1992 (Short, 2017), we needed probabilistic estimations of the spatial likelihood for potential natural ignitions to enable the separation of all simulated ignitions into natural and human caused (given an ignition, we are deciding what was the most likely cause of that fire). The statistical model we created allows for modelling the ignition cause of every simulated fire and can be applied to produce ignition-cause probability maps of higher spatial resolution at the scale of the western US. We found that natural ignitions are the major source of fire transmission and caused 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. We provide for a first time an all-lands community prioritization assessment (see Appendix Figure A3 and Table B4) based on the predicted annual structure exposure of each community from both fires ignited elsewhere or within that community. Community protection planning could benefit from recognizing firesheds. Results revealed that the structure exposure problem in western US communities originated mostly from ignitions on either WUI or private lands, and less from federal lands (national forests and BLM), thus 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 extent and land tenure and fuel model composition of the fireshed differed among the western States, although in general was mostly comprised of a combination of private/community lands, national forests, BLM, tribal and State lands, and characterized by the dominance of shrub and grass fuel models. At the state level, large amounts of burned area did not necessarily mean large numbers of exposed structures, since in cases like Idaho and California with similar amounts of burned area, simulated fires were predicted to expose 90% fewer structures in Idaho compared to California.

These results can help prioritize fuel treatment projects that consider both the anthropogenic and biophysical context of the wildfire problem, which is increasingly drawing the attention of the research community (Bodin and Tengö, 2012; Evers et al., 2019; Palaiologou et al., 2019; Hamilton et al., In press). Establishing cross-

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Several States, 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).

This study is the first comprehensive and systematic approach of estimating cross-boundary wildfire 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 agency decisions on the locations of future fuel management projects. Our methods and concepts were also applied at different scales in Europe (Palaiologou et al., 2018; Salis et al., 2018; Alcasena et al., 2019), but they have not yet been considered in the official wildfire risk assessments at the pan-European level (San-Miguel-Ayanz et al., 2018). We anticipate that our results, which covered an extensive and diverse landscape of the western US, can inform fire management planning and guide how existing wildfire risk assessments can be improved in regions like 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 cross-boundary fire transmission zones to achieve various management and restoration goals like WUI protection, timber production, restoration of areas affected by insects and disease and watershed management. This includes the assessment of both elements of cross-boundary fire risk, i.e. sources (where fires are coming from) and sinks (where fires burn), since effective shared-stewardship projects must deal with both elements to achieve change. Finally, we explored how cross-boundary wildfire transmission relates to communities and the lands surrounding a community where wildfire risk often originates, a critical part of understanding how to mitigate WUI disasters at a time when the western

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US (California 2017-18) and places in Europe (Greece 2018, Portugal 2017) have experienced high death tolls, structure loss and economic costs from recent large wildfires.

5 Conclusions

Of the total simulated fire activity, one third was transmitted from a different land tenure while two thirds were predicted to originate from natural ignitions. Two thirds of community exposure in the western US originated from privately owned lands, more than two thirds of which were developed (part of community WUI). Community exposure from federal land varied by state, from less than 20% (WY) to nearly 50% (AZ and NV). 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 wildfire transmission patterns in the western US. We highlighted the importance of collaboration among different landowners to improve community protection 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 model, fire regime, management history and land tenure composition.

Acknowledgments

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Figures

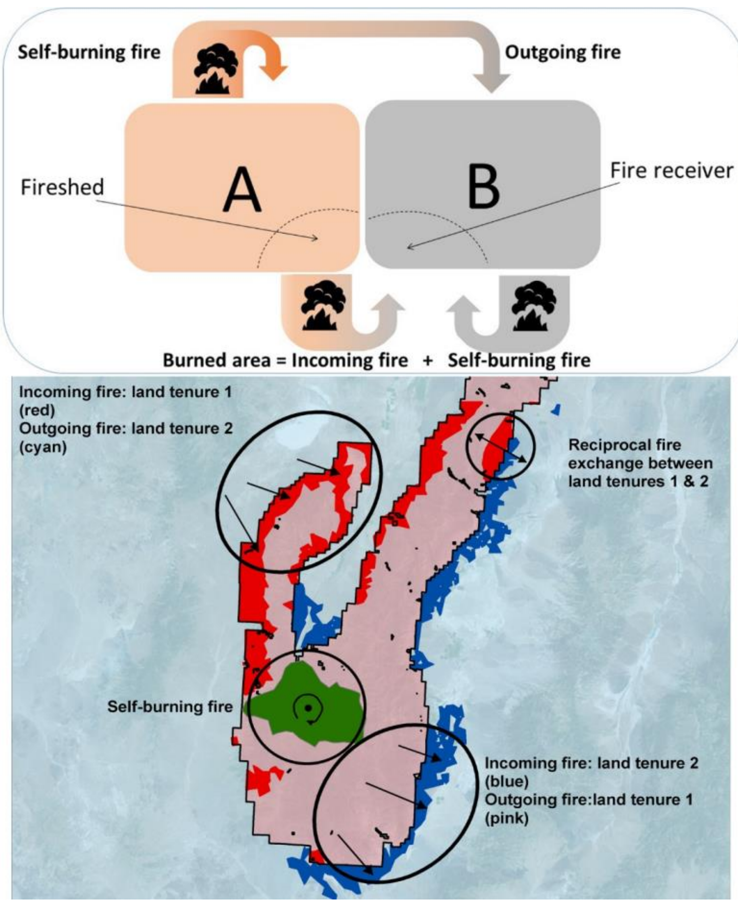

Figure 1: Conceptual map showing the cross-boundary fire exchange (incoming, outgoing, self-burning) between two land tenures.

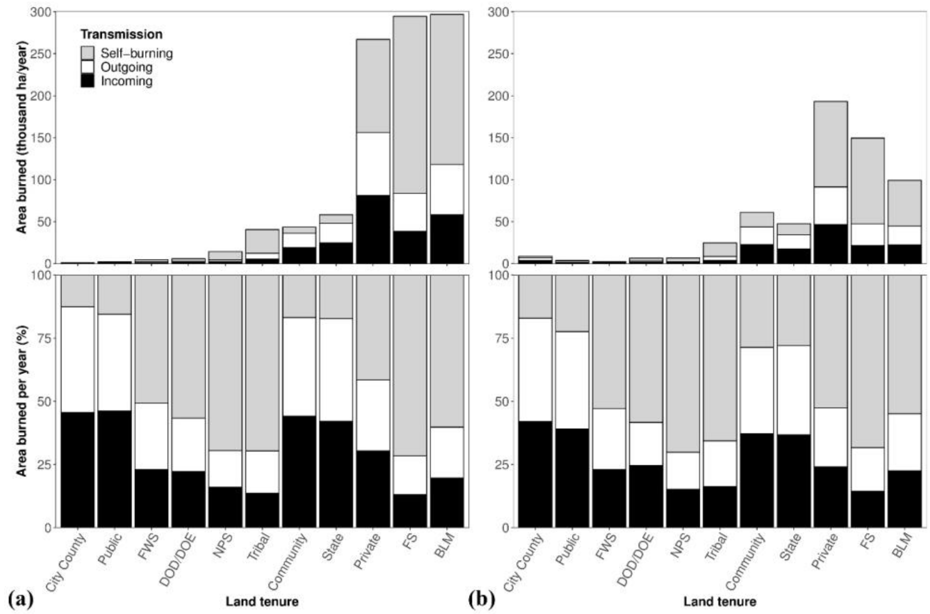

Figure 2: Fire exchange for the major land tenures of the 11 western US States estimated for: a) natural ignitions; and b) human ignitions. FS: Forest Service; BLM: Bureau of Land Management; NPS: National Park Service; FWS: Fish & Wildlife Service; DOD: Department of Defence; DOE: Department of Energy; Public: other public lands and non-government organizations.

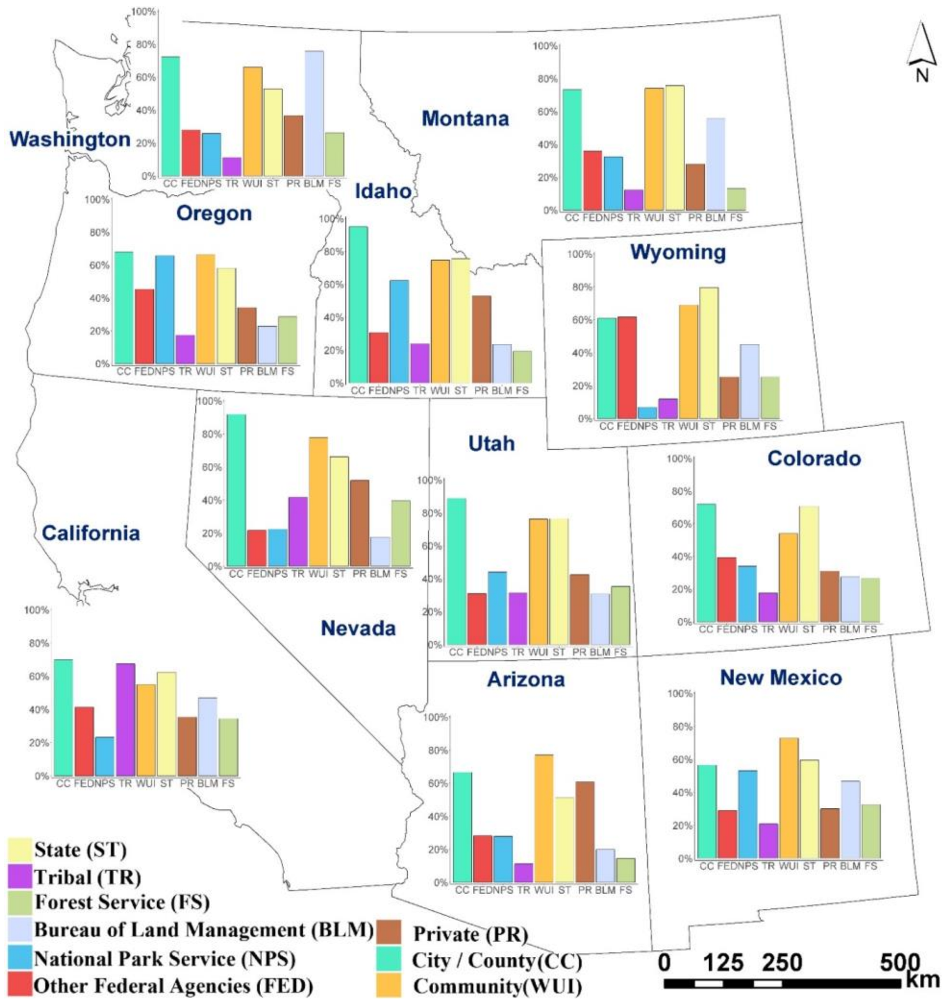

Figure 3: Proportion of incoming fire to the total fire (incoming / (incoming + self-burning) * 100) for each western US State. The Public land tenure was merged with City/County, while all smaller Federal land tenures were merged into the Other Federal Agencies class.

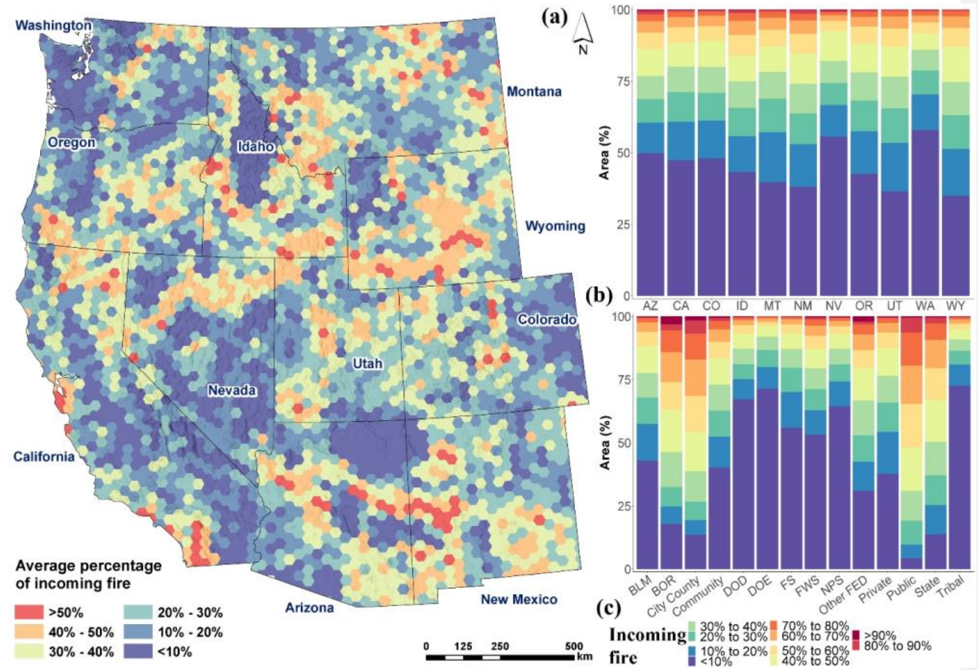

Figure 4: (a) Average percentage of incoming fire across the western US; (b) by state, calculated for its entire area and for all land tenures; (c) by land tenure, across all the 11 western US states.

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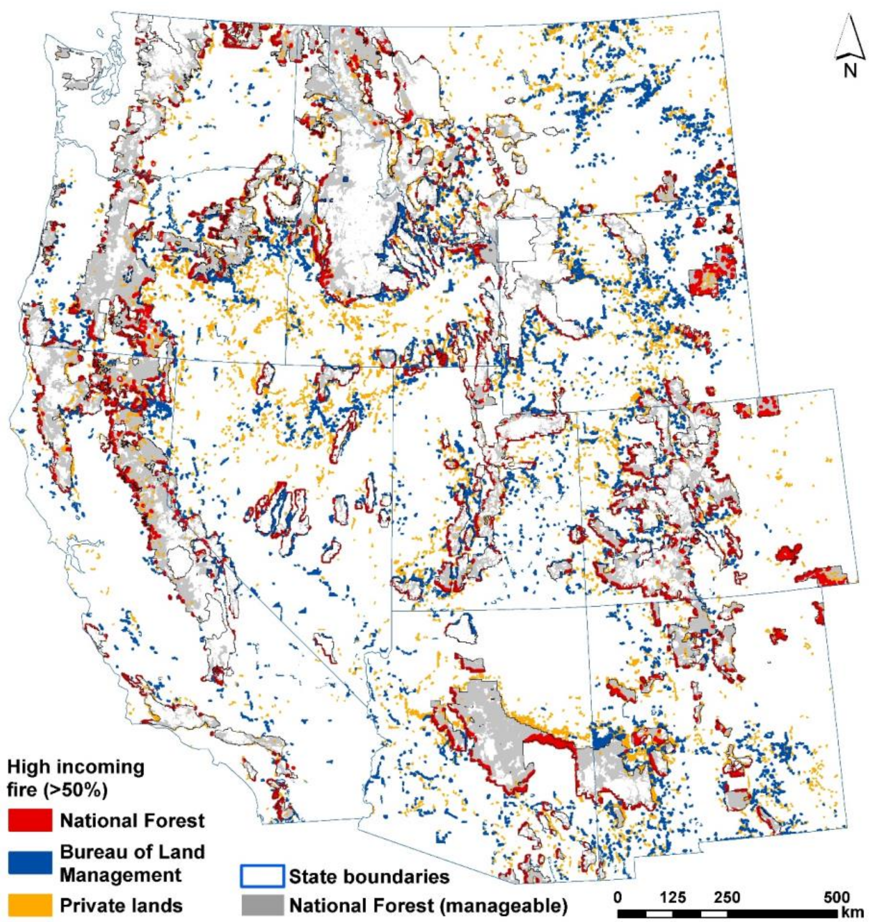

Figure 5: Locations where incoming fire exceeds >50% of the total fire (incoming + self-burning) on the three larger land tenures of the western US.

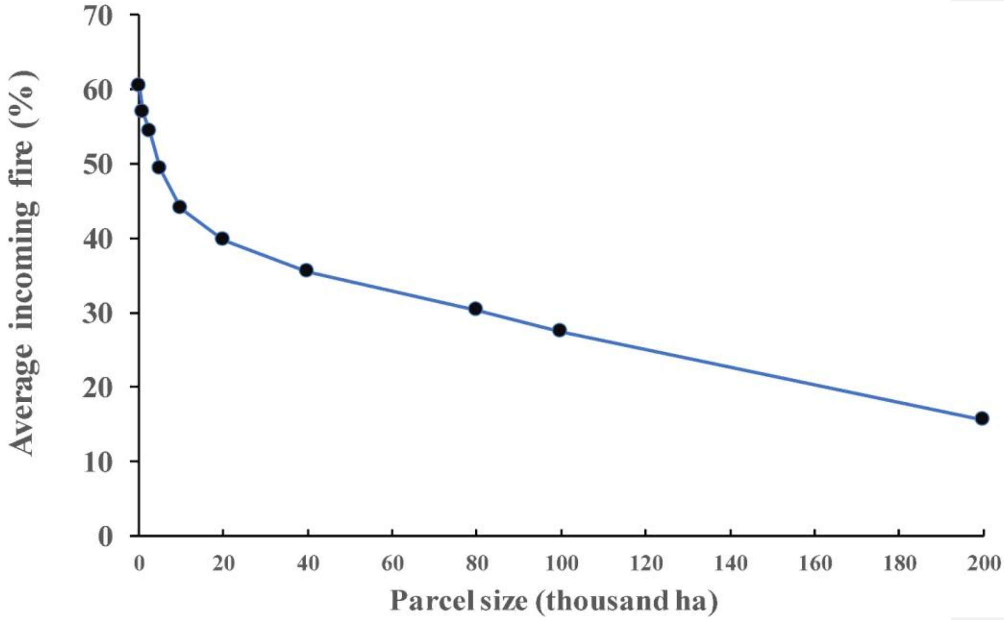

Figure 6: Relationship between parcel size and average percentage of incoming fire.

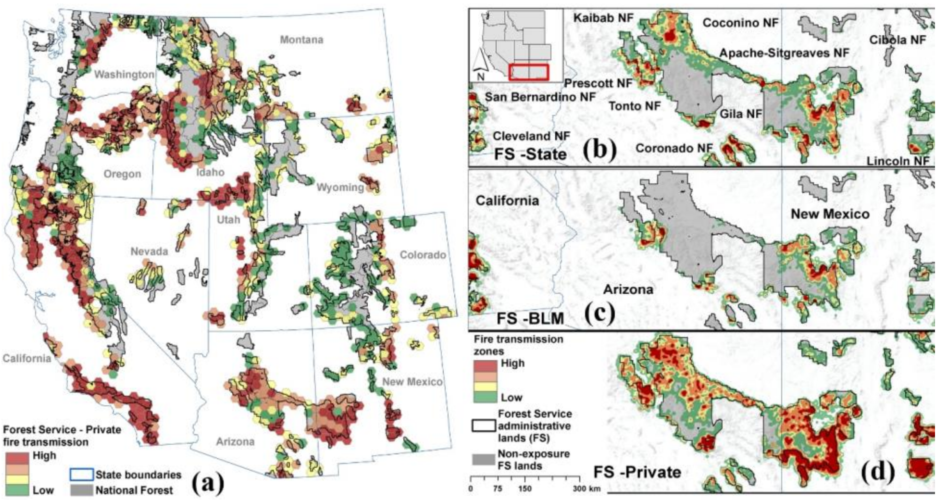

Figure 7: Cross boundary wildfire from Forest Service administrative lands (FS) to private lands (a). Grey areas indicate national forest lands where transmission to other land tenures is very low (high percent of self-burning fire). Panels to the right, zoom in the southern part of the study area, show 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) FS-State; (b) FS-BLM; (c) FS-Private.

Διέγραψε: national forests

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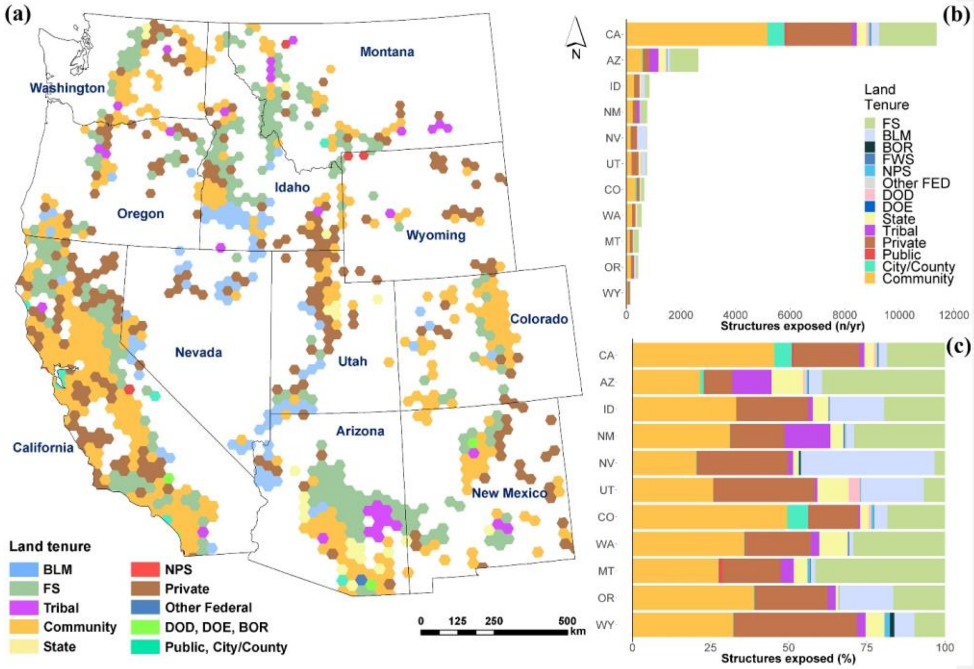

Figure 8: (a) Land tenures contributing the highest structure exposure to communities in the western US. (b) Total annual structure exposure by State; (c) Percent exposure for each State by the land tenure where the fire was ignited. FS: Forest Service; BLM: Bureau of Land Management; BOR: Bureau of Reclamation; FWS: Fish & Wildlife Service; NPS: National Park Service; DOD: Department of Defence; DOE: Department of Energy.

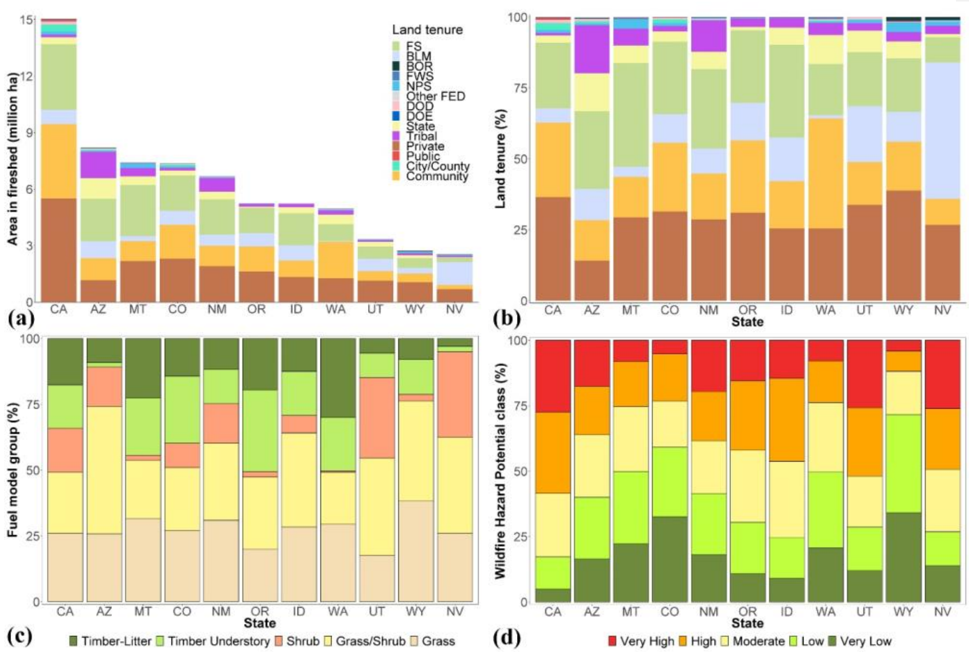

Figure 9: Fireshed characteristics of each western US state in terms of: (a) land tenure area; (b) land tenure percentage; (c) fuel model percentage (Scott and Burgan, 2005); (d) average wildfire hazard potential class percentage (Dillon et al., 2015). FS: Forest Service; BLM: Bureau of Land Management; BOR: Bureau of Reclamation; FWS: Fish & Wildlife Service; NPS: National Park Service; DOD: Department of Defence; DOE: Department of Energy.

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Διέγραψε: State level breakdown for

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Διέγραψε: area

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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” and “public” categories.

Land Tenure	Number of Parcels	Average Parcel Size (ha)	Average Parcel Perimeter (km)	Total Area (ha)
Department of Energy (DOE)	31	19,545	30.8	606,543
National Park Service (NPS)	557	14,528	36.7	8,124,284
Department of Defence (DOD)	513	11,271	21.0	5,808,883
Forest Service (FS)	7,164	8,009	29.9	57,538,442
Tribal	4,674	4,074	13.5	20,218,201
Fish & Wildlife Service (FWS)	1,359	2,213	11.1	3,013,824
Bureau of Land Management (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
Bureau of Reclamation (BOR)	981	591	10.6	611,394
Wildland-Urban Interface (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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Μορφοποιημένος πίνακας

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Table 2: Percentages of the total incoming fire to each land tenure (rows) from other land tenures (columns). Normalized burned area was estimated by dividing the total burned area in each land tenure (incoming + self-burning) by the total area of a given land tenure. FS: Forest Service; BLM: Bureau of Land Management; BOR: Bureau of Reclamation; NPS: National Park Service; FWS: Fish & Wildlife Service; DOD: Department of Defence; DOE: Department of Energy.

	BLM	BOR	City County	Comm.	DOD/DOE	FS	FWS	NPS	Other Fed.	Priv.	Public	State	Tribal	Incoming fire (ha/yr.)	Total burned area (ha/yr.)	Normalized burned area (ha/yr/[illegible] area i[illegible]
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	313,841	0.0044
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	1,022	0.0018
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	5,624	0.0055
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	66,730	0.0030
DOD/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	10,004	0.001[illegible]
FS	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	372,910	0.006[illegible]
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	5,224	0.0017
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	18,059	0.0022
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	417	0.0014
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	340,168	0.0035
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	3,816	0.0041
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	65,393	0.0034
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	53,892	0.0028

Table 3: Percentages of the total outgoing fire from each land tenure (rows) to the other land tenures (columns). Normalized outgoing fire was estimated by dividing outgoing fire from each land tenure by the total area of a given land tenure. FS: Forest Service; BLM: Bureau of Land Management; BOR: Bureau of Reclamation; NPS: National Park Service; FWS: Fish & Wildlife Service; DOD: Department of Defence; DOE: Department of Energy.

	BLM	BOR	City County	Comm.	DOD/DOE	FS	FWS	NPS	Other Fed.	Priv.	Public	State	Tribal	Outgoing fire (ha/yr.)	Normalized outgoing fire (ha/yr./tenure area in ha)
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	0.0012
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	0.0011
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	0.0038
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	0.0017
DOD/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	0.0004
FS	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	0.0020
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	0.0006
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	0.0004
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	0.0009
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	0.0012
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	0.0026
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	0.0021
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	0.0006

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Appendix A

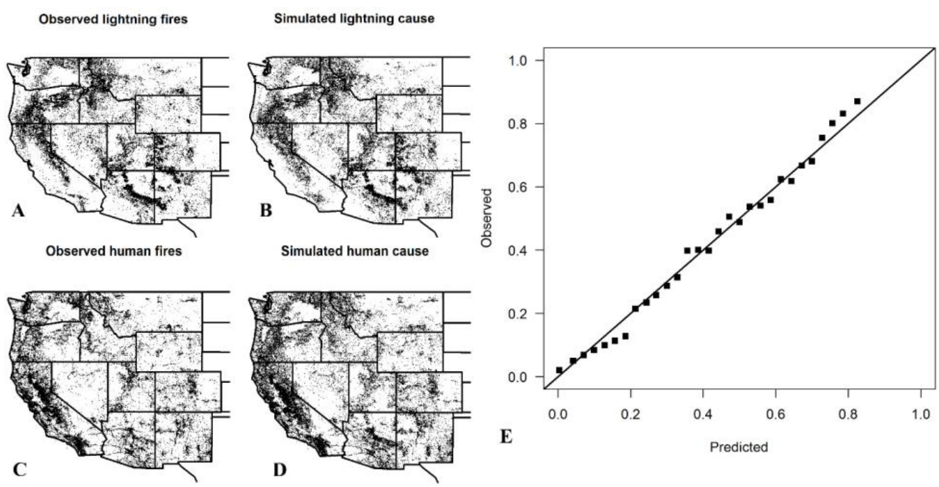

Figure A1: Maps show the locations of observed lightning (A) and human (C) caused fires from a simulation which assigned a cause to each observed ignition from our model (panels B and D). Notice in Southern California, in the observed human ignitions we see two lines of ignitions in the south-eastern part (C). These are the main highways to Arizona and all fires at these locations are human caused, indicating a correct assignment of simulated ignition cause (D). Panel E show the observed relative frequency of natural caused fires plotted against predicted probabilities, after binning the data into 29 classes according to the predicted values.

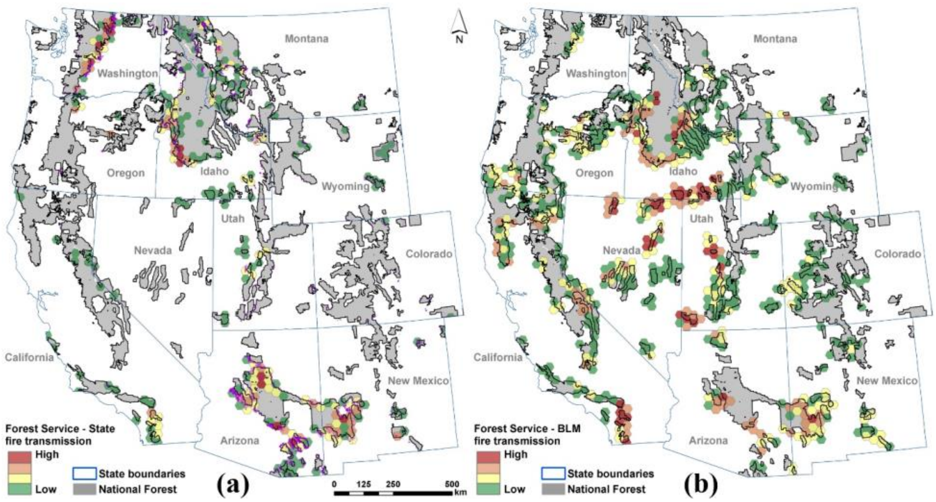

Figure A2: Cross-boundary wildfire transmission zones from Forest Service administrative lands to (a) state and (b) BLM lands. Grey areas indicate national forest lands where transmission to other land tenures is very low (high percent of self-burning fire).

Διέγραψε: 1

Διέγραψε: national forests

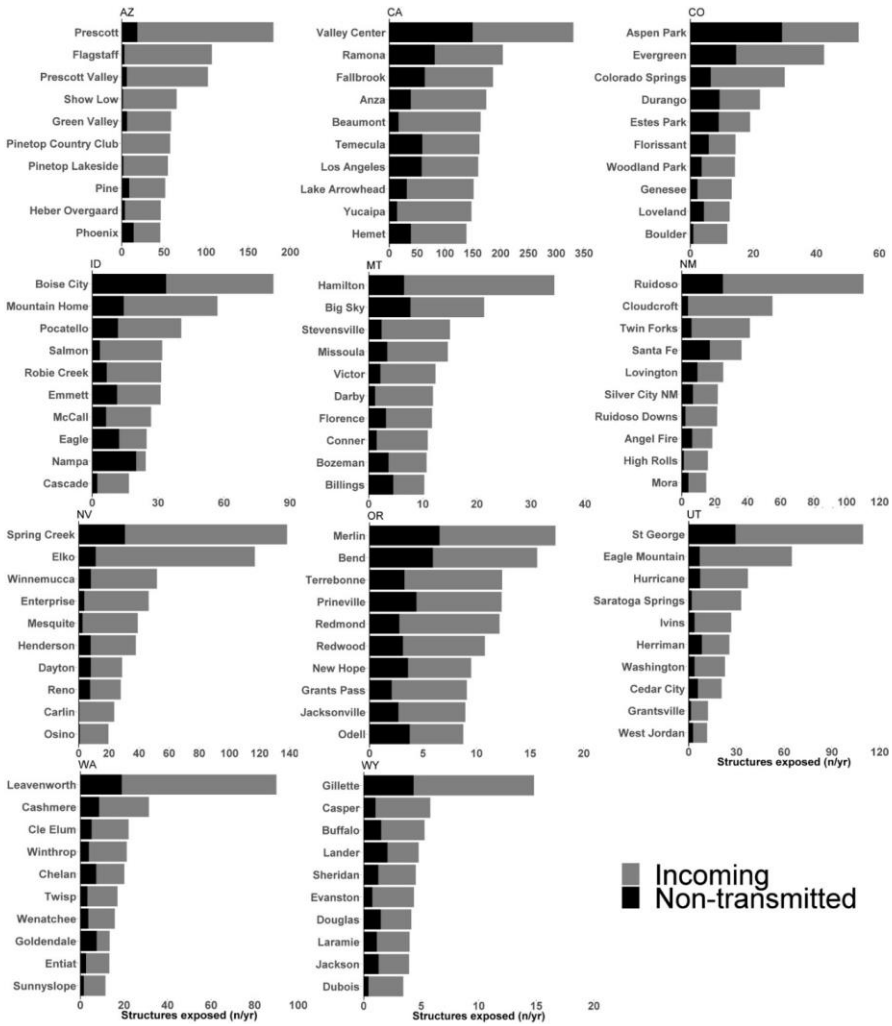

Figure A3: The top-10 communities for each state with the highest predicted fire exposure.

Διέγραψε: 2

Appendix B

Table B1: Percentage of fire adapted area (fire regimes 1 or 3) (source: LANDFIRE 2014) for each land tenure and State. FS: Forest Service; BLM: Bureau of Land Management; BOR: Bureau of Reclamation; NPS: National Park Service; FWS: Fish & Wildlife Service; DOD: Department of Defence; DOE: Department of Energy.

	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	n/a	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
FS	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: Per state comparison between historical and predicted annual burned area.

State	Historical burned area (ha)	Historical annual burned area (ha yr^{-1})	Predicted annual burned area (ha yr^{-1})
Arizona	2,256,677	94,028	117,434
California	5,155,839	214,827	225,094
Colorado	745,557	31,065	33,085
Idaho	5,537,859	230,744	214,470
Montana	2,541,155	105,881	97,815
New Mexico	2,579,351	107,473	126,166
Nevada	3,648,590	152,025	160,665
Oregon	3,404,540	141,856	100,637
Utah	1,665,253	69,386	69,897
Washington	1,935,240	80,635	51,498
Wyoming	971,835	40,493	60,425
Total	30,441,896	1,268,412	1,257,186

Table B3: 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	n/a	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	n/a	n/a	14	565	n/a	1083	745	n/a	n/a	99	n/a	228
FS	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	n/a	51	139	143	n/a	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

Διέγραψε: 2
Μορφοποιήθηκε: Βασικό
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Table B4: 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

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

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

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