Revisiting the existing definitions of wildland-urban interface for California

Mukesh Kumar[1], Shu Li[1], Phu Nguyen[1], and Tirtha Banerjee[1]

[1]University of California Irvine

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Abstract

Past studies reported a drastic growth in the wildland-urban interfaces (WUI), the locations where man-made structures meet or overlap wildland vegetation. There is a perception that damages due to wildfires are mainly located at the WUI. However, there is no clear evidence that wildfire intensity and frequency are highest in these regions. In this work, we have reported the actual occurrences of wildfires with respect to WUI and how much of the WUI are on complex topography in California (CA), the state with the highest burned area and risk of wildfires. We calculated the overlap of the burned area from previous wildfire events in California in the last ten years with the WUI perimeters. Two currently existing WUI definitions are used for this purpose. Furthermore, we also calculated the number of fire ignition points that lie within the WUI perimeters. We found that a very small percentage of wildfire ignitions actually occurred in the WUI areas. Moreover, the overlap between the wildfire burned area and WUI areas was also found to be small. To find out if the wildfires burned in the vicinity of WUI areas, we created buffers around both the WUI areas and the wildfire perimeters separately and computed the impact of buffer distance on the overlap. This behavior has been connected to the importance of firebrand ignition from spot fires in the WUI. Moreover, a majority of WUI areas in CA was found to be situated on complex topography. Therefore, we conclude that in CA, wildfires are not limited to WUI regions only, but their main fire fronts burn farther away from the WUI and are mostly located on complex topography, where controlling large wildfires is more difficult and fire behavior is more complex. Results from this study will give direction for remapping the existing WUI definitions, will be helpful for wildfire management and will benefit policymakers and land managers at the state and local level to focus on the factors that determine the high-risk prone areas for future wildfires.

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Mukesh Kumar*[1] | Shu Li[1] | Phu Nguyen[1] | Tirtha Banerjee[1]

[1]Department of Civil and Environmental Engineering, University of California, Irvine, CA 92697, USA.

Abstract

Past studies reported a drastic growth in the wildland-urban interfaces (WUI), the locations where man-made structures meet or overlap wildland vegetation. There is a perception that damages due to wildfires are mainly located at the WUI. However, there is no clear evidence that wildfire intensity and frequency are highest in these regions. In this work, we have reported the actual occurrences of wildfires with respect to WUI and how much of the WUI are on complex topography in California (CA), the state with the highest burned area and risk of wildfires. We calculated the overlap of the burned area from previous wildfire events in California in the last ten years with the WUI perimeters. Two currently existing WUI definitions are used for this purpose. Furthermore, we also calculated the number of fire ignition points that lie within the WUI perimeters. We found that a very small percentage of wildfire ignitions actually occurred in the WUI areas. Moreover, the overlap between the wildfire burned area and WUI areas was also found to be small. To find out if the wildfires burned in the vicinity of WUI areas, we created buffers around both the WUI areas and the wildfire perimeters separately and computed the impact of buffer distance on the overlap. This behavior has been connected to the importance of firebrand ignition from spot fires in the WUI. Moreover, a majority of WUI areas in CA was found to be situated on complex topography. Therefore, we conclude that in CA, wildfires are not limited to WUI regions only, but their main fire fronts burn farther away from the WUI and are mostly located on complex topography, where controlling large wildfires is more difficult and fire behavior is more complex. Results from this study will give direction for remapping the existing WUI definitions, will be helpful for wildfire management and will benefit policymakers and land managers at the state and local level to focus on the factors that determine the high-risk prone areas for future wildfires.

Keywords: buffer distance; complex topography; firebrands; wildfires; wildland-urban interface; WUI

1. Introduction

The intensity and frequency of wildland fires over the contiguous United States (CONUS) have been increasing remarkably and causing much damage to life and property for the last two decades (Bar Massada et al., 2009; Radeloff et al., 2018; Stewart et al., 2007; Bowman et al., 2009). The damages due to these extreme events are mainly located at Wildland-Urban Interfaces (WUI), which are regions where houses and man-made structures meet or overlap the wildland vegetation as defined in the Federal Register (US Department of Interior (USDI) and US Department of Agriculture (USDA)), 2001. The current definition of WUI includes the concepts of '*Intermix*' and '*Interface*'. *'Intermix'* is the area where human developments and wildland vegetation overlap, while *'Interface'* is that region which is nearby to a densely vegetated wildland, characterized by a buffer distance. This definition of WUI is in concurrence with the National Fire Plan (NFP) which was based on the WUI fire risk report (Teie and Weatherford et al., 2000). This framework consists of three main parameters: (1) housing density threshold of 6.18 h/sq. km (1 house per 40 acres); (2) types of vegetation and (3) buffer distance of 2.4 km (1.5 miles) from dense vegetation (over an area of 5 sq. km with more than 75 % vegetation cover). Out of these 3 parameters, the housing density threshold is the most sensitive parameter in the existing definition of WUI as studied by Stewart et al., (2007) and Radeloff et al., (2005b). Earlier definitions of WUI were centered on the metric of population density (Glickman et al., 2001). However, it was later recognized by Liu et al., 2003 that perhaps housing density was a more appropriate metric compared to population density and therefore the WUI criteria had been modified and was included in the Federal Register (2001) for WUI (for both intermix & interface).

Several earlier studies had been devoted to analyze the expansion of WUI areas across North America over the past several decades and the drivers behind it. A number of studies (Radeloff et al., 2001; Johnson et al., 2005; Bartlett et al., 2000) identified the cultural aspect of human inclination to live in close proximity to the natural amenities provided by forested lands, mountainous regions and seashores. The natural ecosystem is affected by the WUI growth and therefore the growth of WUI is also associated with the impact of humans on biodiversity (Bar Massada et al., 2014; Syphard et al., 2009). Housing growth was widespread in rural and suburban areas in the United States during the mid-1900s and that continued trend contributed to a 41% growth in the construction of new homes within the WUI from 1990 to 2010 (Radeloff et al., 2005a & 2018). Housing density has grown faster than population density in recent decades and the same trend is reflected in the context of WUI (Martunizzi et al., 2015). Moreover, housing density was proved to be a better parameter than population or population density for evaluating WUI change and projecting future WUI location and extent (Liu et al., 2003). Thus, housing growth in the WUI poses higher risk due to wildfires. However, whether this risk is higher or lower outside the WUI is not clear.

Among the US states, California had the highest number of houses (4.46 million) in 2010 within the WUI that were at the risk of burning (Martunizzi et al., 2015). The rapid growth in the WUI area over the past few decades was mainly due to the construction of new houses and the percentage increase in WUI area was 33% from 1990 to 2010 in the CONUS (Radeloff et al., 2018). Kramer et al., (2019) analyzed damages due to wildfires from 1985 to 2013 and found that the number of buildings destroyed out of total buildings present in the WUI (rate of building damage) was highest for WUI interfaces in CA. However, similar proportions of buildings were destroyed by wildfires in the WUI and non-WUI regions. Therefore, the increasing WUI trends not only pose the risk of human ignited fires but also heighten the risk of more damage to life and property due to wildfires.

The existence of the WUI terminology was already in place before the wildland fire policies had taken it into consideration in the 2000s but it was not as widespread in the wildfire literature. It had only become a widely used term in the recent years due to the increasing/maximum damages in this land-use type due to wildfires (Martunizzi et al., 2015; Radeloff et al., 2018). Henry Vaux et al., (1982) had provided a direction to the foresters about future risks due to the emerging interface areas and called WUI as the “hotseat of forestry”. Also, Bradley et al., (1984) had focused on this new interface in his famous book on resource management, but none of them had related WUI with wildfires. Finally, Davis et al., (1990) connected the idea of WUI with the wildland fires. Currently, the term WUI is used mostly in the context of wildfires as the maximum damages due to wildfires occur in the WUI (Kramer et al., 2019). Stewart et al., (2009) demonstrated that WUI definitions vary depending on purpose and context by comparing the two definitions that are based on the National Fire policy (NFP) and Healthy Forest Restoration Act (HFRA) with the study location over the Los Angeles area. The NFP definition had focused on the number of structures (housing-centric definition) nearby the wildland vegetation within a buffer of 1.5 miles for the interfaces and therefore it was more helpful to the policymakers in determining the risk prone housing regions and taking possible steps in reducing the growth rate of the homes in these locations. According to the California Fire Alliance (2001), statistically a firebrand can travel up to 1.5 miles from a wildland fire-front and thus the buffer distance for the interface is the same. The houses within this buffer zone would be at higher risk of burning during wildfire events. On the other hand, the HFRA definition of WUI was more helpful to the land managers and has the aim of finding the sources of fuels for future wildfires within the vicinity of the houses/structures and therefore can be considered a fuel-centric definition. The HFRA defined interfaces that are present within a buffer of 0.5 miles from the houses and called it as a mitigation zone for the Community Wildfire Protection Plans (Walmer and Aplet et al., 2005).

The aforementioned publications focused on the WUI in the US, where it has an increasing trend, while WUI in other countries such as Portugal has been found to be shrinking and is more prevailing in the urban areas. Pereira et al., (2018) defined a novel linear approach for the WUI in Portugal and characterized it in terms of direct WUI, where urban (urban residential) areas are in physical contact with the flammable vegetation and nearby areas lying within 100 m from the flammable vegetation were called as the indirect WUI. Direct WUI is characterized by a comparatively higher risk of wildfires for the urban areas than the indirect WUI. Apart from these many existing definitions of WUI, a new WUI mapping called FRAP was developed by CAL FIRE, the agency to serve and safeguard the people and protect the property and resources of California. The Fire and Resource Assessment Program (FRAP, 2015) of CAL FIRE modified the definition of WUI (Intermix and Interface) in terms of the housing density thresholds in concurrence with the NFP policy and mapped it for California for 2010. Platt et al., (2010) compared five different WUI models, including FRAP, based on the choice of wildland vegetation, housing density with and without public lands, buffer distance from wildland vegetation or human settlements and its magnitude and the point and zonal based approach of defining housing density. It was found that the WUI mapping methods were characterized by different degrees of accuracy, which vary with their utilization and extent of study. For example, in the point-based approach of defining housing density, structures were represented as points and mapped from parcel centroid excluding remote structures which were farther than 569 m (0.35 miles) from another structure. Many other WUI definitions based on different data sources such as remote sensing, census block or their combination and methodologies that were mentioned in Plat et al., (2010) also exist, but none of the studies had looked and compared the predominant definitions of WUI with the context of wildfire occurrence.

Kramer et al., (2019) investigated the WUI areas in CA with the context of structural damage imparted by wildfires. Kramer et al., (2019) reported that in the last three decades, 50% of buildings destroyed in California were at WUI interfaces and 32% of buildings destroyed were in WUI intermix areas. Wildfire events have been increasing within the WUI in the CONUS (Martunzi et al., 2015; Bento-Gonçalves et al., 2020) and the wildfire ignitions are also directly proportional to the WUI expansion (Syphard et al., 2017). The proportion of buildings destroyed within the WUI and non-WUI zones were 69% and 31% respectively in the US (Kramer et al., 2018). However, on overlapping the area of fire perimeters with the building footprints from 2000 to 2013, only 1.1% (1398 sq. km) of the buildings were destroyed within the WUI, while this number was 34% (41,262 sq. km) within the non-WUI regions for the US (Kramer et al., 2018).

Nevertheless, it has been the norm to assume that WUIs are the hotbed of wildfire occurrence in the US, without much quantitative evidence. Without this quantitative evidence, it might lead to a faulty perception of risks in the WUI, leading to non-optimal resource allocation at different jurisdiction levels. Moreover, in states like California, a large area of WUI might be situated on complex topography. If presence of WUI are generally perceived to be high fire risk zones, it is worth knowing how much of WUI are actually on complex topography. This is important from a planning and policy perspective, given that firefighting, rescue and evacuation operations are significantly complicated due to the presence of complex topography. Moreover, only relying on a buffer zone of 1.5 miles from a densely vegetated area to be the hotspot of fires without adequate analysis is unjustified. Overlapping past wildfire events with WUI would help us understand whether wildfires predominantly happen in WUI zones; thereby providing a quantified measure of the perceived risk associated with the wildfire-WUI connection.

In this paper our main goal is to: (i) evaluate the two predominant definitions of WUI against the actual occurrences of wildfires in CA. Specifically, we ask the question; are wildfires actually (1) igniting and (2) burning in the WUI? (ii) assess the impact of buffer distance in the percentage overlap of fire perimeters and fire ignition points in the WUI (iii) evaluate how much of the WUI is on complex topography; we ask where the WUI is located in terms of elevation and how complex is this complex topography? The inherent assumption being more complex topography might mean more complex rescue, firefighting and evacuation operations, and (iv) show the importance of parameters that need to be carefully considered in the future mappings of WUI. Results from this paper will be helpful for the wildfire management and would benefit the policymakers and land managers at the state and local level to focus on the factors that determine the high-risk prone areas for future wildfires.

2. Material and Methods

Our study was conducted to understand the robustness of the existing WUI mappings especially over California and analyze other factors affecting the highly risky prone WUI zones. The state has experienced the maximum number of wildfire events in recent years out of all states in the US and those occurred especially in the WUI regions. This state is suitable for our study because of its complex topography (huge variation in the landforms with the presence of numerous mountains). More influential factors like fire spread rate and wind speed, etc. are more pronounced over higher elevation and slope (Storey et al., 2020). We used two existing WUI data sources for year 2010 that are obtained from Martunizzi et al., (2015) and CAL FIRE (FRAP, 2015) and called them as WUI-A and WUI-B respectively for our study. We plotted the spatial map of WUIs over CA to analyze the variation in the location of the WUI which include both WUI Intermix and WUI Interface. WUI-A used the definition of Federal Register (2001) following the NFPA policy, while CAL FIRE modified the housing threshold and added the wildfire influence zone & moderate or higher levels of fire hazard severity zones. Perimeters of wildfire events were obtained from the Monitoring Trends in Burn Severity (MTBS) dataset that includes all fires having area greater than 1,000 ac (40 ha) and CAL FIRE (2018). The wildfire data obtained from MTBS for CA has a total area of 19,517.675 sq. km wildfires from 2010 to 2017. It also comprises a total 329 fire ignition points (specify the type of fire) in the state from 2010 to 2017. Also, the fire ignition points (329) data are consistent with the wildfire perimeter datasets. We have not included the small fire events because of the limitation of the sources of the dataset available and thus we are considering only the large fire events. Ignition points of the fires were obtained from MTBS Burn Area Boundary & MTBS Fire Occurrence Points for 8 years i.e., from 2010 to 2017 (https://data.fs.usda.gov/geodata/edw/datasets.php?xmlKeyword=Burn). County boundaries for the state of California have been taken from the CA government geographic boundary (https://data.ca.gov/dataset/ca-geographic-boundaries). Elevation data was obtained from Google Earth Engine (GEE) which has basically used USGS DEM elevation maps available at 1/30 arc-second. For our study we resampled the obtained data from GEE at a spatial resolution of 10 m to 30 m using ArcMAP. To calculate the overlap of 2010 WUI and different elevation ranges, we have used ArcMAP 10.7.1 (https://desktop.arcgis.com/en/arcmap/) spatial analyst tool and selected extraction and then extract by mask. First of all, we reclassified elevation data to different elevation ranges and then merged both WUI-A and WUI-B with these ranges to calculate the number of counts falling in each elevation range. Moreover, we have made sure that WUI and Elevation raster layers have the same properties. WUI-A data available in vector form was converted to raster using ArcPy keeping the same 30 m spatial resolution as elevation data have. We have then divided the number of counts in each elevation range to the total count so as to find the percentage WUI over different elevation ranges. We performed similar methods for calculating the percentage overlap of WUI and elevation for CA with both WUI-A & WUI-B for year 2010. To see the surface roughness for the state which has numerous mountains and complex topography, we have basically calculated the rugosity of this region, which is defined as the ratio of actual surface area to the planar surface area of a region. Higher value of rugosity shows presence of more complex terrain in that region and vice-versa. We have used the Digital Elevation Map (DEM) surface tool developed by Jeff et al., (2004) in the ArcMAP to calculate the rugosity (surface ratio) for the state. The DEM surface tool has one advantage over other existing surface ratio calculation tools where we need to do adjustment in Z-units w.r.t X/Y-units while dealing with data in geographic coordinate systems and it is crucial to get it corrected. The WUI (both WUI-A & WUI-B) have been overlapped with rugosity following the same methodology as discussed above for elevation to find its variation with surface roughness for the state. The overlap of wildfire perimeters and WUI has been processed in ArcGIS with varying buffer distances using the buffer tool in geoprocessing followed by dissolve tool to merge each buffer into one feature. Five different buffer radii from 1 km to 5 km have been selected around wildfire perimeters and WUI (both WUI-A & WUI-B). WUI-A data was available in polygon (vector), so WUI-B raster data was converted to polygon using conversion tools in ArcMAP. Finally, the overlapping has been completed using intersect option with fire perimeters (WUI buffers) and WUI (fire perimeter buffers). For the calculation of fire ignition points within WUI buffers, we have used select by location using the selection method as select from layer, choosing target layer as fire ignition points and source layer as WUI buffer layers (both WUI-A & WUI-B).

3. Results and Discussion

3.1. Difference between two types of WUI mappings for California

The definition of WUI varies with different mapping methods and the changes in the major parameters like housing density threshold, buffer distance, etc. Moreover, the consideration of additional dependencies like level of fire hazard severity zones and area of contiguous groups of 30 m cells, etc. play an important role in the spatial variation of WUI and these specifications were added in the CAL FIRE WUI definition. In our study, we call the WUI dataset from Martunizzi et al., (2015) as WUI-A and CAL FIRE (FRAP, 2015) WUI dataset as WUI-B. Figure 1 shows the differences in the WUI distribution for California as mapped by Martunizzi et al., (2015) and CAL FIRE (FRAP, 2015) for the year 2010 (given that the latest census data is from 2010). The housing density threshold used by these two mappings are different and is 6.18 houses per sq. km (40 houses per acre) in the former while it is more than one house per 0.08 sq. km (20 acres) in the latter. CAL FIRE also includes other parameters for the WUI definition and requires moderate to very high fire hazard severity zones. In addition, their definition warrants spatially contiguous groups of 30 m cells having an area larger than 0.04 sq. km (10 acres) for the WUI Interface and larger than 0.1 sq. km (25 acres) for the WUI Intermix. Although the buffer distance of 2.4 km (1.5 miles) is the same in both the cases, for WUI-A, it is the distance from a densely vegetated area and is called WUI-Intermix. Whereas, for WUI-B it is the distance up to which flammable vegetation lie from WUI-Intermix or WUI-Interface and is known as wildfire influence zone. WUI-A consists of more area (27,025.683 sq. km) than WUI-B (9,606.273 sq. km) as shown in Figure 1 because of the difference in the housing thresholds and additional vegetation classification parameters used for

WUI-B. The overlapping results between WUIs and wildfires are similar for both types of WUIs (WUI-A and WUI-B), where Intermixes have higher percentage overlap than Interfaces (Table S1a & Table S1b).

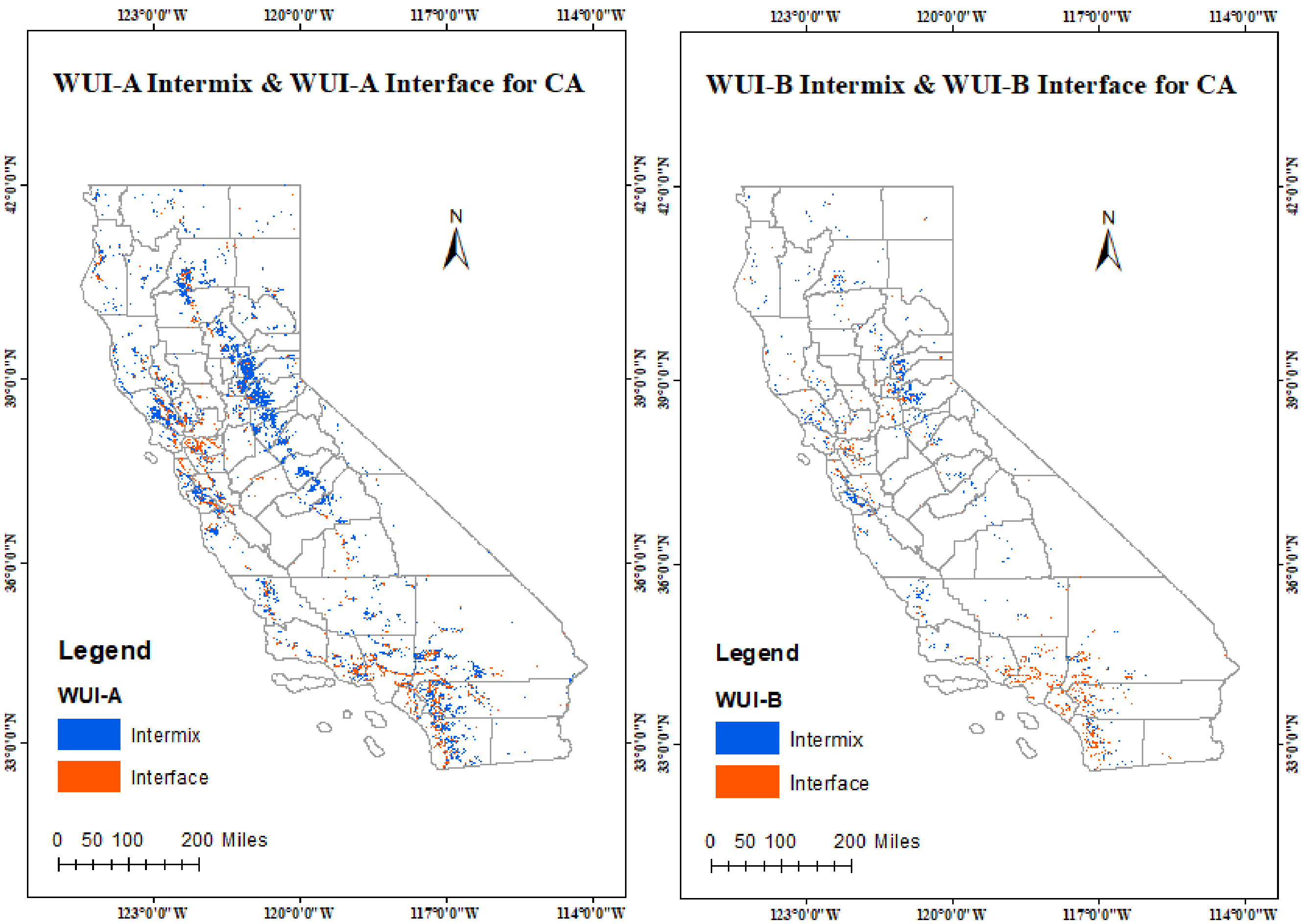

Figure 1. The figure on the left and right panels show the spatial plots of WUI in 2010 over California using WUI data from Martunizzi et al., (2015) and CAL FIRE (FRAP, 2015) and we designate them as WUI-A and WUI-B respectively for our study.

3.2. Overlap of WUI with wildfire burned areas

The wildfire data used in this study are obtained from MTBS (Monitoring Trends in Burn Severity) and report a total burned area of 19,517.675 sq. km for CA. These historical wildfire datasets are from 2010 to 2017 and include all fire events with burned areas greater than 1,000 ac (40 ha or 4 sq. km). Table S1a shows total area of WUI-A in CA to be 27,025.683 sq. km with both Interface (8,046.643 sq. km) and Intermix (18,979.040 sq. km) types of WUI-A. WUI-A Interface has less (49.387 sq. km) overlapping between wildfire burned areas and WUI-A than WUI-A Intermix (747.113 sq.km). The percentage of overlap in wildfire burned areas in

Intermix WUI-A (3.83%) is higher than Interface WUI-A (0.25%), making a total of almost 4.1% of wildfire areas that burned within WUI-A. Note that these aforementioned percentages are computed compared to the total wildfire burned areas (i.e., overlap area/wildfire burned area). The percentage of overlap between WUI areas and wildfire burned areas can also be computed relative to the area of WUI itself (overlap area/WUI area: shown in the rightmost column in table S1a and S1b). From this perspective, the percentage overlap in WUI-A Intermix is 3.94%, i.e., more than six-times the overlap in WUI-A Interface (0.61%). Therefore, only 2.947% of WUI-A areas have been directly burned by wildfires during the study period.

Table S1b represents the total area of WUI-B in CA to be 9,606.273 sq. km with a lower proportion of WUI-B Interface (4,232.847 sq. km) than WUI-B Intermix (5,373.426 sq. km). Clearly, the percentage of overlap between WUI-B Interface and wildfire perimeters relative to wildfire burned areas is lower (0.125%) than Intermix WUI-B (0.662%) for the state. Hence, only 0.79% of wildfire burned areas are contained within WUI-B in CA. When the overlapped area is expressed relative to WUI-B areas, there is a higher percentage overlap in the WUI-B Intermixes (2.4%) compared to WUI-B Interfaces (0.58%). Therefore, only 1.6% of WUI-B in CA has burned directly during the study period. Moreover, the intermixes have more wildfire burned area as compared to Interfaces for both the types of WUIs. The percentage overlap of wildfire burned areas with respect to (w.r.t) WUI areas is less for WUI-B (1.6%) compared to WUI-A (2.95%) because of exclusion of the influence zone from WUI-B definition (Figure 1).

3.2.1: Analysis of buffer distance from wildfire perimeters

From the discussion above, it is clear that a very small percentage of wildfires actually burn within the WUI areas in CA. This invokes the question, whether these wildfires burn in the vicinity of the WUI areas. To investigate the occurrence of wildland fires outside and away from the existing WUIs, we performed a buffer analysis, varying the distance from 1 km to 5 km from wildfire burned areas (Table S2a & S2b) and recalculating the previous statistics reported in tables S1a & S1b. Table S2a shows an increase in the percentage overlap of wildfire burned areas and WUI-A with buffer distance relative to the wildfire buffer area (fifth column) and relative to the WUI area (sixth column). When the buffer radius increased from 0 km to 5 km around the wildfire burned areas, the overlapped region increased by more than 9 times (from 796.5 km to

7,580.4 km). The percentage of this overlapped region in the WUI-A increased from almost 3% (for no buffer) to 28% (for 5 km buffer distance) respectively. On the other hand, a small change of only 4% was noticed in the percentage overlap in wildfire buffers by increasing buffer distance from 0 km to 5 km. This is expected because the wildfire buffer area relative to which the percentages are calculated also increases with the buffer distance. Similarly, the percentage overlap relative to WUI-B (sixth column) increased to 25.5% (Table S2b) with 5 km buffer distance from wildfire burned areas. On the other hand, the increase in the percentage of overlap relative to the wildfire buffers are from 0.8% to 2.5% with no buffer to 5 km buffer distance, respectively. However, the effects of WUI types on the percentage overlap is not different between WUI-A & WUI-B; increasing the buffer distance from wildfires increased percentage overlap in both the WUIs (Table S2a & Table S2b).

Figure 2 shows the spatial distribution of overlap between varying buffer distances from the existing wildfire perimeters and two types of WUI used in this study (WUI-A and WUI-B). Wildfire perimeters are nearer to WUI-A as seen in figure on the left panel and thus will result in higher percentage overlap between wildfire burned area and WUI-A (also shown quantitatively in Table S2a & Table S2b). Also note that the total area of WUI-B: 9,606.273 sq. km is less than that of WUI-A: 27,025.683 sq. km. Figure 3 shows that the percentage overlap with increasing buffer distance with respect to the WUI area in the red line and with respect to the wildfire buffer area in black line. Both increasing trends are found to regress well with a linear trend. These linear trends are found for both WUI types. However, the slope in case of WUI-B is higher as compared to WUI-A, and thus, there is a higher rate of increase in the percentage overlap. On the other hand, the percentage overlap with respect to wildfire buffer areas does not increase in the similar manner for both the cases with varying buffer distances. However, the rate of increase in percentage overlap in wildfire buffers is higher for WUI-B (from 0.8% to 2.6%) as compared to WUI-A (from 4% to almost 8%).

The buffer distance analysis shows the importance of considering spotting fire behavior when considering fire risk in the WUI. While the actual fire front might not burn significantly within the WUI areas, firebrands and burning embers originating from the fire front might travel these buffer distances and under favorable conditions, might be able to ignite structures. Anecdotal evidence of unburnt and unconsumed trees adjacent to destructed structures in the WUI during high intensity fires (such as Paradise, California, during the Thomas Fire, 2018) bears evidence of these effects. WUI areas do not need to see a `tsunami or flood of flames', rather they are at a higher risk from firebrand ignitions (Wildfire Today, 2020). Fire management policies and WUI risk mapping should consider this effect. The analyses also show that wildfires are not only limited to the regions of existing WUIs, but they also burn farther away from the WUI zones. Thus, there is a need for proper evaluation of fire events that have burned in the extended WUI regions. This will reduce the chances of damage and fire threat in the locations which have not been included in the WUI. Extended WUI should consider the optimum housing density threshold and a modified buffer distance for WUI Interface mappings. Moreover, the distance travelled by a firebrand depends on the topography (Storey et al., 2020) and wind speed and is directly proportional to these parameters. In other words, a firebrand can travel more than assumed 1.5 miles (a/c to existing WUI mappings) of distance from a fire source when there is non-planar surface and higher wind speed. Also, we will see in the next subsections that most of the existing WUIs in CA are located in regions of higher elevation, where existing WUI definitions need to be further scrutinized.

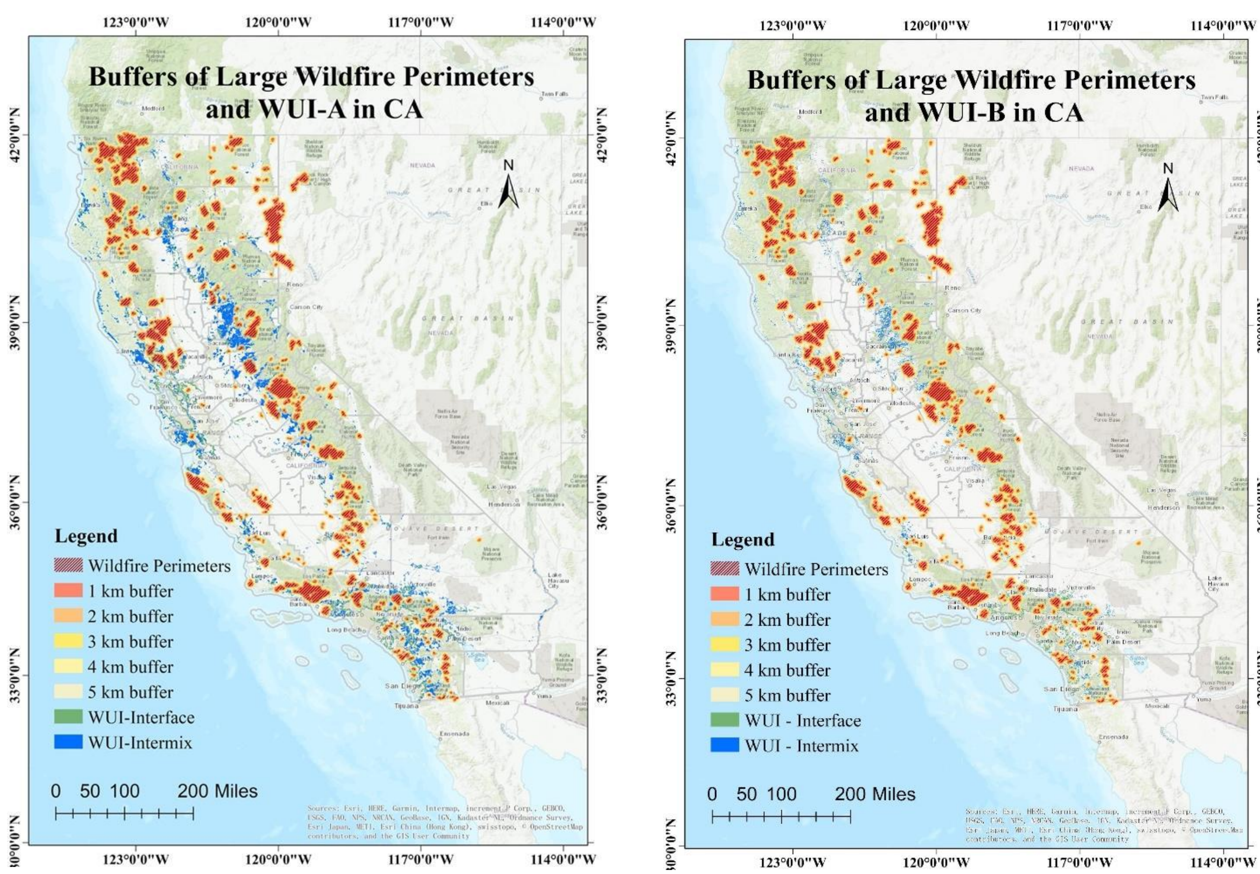

Figure 2. The figure on the left panel shows a spatial plot of buffers of fire perimeters (large fires only, having an area greater than 1,000 ac) and WUI-A for CA; similarly the figure on the right panel represents buffers of large wildfires and WUI-B in CA. Legends in these spatial plots show types of WUI (Intermix and Interface) and the varying wildfire perimeter buffer distances.

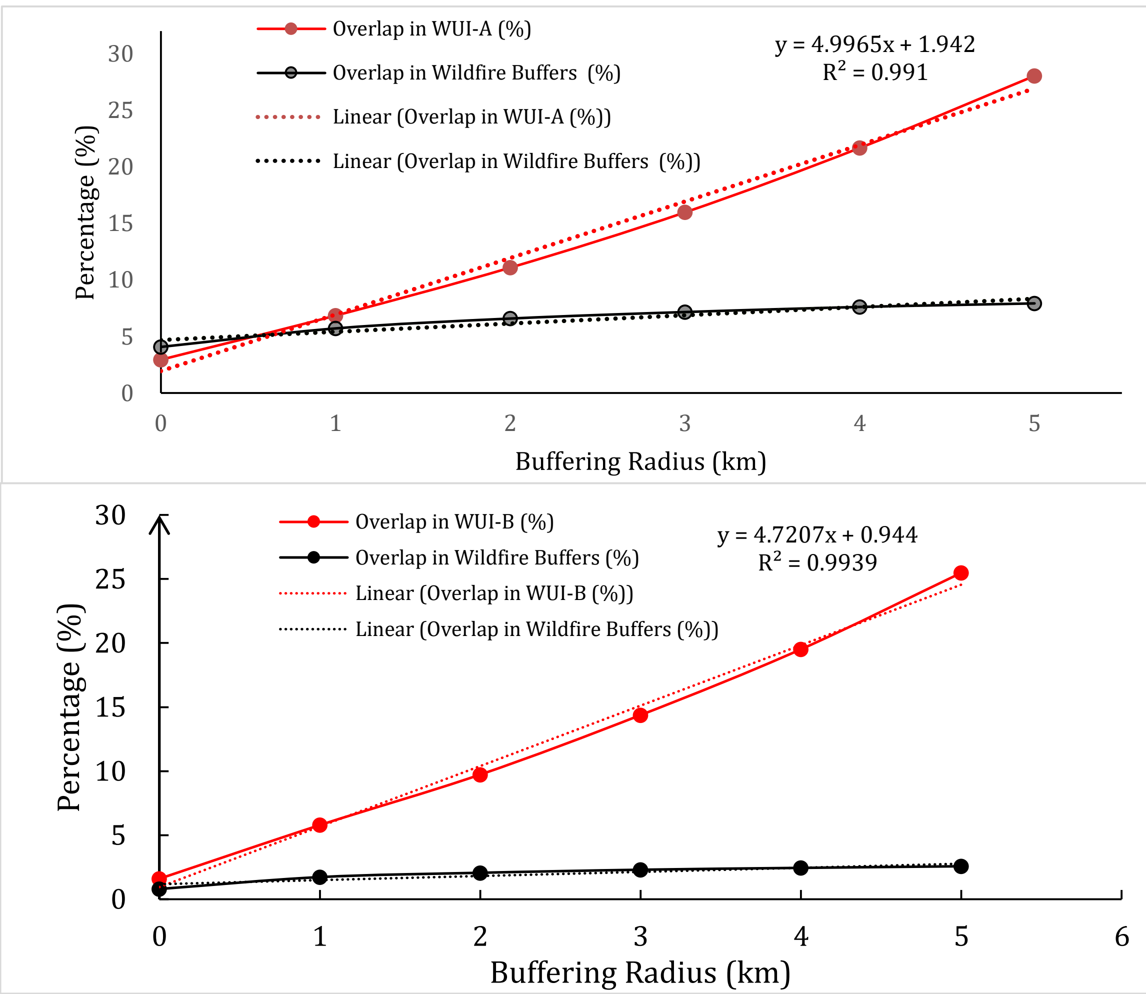

Figure 3. The figure on the top panel shows percentage overlap between wildfire burned area with WUI-A with respect to WUI-A area (solid red line) and percentage overlap with respect to wildfire buffer area (solid black line). The figure in the bottom panel shows the same for WUI-B. Here, Y-axis represents the percentage overlap, while X-axis represents the buffer distance (in km). The dotted line indicates curve fitting (linear) for the percentage overlap in different types of WUIs (WUI-A & WUI-B).

3.2.2: Analysis of Buffer distance from WUI perimeters

In subsection 2.2.1, the buffer distances were calculated from the wildfire perimeters. In this next section, the buffer distances are calculated from the WUI perimeters and similar statistics are calculated. The percentage overlap of wildfire burned areas with varying buffer distance from WUI-A has been shown in table S3a and depicted in Figure 4. The percentage of overlapped regions w.r.t. wildfire burned areas (19,517.675 sq. km) increased from 4% to 56% when the buffer distance from WUI-A changed from 0 km to 5 km. Even with a buffer distance of 1 km, there is a 13% increase in the percentage overlap (from 4% to 17%). Whereas, the same overlapped areas w.r.t. WUI-A areas do not increase in percentage overlap (from 3% to 5%) with 5 km buffer distance, given that the WUI buffer area also increases significantly (the denominator increases as well). Similarly, table S3b shows that the overlap of wildfire burned areas with varying buffer distance from WUI-B. The percentage overlapped w.r.t. wildfire perimeters increased up to 36% with a buffer distance of 5 km from almost 0.8 % overlap without a buffer around WUI-B. While, the percentage overlap in WUI-B buffers did not increase in the same manner and changed to 4.2% from 1.6% with 5 km buffer distance (again, due to the increase of the buffer area itself). Figure 5 shows that the percentage overlap w.r.t. wildfire perimeters increases linearly with buffer distance for both types of WUIs. However, the rate of increase in percentage overlap is higher in case of WUI-A (top panel) as seen from the slope of the linear equation as compared to WUI-B (bottom panel). On the other hand, the percentage overlap wr.t. WUI areas do not increase significantly for both the cases.

Therefore, these results (Table S3a, Table S3b and Figure 4 and 5) give a clear visualization that wildfire events are not limited to the existing WUIs, but are more widespread outside them (extended WUI). Fire risk maps associated with WUI areas should consider the buffer regions as well. The discussion above only considers fire perimeters, and it is worth asking whether fire ignitions also originate within or outside these WUI perimeters. This is discussed in the following subsection.

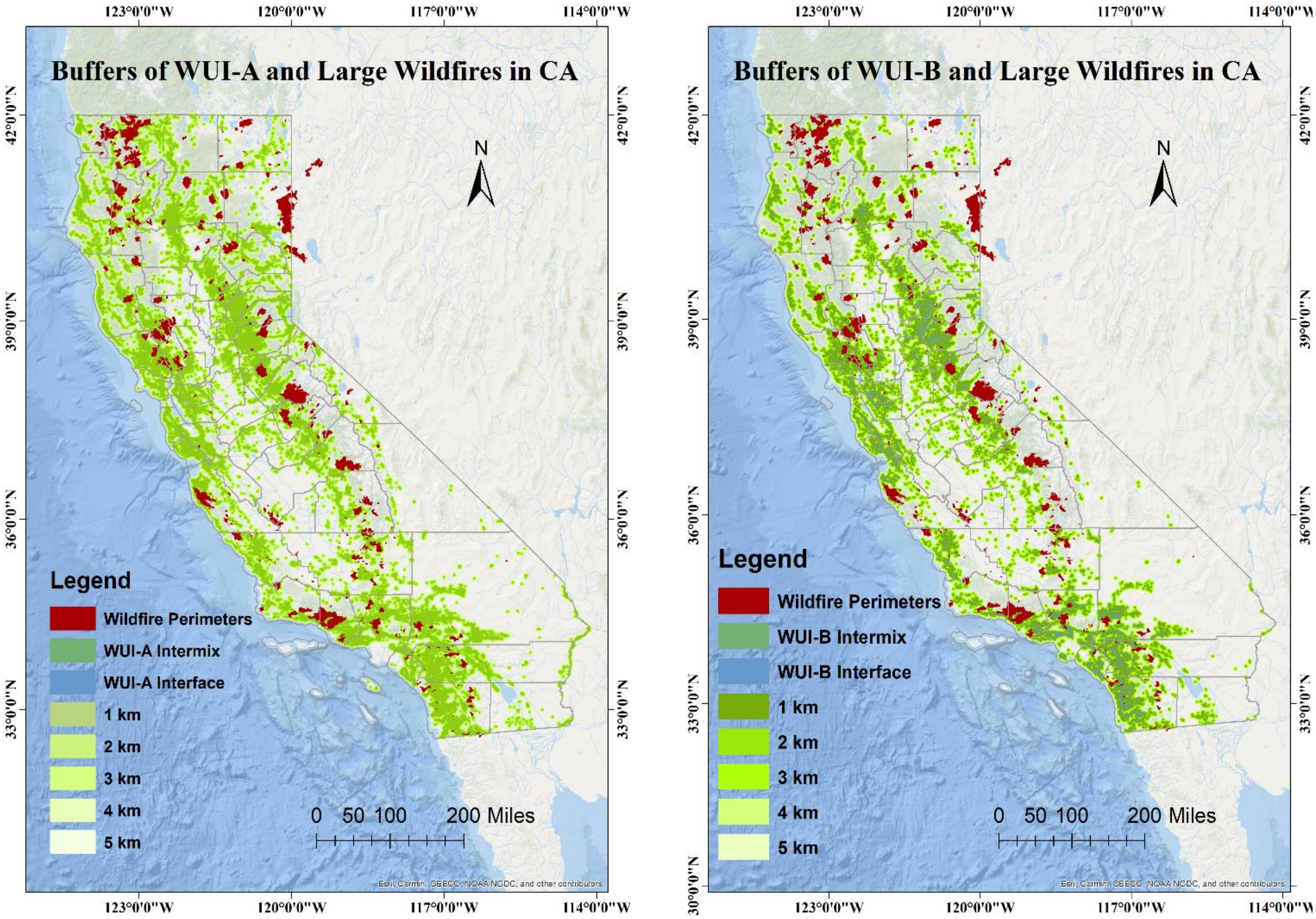

Figure 4. The figure on the left panel shows the spatial plot of overlap of buffers of WUI-A with fire perimeters (large fires only, with area > 1,000 ac). While the figure on the right panel shows the spatial plot of overlap between buffers of WUI-B and fire perimeters (large fires only having area > 1,000 ac). Legend in these spatial plots show types of WUI, wildfire perimeters and the areas of WUI-A & WUI-B with varying buffer distance from WUI. Overall, the percentage overlap between the buffers of the existing WUIs and wildfire perimeters are higher in WUI-A than WUI-B, and it increases in both the cases on increasing buffer radius.

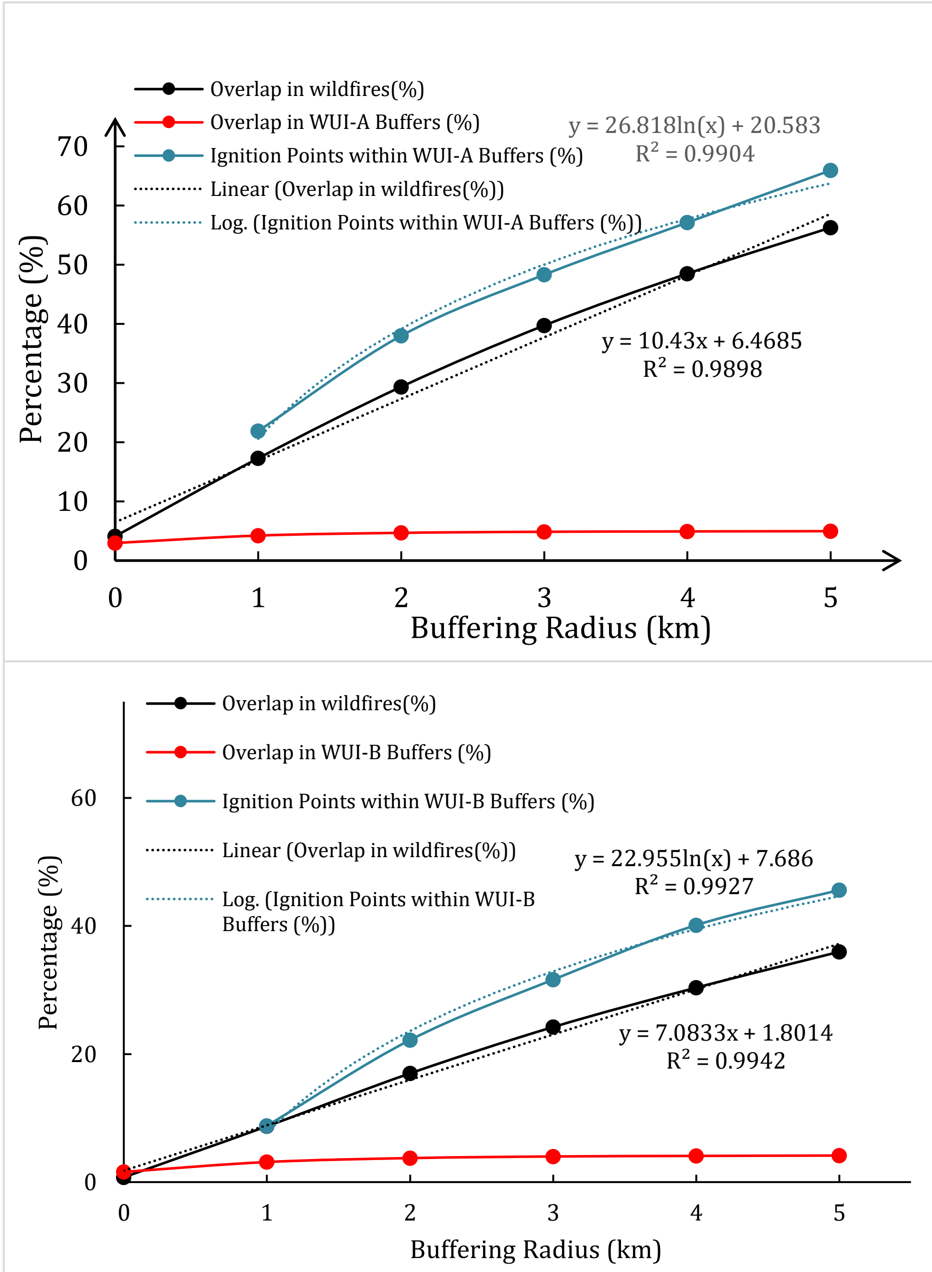

Figure 5. The figure on the top panel represents the percentage overlap of wildfire burned areas with WUI-A buffer areas. The solid red line represents the overlap w.r.t. WUI-A buffer perimeters. Percentage overlap w.r.t. wildfire perimeters is shown by solid blue lines and the fire ignition points within the WUI-A buffers are shown by solid black lines. The bottom panel shows the same for WUI-B. Here, X-axis shows the percentage overlap, while buffer distance (km) has been represented on Y-axis. The dotted line indicates linear curve fitting for the percentage of overlap in the area of wildfire perimeters and logarithmic curve fitting for fire ignition points within WUI buffers.

3.3. Overlap of WUI with fire ignition points

Wildfire data obtained from MTBS, from 2010 to 2017 also comprise a total of 329 fire ignition points (excluding prescribed fires) in the state. Table S1a shows that total 12 wildfires ignited in the WUI-A of which only 8% (1 out of 12) occurred in the WUI-A Interface, while 92% (11 out of 12) ignited in the WUI-A Intermix. While, only 4 wildfires ignited in the WUI-B interface out of 329 fires and no fires ignited in the WUI-B Intermix zone (Table S1b). Thus, more wildfires ignited in WUI-A (3.6%) as compared to WUI-B (1.2%) in California. The percentage overlap of fire ignition points with varying buffer distance from WUI-A has been shown in table S3a and plotted in Figure 5. Here, the number of wildfire ignition points within WUI-A increases drastically when the area of WUI-A increases with buffer distances. The number of ignition points was 72 out of 329 when there was a 1 km buffer around WUI-A and it increased to 217 ignition points at a buffer radius of 5 km, making the percentage overlap to 66 % from 22%. In addition, figure 5 shows the logarithmic increase in the percentage overlap of fire ignition points within the WUI buffers. However, WUI-A (figure on the top panel) shows a higher rate of increase than WUI-B (figure on the right panel). Also, table S3b shows the number of fire ignition points within WUI-B, increases to 150 out of 329 (almost 46%) at 5 km buffer radius as compared to 4 out of 329 ignition points (1.2%) within WUI-B buffers. Clearly, there is a noticeable increase in the number of fire ignition points falling in these WUIs (WUI-A & WUI-B) when the buffer radius increases from WUI. Therefore, our analysis shows that wildfire events do not occur in these predefined WUIs only, rather its frequency and burned area increases as we increase the buffer distance from existing WUIs (extended WUI). It is worth reiterating that existing risk maps used by land management and stakeholders (such as the fire insurance market) might consider the risks outside the WUI areas in terms of ignition as well. Contrary to common perceptions, only a minority of ignitions start at the WUI and the number of ignitions actually increases away from the WUI.

In the previous sections, the existing definitions of WUI have been discussed in the context of wildfire ignition and burned areas, as WUIs are often perceived to be the hotspots of wildfire risk. One of the three factors that influence fire risk and fire behavior is topography (along with fuel and weather). Therefore, whether the WUI areas in CA are strongly associated with complex topography is worth investigating, to place the fire risk perception into context and this is discussed in the next subsection.

3.4. WUI on the complex topography

3.4.1: Elevation

Topography is one of the most influential factors in the fire spread rate. Wildland fires travel much faster over uphill than downhill, and the spread and severity of a fire on an uphill slope are further increased by wind, due the enhanced efficiency of convective pre-heating of fuel elements on an upslope, downwind of the flame front. Wildfires are easier to control over a flat surface and burn less intensely than over a moderate or steep slope. Moreover, complex topography influences wind flow and local turbulence patterns, thereby altering the uplift and dispersion of firebrands. It has been already established that firebrand exposure is extremely important while considering structural and property damage in the WUI. In order to better understand the perception of fire risk in the WUI, we analyzed the locations of the existing WUI in California, which is associated with a very complex topography.

Povak et al., (2018) analyzed 11,000 past wildfires (fire perimeters) across CA and found that topography exerts significant influence on the dynamics of wildfires that occurred in rugged and complex terrain. Figure 7a (top left panel) shows the spatial distribution of elevation across CA with a maximum elevation of 4,410 m. Figure S1 shows the distribution of elevation ranges in CA. In table S4, we show the percentage overlap of WUI-A in 2010 with 9 ranges of elevation for CA. The maximum elevation value for California is 4410 m. The histogram plot (Figure 6a) shows that the maximum WUI percentage lies in the elevation range of 0-100 m for WUI-B (20.17%) and above 800 m for WUI-A: (21.4%). These results show that the WUI regions are more often situated on the complex topography. However, elevation is not the only metric that describes complex topography – and other parameters such as rugosity, slope and aspect are equally important.

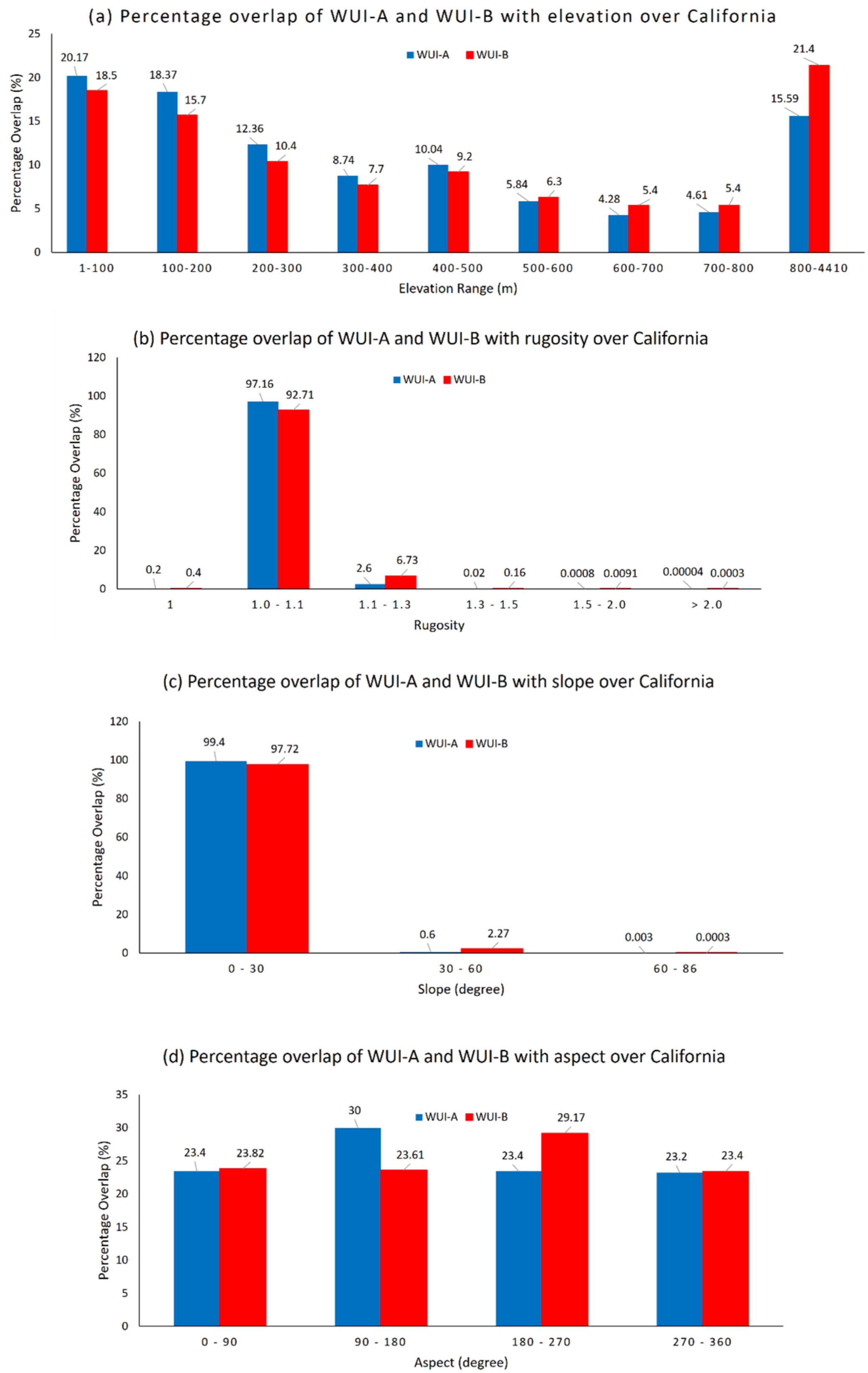

Figure 6. Histogram showing the percentage overlap of WUI for California (CA) with (a) different elevation ranges (b) rugosity (c) slope, and (d) aspect. Two colored columns are used to show the different WUI data sources used here for comparison, red column shows the WUI data from (Martunizzi et al., 2015) while blue

column is used for CAL FIRE (FRAP, 2015) WUI data set. Here, Y-axis represents overlaps in percentage, while X-axis shows different elevation ranges over CA in meters.

3.4.2: Rugosity

Surface ratio or rugosity is the ratio of a planar surface to the actual surface. The values of rugosity vary from 1 to infinity, but in practice it rarely reaches as high as 3. It gives a notion of the complexity of a surface. If the value of rugosity is 1 then it represents a planar surface, while values greater than 1 indicate more complex terrain and thus a high rugosity value of a landscape is a measure of more complicated wind flow, fire behavior, ember dispersion patterns as well as complexity of firefighting, rescue and evacuation operations. For a three-dimensional surface, it could be stated as the ratio of the contoured surface to the area of its orthogonal projection onto a plane. Figure 7b (top right panel) shows the spatial distribution of rugosity over CA and it is clear that a very small portion of landform has a rugosity value equal to 1 (planar surface) as represented with darker green color. In figure 6b, analysis of percentage overlap between WUI areas and rugosity for CA yields an interesting outcome. It shows that only 0.4% of the WUI (WUI-A) are present on the regions with planar surfaces, having rugosity equal to 1. While this number grows to 92.7% and 97.16% for WUI-A and WUI-B respectively for surfaces with the rugosity values greater than 1 and less than or equal to 1.1 (Table S5). Moreover, it shows that almost 99.6% and 99.8% of the WUI-A and WUI-B respectively are in the non-planar regions within CA. Therefore, most of the WUI in this state are located on the complex topography where fire spread rate is higher than the flat surface and controlling large fires are very difficult. This result gives us a notion that the existing WUI mappings needs to be revised keeping the topography of a region to be an important factor in the mapping methods.

3.4.3: Slope and Aspect

Jenness et al., (2004) proposed that rugosity calculation is subject to edge-effect issues and by using the horizontal planimetric area, rugosity is affected by slope. Slope of a surface shows the angle between the plane of best fit and the horizontal plane. This angle is equivalent to the angle between the normal vectors of the two planes and can be obtained from their dot product. The value of slope ranges from 0 to 90 degrees. Figure 7c on the bottom left panel shows spatial distribution of slope over California and most of the regions are in the lower slope ranges. The percentage overlap of WUI-A (WUI-B) with the slope ranges 0-30, 30-60 and 60-86 of the state are 97.72% (99.4%), 2.27% (0.6%) and 0.0003% (0.003%) respectively as can be seen in figure 6c (table S6). The direction that a surface slope faces is called aspect and is defined as the angle between the positive x axis and the projection of the normal onto the x, y plane. The aspect is an angle in the range $(-\pi, \pi)$. Aspect identifies the downslope direction of the maximum rate of change in value from each cell to its neighbors. Aspect can be thought of as the slope direction. The values of the output raster will be the compass direction of the aspect. In figure 7d (bottom right panel), the spatial variation of the aspect has been shown for California and there is almost similar distribution of the direction of the surface slopes as represented by the aspect in all the four quadrants. However, there is almost similar distribution of the percentage overlap of WUI-A and aspect for California in the three quadrants having first (23.82%), second (23.61%), fourth (23.4%) and with a little higher (29.17%) in the third quadrant (figure 6d; table S7). Also, figure 6d shows the percentage overlap of WUI-B and aspect for California and it is highest in the second quadrant (30%), while the other three quadrants have 23.4% (first), 23.4% (third), and 23.1% (fourth), that is, almost equal percentages.

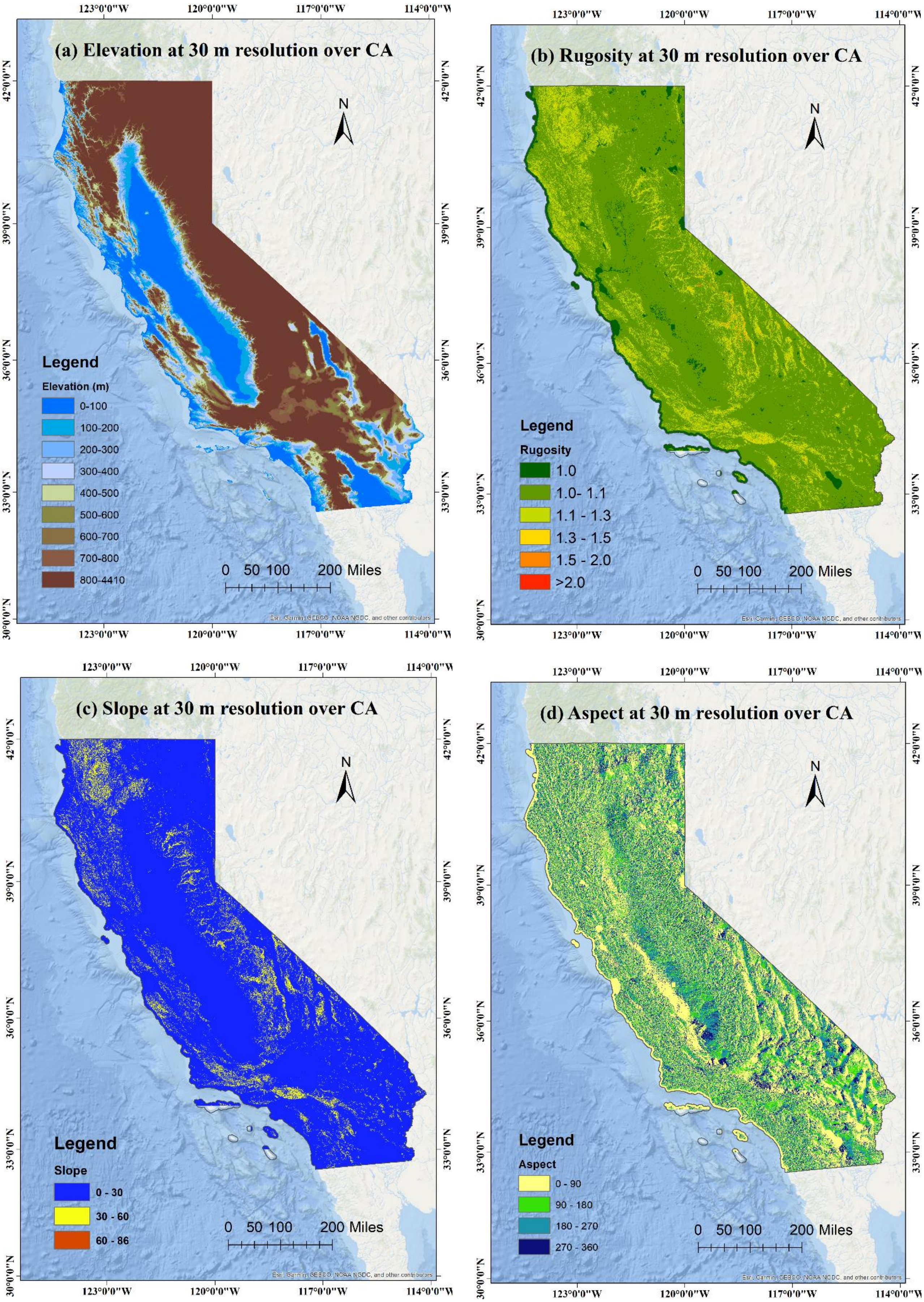
(a) Elevation at 30 m resolution over CA
Legend
Elevation (m)
0-100
100-200
200-300
300-400
400-500
500-600
600-700
700-800
800-4410
(b) Rugosity at 30 m resolution over CA
Legend
Rugosity
1.0
1.0- 1.1
1.1 - 1.3
1.3 - 1.5
1.5 - 2.0
>2.0
(c) Slope at 30 m resolution over CA
Legend
Slope
0 - 30
30 - 60
60 - 86
(d) Aspect at 30 m resolution over CA
Legend
Aspect
0 - 90
90 - 180
180 - 270
270 - 360
N
0 50 100 200 Miles
123°0'0"W
120°0'0"W
117°0'0"W
114°0'0"W
42°0'0"N
39°0'0"N
36°0'0"N
33°0'0"N
30°0'0"N
Esri, Garmin, GEBCO, NOAA NGDC, and other contributors

Figure 7. The figure on the top left panel (a) shows spatial variation of topography with different elevation ranges. The legend shows different ranges of elevation for the entire landform over CA and the magnitude of these values lie between 0 m to 4410 m and also represented with different classes from 1 to 9 as can be referred to table S4, top left panel (b) shows the spatial distribution of rugosity (surface roughness) over California at 30 m resolution. Legend shows the values of rugosity from 1 to more than 2. Spatial distribution of slope has been shown in the bottom left panel (c) and was calculated using 4-cell method over California at 30 m resolution. Here, legend represents the value of slope in degrees. The figure on the bottom right panel (d) shows the spatial distribution of the aspect calculated using 4-cell method over California at 30 m resolution. Legend shows the values of aspect lying in the four quadrants.

4. Conclusions

There is a common perception in the wildland fire community that fire risks are highest in the wildland urban interface (WUI) area. In this work we examine the notion by comparing two pre-existing definitions of WUI with respect to past wildfire events in California. It was found that a very small percentage of wildfire burned areas are actually within the WUI areas. Moreover, only a very few numbers of wildfires were actually ignited within WUI areas. However, when we introduce a buffer distance from the existing WUI perimeters, there is a significant increase in the percentage of wildfire events in terms of fire ignition points. More than 50% wildfire events occurred at a buffer distance of 5 km from the existing WUIs. This shows that not only WUIs are the zones of wildfires occurrence but also the non-WUI or areas larger than the existing WUI (extended WUI) are highly prone to wildfires. Our results highlight a rapid rate of increase in the percentage overlap of wildfire burned areas and fire ignition points in the extended WUIs. Thus, it breaks the notion that wildfires occur mostly in the WUIs, and thus gives direction to think about remapping the existing WUIs for CA to control wildland fires outside the existing WUIs. Therefore, urgent steps need to be taken by the foresters and land managers in order to reduce threat to the communities and damages to the property located within the buffered zone from existing WUIs.

In addition, the topography of a landform plays an important role and knowing the location of existing WUIs would give us a better understanding of fire dynamics and planning adequate firefighting strategies. This study highlights that most of the existing WUIs in California are on complex topography where, a firebrand can travel more than 2.4 km distance as assumed in the USFS WUI mapping method, the meteorological factors like wind speed are more favorable for higher rate of fire spread and firefighting is difficult due to complex terrain. Most importantly, our study suggests a need to modify the existing WUI definitions. Thus, consideration of physical factors like topography, surface roughness, etc. would be helpful for remapping the WUI existing definitions. Methodology and the thresholds of housing or buffer distance should be modified in accordance with these factors. These changes are crucial to the existing WUI mappings in California so as to cover all sets of parameters that increases the wildland fire risk and make it more difficult to control. In this way we will have a more accurate definition of WUI for this state, where the recent decade has seen many deadliest wildfires. On a more hopeful note, implementation of our analysis results would capture a significant area of WUI where maximum fire events can be monitored and would be easier to focus on the policies to reduce the damages due to future fires and a better planning for the firefighters for easy rescue and evacuation during a wildfire event within the WUI.

Acknowledgment

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Supplementary Information

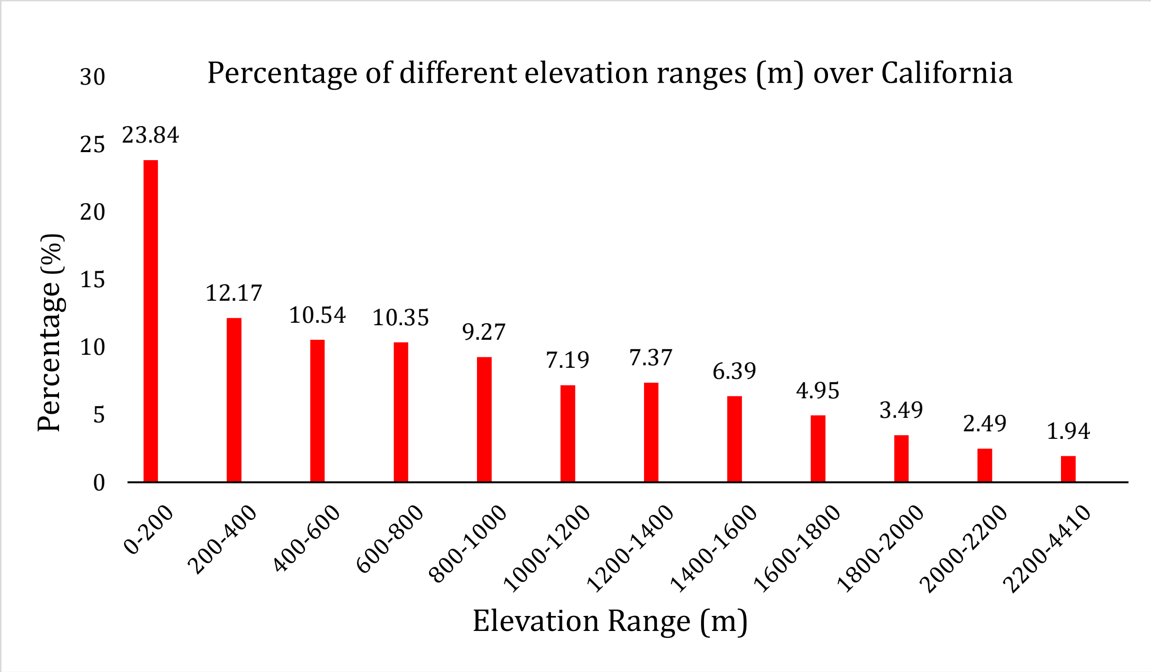

Figure S1. Percentage of different elevation (30 m) ranges over California. It shows the percentage of different elevation ranges over CA are maximum in 0-200 m followed by 200-400 m. More than half of the regions in CA are on complex topography having elevation values greater than 600 m and only 46.36% of landforms lie within 600 m of elevation.

Table. S1a The overlap between wildfire burned areas and fire ignition points with WUI-A.

WUI-A Area (sq. km)		Wildfire burned Area (sq. km)	Overlapping Area (sq. km)	Percentage of overlap in Wildfire burned Areas (%)	Percentage of Wildfires ignited in WUI-A (%)	Percentage of overlap in WUI-A (%)
Interface	8,046.643	19,517.675	49.387	0.253	0.304 (1/329)	0.614
Intermix	18,979.040		747.113	3.828	3.343 (11/329)	3.936
WUI-A (Total)	27,025.683		796.500	4.081	3.647 (12/329)	2.947

Table. S1b The overlap between wildfire burned areas with WUI-B and the fire events, represented by ignition points for the same period with WUI-B.

WUI-B Area (sq. km)		Wildfire burned Area (sq. km)	Overlapping Area (sq. km)	Percentage of overlap in Wildfire burned Areas (%)	Percentage of Wildfires ignited in WUI-B (%)	Percentage of overlap in WUI-B (%)
Interface	4,232.847	19,517.675	24.431	0.125	1.216 (4/329)	0.577
Intermix	5,373.426		129.173	0.662	0 (0/329)	2.404
WUI-B (without influence Zone)	9,606.273		153.604	0.787	1.216 (4/329)	1.599

Table. S2a Percentage overlap of wildfire burned area and WUI-A with varying buffer distances from wildfire perimeter.

WUI-A Area (sq. km)	Buffer Radius (km)	Wildfire Buffer Area (sq. km)	Overlapping Area (sq. km)	Percentage of overlap in Wildfire Buffers (%)	Percentage of overlap in WUI-A (%)
27,025.683	0	19,517.675	796.500	4.081	2.947
	1	32,373.264	1,851.402	5.719	6.851
	2	45,477.682	2,998.147	6.593	11.094
	3	60,238.204	4,319.187	7.170	15.982
	4	76,904.458	5,858.389	7.618	21.677
	5	95,529.777	7,580.403	7.935	28.049

Table. S2b Percentage overlap of wildfire burned area and WUI-B with varying buffer distances from wildfire perimeter.

WUI-B Area (sq. km)	Buffer Radius (km)	Wildfire Buffer Area (sq. km)	Overlapping Area (sq. km)	Percentage of overlap in Wildfire Buffers (%)	Percentage of overlap in WUI-B (%)
9,606.273	0	19,517.675	153.604	0.787	1.599
	1	32,373.264	555.739	1.717	5.800
	2	45,477.682	934.399	2.055	9.753
	3	60,238.204	1,380.736	2.292	14.411
	4	76,904.458	1,874.200	2.437	19.562
	5	95,529.777	2,447.613	2.562	25.547

Table. S3a The overlap of wildfire burned area and wildfire ignition points with different buffer distances from WUI-A.

Wildfire Area (sq. km)	Buffer Radius (km)	WUI-A Buffer Area (sq. km)	Overlapping Area (sq. km)	Ignition Points within WUI-A Buffers (%)	Percentage of overlap in Wildfire burned Areas (%)	Percentage of overlap in WUI-A Buffers (%)
19,517.675	0	27,025.683	796.500	3.647 (12/329)	4.081	2.947
	1	80,066.343	3,372.233	21.884 (72/329)	17.278	4.212
	2	122,611.267	5,732.952	37.994 (125/329)	29.373	4.676
	3	159,640.146	7,757.174	48.328 (159/329)	39.744	4.859
	4	192,297.277	9,467.068	57.143 (188/329)	48.505	4.923
	5	221,335.796	10,984.716	65.957 (217/329)	56.281	4.963

Table. S3b The overlap of wildfire burned area and wildfire ignition points with different buffer distances from WUI-B.

Wildfire Area (sq. km)	Buffer Radius (km)	WUI-B Buffer Area (sq. km)	Overlapping Area (sq. km)	Ignition Points within WUI-B Buffers (%)	Percentage of overlap in Wildfire burned Areas (%)	Percentage of overlap in WUI-B Buffers (%)
19,517.675	0	9,606.273	153.604	1.216 (4/329)	0.787	1.599
	1	54,204.707	1,706.335	8.814 (29/329)	8.743	3.148
	2	87,920.876	3,316.826	22.188 (73/329)	16.994	3.773
	3	117,422.931	4,727.220	31.611 (104/329)	24.220	4.026
	4	143,964.111	5,925.639	40.122 (132/329)	30.360	4.116
	5	168,252.547	7,017.430	45.593 (150/329)	35.954	4.171

Table. S4 Percentage overlap of WUI on different elevation ranges (classes) over California (CA) at 30 m resolution.

Elevation (m)	1	2	3	4	5	6	7	8	9
	0-100	100-200	200-300	300-400	400-500	500-600	600-700	700-800	800-4410
%WUI-A	18.50	15.70	10.40	7.70	9.20	6.30	5.40	5.40	21.40
%WUI-B	20.17	18.37	12.36	8.74	10.04	5.84	4.28	4.61	15.59

Table. S5 Overlap of WUI and rugosity for CA.

Rugosity	1.0	1.0 - 1.1	1.1 - 1.3	1.3 - 1.5	1.5 - 2.0	> 2.0
WUI-A (%)	0.40	92.71	6.73	0.16	0.0091	0.0003
WUI-B (%)	0.20	97.16	2.60	0.02	0.0008	0.00004

Table. S6 Overlap of WUI and slope for CA.

Slope (degree)	0-30	30-60	60-86
WUI-A (%)	97.72	2.27	0.0003
WUI-B (%)	99.4	0.60	0.003

Table. S7 Overlap of WUI and aspect for CA.

Aspect (direction)	0-90	90-180	180-270	270-360
WUI-A (%)	23.82	23.61	29.17	23.40
WUI-B (%)	23.40	30.00	23.40	23.20