# Mapping the wildland-urban interface in CA using remote sensing data

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**Abstract**

Due to the mixed distribution of buildings and vegetation, the wildland-urban interface (WUI) areas are characterized by complex fuel distributions and geographical environments. The behaviors of wildfires occurring in WUIs are significantly different from those occurring only in wildland vegetation or building fires, often leading to more severe hazards. Therefore, WUI areas warrant more attention during the wildfire season. Currently, most of the widely used WUI maps were calculated and drawn based on the housing data in the decennial Census and the vegetation data from the National Land Cover Database (NLCD) updated every three to five years. In the context of the current increase in California's population and housing, this update frequency and map resolution can no longer meet the firefighting frontline's needs. The developments of remote sensing technology and data analysis algorithms have brought opportunities for improvement in WUI mapping. In this study, WUI was directly mapped with the building footprints in California extracted from satellite data by Microsoft along with the fuel vegetation cover from the LANDFIRE dataset based on maximum spot fire distance. This method did not require the calculation of housing density but designated the adjacent area of each building with large and dense areas of vegetation as WUI, which avoided the modifiable areal unit problem (MAUP). This method can not only refine the scope of the WUI area to each building, but also have the capability of updating the WUI map in real-time according to the update frequency of satellite data and operational needs. Therefore, this method is suitable for local governments to map exhaustive local WUI areas, formulating detailed wildfire emergency plans, evacuation routes, and management measures.

# 1 Introduction

The process of suburbanization in the United States, which has continued since World War II, has dramatically increased the impact of human activities on natural ecosystems (Hammer et al., 2009; Simon, 2014). The urban sprawl caused by the migration of the population to the suburbs has intensified the ingression of human structures into the wildlands, forests, and habitats (Zhang et al., 2008). To monitor and evaluate the impact of these human activities on the local climate and environment, the area where human structures and wildland vegetation coexist either adjacent or interspersed with each other were defined as the Wildland-Urban interface (WUI) (Stein et al., 2013; Radeloff et al., 2005). In California, one of the most notable feature of the WUI is that they are perceived as the high-risk areas of human-caused wildfires due to the accumulation of wildland vegetation, the concentration of flammable human structures, and the strewing of sparks left by human activities (Syphard et al., 2007). Although most wildfires occur in uninhabited wildland, wildfires ignited or spread into the WUI pose a more significant threat to human lives and assets due to the proximity of the human community and wildland fuels (Mercer and Prestemon, 2005; Kramer et al., 2018; Kumar et al., 2020). Besides, the disturbance to local species and the introduction of invasive species caused by the construction and development of human communities weaken local ecosystems' resistance and resilience to wildfires (Syphard et al., 2009). Therefore, the WUI area is of great concern in wildfire prevention and management.

The distribution of WUI in the United States is widespread and continues to rise. From 1990 to 2010, the WUI area in the contiguous United States (CONUS) increased rapidly from 7.2% to 9.5%, which caused a 9.6% increase in the number of houses and a 8.5% increase in land area within in the new WUI, accompanied by the increase in housing and population (Radeloff et al., 2018). During the same time span, the WUI area in California increased from 26,263 $km^2$ to 27,255 $km^2$, with a rate of increase about 3.8%. By 2010, the number of houses within the WUI had grown to 4.46 million, and the population had grown to 11.2 million in California, making it the state with the largest number of houses and population in the WUI (Martinuzzi et al., 2015). The growth of WUI not only increased the risk of fire ignitions but also increased the difficulty of fire extinction, because in these areas, firefighters' top priority is to protect people and assets (Ager et al., 2019). Given the above, accurately mapping and timely updating the WUI region to provide firefighters and emergency responders with more complete and practical WUI maps is of prime importance (Calkin et al., 2014).

Based on the definition of WUI from the Federal Register (Glickman and Babbitt, 2001), the current common WUI mapping methods heavily rely on the threshold of building density and vegetation proportion. Due to the data limitation, the housing density was calculated using housing counts in Census blocks, and the threshold is 1 house/40 acre (6.17 houses/$km^2$), and the vegetation proportion was calculated by the vegetation area from the National Land Cover Database (NLCD) within each Census block, the threhold of vegetation is $> 50$ % for intermix and $> 75\%$ for interface (Glickman and Babbitt, 2001). It means that the WUI area should meet the requirements of *high-density houses surrounded by high-density wildland vegetation* (50% of vegetation area in the Census block) or *high-density houses adjacent to , that is within 1.5 miles (2.4km) of a large tract of contiguous wildland vegetation* (75% of vegetation area in the Census block).

However, because of the limitations in the update-frequency (10 years for census data) and the precision of housing and vegetation data, there are uncertainties in the current mapping methods, especially in calculating housing density (Bar-Massada et al., 2013). Radeloff et al. (2005) mapped the WUI of all states in the CONUS based on housing statistics provided by the census data in 2010 and vegetation cover provided by the National Land Cover Database (NLCD). The minimum unit of housing density in this zonal mapping method was census block, and the zone modifiable areal unit problem (MAUP) cannot be avoided (Bar-Massada et al., 2013). Meanwhile, this method removes all the area of public land to get a more precise housing density. However, there are also human structures on public lands, such as the powerline and the airport, and their effect is completely ignored. Subsequently, as an improvement to the zonal mapping method, Platt (2010) used points mapped from the parcel centroids representing building locations to calculate housing density in WUI mapping. The limitation of this method is that these points were not the actual locations of the buildings and would still be erroneous. Bar-Massada et al. (2013) mapped WUI directly from the buildings' location and calculated housing density by "circular moving window analysis". It divides the studied region by grids first and then overlaying a circular moving window to calculate the mean housing density for all the grids in the window. The mean housing density would be assigned to the central grid. Although the WUI maps can be customized based on needs, defining appropriate window sizes in different spatial scale is a challenge. Besides, traditional housing density data are updated at long intervals, as census data are collected and updated every ten years. The current update frequency of WUI maps is far behind its growth rate.

With the improvement of the quality of remote sensing data in terms of acquisition efficiency and resolution, it has become possible to extract detailed housing and vegetation boundaries from it. Over the past few years, Microsoft has made great efforts in applying deep learning, computer vision and AI to mapping and leveraging the power of machine learning in analyzing satellite imagery to trace the shape of buildings across the country. More specifically, Bing Maps (Microsoft, 2018a), a mapping platform from Microsoft, has successfully generated the first comprehensive, high-quality housing footprint database covering the entire United States. This data product used Deep Neural Network and the residual neural network (ResNet34) with segmentation techniques (RefineNet up-sampling) to detect individual building footprints from their imagery data (Microsoft, 2018b). The database is available to download free of charge and contains over 125 million computer-generated building footprints in all 50 US states. In terms of the vegetation data, the LANDFIRE (LF) program from USGS utilizes Landsat 7 Enhanced Thematic Mapper Plus (ETM+) and Landsat 8 Operational Land Imager (OLI) image products to provide national scale vegetation, fuel, and fire regime data (Picotte et al., 2017). The LANDFIRE Reference Database (LFRDB) and Several ancillary datasets such as NLCD 2011 and Prism were also utilized as reference. The fuel vegetation cover data from the LANDFIRE database not only update more frequently than NLCD maps, but also directly provide pixel-level vegetation cover percentage, simplifying and reducing the computational cost in WUI mapping.

Using the above-mentioned data, the WUI map in California as well as the WUI mapping method can be updated. Our goal in this paper is to 1) use housing footprints from Microsoft and Vegetation data from the LANDFIRE program, combining the definition of WUI and, based on the characteristics of the data, design a practical WUI rendering method; 2) compare the new WUI maps to the previous WUI databases, analyze if there are improvements to the previous map; 3) combining with the historical wildfire record, analyze the usefulness of the new WUI map in wildfire risk assessment.

# 2 Data and Method

## 2.1 Housing footprint data

One of the most important components of WUI is the presence of human population, which was represented using the housing footprints in this study. The housing footprint data in GeoJSON format were obtained from Microsoft United States (US) building footprints database releasing in 2018. It contains 10,988,525 computer generated building footprints in California, which were extracted from the aerial image by semantic segmentation and converted to polygons by polygonization (Microsoft, 2018b). Due to the large size of GeoJSON format (2,537 MB) data, it was first split into multiple files in Python before converting to shapefiles in the software ArcGIS Pro (hereinafter ArcGIS), then the shapefile fragments were merged into a complete file. To reduce the computation time and cost, the polygons of housing footprints in the shapefile were converted to 5 meter resolution rasters in the mapping process. The distribution of housing footprints in the entire state of California is shown in Fig1.(a), the inset zoom into a random human community, showing the detailed shape and the layout of extracted housing footprint.

## 2.2 Vegetation data

To simplify the calculation of vegetation density, the fuel vegetation cover in 2018 from the Landscape Fire and Resource Management Planning Tools (LF) (LANDFIRE, 2013, June - last update) were used as the vegetation information. The 30-m resolution fuel vegetation cover layer (FVC) from the LF program adopted "plot-level ground-based visual assessments and lidar observations", providing the information of the canopy cover of herbaceous, shrub and tree in percentages (LANDFIRE, 2013, June - last update). Simplified high-density wildland vegetation profiles can be delineated by selecting an appropriate threshold of vegetation cover percentage. The percentage from 20% to 80% with stride of 10% were tested in this study by sensitivity analysis. Moreover, the land cover information except for the fuel vegetation, such as the developed area, the barren land, the open water and the snow/ice etc., were also included, which were used to identify the non-wildland area in this study. The distributions of the original FVC as well as the wildland and non-wildland areas are shown in Fig1.(b), the inset zoom into the same resolution as the inset in Fig1.(a), showing the detailed distribution of fuel vegetation within the same region.

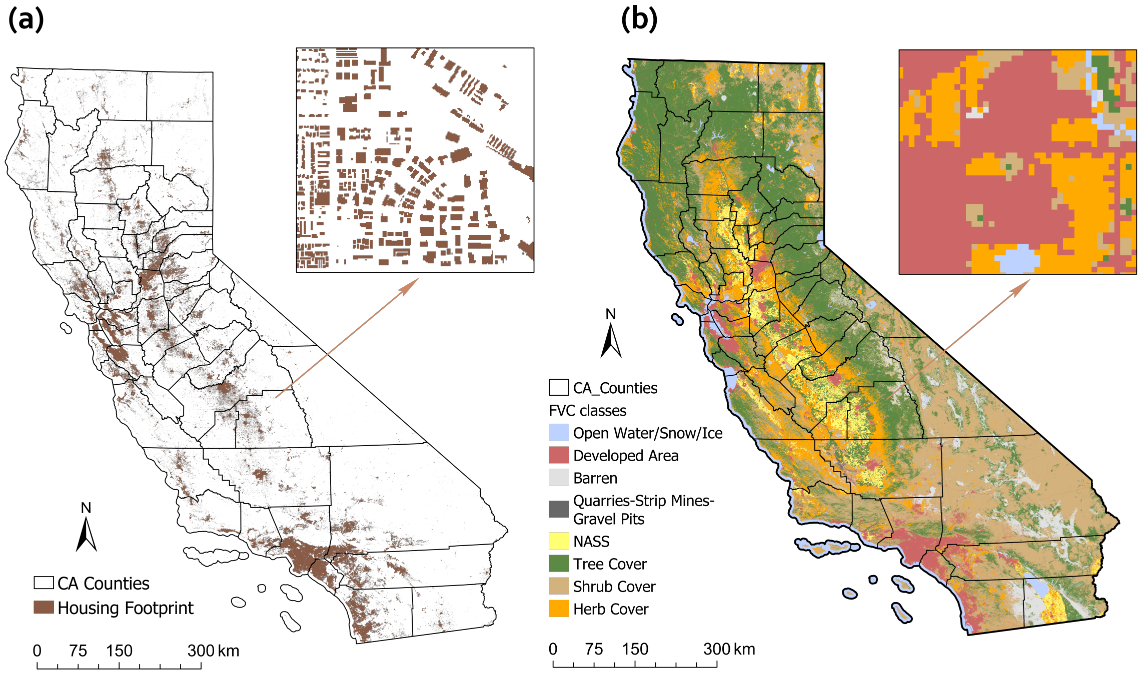


Figure 1: Housing footprint and fuel vegetation cover data in California: (a) Housing footprint distribution from Microsoft United States (US) building footprints database, the inset shows the detailed housing layout and shape; (b) Fuel vegetation cover distribution from LANDFIRE database. The dark blue boundary represents the simplified wildland vegetation boundary which was delineated by selecting pixels with vegetation cover percentage of 50% or higher, the inset shows the detailed distribution of fuel vegetation.

## 2.3 WUI mapping method

Based on the definition of WUI from the Federal Register (Glickman and Babbitt, 2001) and the operational definition from Stewart et al. (2007)'s research, the WUI in this study refers to the area where the houses are adjacent to (interface) or surrounded by (intermix) high-density fuel vegetation cover. Instead of predefining a threshold of housing density, this study treated each house independently, as the location and the perimeter of the houses are known from the building footprint data. Most of the common WUI mapping methods follow the definition of WUI from the Federal Register, adopting

6.17 houses per $km^2$ as the minimum housing density threshold in WUI, which eliminate the areas with low density buildings adjacent to or within the wildland. However, the study by Syphard et al. (2012) demonstrate that the smaller and more isolated housing clusters have higher risk of property loss due to wildfires. Therefore this study treated all the buildings within a certain distance of high-density fuel vegetation cover as WUI. This treatment also eliminates the requirement of housing density calculation which is complicated by zoning issues and the uncertainty due the the variation of housing density threshold (Stewart et al., 2007).

To determine the threshold of fuel vegetation cover density and the distance from the housing footprints to the high-density vegetation, the one factor at a time (OFAT) method was adopted to evaluate the effect of their variations on the total WUI area and the percentage of the wildfire ignitions and burned area contained in the corresponding WUI to the total ignitions and burned area. The vegetation cover percentage were tested from greater than 10% to greater than 90 % with stride of 10%. In terms of the distance from the vegetation to housing footprint, conceptually, the distance of 2.4km (1.5 mile) is appropriate because it represents statistically how far the firebrands can fly from the fire front and was evaluated and used in several previous studies (Radeloff et al., 2005; Lampin-Maillet et al., 2009). To prove that the 2.4 km is still applicable in this method, the distance of 1.2km and 4.8km were also tested to show the variation in the resultant WUI.

When mapping the WUI, the high-resolution distribution of fuel vegetation cover was extracted from the FVC data based on the selected threshold at the beginning. To exclude the parks, recreational green spaces and green belts in the urban area, the vegetation area with a continuous area of less than 5$km^2$ were removed. Subsequently, buffers with 2.4km (or 1.2km, 4.8km) radius were created around the vegetation profile. Selecting all the houses located in the high-density vegetation cover (intermix) and buffer zone (interface), the new WUI map was obtained after aggregating the dispersed houses to a continuous area, and it is referred to as WUI-Remote Sensing (abbreviated as WUI-RS) hereinafter. The flowchart of mapping process is shown in Fig.2.

The new WUI map generated in this study was compared to the WUI data products from 2010 (when the last census data were available) developed by the United States Forest Service (WUI-USFS) and the California Department of Forestry and Fire Protection's Fire and Resource Assessment Program (WUI-FRAP). Both maps used threshold of housing density as one of the basic criteria. The criterion in WUI-USFS is 6.17 houses per $km^2$, which is equivalent to one house per 40 acres, whereas the minimum value of housing density within WUI-FRAP is one house per 20 acres. Regarding wildland vegetation, WUI-USFS calculated the percentage of vegetation in each census block using NLCD data, while WUI-FRAP used the layer of vegetation cover and fire hazard zone from CAL FIRE to determine whether the area is dominated by vegetation. However, the WUI-FRAP added a new classification of "Influence zone", which involved the vegetation within 1.5 miles (2.4 km) from the interface and the intermix. In general, the criteria for WUI-FRAP are more stringent than that for WUI-USFS. Consequently the total WUI area in California in the WUI-USFS is 27,255 $km^2$ while in the WUI-FRAP

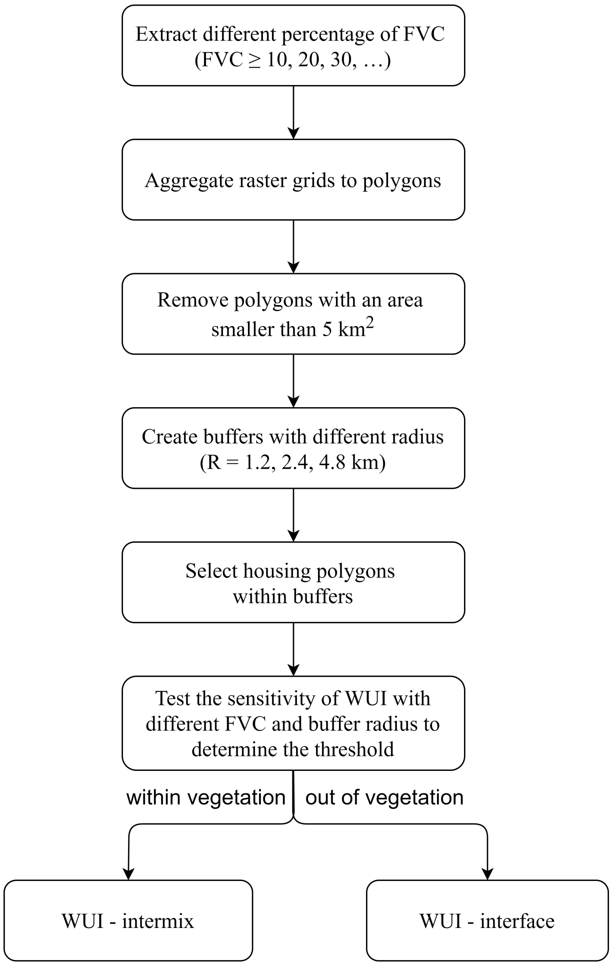


Figure 2: Flowchart of WUI-RS mapping method

is 9,581 $km^2$. And the area including the influence zone in the WUI-FRAP is 71,609.22 $km^2$.

To evaluate the fire risk and its trend in the WUI areas, the wildfire ignition points from USFS (USFS, 2020) and the wildfire perimeters from CAL FIRE (FRAP, 2018) in California were plotted in the maps. The fire ignition point database from USFS dates back to 1970. It includes the ignition points of individual wildfires under the jurisdiction of USFS. The burned area of individual fires varies from smaller than 0.01 acres to 410,203 acres (1660 $km^2$). The fire perimeter database from CAL FIRE collected large wildfires under the jurisdiction of CAL FIRE and USFS from 1950. The minimum burned area of the collected wildfires is 10 acres. Since the WUI area has grown rapidly in the last decade since 1990 (Radeloff et al., 2018), the 2000-2009 wildfires were used to calculate the percentage of wildfires within the WUI area for the 2010 WUI maps (WUI-USFS and WUI-FRAP), while the new 2018 WUI map (WUI-RS) used the 2010-2019 wildfires. The spatial distributions of wildfire ignition points and perimeters between 2000-2009 and 2010-2019 are shown in Fig.3.

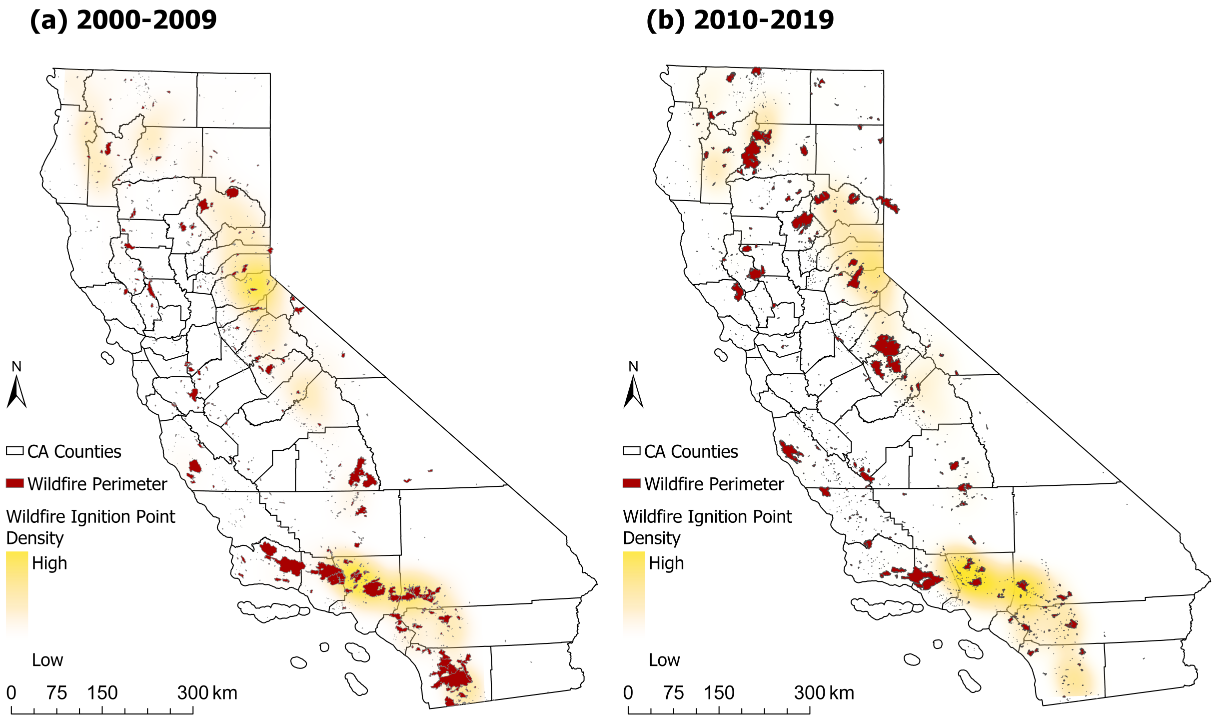


Figure 3: Human-caused wildfire ignition points and perimeters between (a) 2000 to 2009 and (b) 2010 to 2019 in California

# 3 Results

## 3.1 Threshold determination

The threshold of the two main components in the WUI definition - vegetation cover and the distance between housing and high-density vegetation, were tested using the OFAT approach. The validity of the map was evaluated by three indicators: the percentage change of WUI area with changes in the parameter value, wildfire ignition points within WUI and perimeters within WUI. When the percentage changes of the indicators are smaller than the percentage change of the WUI components, the threshold can be seen as stable (Radeloff et al., 2005). The results are shown in Figure 4. For the vegetation cover, when the threshold is lower than 40%, the change in the new WUI area is relatively stable, when the threshold is lower than 50%, the change in the ignition points and the perimeters are relatively stable. Thus 40% of vegetation cover was selected as the threshold. More specifically, the housing within or next to the wildland area with vegetation coverage higher than 40% were seen as WUI area. In terms of how close the housing should be to the wildland vegetation, the results show that the change of 50% increase or decrease based on 2.4km does not have a drastic effect on the three validity indicators, and the range of percentage change in each indicator is within 50%. Therefore, 2.4km is reasonable both conceptually and operationally in this method. Since there is no restriction on the density of houses in this method, the area of the buffer directly determines whether the houses are included in WUI. *Overall, the WUI in this new operational method (WUI-Remote Sensing, abbreviated as WUI-RS) was defined as the area in which man made structures are surrounded by or within 2.4km of wildlands where the vegetation cover is higher than 40%.*

## 3.2 WUI-RS map in 2018

The WUI-RS map in 2018 covers an area of 28,575 $km^2$ in California, with 55.21% intermix area (15776$km^2$) and 44.79% interface area (12,799 $km^2$), accounting for 6.74% of the land area in CA (423,971 $km^2$). About five million housing units, which accounts for 45.13% of total housing in California are included in the WUI-RS. The map of the new WUI is shown in Fig.5(a). The distribution of the new WUI is concentrated along the western coastline and to the west of the Sierra Nevada Mountain range. It is sparse in the central and southeastern California, because most of the San Joaquin Valley in the Central California have been developed and planted, and Southeastern California has vast tracts of barren land and very little human structures.

At the county level, Fig.5(b) and (c) shows the area and percentage of WUI in each county. The San Diego (SD), Los Angeles (LA) and Sonoma (SON) counties contains largest WUI area which are 1909 $km^2$, 1400 $km^2$, 1225 $km^2$ separately. The Contra Costa (CC), Sacramento (SAC) and Santa Cruz (SCZ) counties in the northern California have the highest percent of WUI which accounts for 36.18%, 33.64% and 31.44% of their land area separately.

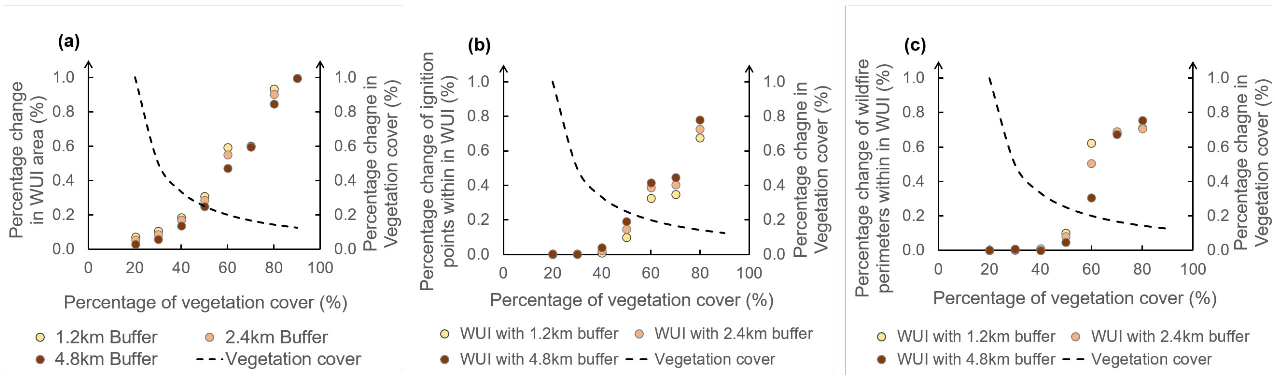


Figure 4: Percentage change of WUI area and wildfires with vegetation cover: (a) WUI area; (b) ignition points within WUI; (c) burned areas within WUI. The x axes represent the percentage of vegetation cover included in the WUI mapping. The colored dots represent the WUI-RS area, ignition points and wildfire perimeters included in the WUI-RS under different vegetation cover and buffer radius. To test the sensitivity of the WUI map, the vegetation cover changed by 10% at a time, and its rate of change is on the secondary Y axis and represented by dash lines.

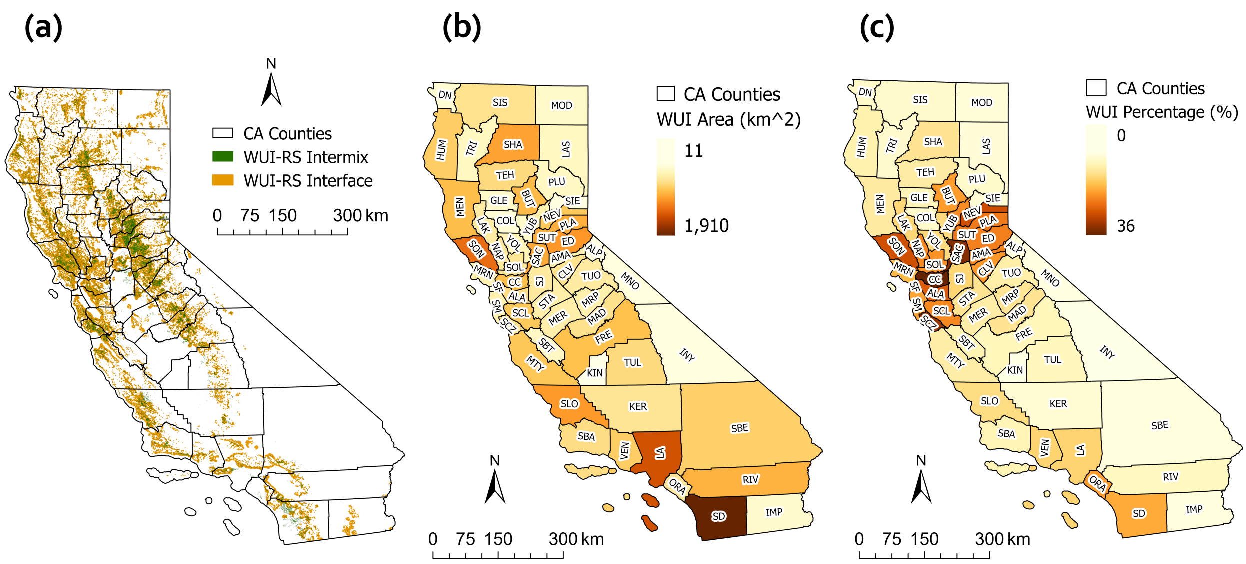


Figure 5: WUI-RS map and spatial distribution in California: (a) WUI-RS map in 2018; (b) WUI-RS area in each county; (c) Percentage of WUI-RS cover in each county

### 3.3 Comparison between different WUI maps

The maps of WUI-RS (2018), WUI-USFS (2010) and WUI-FRAP (2010) are shown in 6 (a), (b) and (c). In general, all three types of WUI areas are concentrated along the Sierra Nevada Mountain and the West Coast. These common features demonstrate that although the new mapping method simplifies the operation steps, it still successfully captures the distribution characteristics of WUI. Since the data used for mapping WUI-RS is almost 10-year more recent compared to the data for the other two maps (WUI-USFS and WUI-FRAP), considering the rapid growth of housing and WUI area during this period, the total area of the three WUIs are not directly comparable in terms of the difference in mapping methods. Therefore in Figure 6 (d) and (e), we selected two representative concentrated WUI regions in northern and southern California, presenting two types of general spatial distribution differences among three types of WUI areas. Fig.6 (d) shows an area in Northern California which has small fragments of WUI-RS but not the other two types of WUIs. This region belongs to the Eldorado National Forest, dominated by high density of trees. Despite the low housing density, the wildfire ignition points were concentrated here between 2000-2009 and 2010-2019, and there have been large wildfires in both ten-year periods. The WUI-RS map includes such low-density houses surrounded by high-density vegetation, supplementing these piecemeal WUI areas with potentially high wildfire risk that would have been missed by previous methods. Besides, 6(e) shows evident differences in the three types of WUI close to the developed areas in Southern California which are dominated by shrubs. In particular, the northeastern region close to the mountains in this figure was treated as non-WUI in the WUI-RS map. This is due to the fact that most of the shrubs cover in this area are under 40% and are not continuous. At the same time, the vast developed area impede this whole region being classified as high-density wildland vegetation. From the perspective of wildland fire risk, no human-caused wildfires ignited in this area from 2010 to 2019, thus this difference is deemed acceptable.

To contextualize the WUI mapping with historical wildfire activity, the number of historical wildfire ignition points and the burned area within the WUIs were calculated within ten years of each of the three maps being most effective. As shown in Table1, WUI-RS captures the majority of human-caused ignition points, and it has the highest percentage to the total ignition points among the three types of WUIs. In terms of the burned area within WUI, none of the three maps included much of human-caused wildfire area (less than 10% in general). This is because WUI maps are primarily used to identify houses and human structures with a high risk of igniting wildfires or be affected by wildfires. When the burned area of a wildland fire overlaps with the WUI perimeter, it means that the wildfire has caused damage to a human community, which has been increasing in recent times but still fairly uncommon (Kumar et al., 2020). The majority of wildfires were still confined to the wildland. Speaking of the risk of human community being effected by wildfires, the number of houses contained within the WUI was also calculated, and the results show that WUI-RS contains the highest proportion of houses, and the housing percentage in WUI-USFS is close to that in WUI-RS. Given that houses in the WUI are at a high risk of firebrand ignition, these results demonstrate that the

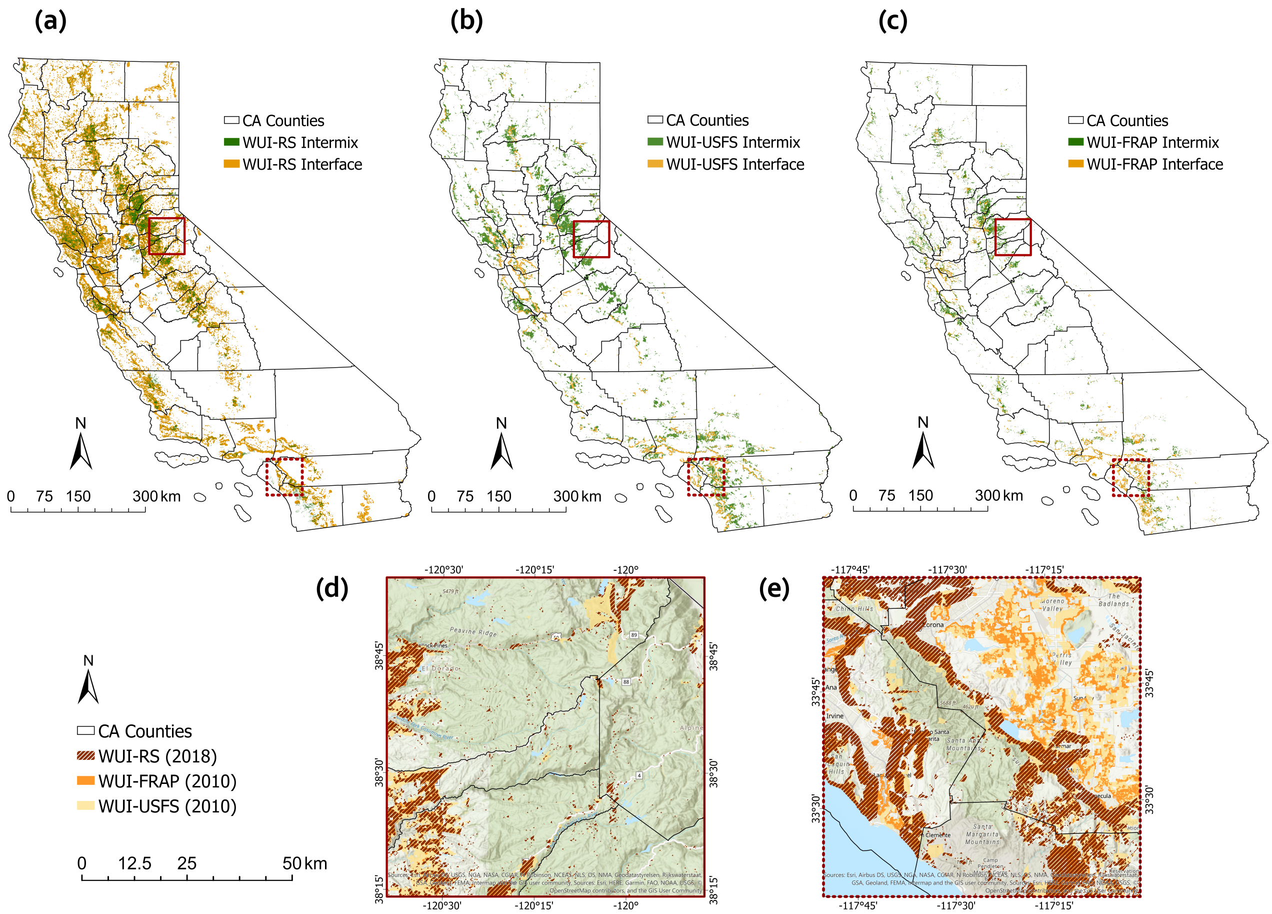


Figure 6: Comparison between (a) WUI-RS,(b) WUI-USFS and (c) WUI-FRAP. The detailed comparison among these three maps of two selected enlarged regions are showin in (d) and (e).

WUI-RS can be used to compute the risk from wildland fires near communities.

| | Total Area ($km^2$) | Number of fires igniting in WUI | Percentage of fires igniting in WUI (%) | Burned area in WUI ($km^2$) | Percentage of burned area in WUI (%) | Number of houses in WUI | Percentage of houses in WUI (%) |
|---|---|---|---|---|---|---|---|
| 2010-2019 | | | | | | | |
| WUI-RS (2018) | 28,575 | 4,277 | 86.25 | 524.45 | 4.09 | 4,959,028 | 45.13 |
| 2000-2009 | | | | | | | |
| WUI-USFS (2010) | 27,255 | 4,414 | 65.71 | 951.06 | 6.70 | 4,457,884 | 40.57 |
| WUI-FRAP (2010) | 9,581 | 2,877 | 42.83 | 3.9 | 0.03 | 709,198 | 6.45 |

Table 1: Wildfire ignition points, burned area and housing within different WUIs in CA. Wildfire ignition points from USFS and wildfire perimeters from CAL FIRE were extracted to evaluate the percentage of wildfires ignited or burned within different WUI maps. WUI-RS (2018) used wildfire data in 2010-2019, WUI-USFS (2010) and WUI-FRAP(2010) used wildfire data in 2000-2019.

# 4 Conclusion

The wildland-urban interface (WUI) delineate the regions where man-made structures and high density vegetation are intermingled or adjacent to each other. WUIs are perceived to be high risk regions due to damage of structures by wildfires. The specific definition and maps of WUI provide managers with a basis for risk assessment and emergency response planning. The current common WUI mapping methods are based on census data updating every 10 years. However, this update frequency is far behind the current speed of suburbanization and the growth rate of WUI. Moreover, the existing WUI mapping methods cannot accurately map the location of buildings because Census data can only provide housing density in each block. The development of remote sensing technologies and the wide applications of remote sensing data provides opportunities to improve the accuracy and update frequency of WUI maps. By using building footprints in CA, which were extracted from aerial image by Microsoft, and the fuel vegetation cover from the LANDFIRE database, a new WUI map in 2018 for California was generated simply by using housing location, vegetation cover and distance thresholds. The new mapping method went back to the essential definition of WUI and simplifies the requirements of WUI backed up by using modern advanced databases. The vegetation cover of 40% and the distance of 2.4km between the wildland vegetation and the housing were validated as the threshold for WUI mapping.

In the new WUI map (WUI-RS), the WUI area in the San Diego county is prominent. When it comes to WUI percentage, the counties with the highest percentage of WUI are concentrated in northern California, north of the Sierra Nevada Mountains. Compared to the two previous WUI maps from USFS and FRAP, the new WUI map is basically overlapped with them, but with the addition of low density housing clusters surrounded by high-density vegetation, which have been shown to be at a higher wildfire risk than areas with high-density houses. Besides, the WUI-RS captures the highest percentage of ignition points of human-caused wildfires and highest percentage of housing among the three maps, demonstrate its capability to be used for wildfire risk calculation.

The comparison of different WUI mapping methods in this study was based on WUI maps released in 2010, which used census data to calculate the housing and vegetation density. Considering the growth of WUI in the past ten years, these old WUI maps and WUI-RS maps generated using data in 2018 have limited comparability. As the 2020 Census data is about to be released, the WUI maps with the original operation definition will also be updated soon. At that time several WUI mapping methods can be compared more thoroughly and in detail. Meanwhile, this research has come up with appropriate thresholds for the simplification of WUI operation definition. With the ability to obtain high-resolution satellite images, WUI maps are expected to be generated in real time and automatically, which is also the direction of this research in the future.

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