

Characterizing Wildland-Urban Interface Fire Typology and Climate Associations Across California, USA

Huiyi Su¹, Pingting Cao¹, Ximei Wu¹, Lu Liang³, Qingqing Xu⁴, Yang Ju⁵, Jiaojiao Diao⁶, Qin Ma^{1,2,*}

¹ School of Geography, Nanjing Normal University, Nanjing, China, 210023. -
suhuiyi749@gmail.com; pingting_cao@njfu.edu.cn; 10210316@nynu.edu.cn; maqin@nnu.edu.cn

² State Key Laboratory of Climate System Prediction and Risk Management, Nanjing, China

³ Department of Landscape Architecture and Environmental Planning, University of California, Berkeley, USA, 94720. -
lianglu@berkeley.edu

⁴ Sierra Nevada Research Institute, University of California, Merced, USA, 95340. - qxu6@ucmerced.edu

⁵ School of Geography and Ocean Science, Nanjing University, Nanjing, China, 210023. - yangju90@nju.edu.cn

⁶ Department of Integrative Biology, University of Guelph, Ontario, Canada N1G2W1. - diaoj@uoguelph.ca

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Abstract

California experiences some of the most intense wildfire activity globally, with substantial human casualties and economic losses that show accelerating trends. Existing research predominantly quantifies the relative contributions of anthropogenic factors and climate forcing to WUI fires at the aggregate level, yet overlooks the heterogeneity in fire initiation and propagation mechanisms arising from differences in ignition locations and dominant spread areas. Using multi-source data from California (2002–2023), we classified WUI fires into four behavioral modes based on whether ignition sites and primary spread areas were located in the WUI: I-I (WUI ignition, WUI spread), I-W (WUI ignition, wildland spread), W-I (wildland ignition, WUI spread), and W-W (wildland ignition, wildland spread). We systematically analyzed size characteristics, inter-annual trends, fuel composition, and climate sensitivity across modes. Results revealed: (1) WUI fires accounted for 96.6% of total burned area from large fires, although only 12.2% of burned area fell within the WUI; both total and mean burned area increased significantly over the two-decade period. (2) Naturally-ignited WUI fires showed significantly delayed ignition dates, whereas human-caused fires occurred significantly earlier, with peaks in fire frequency during Independence Day, Labor Day, and Thanksgiving. (3) I-I fires were predominantly driven by anthropogenic factors with the highest proportion of shrubland fuel and the smallest mean size; W-W and I-W fires exhibited significant climate sensitivity, with I-W showing a higher rate of increase than W-W over the two decades. These findings reveal differentiated driving mechanisms of anthropogenic and climatic factors across WUI fire behavioral types, providing scientific evidence for stratified fire management strategies.

1. Introduction

Climate warming has led to a widespread increase in extreme fire weather conditions, prolonging fire seasons and resulting in wildfires of greater duration and extent (Andela et al., 2017; Bowman et al., 2020). These trends are projected to intensify in the coming decades (Chas-Amil et al., 2013). However, wildfires are not solely driven by climatic factors; they are also profoundly influenced by socio-economic dynamics, including population distribution and land-use (Teymoor Seydi et al., 2025). The wildland-urban interface (WUI)—the zone where human infrastructure intersects with wildland vegetation—has expanded globally over recent decades. This expansion elevates wildfire ignition risk due to increased human activity, posing catastrophic threats to property, land use, and human life. WUI areas represent critical hotspots of current and future human-environment conflicts, impacting numerous residents across diverse ecosystems. Future climate change is expected to further exacerbate the occurrence of extreme wildfire events.

As a globally representative fire-prone region, California exhibits a Mediterranean climate characterized by seasonal separation of precipitation and temperature (Goulden et al., 2012). The state spans diverse climatic zones and has undergone pronounced hydroclimatic swings between extreme drought and wet periods, driving substantial variability in fuel accumulation and moisture content (Lydersen et al., 2017). Over recent decades, California has experienced a marked increase in

destructive wildfires (Abatzoglou & Williams, 2016; Dennison et al., 2014; Westerling, 2016; Williams et al., 2019). Unlike other fire-prone regions such as northern Canada or Siberia, California features more intensive human activity. Historically, human activities have altered California's fire regimes through multiple pathways, including forest management practices, fire suppression policies, and consequent fuel buildup. Concurrent with climatic influences, land-use planning has facilitated residential expansion into forested areas. Since the 1990s, the number of homes located in fire-prone areas across the United States has doubled; California alone added 244,000 WUI dwellings between 2010 and 2020. The urban expansion, combined with changing land use, has subjected vegetation and ecosystems adapted to periodic fire regimes to significant transformation, particularly through elevated ignition frequencies (Hantson et al., 2022). The January 2025 Los Angeles fires exemplify the escalating WUI fire crisis—destroying over 16,000 structures, displacing 180,000 residents, and incurring hundreds of billions of dollars in economic losses (Qiu et al., 2025).

Substantial research has investigated WUI wildfires, employing diverse methodological approaches to elucidate their driving mechanisms in California. Syphard et al. (2007) demonstrated that in southern California shrublands, urban expansion interacts with fire frequency in complex ways: while direct replacement of shrubland fuels by residential development reduced local fire frequency by 40%, landscape fragmentation at urban edges increased fire spread risk in undeveloped areas

by 25% . Chen et al. (2021) examined the Sierra Nevada's elevational gradient and found that the explanatory power of climatic factors for fire occurrence increased from 30% to 45% after 2000, highlighting the growing influence of climate relative to other controls . These studies collectively indicate that California's contemporary fire regimes are driven by an interplay of natural climate variability, long-term climatic warming, anthropogenic land-use change, and WUI expansion. Nevertheless, the mechanisms governing WUI fire dynamics remain insufficiently quantified, particularly regarding the relative contributions of WUI expansion versus climate-induced stress to ignition locations and burned area outcomes.

To systematically unravel the intrinsic drivers of WUI fires, this study leverages historical wildfire data, satellite-derived ignition points, and land cover datasets. We propose a typological classification of WUI fire events based on the differential impacts of ignition locations and fire spread pathways on human settlements. The objectives are twofold: first, to characterize the association between ignition and spread processes across distinct fire behavior regimes; and second, to elucidate the driving mechanisms underlying different WUI fire types by integrating macro-level climatic controls with interactive human influences. The findings aim to provide actionable insights for wildfire prevention and management in California and analogous WUI settings worldwide.

2. Material and methods

2.1 Data Sources

Fire Data. We used the statewide fire perimeter GIS layer from the Fire Resource Assessment Program (FRAP) dataset (California Department of Forestry and Fire Protection [Cal Fire], 2023), which compiles fire records $>0.004 \text{ km}^2$ from multiple agencies since 1950. For the period 2002–2023, we selected 2,501 fire events with burned area $>0.5 \text{ km}^2$ (equivalent to two MODIS pixels), accounting for 99.3% of the total burned area across all 7,429 recorded fires during this period.

Ignition Points Data. Ignition locations were obtained from the Global Fire Atlas (GFA) ignition product (Andela et al., 2019), derived from MODIS Collection 6 MCD64A1 burned area data (Giglio et al., 2018). This product reconstructs individual fire events by tracking the spatiotemporal evolution of burned pixels and identifies ignition points based on the day of burn. We extracted ignition points within 500 m buffers of FRAP fire perimeters for 2002–2023.

WUI Data. We employed the global WUI dataset (Chen et al., 2024) at 400 m resolution with five-year intervals from 2000 to 2020. This product distinguishes two WUI types following U.S. Federal Register definitions.

Climate Data. We used monthly and annual climate data (1999–2023) from PRISM (Daly et al., 2008), including mean, minimum, and maximum temperature (T), mean dew point temperature (DPT), maximum and minimum vapor pressure deficit (VPD), and total precipitation (P). For all meteorological variables, we calculated the mean values for the year of fire occurrence (_current), the year before the fire (_prev1y), and the cumulative two years before the fire (_prev2y) for all grids within each fire event patch, respectively, to use as variables for subsequent analysis of the correlations between different fire events and climatic factors. Additionally, we incorporated multi-timescale Standardized Precipitation-Evapotranspiration Index (SPEI) products from the gridMET dataset at 4 km resolution for the period 2002–2023 (Abatzoglou, 2013).

Land Cover Data. Land cover information was derived from the National Land Cover Database (NLCD) annual products (2001–2022), based on Landsat imagery. We used land cover maps from the year preceding each fire event to quantify vegetation and impervious surface areas affected within FRAP fire perimeters.

2.2 Study Area

California, located in the southwestern United States, is characterized by a Mediterranean climate with hot, dry summers and winter-concentrated precipitation. Vegetation covers approximately one-third of the state, dominated by shrublands, evergreen forests, and grasslands (Jin et al., 2019). Between May and September, dry downslope winds (e.g., Santa Ana winds) frequently affect southern and central California, creating extreme fire weather conditions. Wildfire occurrence in California exhibits a heavy-tailed distribution: while small fires dominate in frequency, a small number of large fires account for the majority of burned area and losses (Strauss et al., 1989). With a population of approximately 39 million, California is the most populous U.S. state, featuring major metropolitan areas such as Los Angeles, San Diego, and Sacramento. Urban expansion, low-density residential development, and the mosaic of agricultural and natural vegetation have collectively fostered extensive, highly fragmented WUI across mountainous and foothill regions.

WUI events (fires with spatial overlap between their burned areas and the WUI) are widely distributed across the Sierra Nevada foothills, the Northern Coast Ranges, and the coastal zones of Southern California. In contrast, Wild fires (i.e., pure wildland fires with no spatial association with WUI zones) are scattered in spatial distribution, primarily concentrated in the arid wildland regions of the eastern and southern parts (Figure 1a). The total burned area of WUI fires accounts for as much as 95.6% (approximately 68,482 km^2), while that of Wild fires only accounts for 4.4% (3,522 km^2). A further analysis of the burned area composition within WUI fires shows that, despite being classified as WUI fires, the vast majority of their burned areas (87.8%) still occur in wildland zones (Figure 1b).

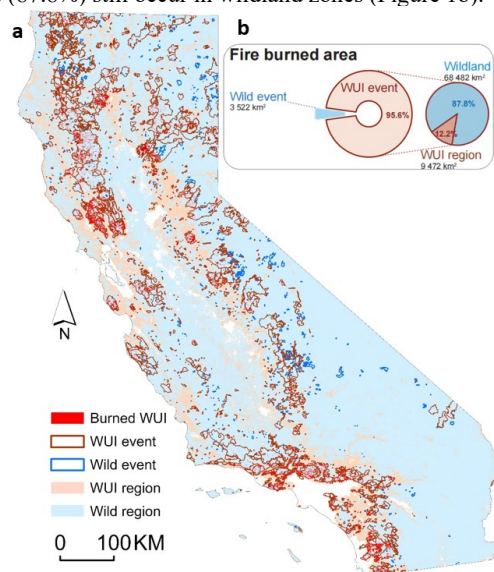


Figure 1. Spatial modes and area statistics of WUI fires and Wildl fires in California (2002–2023). (a) Spatial distribution; (b) Proportional of burned area.

2.3 Analysis Methods

2.3.1 Matching Ignition Points to WUI Fire Events

For the 2,501 fire events ($>0.5 \text{ km}^2$) from FRAP (2002–2023), we identified WUI fire events as those whose burned perimeters intersected WUI areas. Using the five-year interval WUI product (2000–2020), we performed spatial overlay analysis by matching fire perimeters to the temporally corresponding WUI layer: fires occurring between 2002 and 2004 were matched to the 2000 WUI layer, and fires from 2020 to 2023 were matched to the 2020 WUI layer. A total of 1,823 WUI fire events were identified for California during 2002–2023.

To determine ignition points for these WUI events, we first extracted Global Fire Atlas (GFA) ignition points that fell within or within 500 m of FRAP fire perimeters. Given that GFA ignition points are derived from 500 m MODIS pixels, this buffer accounts for potential spatial mismatches between ignition locations and fire perimeters. Second, we retained the ignition point with the smallest temporal difference to the FRAP alarm date for each fire event. In cases where multiple ignition points were associated with the same fire perimeter, we calculated the absolute day difference between each ignition's burn date and the FRAP alarm date. Considering that satellite-based thermal anomaly detection may capture ignition earlier than human reporting, we prioritized ignition points with burn dates preceding the alarm date when multiple points shared the same temporal difference. After this filtering, 981 WUI events with identifiable ignition points were retained, accounting for 97.0% of the total burned area of all 1,823 WUI events (Figure S1).

2.3.2 Classification of Fire Behavior Types

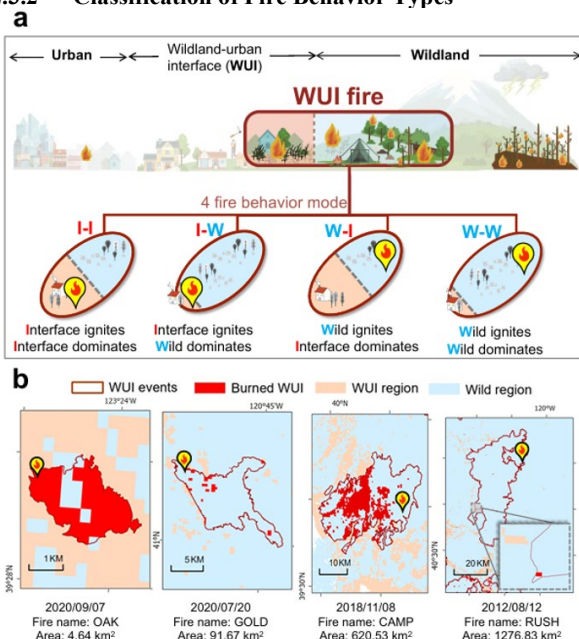


Figure 2. Four behavioral modes of WUI fires: classification scheme and representative cases. (a) Classification based on ignition location and WUI proportion of burned area; (b) Case examples for each behavioral mode.

We classified WUI fire behavior based on two dimensions: ignition location (inside vs. outside WUI) and primary spread area (WUI-dominated vs. wildland-dominated). For ignition location, we determined whether the matched ignition point fell

within WUI areas. For spread area, we calculated the proportion of WUI area within each fire perimeter. Based on the frequency distribution of WUI percentage across all WUI events with ignition points (Figure S2), we defined a threshold of 15%: fires with WUI area $<15\%$ were considered primarily spread in wildland, while those with WUI area $\geq 15\%$ were considered primarily spread in WUI. Combining these two dimensions, we classified WUI fire events into four behavior modes (Figure 2):

- I-W (Interface ignites; Wild dominant spreads),
- I-I (Interface ignites; Interface dominant spreads),
- W-W (Wild ignites; Wild dominant spreads),
- W-I (Wild ignites; Interface dominant spreads).

3. Results

3.1 Inter-annual Trends and Overall Statistics

WUI and wildland fires exhibited contrasting temporal dynamics in both burned area and occurrence frequency. At the aggregate level, WUI fire extent increased significantly over time (Figure 3a, $R^2 = 0.46$), whereas wildland fire area fluctuated with no significant trend. Conversely, wildland fire frequency declined substantially (Figure 3b, $R^2 = 0.41$), driving the overall decrease in statewide fire occurrence ($R^2 = 0.22$). Mean WUI fire size increased progressively (Figure 3c, $R^2 = 0.61$).

Among the four WUI behavioral modes, burned area showed distinct trajectories (Figure 3d): both I-W and W-W modes increased significantly, with I-W displaying a stronger trend ($R^2 = 0.56$) than W-W ($R^2 = 0.40$). I-I and W-I modes showed no significant linear trends. Fire frequency declined only for W-I mode (Figure 3e, $R^2 = 0.35$), decreasing from ~4 fires annually in the early 2000s to 1–2 fires by 2023, while other modes remained relatively stable. Mean fire size increased for I-W and W-W modes (Figure 3f), with I-W showing the most pronounced increase ($R^2 = 0.60$), whereas I-I and W-I modes remained unchanged.

Summary statistics across WUI behavioral modes (Table 1) reveal substantial size and frequency disparities. W-W fires (wildland ignition and spread) dominated all metrics: 39,902.5 km^2 total extent, 395 events, and the highest median size (25.6 km^2). In contrast, I-I fires (WUI ignition and spread) exhibited a "high-frequency, small-scale" profile: 296 events with the lowest total area (6,961.2 km^2) and mean size (23.5 $\pm 60.6 \text{ km}^2$). W-I fires (wildland ignition, WUI spread) were rarest (51 events) but showed high variability in size (41.0 $\pm 115.9 \text{ km}^2$). I-W fires (WUI ignition, wildland spread) had the largest mean extent (144.2 $\pm 455.8 \text{ km}^2$) among all modes.

Table 1. Statistical summary of WUI fires by behavioral mode

	I-I	I-W	W-I	W-W	WUI fire
Total area, km^2	6,961.2	29,845.4	2,091.7	39,902.0	78,799.8
Number	296	207	51	395	948
Mean fire size, km^2	23.5	144.2	41.0	101	83.1
Median fire size, km^2	5.6	19.8	6	25.6	21.7

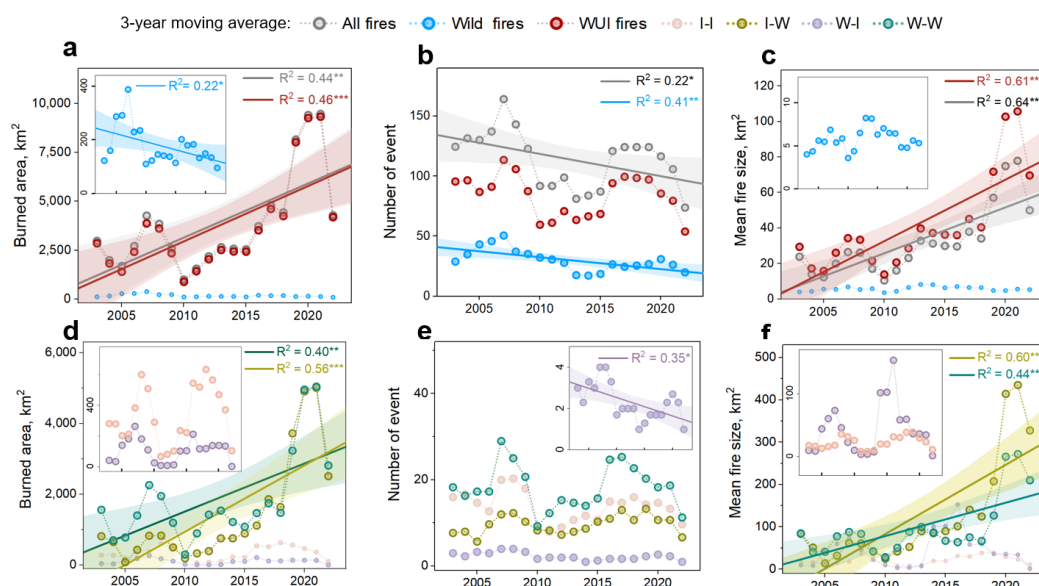


Figure 3. Inter-annual trends in burned area, number of fire, and mean fire size across fire types. Scatter points represent 3-year moving averages; trend lines fitted by linear regression ($p < 0.05$); shaded regions show 95% confidence intervals.

3.2 Fire Ignition, Seasonality, and Fuel

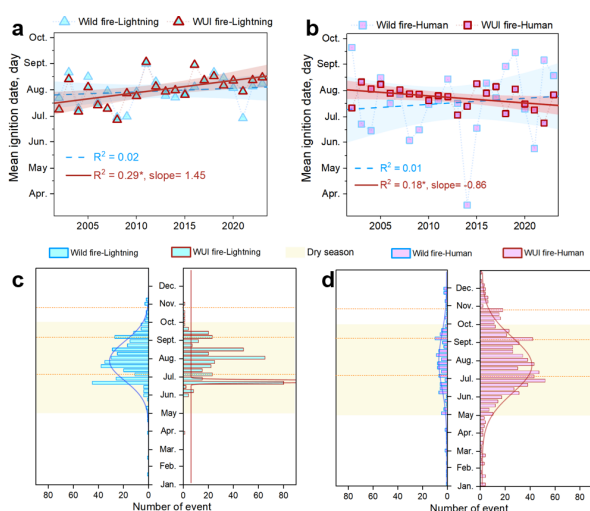


Figure 4. Ignition date trends, and seasonal fire frequency for WUI and wild fires. (a,b) Inter-annual trends in mean ignition date under lightning and human-caused ignition; (c,d) Weekly fire frequency by ignition source, with yellow shading indicating the peak fire season (May–September) and orange lines marking three major holidays (Independence Day, Labor Day, and Thanksgiving).

Ignition Date Dynamics. Analysis of ignition sources revealed distinct temporal patterns in fire occurrence (Figure 4a–b). For lightning-caused fires, WUI fires showed a significant delay in mean ignition date over the study period (Figure 4a, $R^2 = 0.29$, slope = 1.45 days/year, $p < 0.05$), shifting toward late autumn. Wildland fires showed no significant trend under lightning ignition ($R^2 = 0.02$). Conversely, human-caused WUI fires advanced significantly toward spring (Figure 4b, $R^2 = 0.18$, slope = -0.86 days/year), while wildland fires remained temporally stable ($R^2 = 0.01$).

Seasonal Patterns. Within-year fire frequency distributions revealed pronounced seasonality and human influence (Figure 4c–d). Lightning fires (Figure 4c) showed a consistent unimodal

distribution peaking in mid-to-late August, concentrated during the dry season (May–September) for both WUI and wildland fires. Human-caused fires (Figure 4d) displayed a broader temporal window (May–November) with multiple peaks coinciding with major U.S. holidays—Independence Day, Labor Day, and Thanksgiving—indicating strong anthropogenic influence. Across all timescales, WUI fires occurred at significantly higher frequencies than wildland fires, particularly for human-caused ignitions, reflecting elevated fire risk in human-dominated landscapes.

Fuel Composition. Pre-fire land cover composition (Table 2) revealed distinct fuel environments across behavioral patterns. Wildland fires showed greater dependence on forest fuels, with evergreen forest comprising 33.98% of burned area compared to 27.97% for WUI fires. Among the four WUI behavioral patterns, shrub/grass/crop fuels dominated burned area, with I-I mode showing the highest proportion (67.52%). Regarding built environment extent, I-I mode exhibited the highest proportion of high-intensity development (0.02%), though still minimal in absolute terms. Conversely, W-W and I-W modes burned predominantly in open spaces and low-intensity developed areas within the WUI.

3.3 Climate- Correlation Among WUI Fire Behavioral

Correlation analysis revealed significant differentiation in climate sensitivities among the four WUI fire behavioral modes (Figure 5). Fire patterns involving wildland spread (W-W and I-W) demonstrated substantially greater climate sensitivity compared to those confined to WUI expansion (I-I and W-I).

Burned Area. W-W fires exhibited the strongest climate associations (Figure 5a). Burned area was highly negatively correlated with standardized precipitation-evapotranspiration index (SPEI-1, $r = -0.78$, $p < 0.001$) and significantly negatively associated with prior-year maximum vapor pressure deficit (VPD_{max}, $r = -0.66$) and maximum temperature (T_{max} , $r = -0.70$), indicating strong drought-driven expansion. I-W fires showed similar climate sensitivity, with area negatively correlated with SPEI01 ($r = -0.56$, $p < 0.01$), VPD_{max}, and T_{max} . W-I fires exhibited only a significant positive correlation with prior-year precipitation ($r = 0.55$, $p < 0.05$),

suggesting that fuel accumulation from earlier moisture may promote subsequent fire spread. I-I fires showed no significant correlations with any climate variable.

Number of Fire. Climate heterogeneity persisted in fire occurrence patterns (Figure 5b). W-W fire frequency was

significantly negatively correlated with VPDmax_prevly ($r = -0.61$, $p < 0.01$) and showed significant relationships with prior-year precipitation ($r = 0.44$) and T_max ($r = -0.42$). I-W frequency correlated only with SPEI01 ($r = -0.42$, $p < 0.05$). I-I and W-I modes showed no significant climate associations in fire occurrence frequency.

Table 2. Fuel type composition (%) for different WUI fire behavioral patterns based on pre-fire land cover

Landcover type	I-I	I-W	W-I	W-W	WUI fire	Wild fire
Open space, %	1.10	1.39	0.98	1.37	1.27	0.45
Low Intensity, %	0.65	0.69	0.48	0.94	0.77	0.18
Medium Intensity, %	0.14	0.15	0.06	0.16	0.15	0.02
High Intensity, %	0.02	0	0	0	0.01	0
Barren Land, %	0.08	0.06	0.24	0.28	0.17	0.13
Deciduous Forest, %	0.68	0.38	0.29	0.77	0.63	0.47
Evergreen Forest, %	26.68	30.31	30.78	27.34	27.97	33.98
Mixed Forest, %	2.43	1.94	2.90	2.10	2.21	0.59
Shrub/Grass, %	67.52	64.50	63.91	65.82	65.96	62.75

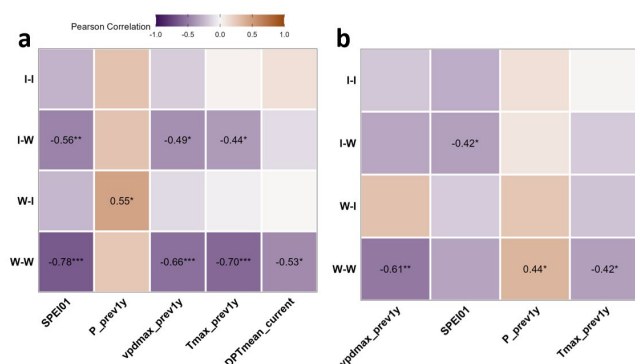


Figure 5. Correlation heatmap (significant relationships only). Values represent Pearson correlation coefficients (* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$). (a) Annual burned area; (b) Number of annual fire.

4. Discussion

4.1 Climate-Driven versus Human-Driven Fire Patterns

The results demonstrate fundamental differences in climate sensitivity among WUI fire behavioral types. W-W and I-W fires, both involving wildland spread, showed significant correlations with multiple climate variables (SPEI01, VPDmax, Tmax), whereas I-I fires exhibited no significant climate associations. The strong climate sensitivity of W-W and I-W fires indicates that wildland-dominated spread remains constrained by inter-annual climate variability, with drought years driving larger fire extents. This finding aligns with prior research: Chen et al., (2021) identified vapor pressure deficit as the dominant driver of regional fire probability in the Sierra Nevada, with particularly strong climate control at high elevations. Kumar et al. (2025) further documented that climate trends from 1990–2022 significantly increased high-risk fire weather frequency, reinforcing the critical role of climatic conditions in controlling fire magnitude.

Conversely, I-I fires showed no climate correlation, indicating primary control by human activity. Figure 3 reveals pronounced fire frequency peaks on Independence Day, Labor Day, and Thanksgiving, directly reflecting anthropogenic influence on ignition spatiotemporal patterns. The dominance of shrub/grass fuels in I-I fires (67.52%, Table 2) combined with their smallest mean size (23.5 km²) and high frequency characterizes this pattern as localized, human-ignited fires confined to WUI areas.

Building and road networks within WUI act simultaneously as dense ignition source zones and natural fuel discontinuity barriers, restricting further fire spread.

4.2 Fire Season Advancement and Wild Spread Drive WUI Fire Intensification

A key finding is that I-W fires (WUI ignition, wildland spread) exhibited the largest growth trend over two decades, with both total burned area ($R^2 = 0.56$) and mean fire size ($R^2 = 0.60$) increasing significantly. Mean I-W fire size (144.2 km²) now exceeds all other types, revealing the underlying mechanism of WUI fire intensification.

Human activity reshapes fire ignition spatiotemporal patterns, subsequently altering fire propagation pathways and magnitude. Figure 3 shows human-caused WUI fires advancing toward spring (earlier ignition dates) with significant peaks on major holidays; Table 2 reveals fuel composition differences between WUI and wildland fires (higher shrub/grass in WUI versus higher forest in wildland). When residential areas interdigitate with shrubland, human ignition sources become embedded in high-fuel-load zones. Successful ignition can then spread via continuous shrub fuels into distant wildland areas. Syphard et al., (2007) similarly found that human settlement drives shrubland fire frequency increases, with landscape fragmentation at urban-wildland boundaries potentially increasing fire spread risk by 25%—consistent with I-W behavioral characteristics in our study.

Notably, W-I fires (wildland ignition, WUI spread) showed significant decline over two decades ($R^2 = 0.35$), contrasting sharply with I-W growth. This trend likely reflects differential fire management effectiveness: fuel management at WUI margins may effectively block wildland-to-WUI spread pathways; improved early detection and rapid response in WUI areas; and spatial attraction of ignition sources to expanding WUI zones, altering fire distribution patterns. Future research integrating detailed fire management records is needed to quantify these mechanisms' relative contributions.

4.3 Limitations

This study has several limitations. WUI data are available at five-year intervals, limiting resolution of inter-annual WUI dynamics. Ignition point matching uses 500 m MODIS pixels, which may introduce spatial location errors. The 15% threshold

for behavioral classification involves some subjectivity. Future research incorporating higher-resolution building distribution data and fire management records can better quantify the relative attribution of WUI fire drivers.

5. Conclusions

This study analyzes California fire data (2002–2023) across multiple sources, proposing a four-category WUI fire classification framework—distinguishing ignition location from spread extent—to quantify the relative contributions of WUI expansion and climate-induced pressure in driving wildfire risk. Key findings are: (1) WUI fires dominate California wildfire losses, yet actual burned area remains predominantly wildland. Both total and mean WUI fire areas show significant increasing trends over time. (2) Distinct seasonal dynamics differentiate WUI from wildland fires by ignition source. Lightning-caused WUI fires show significantly delayed ignition dates over two decades (shifting toward autumn), while human-caused WUI fires advance significantly (toward spring). Weekly frequency distributions reveal human-caused WUI peaks on Independence Day, Labor Day, and Thanksgiving. (3) Different fire behavioral types exhibit distinct mechanisms of human and climate interaction. I-I fires are human-dominated, threatening high-density structures; W-W and I-W fires are climate-sensitive, with both total and mean areas increasing significantly over 22 years—I-W growth exceeding W-W.

The WUI fire classification framework, by distinguishing ignition location and spread extent, reveals differing internal mechanisms among WUI fire events, providing scientific basis for differentiated fire management strategies. This work further supports synergistic amplification between WUI expansion and climate warming. These findings have important theoretical value for understanding WUI fire intensification mechanisms under climate change and provide empirical evidence for wildfire risk management in California and similar regions.

Acknowledgements

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Appendix

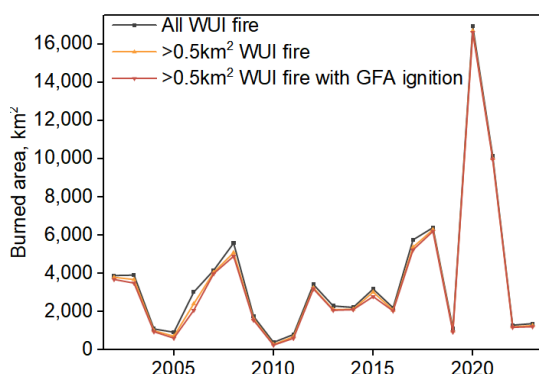


Figure S1. WUI fires included in this study account for 97% of total burned area.

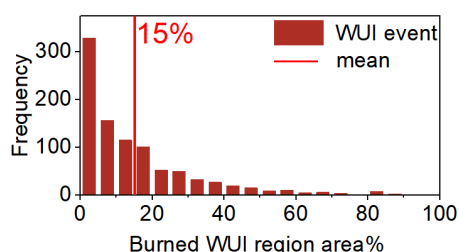


Figure S2. Distribution of WUI area proportion (%) across all WUI fire events. The threshold of 15% (mean) distinguishes WUI-dominant spread from wildland-dominant spread.