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Yearly population data at census tract level revealed that more people are now living in highly fire-prone zones in California, USA

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Abstract

In California (CA), the wildland-urban interface (WUI) faces escalating challenges due to surging population and real estate development. This study evaluates communities along CA's WUI that have witnessed substantial population growth from 2010 to 2021, utilizing demographic data and the 2020 WUI boundaries by the University of Wisconsin-Madison SILVIS Lab. Employing the Mann-Kendall test, we analyze yearly population trends for each census tract along the CA WUI and assess their significance. House ownership, affordability, and wildfire risk are examined as potential drivers of this demographic shift. Our findings indicate that 12.7% of CA's total population now resides in census tracts with significant population increases over the past decade, labeled as 'high-growth tracts.' The Bay Area and Southern California, encompassing 76% of all high-growth tracts in CA, witnessed the most substantial population increase along the WUI. Notably, Riverside County stands out with 29.2% of its residents (approximately 717,000 residents) located in high-growth tracts, exemplifying a significant population surge within CA's WUI. Our analysis identifies a significant relationship between population increase in the WUI, house ownership, and affordability, where lower-priced homes come at the expense of heightened wildfire risk. However, the impact of house affordability on population growth within the WUI varies by region, playing a more prominent role in explaining population proportions in Southern California's WUI, while in the universally low-affordability Bay Area, other motivations may drive residents to live within the WUI. Given the rapid growth and insufficient consideration of wildfire risk in the WUI, policymakers must take prompt action, ensuring adequate infrastructure and resources as more individuals relocate to areas with heightened wildfire risk.

1. Introduction

Wildland-urban interfaces (WUIs) are zones ecologically sensitive to wildfires and have experienced increasing pressure from human activities over the past decade (Balch *et al* 2017, Bento-Gonçalves and Vieira 2020, Caggiano *et al* 2020). A study found that 97% of wildfires in the WUI of the United States were human-caused compared to 59% in the rest of the country (Mietkiewicz *et al* 2020). Also, the WUI accounts for less than 10% of land but involves nearly one-third of wildfires in the United States (Mietkiewicz *et al* 2020). Statistics found 86% to 97% of building losses occurred in areas defined as WUI throughout the U.S. (Caggiano *et al* 2020). This alarming pattern needs to be better investigated in the context of the rapid expansion of WUI from 2010 to 2020, when 2.6 billion homes were built in these communities across the U.S. (Mockrin & Blackburn, 2023).

In California, WUI areas are notably perceived as high-risk zones for human-caused wildfires (Abatzoglou *et al* 2021, Radeloff *et al* 2018). The accumulation of wildland vegetation, concentration of flammable human structures, and dispersal of sparks resulting from human activities near fuel sources all make WUI vulnerable to wildfires (Mercer and Prestemon 2005, Kramer *et al* 2018, Radeloff *et al* 2018, Kumar *et al* 2022, Li *et al* 2022). The escalating real estate development within these fire-prone WUI areas exacerbates the associated risks, contributing significantly to the likelihood of property loss (Syphard *et al* 2007, Radeloff *et al* 2018). This trend has prompted insurance companies to deny coverage to residents in high wildfire-risk zones throughout California (Kramer *et al* 2019, Gonzalez 2023). The substantial proportion of wildfires originating from private land within the WUI intensifies the exposure of properties to risk (Downing *et al* 2022). Additionally, the density of structures in interface communities, coupled with inadequate response time such as fire-fighting compliant road access, poses challenges for preventing loss of buildings(Glickman and Babbit 2001). Enhancing infrastructure in these regions will be crucial to support a growing population and effectively manage the associated risks.

The expansion of real estate development and population growth in the coming decades (Mann *et al* 2014), underscores the significance of scrutinizing this trend at a finer demographic resolution. Analyzing population trends is crucial for understanding the ramifications in areas like California's Wildland-Urban Interface (WUI), where small population shifts can have notable consequences. Efforts to comprehend this phenomenon include (1) tracking and mapping WUI expansion over decades (e.g., Theobald and Romme 2007, Radeloff *et al* 2018, Carlson *et al* 2022) and (2) quantifying the temporal changes in sociodemographic variables—such as population and the ratio of property owner-renter—at a fine scale within high wildfire risk regions, utilizing various statistical models like the general additive model (Yadav *et al* 2023).

Despite the increasing focus on this topic, there has been limited exploration of the magnitude and consistency of population change trends within California's WUI. Challenges arise due to (1) the relatively short period when yearly population data at the census tract or finer geographical unit became available for a valid time series analysis, and (2) the spatial complexity of the issue. In this study, we leverage yearly population data at the census tract level from 2010 to 2021 to conduct a trend analysis at a fine spatial scale across California's WUI.

Beyond population trends, socioeconomic factors drive challenges to address wildfires, particularly in the U.S. context, have been extensively investigated (Syphard *et al* 2007, Theobald and Romme 2007, Davies *et al* 2018, Gabbe *et al* 2020, Masri *et al* 2021) due to the abundance of available socioeconomic and demographic data. House availability, often cited as a driving factor for migration from the 1990s to the 2010s (Roger *et al* 2007, Theobald and Romme 2007, Gosnell and Abrams 2009, Bar-Massada *et al* 2014, Carlson *et al* 2022), is intertwined with concerns about wildfire risk in WUI areas, prompting government regulations on development and resident activities. Real estate development is notable in the interface WUI, where fuel density is relatively low. Studies have also extended to pinpoint disparities in resources available to combat wildfire risk between socioeconomically affluent and underprivileged communities (Garrison and Huxman 2020, Masri *et al* 2021) now residing in the WUI, revealing different reasons for their relocation over a decade ago. Recognizing the varied impact of wildfires across socioeconomic status, a thorough investigation to identify the most socially and economically vulnerable census tracts, where the population has increased the most in the past decade, provides insight into how policy change can happen through proper resource allocation.

In this work, we address three questions regarding the population change at the census tract level along California's WUI during the past decade, including (1) How did the population change along California's WUI? (2) Which communities/counties were significantly affected by such change? (3) How did the most likely drivers of such change influence the population trend? We answered these questions by analyzing the monotonic trend of population changes across counties and comparing observed population shifts with potential socio-economic drivers, such as house ownership, affordability, and wildfire risk. The results of this study will determine if there is a potential change in risk due to the population's effect on the indicators mentioned above.

2. Data and methods

Table 1 summarizes the name and specifics of datasets adopted in this analysis, including deriving the population change trend and investigating the potential drivers of such trend. Trend analysis for population was conducted at census tract level as yearly population data are only available at this spatial scale. The 2020 version of WUI boundaries and types of WUI from University of Wisconsin-Madison, SILVIS Lab (Radloff *et al* 2005, Radeloff *et al* 2018) was adopted to ensure that the analysis reflects the latest population distribution across WUI and enables the comparison across different types of WUI with varying population density. High density interface, the WUI type where vegetation occupies less than 50% of land and the population is the highest,

Table 1. Data used in the analysis of population trend inside WUI and potential drivers of such change.

Dataset	Years available	Spatial resolution	Source of Data[a]
Population	2010 to 2021	Census tract	American Community Survey (ACS) by U.S. Census Bureau (2022a)
Wildland-urban interface (WUI) boundaries	2020	Originally block level, dissolved to census tract level	University of Wisconsin-Madison SILVIS Lab (2023)
Percent of housing units owned by occupants	2021	Census tract	ACS by U.S. Census Bureau (2023a)
House Affordability Index (HAI)	2021	Census tract	Derived by Esri Demographics (2022) with data from U.S. Census Bureau (2022b)
Wildfire Hazard Potential (WHP)	Multi-year average, latest update date in 2020	270 m (aggregated to median within census tracts)	U.S. Forest Service (Short *et al* 2020)

[a] Refer to the Reference section for detailed citation of these data sources.

consists of 22% and 23% of California's WUI tracts in the 2010 and 2020 version of SILVIS data, respectively. The medium density interface is the second largest group of tracts inside WUI, occupying 14% of WUI tracts in both versions of WUI boundaries. During the period from 2010 to 2020, 94.5% of WUI blocks in California maintained the same WUI classification, comprising 116,634 out of 123,423 blocks within California's WUI (table S1). The conversion between WUI types did not introduce significant boundary differences between 2010 and 2020. Consequently, the 2020 boundary remains suitable for quantifying population changes within California's WUI.

We extracted annual population data at the census-tract level from 2010 to 2021 using the ACS dataset. As the census tract is the finest spatial unit with yearly population data available, we also aggregated the WUI boundaries from its original spatial scale (blocks) to a coarser scale of the census tract using the dissolve function from ArcGIS Pro. A block is a finer spatial unit than a census tract and contains an identifier with the information of the census tract to which it belongs. Therefore, we were able to scale the original WUI boundaries from block to census tract level and match the spatial unit of the annual population data. Meanwhile, we also determined the WUI type of the aggregated census-tract-level WUI boundaries using the most commonly found WUI type among all blocks within each census tract. These results are provided in a public-facing repository (Jia 2024).

Monotonic population trends within California's WUI from 2010 to 2021 were determined for each census tract using the Mann-Kendall (M-K) test (Hamed 2009, McLeod 2005). This test, suitable for count data with sparse observations (i.e., yearly population count), does not assume normal distribution. It assesses the null hypothesis of no monotonic trend versus the presence of a monotonic trend. The reported M-K test's τ value and p-value gauge the consistency and significance of the monotonic trend. A positive τ and a significant p-value (< 0.05) indicate statistically consistent population increase over the ten-year analysis period. While the τ value itself does not directly convey the magnitude of change, recent studies suggest its ability to reflect such magnitude (Wang *et al* 2020). As a point of comparison, results from Poisson and ordinary least square (OLS) linear regression models between population and study year (2010–2021) aligned with M-K test outcomes (figure S2). The reporting is organized by county for clarity.

Subsequently, we investigated potential drivers of population increase within California's WUI, focusing on tracts with significantly increasing trends ($p < 0.05$, referred to as high-growth tracts). Pearson and Spearman correlations were conducted between the proportion of the county population residing in high-growth WUI tracts and three potential drivers or deterrents: house affordability, house ownership, and wildfire risk.

House affordability and ownership have consistently been identified as drivers of population growth in California's WUI over the past decade, driven by housing demand in a thriving economy and ample development land in this suburban region dating back one to two decades (Hammer *et al* 2007, Carlson *et al* 2021). Wildfire risk acts as a potential deterrent to population influx in the WUI due to its imminent threat to lives and properties (Bar-Massada *et al* 2014, Bento-Gonçalves and Vieira 2020). These factors are quantified by the House Affordability Index (HAI) (Esri Demographics 2022), the percentage of housing units owned by occupants (U.S. Census Bureau 2022b), and Wildfire Hazard Potential (WHP) (Scott 2020, Short *et al* 2020). WHP, chosen for its high spatial resolution (270 m) and incorporation of the latest five years of wildfire risk with considerations of moisture and wind-based vegetation flammability (Dillon *et al* 2015), represents the current state-of-the-art in measuring wildfire risk. It is a key component of the Wildfire Risk to Community program (Short 2020), the latest tool for wildfire risk awareness and preparation by the U.S. Forest Service.

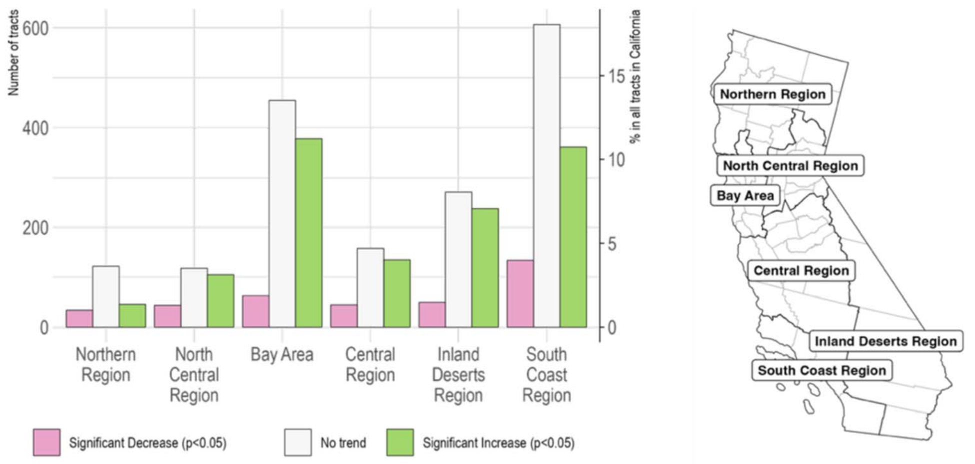

Figure 1. Population trends in the Wildland-Urban Interface (WUI) of California by region (left). Left *y*-axis shows the total number of tracts by trend type, whereas the right *y*-axis showed the percentage of all tracts in California. A reference map is provided to illustrate the six regions used in analysis (right).

3. Results

3.1. Population trends in WUI by region

The regions of the state have varying trends in the WUI. Nearly one-third of census tracts (29.2%) inside California's WUI are high-growth tracts (figure 1), which are homes to 12.7% of total population of California in 2021. For comparison, proportions of California's WUI tracts that experienced a significant population decrease or no significant change were 9% and 61.8%. The Bay Area and South Coast region have the most tracts with increasing trends compared to other regions. While there are tracts with declining populations in the Bay Area and South Coast Region, it is crucial to emphasize the significant proportion of high-growth tracts within these regions and the considerable proportion of the high-growth tracts out of all tracts in California, not just within WUI (figure 1). Furthermore, more tracts inside high population density interface of WUI showed a significant population increase (figure S1). Bay Area and South Coast Region are also the leading regions of population increase in this type of WUI.

3.2. Difference in the population increase pattern in the Bay Area and Southern California

Our analysis found that South Coastal Region and the Bay Area account for 82.6% of all high-growth tracts in California. However, the two regions showed different patterns in terms of degree of change and the impact on total population. Bay Area counties had a greater increase of population and a higher proportion of population living inside the high-growth tracts in WUI, shown as darker green shades in figures 2(a) and (c). The most populous counties in the Bay Area (Contra Costa, Alameda, Santa Clara, and San Mateo) all had a significantly consistent population increase from 2010 to 2021, with at least 15% and up to 35% population now living in the high-growth tracts of WUI. However, the arbitrary population living inside the high-growth tracts in Bay Area is relatively small, as indicated by the smaller circle size in figure 2(c). For less populated counties in Bay Area's Wine Country (Napa, Solano, Sonoma, and Marin), although they had a high proportion of population living in high-growth WUI tracts (dark grey color in figures 2(a) and (c)), the magnitude of population increase is less drastic than other Bay Area counties. In contrast, half of counties in Southern California (South Coastal Region combined with populous counties in Inland Desert Region, including San Bernardino and Riverside) had less than 15% of their population living in high-growth tracts (light grey polygons in figure 2(b)), but all of them had at least 170,000 people living in such tracts. However, Southern California counties showed a less drastic increase of population compared with the Bay Area. All but one (Riverside) of the counties with a median M-K τ in the top tertile ($\tau > 0.6$) are in the Bay Area (figure 2(c)).

The different population increase pattern between Southern California and the Bay Area can be better observed in figure 3. The population increase within WUI zones encompassed much more residents in Southern California (around 2,729,000) than Bay Area (around 1,894,000 residents). Only 6.1% of Los Angeles County's population live in high-growth tracts, but accounting for approximately 768,000 residents. This is almost twice as many as the top county (Alameda) in the Bay Area (figure 3(b)). Among all 16 counties in both regions, Riverside is the only county where a high degree of population change ($\tau > 0.6$) encompassed many residents (721,000) that represent a high proportion of county population (29.2%).

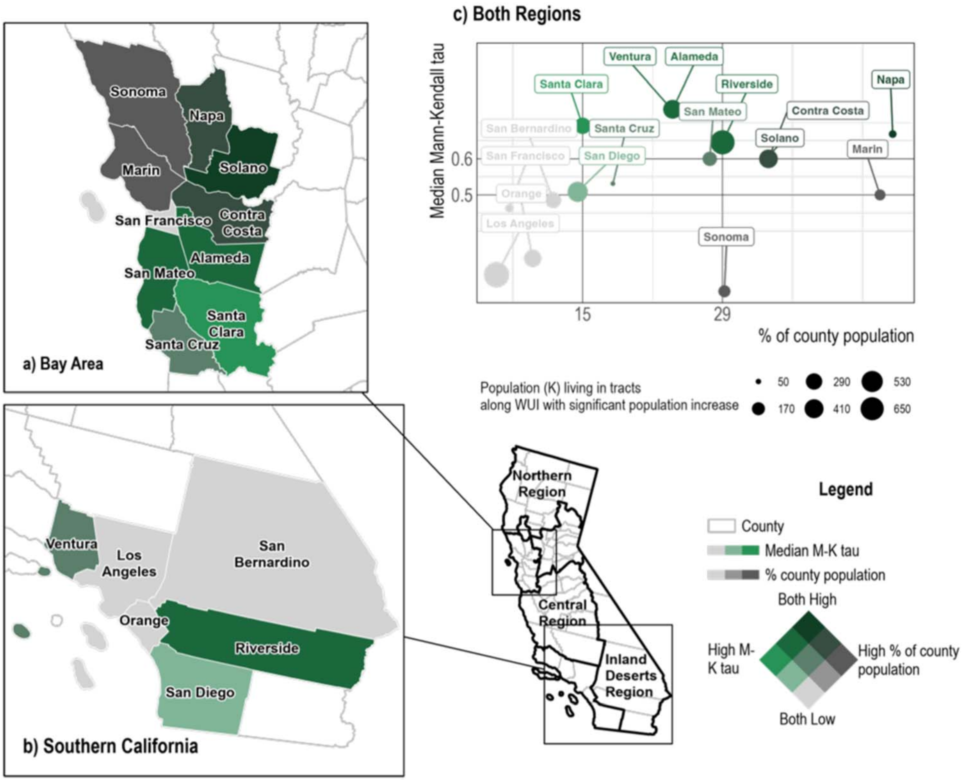

Figure 2. Consistency of population increase (median M-K's τ) and percent of county population living in high-growth tracts of WUI in Southern California and the Bay Area. Different shades of green indicate the value of M-K's τ. Greener means higher M-K's τ, or higher consistency of the population increase. Darker shade of grey indicates a higher percentage of the county's population living in the high-growth tracts inside WUI. A darker green color means high in both metrics. Circle size of panel c indicates the population (in thousands) living inside the high-growth tracts in WUI.

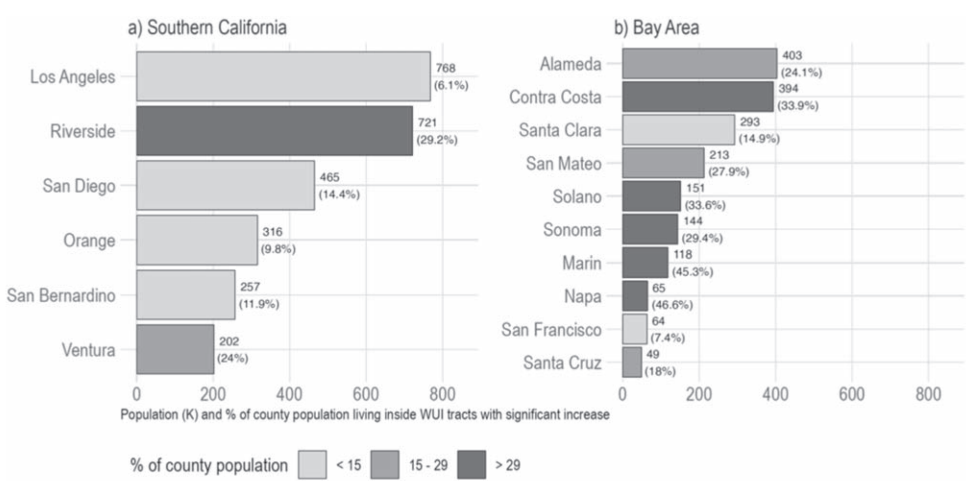

Figure 3. Number of residents and percent of county population living in WUI tracts with significant population change for Southern California and Bay Area by counties.

In summary, highly urbanized counties such as Los Angeles, San Francisco, Orange, and San Bernardino exprienced a less drastic population increase inside WUI (figure 3(a), lightest gray bars) compared to counties with wide-spread suburb communities (figure 3(a), darker bars). Bay Area counties showed a more consistent population increase inside WUI and such increase encompassed a higher proportion of residents of each county. Although such proportion is low in Southern California, due to the large population size in each county, the significantly consistent population increase inside WUI still encompassed a large number of residents.

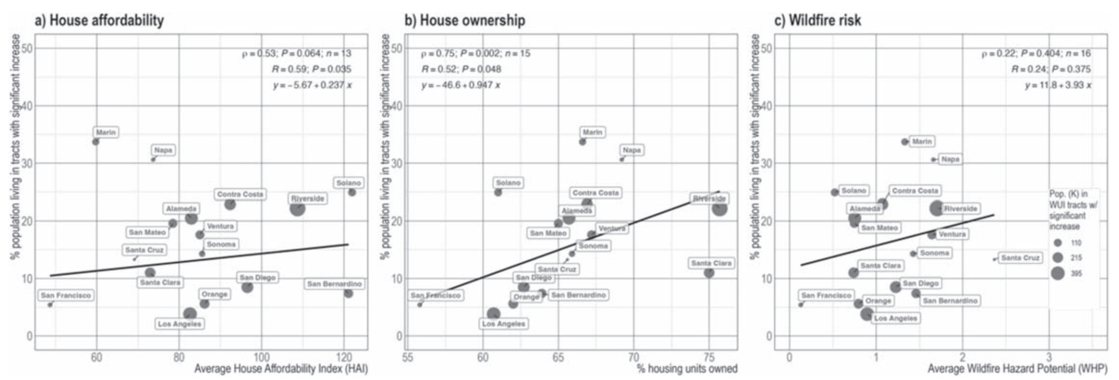

Figure 4. Potential factors contributing to the distribution of the proportion of population living in WUI tracts with significant population change in counties in Southern California and Bay Area. Size indicates county total population.

3.3. Possible drivers of population increase along WUI

House affordability has been frequently cited as a key driver of the sprawling toward WUI in California. Both Spearman and Pearson's correlation coefficients (figures 4(a)–(b)) demonstrated that counties with a higher proportion of residents living inside WUI's high-growth tracts are positively correlated with increased housing affordability ($\rho = 0.53$, $R = 0.59$) and house ownership ($\rho = 0.75$, $R = 0.52$). However, the proportion of residents living in high-growth tracts did not significantly change with an increased wildfire hazard ($p > 0.05$, figure 4(c)), indicating the sprawling is curbed under a tolerable level of wildfire risk. The same, but less pronounced pattern can be observed when all tract inside WUI were included in the analysis (figure S5). Nevertheless, the positive slope in the linear regression suggested that the wildfire risk is not a deterring factor of sprawling in many counties, including Sonoma, Riverside, and Ventura. Outliers of all the indicators above include Napa, and Marin counties, driven by the sparse population distribution and large parcel size associated with the wine industry.

The spatial difference between potential drivers of population growth is prominent, within and across geographical regions. Census tracts with both high house affordability and high percentage of county population living inside WUI (top 33% in both metrics) are mostly large, suburban and rural ones, for example, WUI tracts in Imperial, Riverside, Santa Barbara, Fresno, Solano, Chico, Redding, and Lasson County (brown dots in figure 5(a)). In these tracts, high house affordability coincides with high proportion of people living in these areas, indicating house affordability can better explain such choice.

However, such coincidence does not always occur. In many inland areas of South Coast and Inland Desert Regions, house affordability is a better indicator of significant population growth as a high proportion of population living inside WUI often occurs concurrently with a high house affordability in those tracts (blue and dark blue dots, figure 5(b)). However, in more affluent, less populous South Coast counties (Ventura and Santa Barbara), a higher percentage of population choose to live in WUI tracts where house affordability is low, indicating a different driver is responsible to explain such pattern (red and dark red dots, figure 5(b)). The similar pattern can be found in the Bay Area, especially in the South Bay which encompasses the San Mateo and Santa Clara County, where a large proportion of these counties' residents live in WUI tracts with low house affordability (red and dark red dots, figure 5(d)). Considering the much lower house affordability and higher population density in the Bay Area than the South Coast counties, this similar pattern can be driven by different factors. The East Bay area (Alameda, Contra Costa) showed a slightly different pattern than the South Bay as house affordability better coincides with the high proportion of population living in high-growth WUI tracts compared with its South Bay counterpart (pink dots, figure 5(d)). Finally, although the Great Sacramento region was not mentioned as an area with the most prominent population growth inside WUI, its recent population increase shows a similar pattern to Southern California suburban counties, where high house affordability is prominent in tracts with high population growth but accounts for a relatively small proportion of county population (blue dots in figure 5(c)).

4. Discussion

4.1. Socio-economic indication of population increase inside CA WUI

Our analysis unveils a noteworthy population surge along California's WUI in the past decade, particularly in proximity to major population centers like the Bay Area and Southern California. Contrary to suggesting a migration to rural areas, this uptrend in population results from urban sprawl. Notably, the increase in

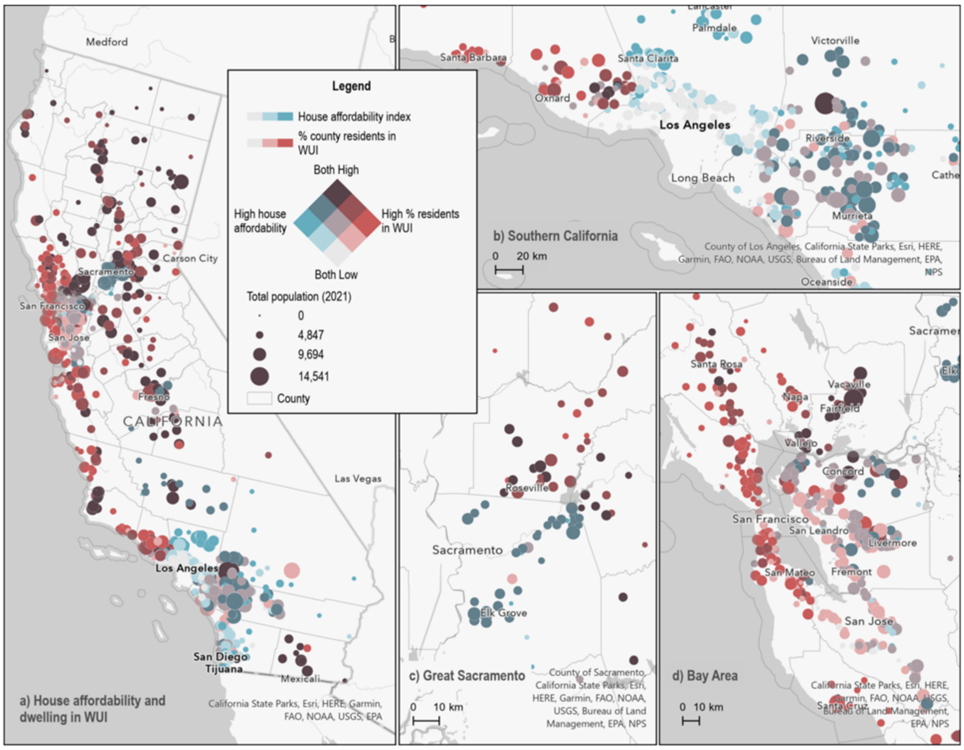

Figure 5. House affordability (blue) in high-growth tracts of WUI and the proportion of county population (red) living in these tracts. A brown color indicates the two metrics are both high (top 33%) in the tract. Panel b-d show three highlighted regions in our analysis.

homeowners within the WUI is driven by house affordability in numerous regions. Our findings highlight a correlation between house ownership and population growth in high-growth tracts, signaling improved economic well-being among residents in wildfire-prone areas like the WUI.

These demographic shifts are reshaping the WUI's composition, with continued population growth near urban centers despite a temporary setback during the COVID-19 pandemic. However, these shifts also place socially vulnerable communities at a heightened disadvantage. The demand for more affordable homes, without due consideration for wildfire risk, exposes individuals in vulnerable areas to greater fire hazards. The escalating frequency of wildfires within and near the WUI establishes a cycle of aggressive construction and housing destruction. This cycle may exacerbate the exclusion of less affluent residents from the market, as land prices in post-wildfire reconstruction become less affordable, potentially forcing them to seek options in even more wildfire-prone areas. An illustrative case is the predatory land buying observed after the August 2023 wildfire in Lahaina, Hawaii (Spencer 2023). Although a housing price hike is not guaranteed post-wildfire (Garnache 2023; Ma *et al* 2023; Mueller *et al* 2009), the observed population expansion in this study, coupled with the growing emphasis on home affordability, suggests an increasing wealth gap along the WUI, favoring more expensive homes in the rebuilding process (Garrison and Huxman 2020).

Moreover, the population increase signifies the expansion of private land, raising concerns as private land fragmentation interferes with public land and undermines mitigation efforts. Given that most wildfires initiate on private land (Downing *et al* 2022), the prevalence of human-induced fires, combined with personal property serving as a wildfire starting point, underscores population change as a significant factor contributing to heightened wildfire risk.

4.2. Regional difference of population increase in California's WUI

The geographical areas housing major cities, notably Southern California and the Bay Area, exhibit the most significant population changes along the WUI. Specifically, the rise in high-density interface communities within the WUI is particularly noteworthy due to the heightened vulnerability of this type of WUI to property damage. Counties in the Bay Area, such as San Mateo, Alameda, and Santa Clara, exemplify interface communities and experienced the most substantial overall population growth. In these counties, a larger proportion of the population resides within WUI tracts compared to other regions. Our findings reveal a concerning trend: though WUI land comprises only 6.5% of California's total land area, it is now home to 33% of the state's population. This pattern is most pronounced in the Bay Area, where all counties, except densely urbanized San Francisco County, have 18% to 47% of their population residing in high-growth WUI tracts (figure 3(b)).

While Southern California counties have a smaller proportion of residents in high-growth tracts, the absolute number of individuals in these tracts (approximately 2,729,000) exceeds that in the Bay Area (approximately 1,894,000), posing a significant wildfire risk in this ecologically sensitive zone. Riverside County stands out as a prominent example among all California counties, experiencing an increased risk along the WUI due to population growth coupled with a high proportion of affected residents. Given the potential impact on a large population, careful implementation of mitigating measures such as Public Safety Power Shutoffs and regular fuel removal in residential areas is essential to reduce wildfire risk during fire-prone weather conditions.

In contrast, the Central and Northern regions exhibit distinct population trends compared to the Bay and Southern California. These areas feature more intermixed communities and less prominent interface regions (figure S1), resulting in less dramatic changes in intermixed communities due to their lower population density.

4.3. Interpreting the drivers of population increase inside California's WUI

Our findings suggest that while house affordability plays a role in driving population growth within many WUI tracts in California, its influence varies across regions. It is a significant factor in explaining the population increase in many inland Southern California counties, such as Riverside, San Bernardino, and parts of Orange and San Diego. However, its explanatory power diminishes in more affluent and less populated counties like Ventura and Santa Barbara. Limited available land for construction, especially in Santa Barbara, compels residents to live within the WUI, as alternative options are not feasible. Additionally, more affluent residents in these counties prefer larger parcel sizes, achievable only by expanding into the wilderness of the WUI. This trend is also notable in the South Bay Area (San Mateo, Santa Clara), where house affordability is the lowest in the U.S. (Esri Demographics 2022). Living in the WUI becomes the sole option for those who desire proximity to their office space in San Mateo County due to limited land availability. The East Bay (Alameda, Contra Costa), with more available land, sees house affordability becoming a crucial factor in people's decision to reside within the WUI. Generally, house affordability better explains population growth in WUI areas where land is more available, and commuting needs are high, as seen in Southern California and the Greater Sacramento area. In regions where house affordability is generally low, living in the WUI may be the only viable option.

Over the past decade, there has been significant real estate development within and along California's WUI to meet the rising demand for homes with the growing population. This development has led to an expansion of the interface type of WUI compared to the 2000s, pushing the WUI further into the wilderness (Chen and Jin 2022). Pre-2021 zoning laws and local resistance to development have contributed to sprawl by limiting apartment complex construction in single-family zoning areas (Rothwell 2019). With the slowing down of development within the WUI due to limited available land and heightened concerns over wildfire risk, it is imperative for lawmakers, community leaders, and the general public to integrate the elevated risk of wildfire into community planning. Plans should be devised to better protect existing communities within the WUI. In census tracts where our analysis detected consistent and significant population increases over the past decade, there is a need to establish a more wildfire-resilient emergency response system. Strengthening wildfire risk awareness and firefighting resources in these communities is crucial (Calkin *et al* 2014), as key infrastructure development may lag behind the heightened demand resulting from the population influx. Such a system can facilitate a proactive and swift response to imminent wildfire risk, reduce wildfire-induced loss of lives and properties, and potentially lower property insurance rates for WUI residents.

4.4. Limitations in analysis

To comprehensively address the spatial clustering observed in our study, we advocate employing the geographically weighted regression (GWR) method at the census tract level. Our results unmistakably reveal a spatially aggregated pattern, and it is evident that potential drivers for population growth within the WUI vary across different regions in California (figures 2 and 5). A GWR model is crucial for adequately handling the spatial autocorrelation inherent in the data. It can construct distinct models to assess the contribution of different determining factors to population growth within the WUI across various California regions.

Furthermore, our study does not delve into the temporal variation of driving factors for population change within California's WUI. In a snapshot analysis, we did not find the same significant correlation between percent of population living in WUI and the home ownership in these tracts using the data of 2010 (figure S6). We also found the population inside WUI tracts and home ownership increased in parallel to each other from 2010 to 2021 (table S2). This finding suggests a correlation where areas with increased homeownership also saw population growth. While this does not establish a direct cause-and-effect relationship, which warrants further study, it suggests that higher homeownership rates may play a role in driving population increases in California's most populous WUI regions. Due to the lack of necessary data for earlier years, we were not able to conduct the same analysis for HAI and WHP. To further investigate the robustness of the relationship we have identified in the data of 2021, a subsequent analysis could focus on comparing the monotonic trend of population and selected driving factors, especially those related to house availability, within census tracts where a significant population increase has been identified. This additional analysis can confirm whether the driving factors that prominently determine the spatial pattern of population change have also undergone parallel changes with the population over the past decade. In addition to the temporal variation of potential driving factors of population change, WUI type has also changed in some part of California from 2010 to 2020. The most notable changes involved WUI types with a transition from lower to higher population density. A further investigation can be conducted to highlight blocks or census tracts with a change in WUI type.

Lastly, to better elucidate the reasons behind individuals choosing to reside in WUI tracts, particularly in areas with low house affordability in two South Coastal counties (Ventura, Santa Barbara) and the Bay Area, more meaningful variables should be incorporated. One approach could involve comparing the relative house affordability in these regions and their adjacent tracts outside the WUI. This comparison operates on the hypothesis that WUI tracts remain more affordable than non-WUI tracts in the same region and offer more development potential. Additionally, the use of parcel size can test the hypothesis that individuals who can afford it opt to live within the WUI for more spacious homes. An extension of this inquiry could explore whether households residing in these WUI tracts, where parcel size is generally larger, are relatively wealthier than those who do not.

5. Conclusion

Our investigation reveals that between 2010 and 2021, a significant increase in population within California's WUI, an ecologically sensitive area at high risk of wildfires. This trend is most pronounced in Southern California and the San Francisco Bay Area, the state's two most populous regions. While the Bay Area counties exhibit a more consistently increasing trend in WUI population and have a higher proportion of the county population residing in the WUI, Southern California counties house more individuals in high-growth tracts within the WUI. Our analysis identifies that this increase is partially driven by more affordable home prices within the WUI, where homes can be constructed at a lower cost despite heightened wildfire risk (e.g., Riverside and San Bernardino County). However, house affordability alone cannot account for other factors such as a desire for an enhanced quality of life, limited land availability, and alternative choices. These findings suggest opportunities for further research: (1) utilizing a geographically weighted regression model to address spatial clustering patterns, and (2) incorporating more meaningful explanatory variables, particularly in regions where house affordability has limited explanatory power (Glickman and Babbitt 2001, Gosnell and Abrams 2011, Radeloff *et al* 2018).

In conjunction with the impact of climate change, the rise in population within the WUI significantly amplifies the risk of wildfires, given increased human activities in proximity to fuels. Despite this heightened risk, people have continued to migrate to high-risk areas like the WUI over the past decade, leading to unavoidable cascading consequences. These consequences include a heightened state budget for wildfire suppression, economic relief for affected individuals, further burdens on taxpayers, and reduced chances of economic relief from property insurance policies, particularly affecting the less affluent. These real-world processes underscore the far-reaching ramifications of climate change. Our work contributes to evidence-based decision-making by advocating for constraints on further development in high-risk areas and identifying the most vulnerable communities in wildfire suppression and emergency response to mitigate the cascading effects discussed above and reshape population dynamics within the WUI.

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Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://github.com/jiashenyue/ca-wui-pop.

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