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Fire frequency and vulnerability in California

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Abstract

Wildfires pose a large and growing threat to communities across California, and understanding fire vulnerability and impacts can enable more effective risk management. Government hazard maps are often used to identify at-risk areas, but hazard zones and fire experience may have different implications for communities. This analysis of three decades of fire footprints, hazard maps, and census and real estate data shows that communities with high fire experience differ substantially from communities with high fire hazard. High-hazard communities average higher incomes than low- and no-hazard communities; conversely, communities with high fire experience average lower incomes than those with little to no experience. Home values have grown more slowly in communities with high fire experience, translating to differences in total appreciation of $165M-$630M per year relative to communities with no fire experience. Warming over the remainder of the century could add tens of thousands of homes to high-experience zones. This relationship between income and fire experience may be a reflection of the impacts of repeated fires relative to mapped hazards or single fires, or it could point to a relationship between income and the success of fire prevention or suppression. The discrepancies between dimensions indicates that considering fire frequency can support efforts to equitably target risk management resources.

Introduction

Driven by climate change, development patterns, and forest management practices, wildfires pose a large and growing threat to communities around the world. Record-setting losses in recent years have triggered new urgency for households, businesses, and governments to adjust to increasing risk. The need for adaptation is especially acute in California, where 15 of the 20 most destructive fires on record have occurred since 2015, and climate change is projected to exacerbate wildfire risk [1, 2]. Understanding the relationships between fire hazard, exposure, and vulnerability of households and communities is critical for developing and targeting response and adaptation strategies.

Fires cause a diverse set of social, economic, and environmental harms, and many questions remain about the full range of impacts and their geographic and temporal scales. Many wildfire damage estimates focus primarily on the direct physical damages from the fire; for

publicly through their GIS database: https://frap.fire.ca.gov/mapping/gis-data/. The wildfire projections used are publicly available through Cal-Adapt's website: https://cal-adapt.org/tools/wildfire/. The income and race data used are publicly available through the US Census Bureau (data.census.gov). The property-specific data, including locations, characteristics, sale prices, sale dates, and assessed values are provided through a data use agreement with CoreLogic and can only be accessed through CoreLogic. The scripts used in this analysis are available at the Carolina Data Repository (https://doi.org/10.17615/96dc-q571).

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example, the California Department of Forestry and Fire Protection ("Cal Fire") tracks the number of structures that are damaged or destroyed, and their loss estimates are based on the value of those buildings [3]. However, beyond direct damage to housing and other infrastructure, documented impacts include harm to mental and physical health, property value losses, and reductions in tourism [4–6]. These "indirect" impacts can spread beyond the area burned. The negative health impacts of wildfire smoke, for example, are large and extend far beyond fire perimeters [7, 8]. One estimate suggests that the majority of economic losses from wildfires in California in 2018 were due to indirect losses, such as disruptions to supply chains for key industries [9]. Some impacts materialize over longer periods of time, such as post-trauma mental health effects or prolonged closures of schools and health care facilities [10, 11]. Repeated fires can also have distinct effects: properties near a severe fire experience at least a short-term reduction in sale prices, and a second fire can cause larger impacts than the first [5, 12–14].

Due to the different geographic and time scales associated with different impacts, efficiently targeting risk management efforts is challenging. The criteria used to target government resources and policy to mitigate fire risk vary across jurisdictions. In California, fire hazard severity zone (FHSZ) maps are core tools for tracking, communicating, and mitigating fire risk. These publicly available maps assign local hazard levels based on "fuels, fire history, terrain influences, housing density, and occurrence of severe fire weather" [15]. The FHSZs are used in multiple regulatory and decision-making applications. For example, different building codes apply to new construction in high FHSZs, and zones dictate whether or not information about fire hazard must be disclosed in real estate transactions [16]. The zones also affect Cal Fire's identification of "Priority Landscapes" for reducing wildfire risk to communities, which in turn shape how fire risk management projects are prioritized [17]. For post-wildfire relief programs, determinations of eligibility typically depend on the burn perimeter and are often set at the county level.

FHSZ maps and other indicators can be used to evaluate the distribution of fire risk and impacts. Across the western US, properties in the top decile of property value are more likely to be in high-hazard areas than the median property. The highest-value properties were also more likely to be affected by a wildfire from 2011 to 2018, though these statistics were heavily influenced by the particularly-damaging Tubbs and Camp Fires [18]. Ambient exposure to air pollution from wildfire smoke is also relatively higher for counties with a higher proportion of non-Hispanic whites, though actual exposure is moderated by time spent outdoors, structural characteristics of residences, and other factors [7].

Here, we explore the implications of a different indicator of fire impacts: historical fire experience, or the frequency with which fires affect a neighborhood. Focusing on hazard maps and catastrophic events may miss the consequences of frequent, smaller events. Repetitive exposure to fires, even when those fires do not cause widespread structure damage, may have cumulative harmful effects through the kinds of indirect impacts noted above, such as health impacts or disruptions to local economic activity. A single fire, even a damaging one, may be seen as a rare, "once-in-a -lifetime" event. In contrast, repeated fire exposure may become internalized as a permanent characteristic of a community, leading to long-term demographic or economic responses, such as out-migration and declines in property values. It is also possible that repeated fire experience is not so much a cause as a symptom, indicating lower levels or effectiveness of investment in prevention or suppression [19].

This analysis begins by examining differences across three metrics related to fire risk: hazard as defined by FHSZs, fire damage, and fire experience. While these do not fully encompass risk, each offers a different way of identifying who bears the burden of wildfires in CA. We evaluate the relationships between those metrics and community-level social and economic characteristics at the census tract and block group levels. We also analyze how property value appreciation over time relates to the frequency and timing of fires. Finally, we use projected wildfire patterns to assess how climate change may lead to changes in the number and distribution of communities experiencing high levels of fire frequency.

Materials and methods

Metrics of fire risk

We begin by calculating three metrics of fire risk at the census tract and block group levels. The three metrics are defined as follows:

1. Fire hazard: the share of residential parcels in one of Cal Fire's moderate, high, or very high FHSZs
2. Fire experience: the number of fires with at least one residential parcel within the fire perimeter from 1990–2019
3. Fire damage: the maximum number of residential parcels within a single fire perimeter from 1990–2019

We calculate these metrics based on three data sources: property characteristics and construction data from CoreLogic, wildfire hazard maps from Cal Fire, and fire footprints from Cal Fire.

To focus on the risk to people and minimize the influence of large, uninhabited areas, we begin by identifying the locations of residential parcels across the state using property tax assessment data from CoreLogic, which include the coordinates of the property, a number of different property characteristics, and a land use classification. We subset to only residential properties: single-family homes, duplexes and condominiums, and apartment buildings. The coordinates are used to assign each property to a census block group and tract.

For fire hazard, we use FHSZ maps produced by Cal Fire to assign each residential parcel to none, moderate, high, or very high FHSZ. These maps are developed separately for State Responsibility Areas (SRA) and Local Responsibility Areas (LRA). SRA refers to unincorporated, non-federal land that contains wildland vegetation. The LRA covers incorporated areas with a local fire authority. Cal Fire initially develops the FHSZ maps for the LRA, which are then potentially modified and adopted by local authorities. The adopted maps for the LRA show only Very High FHSZ. In the SRA, land is assigned to any of the moderate, high, or very high categories. Shapefiles representing the SRA and LRA were downloaded from the Cal Fire website. We used only the LRA files classified as "recommended" by Cal Fire, as those most closely match the adopted zones; however, recommended LRA zones were not available from Cal Fire for several counties. Properties that are not included in the available FHSZ maps or are in "Urban Unzoned" or "Non-Wildland/Non-Urban" categories are marked as no hazard. To preserve the focus on state policy and resources, we also designated Federal Responsibility Areas as no hazard because they are not regulated the same way as SRA and LRA zones. Across SRA and LRA zones, we calculate the share of residential parcels in each census block group or tract that are located in moderate, high, or very high fire FHSZ. Groupings are based on this percentage: none denotes zero properties in a fire zone, low is up to 25%, moderate is 25–75%, and high is over 75%.

We measure fire experience using Cal Fire's database of fire perimeters. The database contains the footprints and dates of 20,820 fires dating from 1878 to 2019, regardless of whether local, state, or federal agencies led the response. For fires under state responsibility, timber fires ten acres or greater, brush fires 30 acres or greater, and grass fires 300 acres or greater are included. For U.S. Forest Service fires, there is a ten acre minimum for fires since 1950. However, the database also includes smaller fires, perhaps due to differences in reporting or errors in the perimeters. This fire dataset does not include prescribed burns.

We define a census block group or tract to be "affected" by a fire if at least one residential parcel within it is within the fire perimeter. We consider only residential parcels that had been developed by the year of the fire, so residences built in 2010 do not count as being affected in fires that preceded 2010. Fire experience is the number of fires that affected the tract between 1990 and 2019. None denotes zero fires within the tract, low is 1–2, moderate is 3–5, and high is six or more. This definition of "affected" is not equivalent to structures damaged or burned, which Cal Fire reports for some but not all fires. When the Cal Fire data include a count of structures damaged or burned, that count includes all types of structures, which makes it difficult to compare to our estimates of affected residences.

Fire damage is intended to capture the magnitude of physical impacts on a community. Using the same data on fire footprints as described above, we extract the maximum number of residential parcels affected by any single fire in the block group or tract between 1990 and 2019. None represents no properties, low is 1–10 properties, moderate is 11–100 properties, and high is over 100 properties. Similarly to the definition of fire experience, the count of parcels within the fire perimeter is sensitive to the year built and the year of the fire, so only properties that were built before the fire are considered.

We test the sensitivity of our results to different cut-offs for the groupings of high, moderate, and low hazard, experience, and damage. Results based on census tracts are presented in the main text, and results based on block groups are included in S1 Appendix.

Social and economic characteristics of communities at risk

We next evaluate differences in social and economic characteristics of census tracts and block groups based on level of hazard, experience, and damage.

First, we consider income and property values as indicators of financial wellbeing. Income data are drawn from the American Community Survey 2015–2019. Census tracts that do not contain any parcels designated as residential are excluded from our analyses. These are generally "Special Use Census Tracts" that cover airports, parks, or military bases. Income statistics are based only on tracts that have specific median incomes, which yields a final sample of 7,926 census tracts. We also examine assessed property values, focusing only on single-family homes and condominiums, as another indicator of financial resources. These are extracted from CoreLogic records.

We also assess patterns in racial composition of communities with different levels of fire risk. Tract-level data on the share of the population that is white are taken from the American Community Survey 2015–2019. Similarly to income, race statistics are based only on tracts that have reported the share of population that is white, which results in 7,969 tracts.

Finally, we evaluate differences in home price appreciation across tracts with different levels of fire experience using the Federal Housing Finance Agency's local house price indices [20]. Housing prices have been found to be sensitive to fire incidence, but it is challenging to attribute any specific changes in income or property values to fire experience due to the long-term, latent nature of fire experience. Accordingly, while we do not isolate the impacts of frequent fires here, we examine whether trajectories of housing prices are consistent with the concept that the effects of frequent fires accumulate over time, rather than materializing suddenly. We use housing price indices that represent constant-quality house price changes, so they are not affected by new builds and changes in the composition of the housing stock. The house price index (HPI) is generated at the census tract level for each year, but only for tracts with sufficient sales volume. 6,946 tracts have HPI values since 1990. For the 1990–2019 time period, 5,001 tracts have complete time series, and 6,360 have at least 25 years of HPI values. The HPI dataset includes an index with a 1990 baseline as well as an annual change value.

Projections under future climate change

To estimate future changes in fire frequency, we use wildfire simulations conducted for California's Fourth Climate Change Assessment [21]. Monthly fire simulations covering 1953–2099 at the resolution of a 6 km x 6 km grid were extracted for four possible futures: a cool/wet model with medium and high emissions scenarios (CNRM-CM5, RCP 4.5 and RCP 8.5), and a warm/dry model with medium and high emissions scenarios (HadGEM2-ES, RCP 4.5 and RCP 8.5). The average area burned per pixel across ten different land use scenarios, each comprised of 100 simulations, was used. We define the "present" as 1990–2019 and the "future" as 2070–2099. For each time period, the locations of current residential parcels were overlaid on the modeled fire data. If the parcel fell within a pixel with at least 10 ha burned, the month was counted as a fire month for that parcel. Then, at the tract level, if any parcel within the tract recorded a fire-month, it was considered a fire-month for the tract. The number of fire-months over the 30-year period was tallied for each census tract. This calculation most closely mirrors our fire experience metric as described above. Then, we calculated a "fire change factor" for each tract: the ratio of the number of months with fire from 2070–2099 to the number of months with fire from 1990–2019. If a tract had zero fire-months in the present and non-zero fire months in the future, then the fire change factor was calculated as if it had one fire-month in the present to avoid dividing by zero. This "fire change factor" is combined with the historical fire experience metrics to identify locations that may move into the "high experience" category in the future. To focus this measure on changes in fire hazard, we keep the distribution of residential parcels constant and do not incorporate past or potential future housing development.

Results

Metrics of fire risk

The three metrics differ substantially in their geographic pattern, as shown in Fig 1. In particular, while FHSZ maps suggest uniformly high hazard in the inland mountains and northern forests, the experience and damage maps show much more variation within those regions. The coast features high hazard levels but a mix of experience and damage levels. All three maps point to a low level of fire concern in the Central Valley and urbanized areas.

Social and economic characteristics of communities at risk

The three metrics also paint different portraits of the communities who face wildfire risk. Incomes are relatively higher in communities with high fire hazard according to the FHSZ maps and lower in communities with high fire experience (Fig 2). Median incomes across high-hazard tracts average $97,643, compared to $76,642 in tracts with no fire hazard. Results are similar with fire damage: across high-damage tracts, the average is $101,924, compared to $79,661 in a tract that has not experienced any damaging fires. Conversely, incomes are lowest in communities with high fire experience. On average, communities that have experienced six or more fires since 1990 have a median income of $66,128, compared to $79,661 in communities with no fire experience and $100,063 in communities with 1–2 fires. The trend holds with block groups rather than tracts: the highest-experience block groups average $60,266 in median household income, compared to $82,679 for those with no fires and $101,412 for those

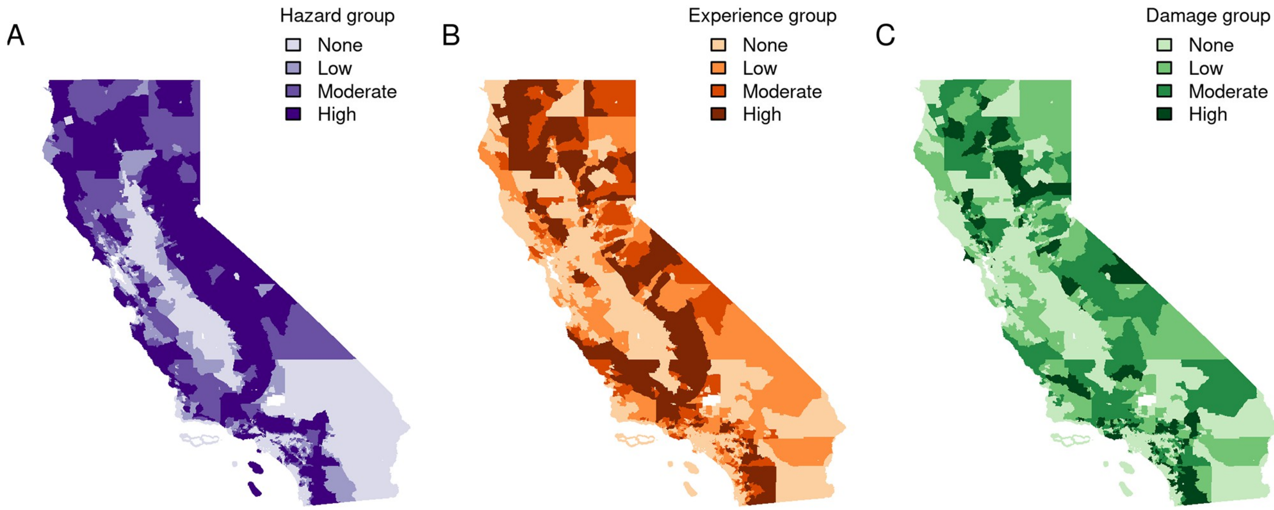

Fig 1. The geographies that appear at risk differ based on hazard, experience, or damage. (A) Hazard: census tracts are color-coded based on the share of residences in Cal Fire-designated fire zones within the tract. A fire zone is any area with moderate, high, or very high fire hazard, in either local or state responsibility areas. None denotes zero properties in a fire zone, low is up to 25%, moderate is 25–75%, and high is over 75%. (B) Experience: census tracts are color-coded based on the number of fires that have affected residential property within them between 1990 and 2019. To be counted, a fire perimeter must include residential property; fires that do not contain any residential property within it are not included in this count. Properties within fire perimeters may or may not have been damaged by the fire. None denotes zero fires within the tract, low is 1–2, moderate is 3–5, and high is six or more. (C) Damage: census tracts are color-coded based on the single most damaging fire experienced between 1990 and 2019, as defined by the number of residential properties within a single fire perimeter. None represents no properties, low is 1–10 properties, moderate is 11–100 properties, and high is over 100 properties. Base layer for all three maps is from the US Census Bureau (https://www.census.gov/programs-surveys/geography/technical-documentation/user-note/tiger-geo-line.2019.html).

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with 1–2 fires (Fig A in S1 Appendix). The differences between the three metrics also persist when examining other indicators of financial resources such as assessed property values (Fig B in S1 Appendix). Alternative groupings, including the distribution of incomes at every level of fire experience, from 0 to 21 fires, are shown in Figs C and D in S1 Appendix.

Conclusions about the overlap between fire risk and low-income populations depend on the metric. Of the tracts that are high hazard, 11% are in the bottom quintile of income, and 33% are in the top quintile in income. However, with fire experience, the pattern is the opposite: 34% of high-experience tracts are in the bottom income quintile, and 8% are in the top quintile, indicating that fire experience is skewed toward communities with lower incomes.

While incomes differ sharply between high-hazard and high-experience communities, the pattern for racial composition is less varied (Fig E in S1 Appendix). The average share of the population that is white increases with fire risk for all three metrics. High hazard, experience, and damage tracts average 79%, 83%, and 80% white, respectively. This pattern in part reflects the concentration of non-white populations in urban centers with low fire risk.

The trajectory of real estate prices provides another window on the way that communities evolve with respect to different dimensions of fire risk. Property values are known to be sensitive to the effects of fire shocks, at least temporarily. It is difficult to discern the cumulative effects of repeated exposures to fires because communities with high fire frequency generally do not have 15 fire-free years, followed by 15 years of experiencing fire. Rather, effects would likely emerge and grow over time, with less of a clear time-delineated shock.

From 1990 through 2019, home prices have appreciated more in communities with no fire experience than in communities with high fire experience (Fig 3). Among the no-experience tracts, property prices increased by a factor of 2.91 (median; mean = 3.01) over that time period. In contrast, among tracts with six or more fires from 1990–2019, the median price

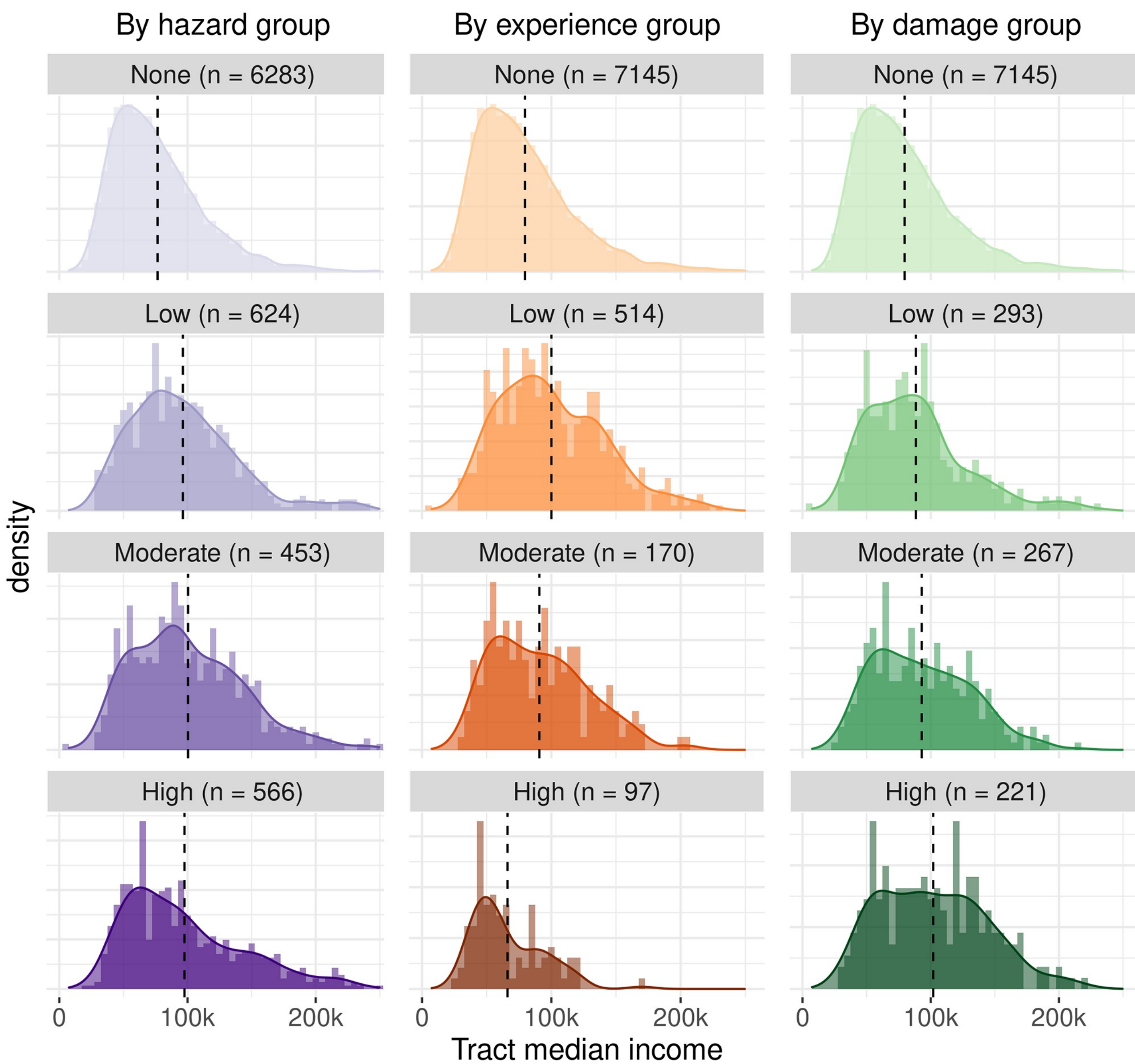

Fig 2. The relationship between income and fire risk varies across indicators. When categorized by fire hazard or fire damage, median incomes are steady or increase with higher risk. However, communities with high fire experience average lower incomes than communities with low or no fire experience. Histograms show distribution of census tracts by metric, and dashed lines show group means. *n* denotes the number of census tracts in each group.

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appreciation was 2.34 (mean = 2.35). The gap between the two sets of communities has emerged in particular over the 2010–2019 time period. The discrepancies in property value appreciation persist when considering only tracts with high fire hazard: among that subset, those with no fire experience saw prices grow by 2.77 times, and those with six or more fires grew by a factor of 2.31.

We conduct several additional comparisons to further examine how price appreciation relates to fire incidence. We identified a set of 13 "recent fire" tracts with most of their fire experience in the past decade: four or more fires from 2010–2019 and three or fewer from 1990–2010. We refer to this group as the "recent fires" group. This group's home price

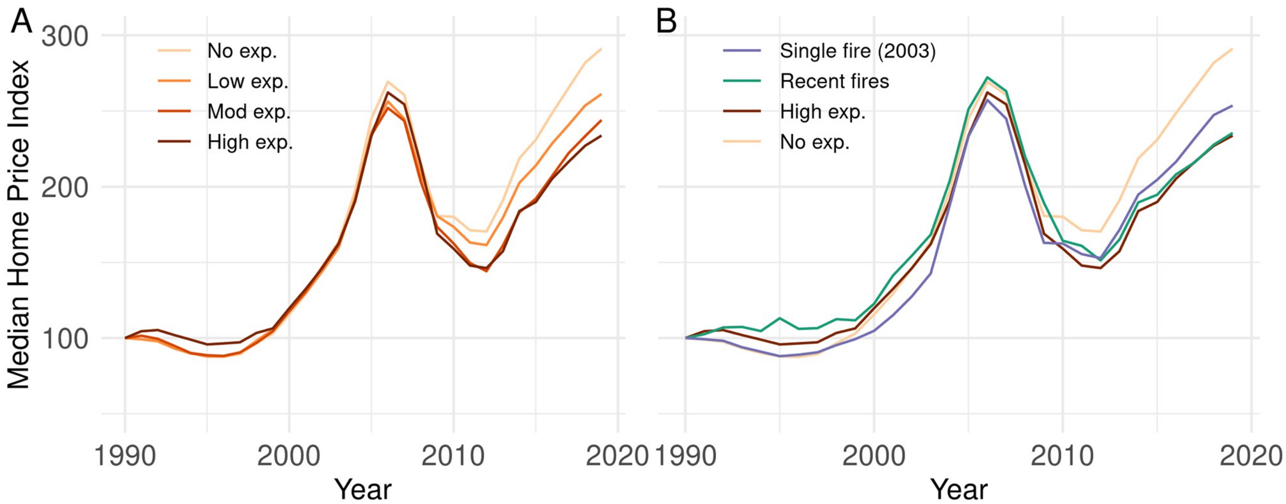

Fig 3. Property prices have appreciated more slowly in communities with high levels of fire experience. (A) HPI values over the last 30 years for communities with different levels of fire experience. Lighter shades indicate less fire experience. (B) HPI values among four groups: tracts with no fire experience, tracts with high fire experience, tracts with a single damaging fire in 2003, and tracts where most of their fire experience has occurred in the last decade.

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appreciation closely tracks that of the communities with no fire experience until the late 2000s, with prices dropping farther during the recession and growing more slowly after that (Fig 3, green line).

As a final comparison group, we examine tracts that experienced a single severe fire that affected over 100 homes within the tract. To enable straightforward comparison, we include ten tracts where this single fire occurred in 2003. The trajectory of their home price indices is shown in Fig 3 (purple line). While this group shows slower growth in the 1990s and early 2000s, their price growth has outpaced both sets of communities with higher fire frequency since then. In conjunction with other findings that the negative effects of a fire shock dissipate over time [5], this trend suggests that the current differences among groups with different fire frequencies are not due to the long-term shocks of a single event.

We use the differences in property value appreciation as a way of exploring the consequences of high fire experience. This calculation is based on the concept that the substantial differences in property values across fire experience categories are due to fire-induced differences in annual price increases that have accumulated over time. However, many factors influence property values beyond fire incidence, and we do not aim to isolate the impacts of fires here.

Grouping all tracts based on the fire experience in their tract (as in Fig 3), the median annual growth rate from 1990 through 2019 was 4.38% among high experience tracts and 4.77% among tracts with no fire experience. The approximately 182,900 single-family homes and condominiums in high-experience tracts comprise $41.9B in assessed value as of 2017. In a year in which they appreciate at 4.38% rather than 4.77%, those homeowners accrue approximately $165M less in property value. Over the 2010 to 2019 period, median growth rates were 4.35% for the high-experience group and 5.85% for those with no experience; using those appreciation rates, the annual difference increases to $630M. These estimates are based on assessed values, which are often lower than market values in California.

In comparison, the annual losses from wildfires as documented by Cal Fire range from the hundreds of millions in relatively low-loss years ($148M in 2016, $404M in 2019) to the billions in severe years—the Camp Fire alone represents about $12B in losses [22]. These loss estimates are based on the cost to replace the property and contents damaged or destroyed by fire, smoke, water, and overhaul. They do not include suppression costs or indirect loss, such as reductions in property value or business interruption losses. Thus, the indicative magnitude of differences in property value appreciation are comparable to direct losses in years without catastrophic fires but much less than direct damages from the most destructive fires.

Projections under future climate change

Fire models project substantial increases in wildfire incidence in California across most climate models and emissions scenarios, increasing the number of people at risk and the number of communities likely to end up with high-fire experience. We consider two sets of census tracts at risk of moving into the high-experience category by 2070–2099. These "transition tracts" include those currently categorized as moderate experience (3–5 fires from 1990–2019) where fire frequency is projected to double, and those currently categorized as low experience (1–2 fires from 1990–2019) where fire frequency is projected to triple by the end of the century. We identify transition tracts under four scenarios: warm/dry and cool/wet climate models, and medium (Representative Concentration Pathway (RCP) 4.5) and high (RCP 8.5) emissions scenarios. A warm/dry simulation with medium emissions results in 47 transition tracts by the end of the century, representing 82,490 single-family home and condominiums. 30 of the 47 census tracts are currently in the low experience category.

The location and number of transition tracts vary across climate models and emissions scenarios. 11 tracts, all in the northern half of the state, meet the requirements for transition tracts in all four future scenarios examined (Fig 4). They comprise over 20,000 residential properties.

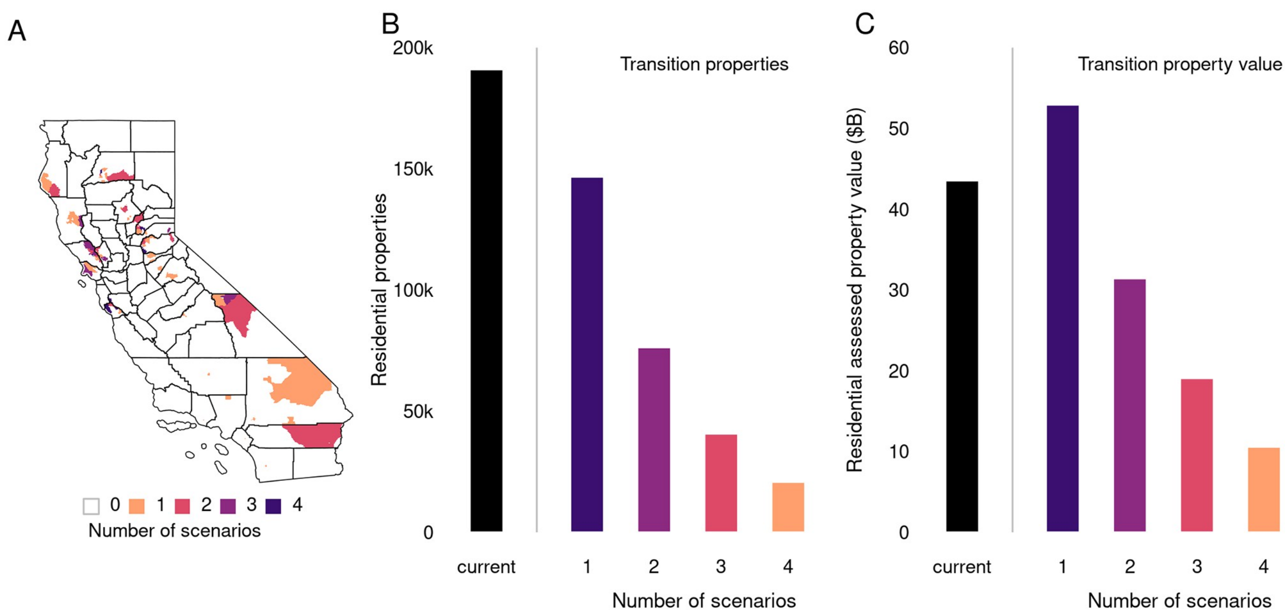

Fig 4. Wildfire projections indicate substantial increases in fire incidence across California, with census tracts across the state at risk of transitioning into areas of high fire experience. (A) Census tracts are shaded based on the number of future realizations in which they are counted as "transition tracts." Base layer is from the US Census Bureau (https://www.census.gov/programs-surveys/geography/technical-documentation/user-note/tiger-geo-line.2019.html). (B) Changes in fire incidence increase the number of properties likely to experience higher fire frequency. The number of properties in transition tracts is projected to increase under all future realizations, ranging from an additional 20,738 properties in all four scenario/model combinations to 146,688 in at least one scenario/model combination. (C) The amount of property value exposed to frequent fire experience is projected to increase. Properties assessed at $19.1B are projected to transition into high-experience areas under three of four future scenario/model combinations examined.

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24 tracts are at high-risk for future increases in fire experience in three of four future scenarios, 44 tracts in two or more, and 86 tracts in one or more. Increases are more widespread in the higher emissions scenario, especially with the warm/dry model (Fig F in S1 Appendix). The cool/wet, medium emissions scenario results in only 15 transition tracts, whereas 63 tracts are projected to transition into the high-experience category under the warm/dry, high-emissions scenario.

Discussion

Wildfire risk has many dimensions, and metrics provide different lenses on who and what is at risk. Considering fire history, including relatively smaller, less-damaging fires, adds information that strongly distinguishes between communities with similar levels of fire hazard. Communities with high levels of fire experience, on average, have lower incomes and lower property values than communities with high hazard levels based on FHSZ maps and communities that have previously experienced rare, damaging fires. The mismatch indicates that considering fire experience in prioritizing fire prevention and suppression investments can potentially contribute to a more equitable distribution of public resources.

There are two potential explanations for this pattern. First, repeated fire exposures, even to small events, may have a cumulative impact on incomes and property values [13]. Under this scenario, repeated fires drive a change in communities over time, ultimately yielding the outcomes we observe today. Our results show that home prices in communities that have experienced a single severe fire do not show the same long-term trajectories as communities experiencing frequent fires, suggesting that the pattern is not the consequence of a single event. A second potential explanation is that investments in fire prevention and/or suppression can be unequal, leading to wealthier communities being better protected and less likely to experience a fire [23]. An analysis of fire suppression indicates that fires are more likely to stop spreading in areas where property values are higher [19]. The actual explanation likely has elements of both possibilities, with fires negatively affecting community financial and political capital, which in turn decreases investments in fire mitigation and increases the likelihood of another fire.

The strong patterns linked to fire experience highlight the benefits of considering multiple dimensions of risk in delineating need for fire-related assistance and adaptation, rather than primarily based on FHSZ maps or single extreme events. FHSZ maps are valuable tools for identifying and communicating geographic differences in fire risk, and large, damaging events of course require response and recovery investments. However, less-newsworthy fires—especially repeated ones—may also have social and economic consequences that are often overlooked. Fires with substantial impacts on mental health or local economies may not appear extreme on other metrics, such as area burned, duration, or physical damage [24]. Considering the full range of impacts in resource allocation is necessary, especially for socially vulnerable communities that are more susceptible to negative effects of fires. Cal Fire has already recognized this need, using socioeconomic characteristics in its criteria for setting priorities in its Community Wildfire Prevention and Mitigation Report in 2019.

Isolating the effects of a long-term feature of a community, fire experience, is challenging. We use three decades of fire events to define communities' fire experience. The finding that communities with more recent fire experience have had their property price appreciation slow in more recent years suggests that three decades is a suitable window for this analysis. Nonetheless, fire incidence has a random component, so tracts could be designated differently based on fire histories covering different time spans, leading to different income and property value results. Our results do not necessarily point to what happens when communities transition from low-experience to high-experience areas, nor do they necessarily indicate the benefits from transitioning to a high-experience to low-experience area.

Future-oriented assessments are also uncertain due to wildfire projections, the role of housing and infrastructure expansion, and land and fire management policies [21]. Wildfire projections are inherently uncertain, which is clear from the divergence between the fire record observed over the last thirty years and the modeled fire estimates for the same time period. To minimize the effect of this uncertainty, we use the rates of change between the models' current and end-of-century outputs, rather than the absolute numbers of modeled fire months. However, our results for the areas that may transition into high-experience areas are sensitive to specific data processing choices (Figs F and G in S1 Appendix). In addition, continued housing development in the wildland-urban interface increases the likelihood of human-started fires and the probability that fires occur near where people live [25].

Additional research is needed to better understand the relationships between a fire's characteristics and its societal impacts. We use residences within fire perimeters as our definition of magnitude, but a variety of other metrics may also be useful. For example, mental health impacts may be associated with how quickly a fire grew or extent of news coverage, whereas burned area may be particularly important for communities with a strong reliance on natural resources. Our definition of "fire-affected" tracts relies on the accuracy of the fire perimeter boundaries from Cal Fire and the locations of residential parcels according to CoreLogic, and slight differences in the boundaries can lead to classification errors about which parcels were within the perimeter of a given fire.

Our analysis reinforces the added value of examining the full spectrum of historical fire events, their impacts, and their overlap with dimensions of social vulnerability. Small fires may be affecting communities through a variety of mechanisms, including loss of natural resources, health impacts, or changes in economic opportunities [26]. At the same time, relatively small fires can also be beneficial, reducing fuel loads or creating fuel breaks that reduce the likelihood of catastrophic fires. Understanding the range of direct and indirect effects from fires can help navigate potential trade-offs.

More broadly, an emphasis on the most severe extreme events is common across climate hazards. These are clearly important, but other dimensions of damage can arise from repeated exposure to small floods or minor heat waves. Wildfire in California is a good test case for impacts of repeated but more modest extremes, based on records that contain footprints for relatively smaller events. In contrast, small floods are rarely documented. When they are documented, they are recorded at the county level, likely masking sub-county variation in experience. Future research could examine whether the disparities that we identify here are common to other hazards and other geographies.

Wildfire risk is a long-term feature of California, but the risk is rapidly changing [21, 27]. Adapting to it successfully will require additional research to understand the diverse impacts of fires, including consequences of repeated fires. Key questions include the influence of historical fire experience on the perception of risk and variation in fire impacts across communities with different socioeconomic and demographic characteristics. As patterns of fire risk evolve, being able to respond effectively will rely in part on understanding the heterogeneity in impacts across communities and the effects of fire size, severity, and recurrence intervals. Such evidence is urgently needed to prepare communities of all types for the wildfire risk they face today and in the future.

Supporting information

S1 Appendix. Additional figures and maps.
(PDF)

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