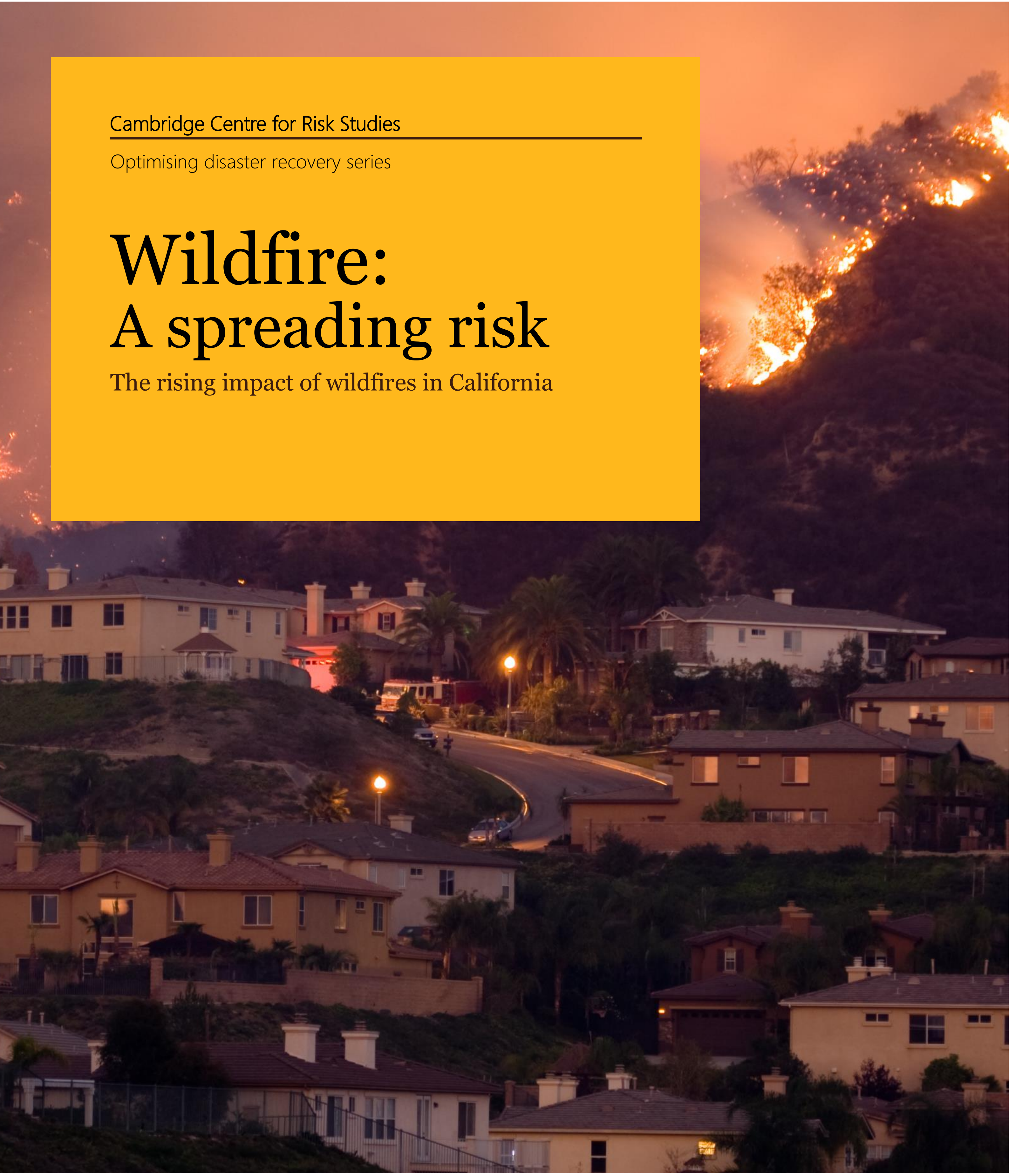

Cambridge Centre for Risk Studies

Optimising disaster recovery series

Wildfire: A spreading risk

The rising impact of wildfires in California

Centre for **Risk Studies**

UNIVERSITY OF CAMBRIDGE
Judge Business School

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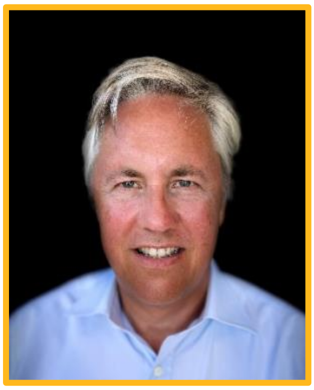
Foreword



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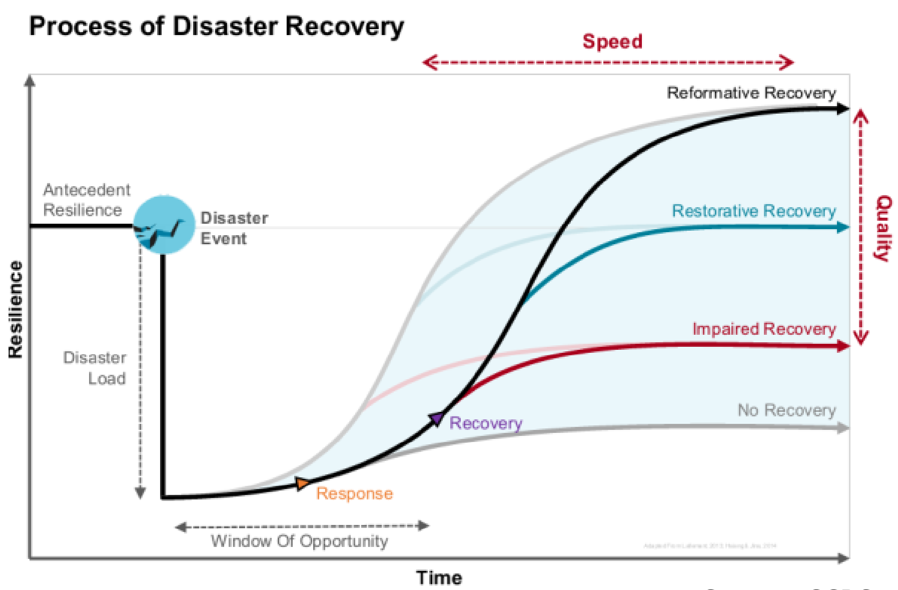
Wildfire is a naturally occurring phenomenon, often an important part of a natural ecosystem; helping to keep vegetation growth in check, restoring soil or helping with seed dispersion and germination. As the climate evolves, populations continue to expand and urban areas keep growing, the intersection between this natural event and society is changing and creating a peril that is increasing in impact to rival hurricanes and earthquakes.

For this study we asked the Cambridge Centre for Risk Studies (CCRS) to focus on the peril of wildfire in California, building on their previous studies into resilience, recovery and the role of (re)insurance. The devastating fires in Los Angeles (LA) in January emphasised the need to better understand the peril to better protect people and property in a rapidly changing environment in terms of both hazard and exposure offset by stricter building codes.

The role of (re)insurance, immediately injecting billions of dollars of non-recourse funding to families and businesses in a structured way, is the best way to get people back on their feet quickly and, hopefully, in a better state ready to face future events – a reformative recovery.



Source: CCRS

The 2020 Cambridge report, "Optimising Disaster Recovery", showed that every 1% increase in insurance penetration (non-life premiums divided by a country's Gross Domestic Product or 'GDP'), reduced time of disaster recovery by 12 months – except for the US. Unfortunately, despite high levels of insurance penetration in California (outside of earthquake insurance) CCRS noted that disadvantaged or lower income communities were at greater risk of longer term, adverse impacts on population and GDP. They found that the town of Paradise in Butte County, California suffered a 20% decline in GDP growth following the devastating Camp Fire in 2018. We will follow what happens after the more recent fires in Eaton and Palisades with the different socio-economic profiles of the two areas in future reports.

A Fast Evolving Risk

In the (re)insurance market, when we look at the impacts of physical risk associated with a changing climate we break this down into; hazard, exposure and vulnerability, recognizing the importance of understanding changes to all these aspects. Exposure growth (which includes the ongoing impact of inflation) is normally the leading factor increasing catastrophe-related losses in the near term, with hazard change, all other things being equal, increasing catastrophe-related losses incrementally over time.

With wildfire, the hazard change is clearly happening at a much faster rate, driven by a number of factors. The last 10 years are the hottest on record since 1850 and this heat dries out vegetation creating fuel for fires. Changing rainfall patterns, sometimes encouraging excessive vegetation growth followed by drought, along with an extension of the wildfire season and increase in the number of "fire weather" days, are creating an environment much more conducive to wildfires, with the number of properties recently destroyed in California alone increasing by a factor of 13 compared to 2017 levels.

Wildfire is considered a secondary peril by the insurance industry but, to our mind, there is a significant difference in terms of potential damage, in addition to model deficiency relating to extreme or tail events for this peril. Put simply, we consider wildfire to have an equivalent potential to a major hurricane or earthquake and the models do not currently reflect this. Since the 2016 Fort McMurray fires in Canada, we have seen the peril attach to and exhaust multiple nationwide programmes and far exceed vertical limits purchased by regional carriers. This demonstrates the dangers of relying on models that underestimate extreme events. This impacts risk appetite, pricing, aggregation and the amount of cover purchased by (re)insurance companies.

The very clear hazard change signals are in addition to the rapid exposure growth we are seeing in the Wildland Urban Interface (WUI), which CCRS estimate as 10% of land in the US but including almost 40% of the housing, including 1 in 3 houses in California. The charts from CCRS clearly show that any expansion of Los Angeles and San Diego can only really come from building in high hazard zones presenting a planning and (re)insurance problem for the future.

Mitigation

We have adverse trends for hazard and exposure but there is a meaningful offset from more stringent building codes, specifically the California Building Code (CBC) Section 7A issued post 2008. CCRS's review of FEMA literature found that houses built to code were almost three times as likely to survive a fire and that future savings on structures built to code would be $24bn over 75 years for residential property or $325m annually. This echoes our previous collaboration with CCRS, albeit focused on hurricane losses, which also showed the pre-disaster planning and preparedness by FEMA saved $16 for every $1 invested in risk mitigation.

There is rapid exposure growth in California's insurer of last resort, the Fair Plan, which is up 42% since September 2024 and up almost 300% since September 2021. Recent growth in the excess and surplus (E & S) lines market for the usually admitted line of residential risk is also a symptom of the problems the market is facing. Inadequate pricing makes it unsustainable for insurers to keep offering covers, jeopardizing the pivotal role (re)insurance plays in disaster response for families, communities and businesses. Allowing insurers to use risk-based pricing to assess and price risk will ensure a more robust and sustainable insurance market.

We very much value our association with CCRS and their series of reports on Disaster Recovery and Disaster Resilience. With the climate changing and exposure continuing to grow in areas of high risk, understanding the value of the (re)insurance industry and its impact in disaster recovery and ongoing resilience is a critical part of ensuring ongoing societal resilience.

Executive summary

On 7 January 2025 the Palisades and Eaton fires started in Los Angeles County causing the tragic loss of 28 lives. More than 18,000 structures were destroyed, and economic damages are, at the time of publication, variously estimated as greater than USD 52 billion, of which over 70% was insured. Intensified by strong Santa Ana winds, dry conditions due to climate change, and growing exposures from urban expansion and housing sprawl into areas of high wildfire risk, the destruction caused by these fires has placed wildfires as a catastrophe hazard requiring greater attention and consideration, raising their threat profile as they become more destructive, similar to hurricanes. The combined loss fell just short of Hurricane Harvey in terms of insured loss, placing Palisades/Eaton in the top 10 largest catastrophe losses in the US, adjusting for inflation.

This report explores the growing risk of wildfires by focusing on California. We analyse recent statistics, looking at the effects of climate change and urbanisation, the time to recover and the impacts on population and local GDP when wildfires strike, the role of building codes to reduce losses, the impacts on poorer communities and the response of the insurance industry and regulators. The key headlines of this paper are:

- Extreme wildfire rates have more than doubled globally.[1]
- In California there has been a step change in area burned (16x), properties damaged (13x) and economic losses (50x) from 2017 onwards compared to the previous 36 years.
- The Camp fire (2018) was followed by a 20% reduction in the annual rate of GDP growth in Butte County and a significant and lasting decline in population, massively affecting the entire town of Paradise, CA.
- Urban development and sprawl in California is spreading at the fastest rate into areas designated with the highest fire hazard severity risk. Most of the land of the Wildland-Urban Interface is designated as "very high" risk at 54.6%, an additional 32.7% is "high" risk, and 12.7% "moderate" risk.
- The "high risk" designation often surrounds major metropolitan areas of California, leaving cities with little room to expand, other than into the highest wildfire risk areas.

[1] Extreme fires are those above the 99.99 percentile of fires globally measured by their Fire Radiative Potential (FRP) level from MODIS satellite observations. Over the 21 years from January 2003 to November 2023 there were 2913 extreme fires according to: Calum X. Cunningham, Grant J. Williamson, and David M.J.S. Bowman, "Increasing frequency and intensity of the most extreme wildfires on Earth", *Nature Ecology & Evolution* 8, no. 8 (2024), pp. 1420 – 1425.

- Fires can devastate regions and are hard to recover from. Nightlight analysis of the Woolsey fire in November 2018 that affected Los Angeles and Ventura counties shows that the area had not recovered 2 years after the fire.
- Strong building codes reduce damages. Studies show that properties built to Chapter 7A code are 2.8x more likely to survive a fire.
- Insurance penetration in California had been falling until the major wildfires in 2017-18 and has since grown rapidly.
- The number of policies in the FAIR plan has grown 4.3x since 2014 as insurers have withdrawn from high-risk zones.
- Forward looking Catastrophe models will be allowed in California to be used in setting premium rates for wildfire covers – a welcome step towards wider risk-based pricing

The following summary describes the major statements in the report which contains the full analysis and results.[2]

Climate change so far and in the future

Hot dry and windy conditions known as "Fire Weather" create an ideal environment for wildfire formation. Studies show that the season length for fire weather may have increased by 20% in multiple regions globally, potentially increasing the number of fires that can form. As global average annual temperatures rise, this leads to warmer weather in every season, which prolongs the duration of the wildfire season, and increases the intensity of events. Climate change adversely affects the Vapour Pressure Deficit (VPD), which measures atmospheric dryness: higher VPD creates conditions more favourable to ignition and rapid fire spread, and VPD is expected to increase with climate change. California's seasonally dry climate lends itself to wildfires, as rising temperatures, and prolonged droughts are leading to increasing risk and intensity for the occurrence of wildfires. In California, climate change may reduce the formation of Santa Ana winds which fans the flames – but *not* at the peak of the wildfire season, so major fires are still expected and will likely be exacerbated by other climate change effects.

Additionally, the WUI is the unique ecological zone where human settlement and natural vegetation, such as grassland, shrub vegetation, and forest, mix. As this zone has expanded through increasing urban sprawl and growth, and as it has been identified as risk factor for wildfires, research and discussion of wildfire risk has concentrated on analysis of the WUI. Research has focused on various methodologies for mapping and identifying the WUI, which approximately covers 10% of land in the US, but has 39% of houses. Additionally, the WUI area has expanded by 33% between 1990 to 2010, accompanied by a 41% increase in the number of homes. Approximately 1 in 3 Californians (14m) live in the WUI. As the WUI has expanded

[2] For brevity, this summary does not include citations. The following statements come from a mixture of Centre for Risk Studies original research and a deep literature review of academic, press, and industry publications. Please see the main body of the report for citations and the bibliography.

in California from growing housing developments, the wildfire risk has also expanded. This study finds that the majority of the WUI in California is now designated as "very high" risk, at 54.6%, with "high" risk zones covering 32.7% of WUI land area, and "moderate" risk at 12.7%. Hence, the large and expanding size of high hazard zones is a material driver for increasing risks.

As climate change continues to accelerate with rising global average temperatures, and 2024 being the hottest year on record according to Copernicus Climate Centre, this continues to impact the catastrophe exposures facing the re/insurance industry. The hottest 10 years globally since 1850 occurred in the last decade. Wildfires are becoming larger, more deadly and more destructive with climate change being a major cause. For 11 key states in the US, the area burned jumped from 1.69m acres from 1984-2000 to 3.35m acres between 2001 and 2018. California is considered a very high-risk state for wildfires and 15 of the top 20 most destructive fires in California since 1950 occurred from 2010.

Urbanisation and fire hazard

The area burned by wildfires in California has increased materially since 2017. A step change in the number of buildings destroyed has occurred since 2017, where the annual average from 2017 to 2024 is over 13,000 buildings destroyed, and the annual average for the years from 1979 up to 2016 was under 1,000. Similarly, a step change is observed in the estimated total amount of direct economic damages, including buildings destroyed, businesses lost, and damage or destruction of public infrastructure; see figure E1 which adjusts direct economic damage by inflation.

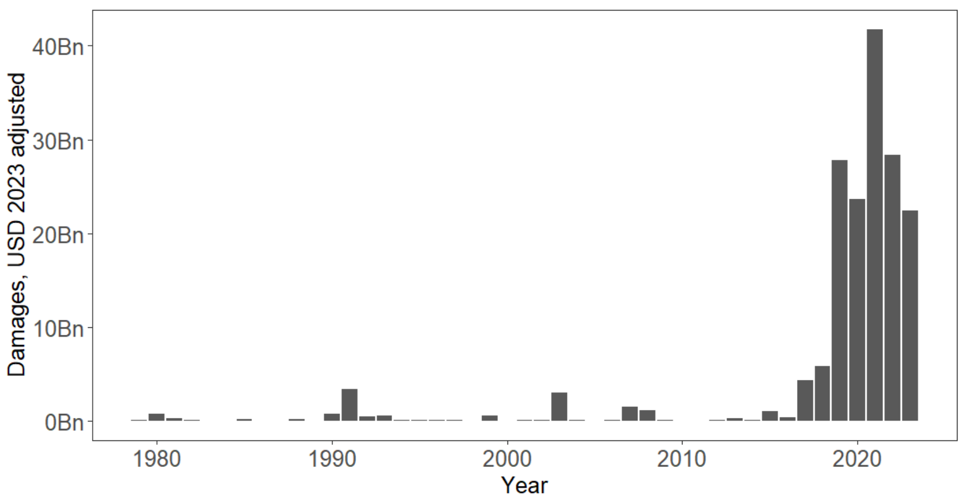


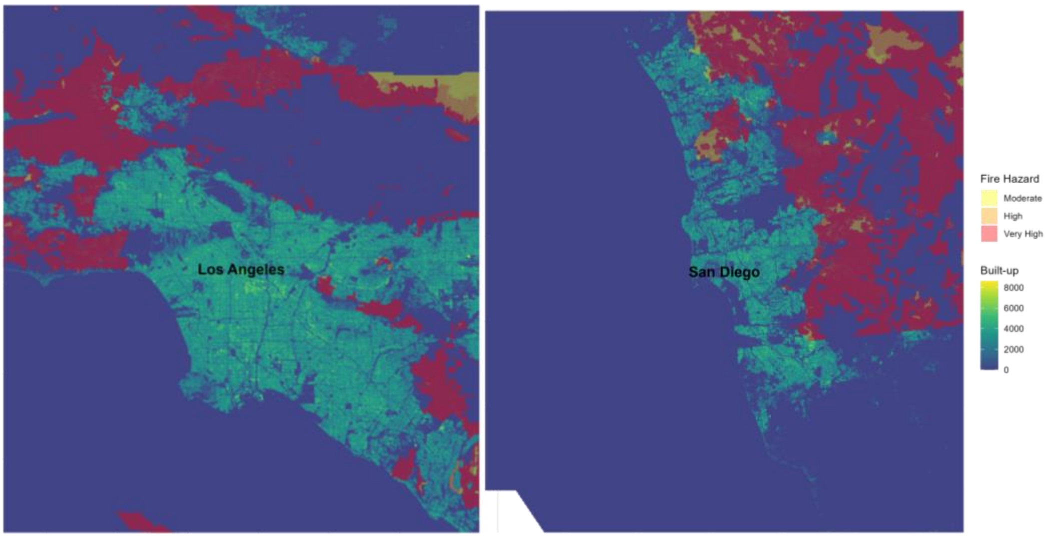
Figure E1: Annual aggregate economic damage estimates by year from wildfires in California, 1979 – 2023, adjusted to 2023 USD.[3]

[3] CCRS analysis from data taken from Cal Fire Damage inspection dataset, and National Oceanic and Atmospheric Administration, Climate at a Glance datasets. 2025.

From 2000 to 2020 the growth rate of urbanisation into the "very high" Fire Hazard Severity Zone (FHSZ), as assessed by the California Department of Forestry and Fire Protection (Cal Fire), was higher than the rate in "moderate" and "high" risk zones. Urban growth in these three severity zones had slowed by 2020, compared to 2000-2015. It is notable that the reduction in growth occurred after the 2017/2018 extreme fires, although we have not carried out a causation analysis. Findings show that urban growth into high severity zones extends from the urban sprawl of large metropolitan areas regardless of fire hazard risk warnings, since the surrounding area of the largest cities in California are designated with the highest fire severity risk. This is illustrated from figure E2, which shows the highest level "very high" risk fire hazard severity around the metropolitan areas of Los Angeles and San Diego. Hence, urban growth and sprawl in these two major metropolitan areas is effectively forced into areas of the highest wildfire risk.

Social and economic impacts

There is a statistically significant and lasting loss in population in Butte County that was caused by the deadly Camp fire in 2018 as shown in figure E3. In fact, we find that 50 out of 58 counties in California have seen their population growth trajectory negatively affected by the largest wildfire for that county; see, for example, figure E3 which shows the drop in population of Butte County following the 2018 Camp fire. Counties that are less affected are the more urban counties of southern and coastal California, while rural and less populated areas with a significant WUI component are more significantly affected by population and GDP loss from wildfires. Consistently, counties with a higher GDP per capita see a lower population and GDP loss effect compared to poorer counties.



E2: Fire hazard severity zones and level of urbanisation (2020). Panel A: Los Angeles, Panel B: San Diego.[4]

[4] CCRS analysis of data provided by European Commission, *Global Human Settlement Layer Data Package 2023,* and the Cal Fire. (2023). *Fire Hazard Severity Zones (FHSZ) [GIS dataset]*.

Our analysis shows that the Camp fire caused a 20% reduction in GDP growth in Butte County. The Tubbs and Valley fires reduced GDP growth by 4% and 6% respectively, having less of an impact compared to the Camp fire, even though the Tubbs fire caused significant destruction of homes and structures in the town of Santa Rosa, Sonoma County. We do not see a clear GDP impact trend in the more southern highly urban counties and believe that this is due to the large size of their GDP compared to the fire effects.

Research shows that disadvantaged communities are more affected by wildfires than the average, with one study finding that homes in disadvantaged areas are 29% more likely to be destroyed by wildfires. Other analysis has shown that less firefighting resources are allocated when wildfires strike poorer communities and health effects from wildfires unevenly affect poorer communities.

Rates of recovery

To observe the rate of recovery for local communities after a wildfire, we have carried out an analysis using nightlight luminosity based on satellite image data observing the area around three wildfires. Using lights as a proxy for human development and economic activity, we find that economic activity of affected towns and communities fell significantly after wildfires, and that subsequent rates of recovery vary substantially. In the case of the Woolsey fire (2018), there was no evidence of recovery 2 years after the fire. For the Camp fire (2018), it took 2 years to recover to former nightlight luminosity levels, but the area did not see growth in activity that has been observed in neighbouring areas which were unaffected by the fire. The Valley fire (2015) shows evidence of a much quicker recovery after 1 year. Observing rates of recovery for local communities after a wildfire demonstrates wide variation: while some communities recover quickly, some have slow recovery, and some never appear to recover at all.

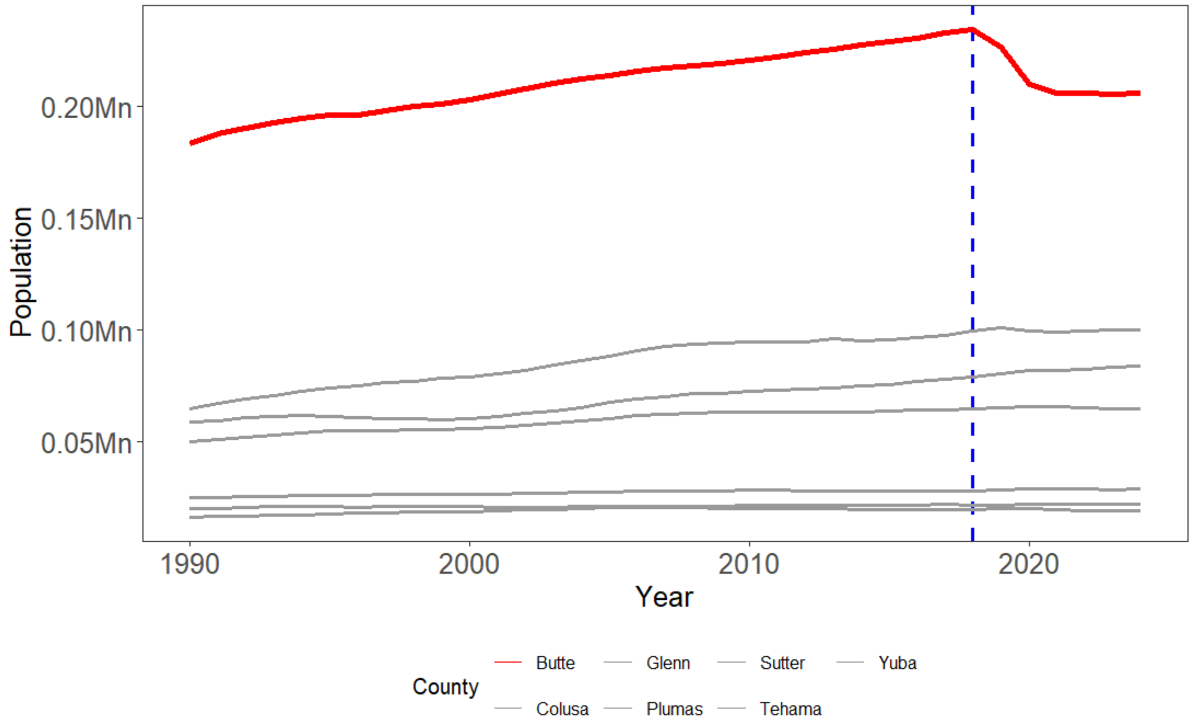


Figure E3: County-level population trends 1990 – 2023, around Camp Fire, 2018 .[5] *Grey lines refer to neighbouring counties.*

Building codes

California arguably has the strongest wildfire building codes in the world. Defensible spaces around properties have been a requirement since the 1960s. It appears that significant building code changes occur after major disasters:

- The Tunnel fire in Oakland 1991 led to multiple legislative changes requiring severity maps to be created and a requirement for ignition resistant materials to be used in high severity regions.
- The Cedar fire in 2005 likely encouraged the next major building code change – leading to "Chapter 7A" requiring a much larger defensible space around properties and stronger more fire-resistant materials.
- The Eaton and Palisades fires in 2025 may have expedited the adoption of the Wildland Urban Interface code and the introduction of the new ember-resistant defensible area "Zone 0" (see section 6.2) for all properties (including existing buildings)

Strong building codes reduce damages, for example a FEMA study suggests Chapter 7A building codes will save USD 24 billion over the next 75 years. Studies have found that the chance of property destruction is reduced by 30-40% for homes built after 1997. A different

[55] CCRS analysis from data provided by the US Census Bureau.

study found that in the Camp fire, 51% of homes built to the Chapter 7A standard survived compared to just 18% for homes built prior to this code. A survey showed that 80% of Californians would support stronger building regulations and 70% would support restrictions on building homes in high-risk areas.

Insurance impacts and response

Insurance loss ratios for homeowners policies in California peaked above 150% in 2017 and 2018, following major wildfires. The 2020 wildfires were still material, costing over USD 12 billion, but did not result in a similar peak, however, due in part to increases in premium rates, higher deductibles and insurers' withdrawal from some high-risk areas. Insurance penetration (homeowners premiums written divided by GDP) has risen by 16% from 2013 to 2024 due to several factors. Penetration had been falling until the fires in 2017 and then began to sharply rise. We have carried out case studies of two major fires since 2018 and find that insurance penetration rose even faster in counties neighbouring those affected by the fire, suggesting societal response to near misses.

Following the major fires of 2017, 2018 and 2020 many insurers have reduced their exposure or exited the state. Regulators have responded by banning non-renewals – where a company offering fire insurance in California declines to extend policies at the end of their annual cycle – for one year from January 2025 but also allowing the use of forward-looking catastrophe models in the calculation of premium rates for the first time. By allowing risk-based pricing they hope to encourage insurers to increase their capacity to protect the region. The FAIR plan is the insurer of last resort offering basic cover when local insurers cannot. The number of policies in the plan has risen 4.3x since 2014 with surges after the 2018 fires and again in 2022. To be able to meet payments arising from the 2025 fires, the FAIR plan will collect USD 1 billion in funds from authorised insurers in proportion to their market share. Up to 50% of this can be passed back to policyholders with the incumbent insurers picking up the balance. It seems likely that the plan will need to request further funds given the size of future claims.

Introduction and background risk analysis

On 7th January 2025 two wildfires began to burn. One starting in the Santa Monica mountains became known as the Palisades fire and the second in the San Gabriel mountains would be named the Eaton fire. Tragically, at least 28 people died in these fires and between them they destroyed over 18,000 structures. Estimates of the economic damages vary with a likely average at approximately USD 52 billion (omitting some very low or high estimates).[6] Economists have estimated an insurance loss of around USD 45 billion,[7] whereas the industry itself suggests lower estimates from USD 25 billion to USD 37.5 billion.[8] Time will tell the true cost, but whichever proves to be correct, these wildfires are very significant. In financial terms, the Palisades and Eaton events are the largest wildfire losses ever recorded in the United States, of a similar magnitude to each of the ten costliest hurricanes on record. These are true catastrophic losses to the (re)insurance industry in every sense.

This report explores the growing risk of wildfires to society, focussing on California. First, we summarise the scientific consensus on the impact of climate change to this hazard. Climate change exacerbates the risk and has the potential to increase the severity of events. Data from the last 50 years clearly shows a step change in impacts, including increases in area burned and the financial costs.

Second, we look at the evolving fire risk across the state based on the increase in vulnerabilities and exposures. Using fire hazard severity zone mapping, along with geospatial urbanisation data over time, we track how urban growth and sprawl across California is leading to higher exposures due to increased settlement into areas that are at high risk of wildfires. Analysis shows that it is often the case that housing developments are pushing into high wildfire risk areas, not because they are ignoring the vulnerability to wildfires, but instead, because in many of California's metropolitan areas, the surrounding areas are designated with the highest fire severity risk. This trend suggests that future wildfires may be even more damaging because there will be more properties in high risk areas.

Third, we look at the long-run impacts of wildfires on social and economic trends. We look at the largest wildfire to affect each county of California and compare how trends in social and economic variables are affected by the occurrence of wildfires according to population and

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[6] Zhiyun Li and William Yu, "Economic Impact of the Los Angeles Wildfires," *UCLA Anderson Forecast*, March 3, 2025, https://www.anderson.ucla.edu/about/centers/ucla-anderson-forecast/economic-impact-los-angeles-wildfires#1; Aon, *Q1 2025 Global Catastrophe Recap*, March 2025, https://assets.aon.com/-/media/files/aon/reports/2025/q1-2025-global-catastrophe-recap.pdf.

[7] Li, Zhiyun, and William Yu. 2025. "Economic Impact of the Los Angeles Wildfires." UCLA Anderson Forecast.

[8] Sheri Scott, Nickolas Alvarado, and Daniel Quiñonez. (2025). *Industry Insured Losses for the Los Angeles Wildfires*. Milliman.

GDP loss. Findings show that the extent of the wildfire impact largely depends on the wealth or urbanisation of each county, where wealthier and more urban counties show less of an impact from wildfires, whereas poorer or more rural counties show significant impacts in population and GDP loss. This indicates a wealth disparity in the effect of wildfires on different communities, where poorer communities are more vulnerable to losses. This is related to the lack of ability for poorer homes or communities to invest in proper building material for wildfire protection, the lack of firefighters or local community prevention measures, and the network effects that come from individual home protection which either prevents further wildfire spread or facilitates further spread by acting as a fuel through which a wildfire affects an entire neighbourhood or community.

Fourth, we consider from the rate of recovery or rebuild in a community after a wildfire, which is to be distinguished from GDP impacts of wildfires. With previous analysis looking at the overall growth rate of urbanisation into higher wildfire risk areas over the past 20 years, and county-level analysis determining the extent of long-term damages from wildfires, our analysis looks at the rate of community recovery after a wildfire using monthly data. We use satellite images of nightlight luminosity data as a proxy for urban activity, specifically to infer the rate of recovery after a wildfire. Luminosity data is well-suited to this due to its high resolution (geospatial granularity) and monthly observations. Mapping the wildfire perimeter for three different wildfires, we compare the change in nightlight luminosity from pre-wildfire to post-wildfire to assess the rate of recovery. Findings indicate that there is widespread variation in community recovery; with some towns recovering back to pre-wildfire activity levels between six months to one year after a wildfire event, such as the Valley fire in Lake County, CA, others take up to two years to return to pre-wildfire levels, such as the Camp fire in Butte County, CA, and yet others that did not recover within two years, such as the area affected by the Woolsey fire in Los Angeles and Ventura Counties.

Our fifth section explores the impact of risk mitigation including a review of literature that explores the efficacy of building codes. We note that several studies find strong evidence that building codes established in the late 1990s and early 2000s have materially reduced the probability of property destruction.

In our final section we explore insurance effects. Insurance penetration in California was falling prior to the major 2018 wildfires but has since risen. However, capacity has declined, and the FAIR plan has bridged the gap.

The report concludes that wildfires are becoming a major catastrophic risk for society in general and for the financial industry in particular. Strong building codes and effective land planning are key to controlling the risks in future.

Section 1: Climate change and wildfires

Section 1.1 Background

As climate change continues to accelerate with rising global average temperatures, and 2024 being the hottest year on record, this is continuing to impact catastrophe exposures. It is broadly accepted that CO2 concentrations have now reached 422 parts per million, some 50% higher than the pre-industrial era with nearly 40% of the growth in the last 25 years alone. Sea levels are rising at double the rate now than most of the 20th Century.[9] The 10 hottest years globally have occurred in the last decade with 2024 having a global average temperature of 1.55 degrees above the pre-industrial average and already in excess of the Paris target.[10] The frequency of drought-and-heatwave events has doubled.[11] The frequency of more intense hurricanes has increased.[12] Multiple studies show that recent flood events were exacerbated by climate change.[13]

Climate change is also impacting the frequency and severity of wildfires and likely increasing the length of the seasons over which they occur in some regions. This section explores the impacts globally for this hazard and then focuses in on the United States and California.

Section 1.2: Global wildfire risk levels

Wildfire risks are increased by a changing climate in the following ways: increases in temperature driven by higher emissions leads to dryer vegetation compared to what has been seen historically, creating more fuel for fires. This excess heat creates more areas that are exposed to wildfire than what has previously been the case, meaning there is more fuel over a bigger area, creating the potential for more intense and larger fires.[14]

Wildfires are having a larger environmental, social and economic effect globally, as scientists and researchers have predicted, which is driven by climate change, human activity and land

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[9] Royal Society. 2024. *Climate Change: Evidence and Causes.;* NOAA Climate. 2024. *Climate Change and Global Sea Level.*

[10] The New York Times. 2025. *Global Temperatures and WMO Report.;* World Meteorological Organization. 2025. *WMO Confirms 2024 as Warmest Year on Record.*

[11] University of Oxford. 2025. *Climate Change Doubles Frequency of Concurrent Drought and Heatwave Events in Low-Income Regions.*

[12] Environmental Defence Fund. 2024. *How Climate Change Makes Hurricanes More Destructive.*

[13] Royal Meteorological Society. 2024. *Climate Attribution: Linking Extreme Weather.;* World Weather Attribution. 2025. *Extreme Weather Events and Attribution Science.*

[14] Royal Meteorological Society. 2023. *Wildfire: Causes, Impacts and Responses*. MetLink.

use.[15] Extreme wildfire rates have more than doubled globally also becoming more severe and covering a wider area.[16]

Wildfires are a feature of many natural ecosystems and have many positive benefits such as killing pests, encouraging seeds, thinning undergrowth and removing small trees.[17] Extreme wildfires are detrimental to society, because they remove ancient (carbon storing) trees, threaten life, cause harmful smoke and damage homes and infrastructure.[18] Climate change has increased the prevalence of such conditions.[19]

"Fire weather" describes conditions that increase the risk of wildfires, including warmer temperatures, low humidity and strong winds. Climate change is affecting fire weather.[20] Some studies suggest the fire weather season has lengthened by 20% between 1979 and 2013, especially in the Amazon, Australia, Canada, East Africa, Central Asia and North America.[21]

The size of the total burned area has also been increasing.[22] Area burned by fires has increased by about 5.4% p.a. since 2000. Such fires now result in an increase of 6 million hectares, or 8 million football pitches, of tree loss globally compared to 2001. Indeed, fire is now responsible for a greater proportion of global tree cover loss compared to drivers like mining and forestry, being 33% of the cause today compared to 20% in 2001.[23] Some 26-29% of forest loss globally between 2001 and 2009 was due to fire.[24]

In addition to climate change, land use changes can have a significant effect such as the move towards large plantations of more flammable non-native plants which led, for example, to ideal fire conditions in Greece in 2021 and 2023.[25]

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[15] IPCC. 2019. *Summary for Policymakers*. In *Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems*, edited by C.P.R. Shukla, J. Skea, E. Calvo Buendia, et al.; Pande, R., et al. 2023. "A Global Outlook on Increasing Wildfire Risk: Current Policy Situation and Future Pathways." *Trees, Forests and People* 14: 100431.; Center for Climate and Energy Solutions. *Wildfires and Climate Change*.

[16] Calum X. Cunningham, Grant J. Williamson, and David M.J.S. Bowman, "Increasing frequency and intensity of the most extreme wildfires on Earth", *Nature Ecology & Evolution* 8, no. 8 (2024), pp. 1420 – 1425.

[17] Royal Meteorological Society. 2023. *Wildfire: Causes, Impacts and Responses*. MetLink.

[18] Ibid.

[19] IPCC. 2022. *WGII Chapter 14: North America*.

[20] World Resources Institute. 2024. *Global Trends in Forest Fires.*

[21] Royal Meteorological Society. 2023. *Wildfire: Causes, Impacts and Responses*. MetLink.

[22] IPCC. 2022. *WGII Chapter 14: North America*.

[23] World Resources Institute. 2024. *Global Trends in Forest Fires.*

[24] Tyukavina, A., et al. 2022. "Global Trends of Forest Loss Due to Fire From 2001 to 2019." *Remote Sensing Time Series Analysis* 3.

[25] World Resources Institute. 2024. *Global Trends in Forest Fires.*

The Intergovernmental Panel on Climate Change (IPCC) has high confidence that the boreal forests globally such as in North America will see increased droughts, pest outbreaks and wildfires.[26] Pests such as the mountain pine beetle weaken trees and create more fuel for fires and warmer drier conditions increase their number.[27] The effects will be accentuated by increases beyond 1.5°C.[28]

Section 1.3: United States

The impact of wildfires on the western United States and Alaska has been significant in recent years.[29] It is estimated that anthropogenic climate change doubled the severity of drought in Northwest America from 2000 to 2020, soil moisture levels have been reduced to the lowest levels since the 1500s and studies indicate this accounted for 50% of the increase in burned area. An attribution study suggests that the burned area in a peak year increased by 7x to 10x due to climate change. [30]

In the Western US the amount of summertime rainfall is the biggest determinant of area burned.[31] Vapor Pressure Deficit (VPD) measures atmospheric dryness: it marks the difference between the moisture in the air and the maximum it could hold. High deficits encourage evaporation from soil and transpiration from leaves. Modelling suggests that increasing deficits have significantly increased fire activity in the western United States.[32] Forest management and fire suppression methods have also affected the level of fire risk compared to the past.[33] Suppression tends to lead to the build-up of vegetation that would normally be removed by smaller fires.[34] In turn this can lead to much more devastating fires when they finally take hold leading to calls for safe-burning practices.[35] From 1984-2000 the area burned over 11 states in the US was 1.69 million acres; this increased to 3.35m acres in the period 2001-2018.[36] Anthropogenic climate change has been shown to explain the increase of VPD

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[26] IPCC. 2019. *Summary for Policymakers*. In *Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems*, edited by C.P.R. Shukla, J. Skea, E. Calvo Buendia, et al.

[27] Centre for Climate and Energy Solutions. *Wildfires and Climate Change*.

[28] Ibid.

[29] USGCRP. 2017. *Climate Science Special Report: Fourth National Climate Assessment, Volume I*, edited by D.J. Wuebbles, D.W. Fahey, K.A. Hibbard, et al. U.S. Global Change Research Program.

[30] Royal Meteorological Society. 2023. *Wildfire: Causes, Impacts and Responses*. MetLink.

[31] NASA. *Wildfires and Climate Change*.

[32] USGCRP. 2017. *Climate Science Special Report: Fourth National Climate Assessment, Volume I*, edited by D.J. Wuebbles, D.W. Fahey, K.A. Hibbard, et al. U.S. Global Change Research Program.

[33] IPCC. 2022. *WGII Chapter 14: North America*.

[34] Hu, T., et al. 2024. "Impacts of Forest Fire Management on Risk in Boreal China." *Ecological Indicators* 169: 112806.

[35] Kreider, M.R., et al. 2024. "Fire Suppression Makes Wildfires More Severe." *Nature Communications* 15: 2412.

[36] National Integrated Drought Information System. 2024. *Study Shows Climate Change Main Driver of Increasing Fire Weather in Western U.S.*

since 2000 and to be the dominant cause of the increase in wildfire risk. The increase in VPD is expected to continue leading to more frequent and more intense wildfires in the Western United States.[37]

Figure 1.3.1 from Dennison et al. clearly illustrates a rising trend in large fires in almost all areas of the United States since the mid-1960s.[38] In the US the 10 years with the largest area burned have occurred since 2004.[39]

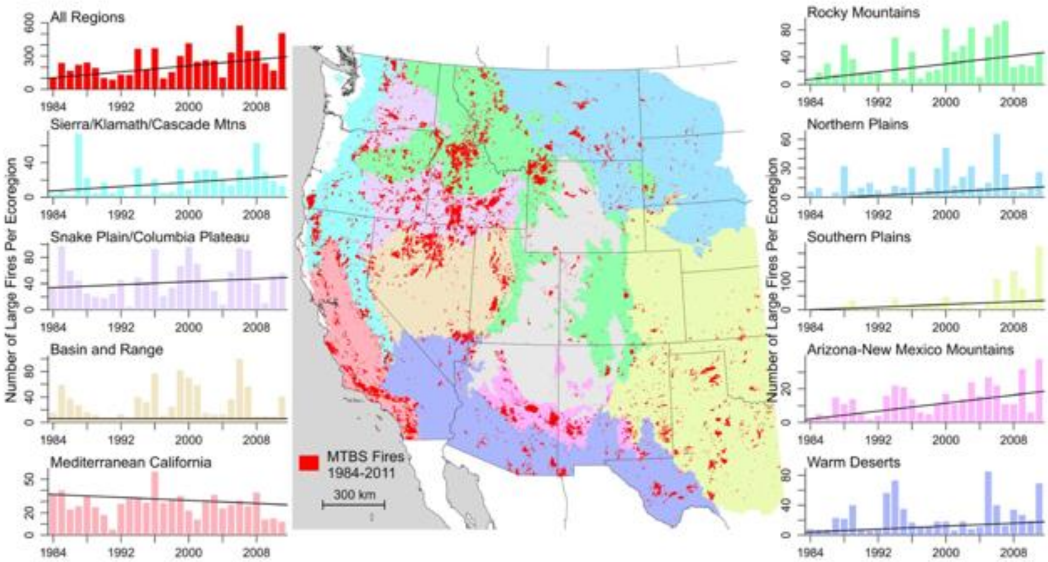

Figure 1.3.1: Western U.S. trends for number of large fires in each ecoregion per year.[40]

The US Forest Service has found that fire seasons over the last 35 years are starting earlier in Spring and ending later in the Autumn.[41] The peak of the season is also occurring earlier by one month and is now in July.[42]

Section 1.4: California

California has the second highest wildfire risk amongst US states.[43] Since 2000, the number of large fires (>10k acres) in the state has increased materially with all but 2 of the largest 20

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[37] Zhuang, Y., et al. 2021. *Quantifying Contributions of Natural Variability and Anthropogenic Forcings on Increased Fire Weather Risk Over the Western United States. Proceedings of the National Academy of Sciences* 118(45): e2111875118.

[38] Dennison, Philip E., S. C. Brewer, J. D. Arnold, and M. A. Moritz. 2014. "Large Wildfire Trends in the Western United States, 1984–2011." *Geophysical Research Letters* 41 (8): 2928–2933.

[39] United States Environmental Protection Agency. *Climate Change Indicators: Wildfires*.

[40] Ibid.

[41] NASA. *Wildfires and Climate Change*.

[42] United States Environmental Protection Agency. *Climate Change Indicators: Wildfires*.

[43] USDA Forest Service. 2018. *Wildfire Risk to Communities*.

since 1950 occurring in this period.[44] Similarly, all but 2 of the most destructive fires have occurred since 2000 with 15 of them since 2010.[45] 4.2 million acres burned in California in 2020 doubling the record of previous years. This period included the first fire in the region that destroyed more than one million acres (a gigafire).[46]

Californian wildfires are particularly affected by the Santa Ana Winds which bring fast travelling dry desert air to fan the flames. Global Climate Models suggest that the frequency of these winds may decrease as the climate warms, although there are some limitations in downscaling these global models project local patterns and changes.[47] However, the trend is weakest at the height of the wildfire season.[48] We therefore still expect to see many major events at this critical time with no modelled reduction in their ferocity and when they occur the climate multiplier may exacerbate them.[49] High resolution simulations show that VPD will worsen and so future Santa Ana Winds will be drier and will pose a greater risk to southern California.[50]

The effects of climate change are complex. For example, major rainfall during 2022/23 caused rapid and dense plant growth in Californian forests. The following arid conditions of 2024/25 dried the undergrowth making it ideal fuel for the devastating fires that followed.[51] This is seen as part of a general trend where the frequency of weather patterns conducive to wildfire is growing but weather features that bring rainfall are becoming less likely.[52]

The effects of climate change on the state have been succinctly summarised by the Office of Environmental Health Hazard Assessment when they said "Human-caused warming has significantly enhanced wildfire activity in California and will likely continue to do so in the coming decades."[53]

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[44] Climate Signals. *Chart: 15 of California's 20 Largest Wildfires Have Burned Since 2000*.; Office of Environmental Health Hazard Assessment (CalEPA). 2022. *EPIC 2022: Wildfire Impacts on Vegetation and Wildlife*.

[45] California Department of Forestry and Fire Protection (CAL FIRE). 2025. *Fire Incident Data and Statistics*.

[46] Office of Environmental Health Hazard Assessment (CalEPA). 2022. *EPIC 2022: Wildfire Impacts on Vegetation and Wildlife*.

[47] You, Yujia, and Thomas L. Delworth. 2025. *Projected Response of Santa Ana Winds to Global Warming.*

[48] Guzman-Morales, J., and A. Gershunov. 2019. *Climate Change Suppresses Santa Ana Winds of Southern California and Sharpens Their Seasonality.;* Scripps Institution of Oceanography. 2024. *California Wildfire Analysis by Climate Experts.*

[49] Scripps Institution of Oceanography. 2024. *California Wildfire Analysis by Climate Experts.*

[50] You, Yujia, and Thomas L. Delworth. 2025. *Projected Response of Santa Ana Winds to Global Warming.*

[51] Climate Centre (IFRC). 2024. *The Climate Science Behind the California Wildfires.*

[52] Guirguis, K., A. Gershunov, B. Hatchett, et al. 2023. *Winter Wet–Dry Weather Patterns and Increasing Wildfire Hazard.*

[53] Ibid.

Section 2: Long-term trends in wildfire damages in California

California is characterized as one of the most "climate-challenged" regions in the US and is projected to be at the greatest risk to climate-induced hazards.[54] This is due to the state's high exposures to heat waves and excessive dry conditions. Additionally, with several major cities and metropolitan areas, the state also has the largest population of any US state, extensive infrastructure, and high social and economic vulnerability.[55] Although climate hazards such as heat waves and dry conditions are estimated to directly impact the state's farming and agriculture sector, it is the combination of these changing climate conditions that drive the occurrence of wildfires, which subsequently can affect all other sectors of the California economy.

The high concentration of urban areas and large extent of urban sprawl in areas of high wildfire hazard make the state particularly vulnerable to damage from wildfires and make the occurrence of climate disasters some of the most damaging and devastating in the country. As the state with the largest GDP, climate hazards represent a major disruption to the state and federal economy. In 2023, California experienced 28 different billion-dollar weather and climate related disaster events, totalling USD 92.9 billion, with most of these disasters being wildfire-related.[56]

While wildfires in California are a regular occurrence, there have been growing frequency of reports citing their size and extensive damages to structures. The 2017 and 2018 wildfire season witnessed several wildfires that became some of the largest and most destructive. For example in 2017, the Tubbs fire in Napa, Sonoma and Lake counties, damaged or destroyed over 7,200 structures, burning over 318,000 acres. In 2018, the Woolsey fire in Los Angeles and Ventura Counties damaged 1,990 structures and burned 97,000 acres. The most destructive wildfire in California's history, as measured by number of buildings destroyed as well as the estimated cost of damages and value of lost property, was the Camp fire around the town of Paradise, which damaged 19,531 structures. As wildfires increase in size and frequency, they pose a greater destructive threat to communities and the economy, becoming a greater priority for local, state, and federal authorities spending over 1 billion USD per year on fire suppression and mitigation.[57]

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[54] Xu Yue, Loretta J. Mickley, and Jennifer A. Logan, "Projection of wildfire activity in southern California in the mid-twenty-first century," Climate Dynamics 43, no. 7-8 (2014), pp. 1973 – 1991.

[55] Binita KC, J.M. Shepherd, Anthony W. King, and Cassandra Johnson Gaither, "Multi-hazard climate risk projections for the United States", *Natural Hazards* 105 (2021), pp. 1963 – 1976.

[56] Erin Shives, Tzu-Hsin Karen Chen, Karen C. Seto, "Multiple hazards and exposure in California: A space-time analysis of temperature, drought, and wildfire", *International Journal of Disaster Risk Reduction 120,* no. 1 (Apr., 2025).

[57] A. L. Westerling and B.P. Bryant, "Climate change and wildfire in California", *Climatic Change 87,* no. 1 (2008), pp. 231 – 249.

In order to assess trends over time in wildfire size and damages in California, aggregated assessments damages are collected from several databases. This includes the extent of the wildfire perimeter from Cal Fire, and the Resource Assessment Programme (FRAP). These datasets provide geo-referencing for fire perimeters dating back to the 19th century; however, analysis only focuses on trends in wildfires from 1980. These databases map the perimeter of the wildfire, which allows for analysis of the evolution of the size and extent of wildfires by acres burned. To illustrate the distribution and relative coverage of wildfires, figure 2.1.1 illustrates the size and distribution of all wildfires in California since 2000, as reported by Cal Fire.

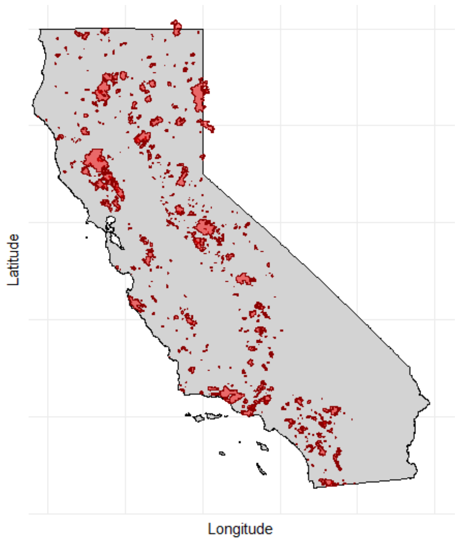

Figure 2.1.1: Location and size of wildfire perimeters since 2000.[58]

From the distribution of wildfires by size and location, the wildfire burn areas are added together for each year, and the trend in wildfire size is illustrated by the total number of acres burned per year. Taking the wildfire perimeters from figure 2.1.1 and aggregated per year since 1980, the annual trend in acres burned is shown in figure 2.1.2 and plotted against the average annual surface temperature for the state of California. First, the figure illustrates a clear increasing trend in the acres burned by wildfires over time, with 2017 showing a particularly large step change. Indeed, the 2017 wildfire season became the most devastating on record, though that peak has since been surpassed.

Second, for the entire period from 1980 to 2016, the average annual acres burned was around 14,600 acres compared with 236,000 acres since 2017. This suggests a distinctive discontinuity in the aggregate annual acres burned in more recent years, broadly confirming that the acres burned and the scale of wildfires has increased over time.

[58] CCRS analysis based on US Department of Agriculture Forest Service, National final fire perimeter. 2025.

Third, comparing the trend in annual aggregate acres burned across the state to the trend in average annual surface temperatures shows a similar increase in both. Although there is a low degree of correlation, with a coefficient of 0.302 for the linear relationship between acres burned and the annual average temperature in California, both variables show a significant growth trend over the period 1980 – 2023. Regressed over time, both values show significant positive growth with an annual increase in temperature of 0.027 degrees Celsius over the period, and an average annual increase in acres burned of approximately 4,000 acres per year.[59]

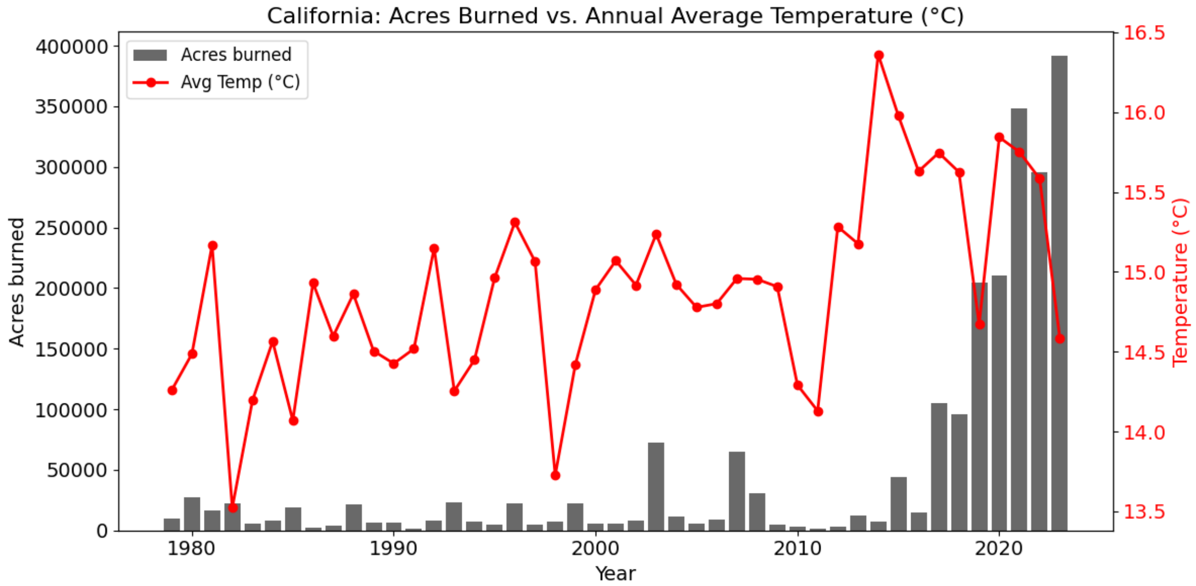

Figure 2.1.2: Number of acres burned annually by wildfires in California, 1980 – 2023.[60]

In addition to determining trends in the number of acres burned and extent of wildfires over time, it is important to consider whether these wildfires have also become more destructive to society and local communities. Measures of the destructiveness of wildfires takes account of the number of buildings that were directly damaged or destroyed. Structures are catalogued as damaged or destroyed by surveys of the wildfire, conducted by Cal Fire, and subsequently made available on the Damage Inspection database (DINS). This data has been collected and published by the Nature Conservancy for data up to 2018.[61] For more recent wildfires since 2018, this data has been collected from the Cal Fire Historical Wildfire Activity Statistics, also referred to as Cal Fire "Redbooks". These reports have been published annually since 1943 and

[59] CCRS analysis based on statistics compiled by Cal Fire Damage inspection dataset, and NOAA National Centres for Environmental Information climate statewide time series. 2025.

[60] CCRS analysis based on compiled statistics from Buechi et al. "Long-term trends in wildfire damages in California", (2021) and from Cal Fire Damage inspection dataset. 2025.

[61] Hanna Buechi, Dick Cameron, Sarah Heard, Andrew J. Plantinga, and Paige Weber, "Long-term trends in wildfire damages in California", *The Nature Conservancy* Issue Brief (2018).

include data on the number of structures damaged or destroyed, the start date, and acres burned.

Data on the number of structures damaged or destroyed is matched to each wildfire according to the DINS database. For each wildfire, the total number of buildings damaged or destroyed is aggregated across wildfires for each year to observe whether wildfires have also become more destructive as they have burned more acres. Trends in the number of destroyed buildings is shown in figure 2.1.3. From the figure, a similar trend that has been previously observed in the case of acres burned is also observed for buildings destroyed. The annual number of affected structures appears fairly low, and generally less than 5,000 buildings for each year from 1980 to 2016. 2017 shows the record high in the number of buildings destroyed up to that point, but continues to grow in subsequent years, with 2018 having the most affected buildings over the entire period. The differences in the average number of buildings affected in the period prior to 2017 was 723 buildings damaged or destroyed, whereas in the period from 2017 to 2023, the average was around 13,400. Moreover, the highest annual number of affected between 2000 to 2016 was around 7000 structures, while the lowest annual number from 2017-2020 exceeded this. This trend is similar to that which has been observed for the number of acres burned, with the annual trend highly correlated, with a correlation of 0.70. This indicates that the number of acres burnt is correlated to the number of buildings destroyed, and that both have shown a distinct increase over time, and in particular for the period from 2017 onwards.

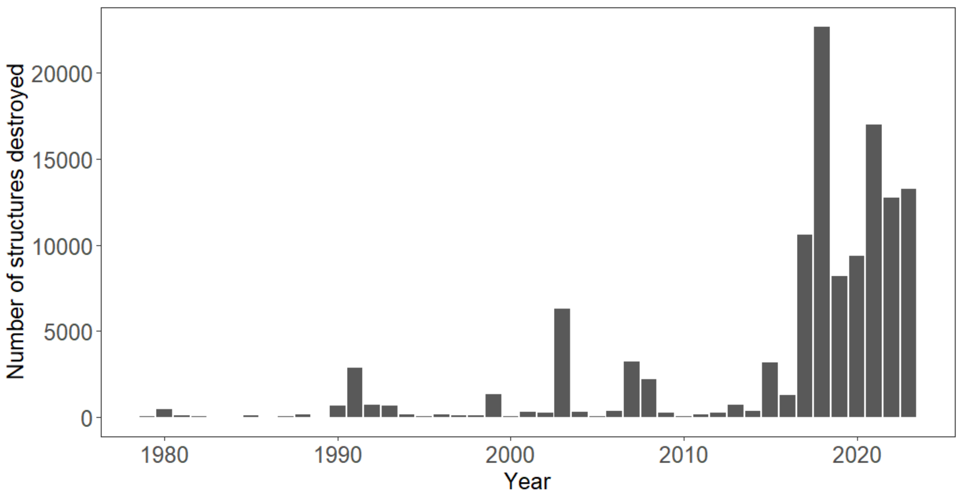

Figure 2.1.3: Number of buildings destroyed annually by wildfires in California, 1980 – 2023.[62]

Data from the acres burned and the number of buildings that have been destroyed is subsequently applied to estimate the amount of direct damages resulting from each wildfire. Estimates of direct damages include losses from physical damage such as buildings destroyed, as well as disruption to businesses, and subsequent loss of employment. We focus on direct

[62] CCRS analysis based on compiled statistics from Buechi et al. "Long-term trends in wildfire damages in California", (2021) and from Cal Fire Damage inspection dataset. 2025.

damage because assessing economy-wide direct or indirect effects of wildfires is complicated, e.g., it is not easy to link the amount or extent of business loss or the subsequent job loss specifically or directly to a wildfire.[63] Hence, we make direct estimates on property value impacts and building losses as they have been reported in the Cal Fire DINS, making use of economic damage estimates provided by the Cal Fire Redbooks, which are subsequently the most conservative damage estimates.

Headline news reports on the estimated losses and costs of recovery are much broader based and take into consideration indirect damages including the secondary costs of wildfires, such as insurance losses and payouts. However, this report focuses on estimates of direct damages and has omitted secondary insurance losses due to difficulty in data availability, and in reconstructing estimates from historical records from wildfires dating back to 1980. Additionally considering inflationary effects on damages from the DINS or red books, which report values in current USD, the price series has been inflated to 2023 USD values using the 2023 California consumer price index to inflate and match values so that damages can be compared over the entire period. Hence, observed trends on the increase in economic losses from wildfires take the most conservative estimates of these costs, rather than accounting for any other secondary losses. Even then, there is a clear growth trend in the cost of wildfires, trends which would only be expected to be larger when accounting for secondary losses from insurance or other sectors. These estimates on the economic costs of wildfires are illustrated in figure 2.1.4.

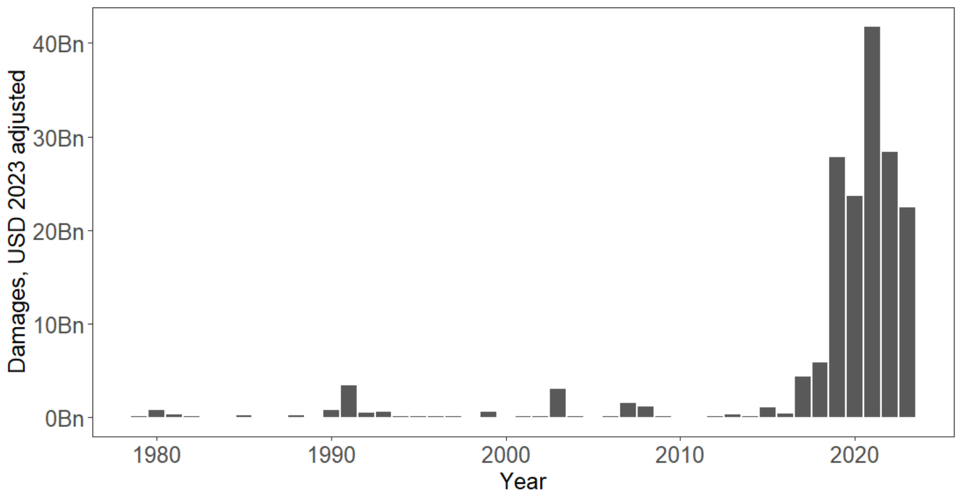

Figure 2.1.4: Economic damage per annum from wildfires in California, 1980 – 2023.[64]

[63] Euijune Kim and Younghyun John Kwon, "Analysing indirect economic impacts of wildfire damages on regional economies", *Risk Analysis 43,* no. 12 (Dec., 2023), pp. 2631 – 2643.

[64] CCRS analysis based on compiled statistics from Buechi et al. "Long-term trends in wildfire damages in California", (2021) and from Cal Fire Damage inspection dataset. 2025.

Trends in figure 2.1.4 reflect a similar pattern to what has been previously observed for trends in acres burned and buildings destroyed. Economic losses appear stable for most of the period from 1980 to 2016, with the average amount of damages for the entire period estimated at USD 440 million per year. For the period from 2017 to 2023, there is a steep increase in damages, which is reflective of the exceptionally damaging wildfires witnessed in 2017 and 2018, with the average damage estimates at USD 22 trillion, which represents a staggering 500-fold increase in the average annual economic damages in the post-2017 period relative to the entire period from 1980 to 2016.

Correlation in the trends between economic damages and buildings destroyed is also high with a coefficient of 0.93. This is expected since the calculation of economic damages takes into account the number of buildings destroyed as one of several factors for overall economic damages, but estimation of economic damages also accounts for other factors including business disruption and destruction of public infrastructure. Hence, lost structures is a close proxy for the estimation of overall damages rather than the number of acres burned but is not fully correlated. The corelation between economic damages and acres burned is high at 0.80, but still lower than the relationship between buildings destroyed and economic damages.

The comparison of correlations between the three trends suggests that from an economic perspective, the factor that is most related to driving damages is not the number of acres burned in a wildfire, but how many buildings are destroyed. This emphasizes the importance of ensuring wildfire resilience and resistance in infrastructure to minimise damages, as wildfires become larger in the number of acres burned. However, while wildfire damage is more related to buildings destroyed rather than the overall size, all three measures reflect a similar pattern, which is that wildfires are becoming increasingly destructive and larger.

What is most distinctive from all three measures of wildfire impacts is that there is a clear and consistent growth trend over the period, and that from the 2017 wildfire season, there is a distinctive shift in the trends, where damages were particularly high, and have continued to be much more damaging compared to the previous decades prior to 2017. Taken together, the evidence from broad historical trends of wildfire extent and damages indicates that wildfires are increasing in both the number of acres burned and the destructiveness of buildings destroyed. Precautions for developers, city planners, and government need to consider the increasing risks from wildfires for the state. As wildfires become a greater threat in California, the unique feature to the state that makes it one of the most climate-vulnerable states is not purely based on the increased exposure to wildfire risk due to heat extremes or dryness, but the fact that there are also so many social and economic vulnerabilities, as it is the most populous and highest GDP state in the US with some of the largest metropolitan areas in the country, with structures built in high wildfire prone areas.

Section 3: Urbanisation and fire hazard

Section 3.1: Introduction

The WUI is where urban settlement and wildland vegetation intersect, and where human and environmental conflicts are generally concentrated, including biodiversity and habitat loss, the spread of zoonotic diseases, and exposure to wildfires. The interface defines the geographic intersection between the areas where anthropic processes prevail and those that remain dominated by natural processes. Combining vegetation with the land use activities of the urban systems, these regions create a unique type of interactive landscape that form a more complex territory: the demarcation between the interaction with and interface of two distinct biological and ecological systems.[65] Initially, the identification of this unique type of ecological region was developed with a particular focus on wildfires, as "any point where fuel consumed by a fire changes from being natural fuel (trees, bushes, and grass) to artificial or man-created fuel (houses, annexes, etc.)".[66] The topic of the WUI has increasingly become a focus for research as wildfires increase in size, frequency, and destructiveness, where the destructiveness and frequency are directly related to human interventions in the WUI.

As it has increasingly become the focus of research related to the occurrence and spread of wildfires, several studies have created methodologies for determining and mapping the WUI.[67] Analysis maps the global WUI as covering only 4.7% of the land surface area, however it accounts for nearly half of global population settlement at 3.5 billion people.

This report considers the WUI in California as it relates to fire risk, by comparing urban settlement density and growth, and wildland interface according to level of fire hazard severity. Global human settlement data measures the degree of urbanisation on a global spatial grid. Data is provided by the Copernicus satellite from the Earth Observation Unit of the European Union's space programme.[68] Satellite images of Earth's surface are taken at five-year intervals, and processed from images into geospatial data points on the extent and spread of land use

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[65] A. Bento-Goncalves and A. Vieira, "Wildfires in the wildland-urban interface: Key concepts and evaluation methodologies", *Science of the Total Environment* 707, no. 135592 (2020).

[66] C.P. Butler, "The urban/wildland interface", *Proceedings of the Western States Section Symposium Combustion Institute Papers* 74 (1974), pp. 1 – 17.

[67] Franz Schu, Avi Bar-Massada, Amanda R. Carlson, Heather Cox, Todd J. Hawbaker, David Helmers, Patrick Hostert, Dominik Kaim, Neda K. Kasraee, Sebastian Martinuzzi, Miranda H. Mockrin, Kira A. Pfoch, Volker C. Radeloff, "The global wildland-urban interface", *Nature* 621 (2023), pp. 94 – 99.

[68] Copernicus is a set of several dedicated satellites, formed of the Sentinel family of satellites, which are specifically designed for geographic and spatial data observation of Earth's surface. It is publicly available, and satellite images have various data applications to research for several uses including urban area management, sustainable development, nature protection, regional and local planning, agriculture, forestry and fisheries, health, civil protection, infrastructure, transport and mobility, and tourism.

changes from urban settlement in order to measure the level of urbanisation according to the total amount of built-up surface area per 100 metres squared.[69]

Satellite images and data on measures of urbanisation are taken at five-year intervals, and available via the European Commission's Joint Research Council. Growth in urbanisation in California is measured by the change in built-up-surface-area per 100 metres squared. The focus on measuring the amount of built-up surface area is to specifically observe urban growth and development in terms of physical building structures, rather than including other features such as roads or other infrastructure. These geospatial urbanisation datasets are compiled between 2000 to 2020.[70] Figure 3.1.1 illustrates what the mapped geospatial dataset looks like in California, the lighter blue to green represents a colour gradient of the level of urbanisation from lowest to highest, respectively, and purple represents no urbanisation. From the figure there is a clear identification of urban clustering and higher urban density around the major metropolitan areas of Los Angeles, San Francisco, and San Diego. As a spatial mapping of urbanisation across the state, the data overwhelmingly show the lowest levels of urbanisation.

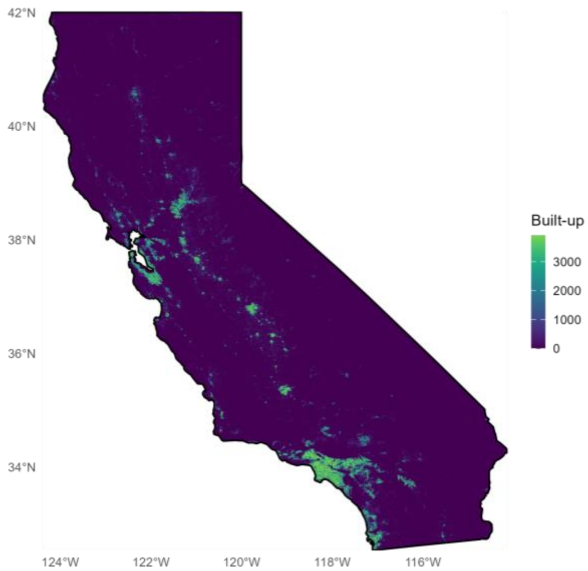

Figure 3.1.1: Urbanised area of California. Built-up surface area per 100m squared, 2020.

From figure 3.1.1, urban density mapping clearly identifies the major metropolitan areas of California, however these density levels are outlying levels of urbanisation compared to the

[69] Satellite images of Earth's surface are converted into spatial data points at a 100 metres squared grid. Images are then matched against sensor data, including radiometric, textural, and morphological features in a multi-faceted image processing framework merging global unsupervised rule-based reasoning and inductive locally-adaptive methods leveraging on pixel-wise spectral indexes, textural assessments, and objective-oriented shape analysis. This is then applied to convert satellite image mapping to data points of levels of urbanisation, which is measured as the total number of built-up surface area per 100 metres squared.

[70] European Commission, *Global Human Settlement Layer Data Package 2023,* Publications Office of the European Union, Luxembourg, 2024.

state average. Figure 3.1.2 shows the distribution of urban density values across the state with most observations at the lowest density level, indicating that large parts of the state have little or no density, with high levels of urbanisation concentrated only in a small number of places. Hence, although urban mapping and trends in urbanisation that track the rate of growth show fairly high levels of urbanisation growth, in most cases percentage changes are from very low levels of urban density, so marginal changes in development of built-up surface area can appear as higher percentage changes at low levels in more rural areas of the state.

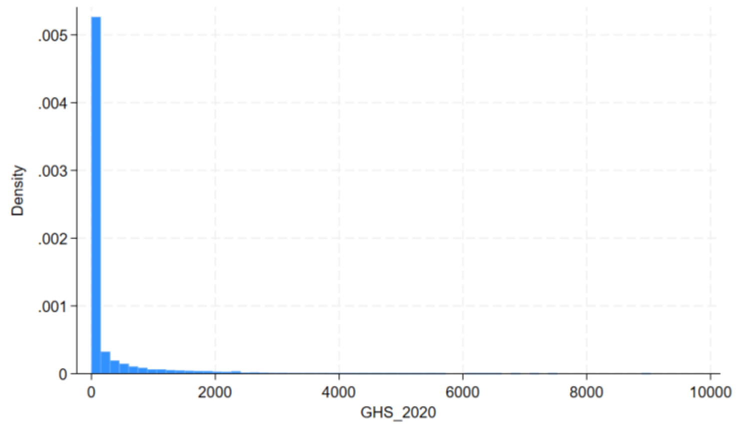

Figure 3.1.2: Distribution of levels of urbanisation by built-up surface area per 100m squared, 2020.

To observe the spread of urbanisation across the WUI, the change in urbanisation in each five-year period is measured against the classification of wildland use according to degree of vulnerability to fire hazard. This is taken from Cal Fire's fire hazard severity zone mapping (FHSZ), which published by the State Fire Marshall to designate the potential wildfire risk of certain areas.[71] FHSZs are classified into three risk categories of "moderate", "high", and "very high" risk, with areas outside FHSZs corresponding to low or no wildfire risk. From the map in figure 3.1.3, we see that most of the areas designated as FHSZs fall in the highest risk category, with 54.6 percent being designated as "very high" risk. "High" risk covers 32.7 percent of the FHSZs, leaving just 12.7 percent for "moderate" risk FHSZs. Each of the three categories is based on the compilation and assessment of three different factors. First, is the demarcation of the wildland zone, which is based on a classification of the type of vegetation, and the topographic slope of the area. Second, flame length is the potential fuel for fires, which consists of the forested type, the forest canopy fuel characteristics, fuel moister, climate, weather, and the Fosberg Fire Weather Index (FFWI) above the 95th percentile. Finally, the burn probability is calculated from the fire history data of the area from 1991 – 2020. This considers fire rotation based on vegetation life form, and the climactic region.

[71] California Department of Forestry and Fire Protection (CAL FIRE). (2023). *Fire Hazard Severity Zones (FHSZ) [GIS dataset]*. California Department of Forestry and Fire Protection. Retrieved May, 2025.

FHSZ maps are managed and regularly updated by Cal Fire and are used for a variety of other services and risk assessments done publicly by the state and by private companies, including insurers.

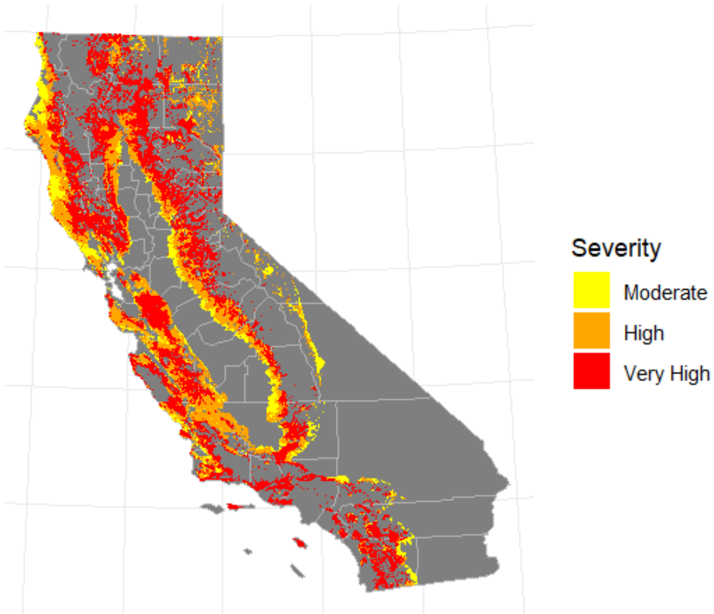

Figure 3.1.3: Classification of areas of California according to the FHSZ maps.[72]

Section 3.2: Analysis

Mapping both the levels of urbanisation against FHSZs, this report assesses the spread of the WUI across the state, and the relative increase in risk from the spread of settlements into the WUI over time. First, the overall trend of urbanisation into FHSZs over time, from 2000 to 2020, in figure 3.2.1, shows increasing urbanisation by the amount of built-up surface area into all three FHSZ risk categories. Generally, this increase in built-up area into FHSZs is consistent with the overall growth of population and GDP across the state.[73] The overall average population growth rate of California from 2000 to 2020 was 16.5 percent, representing an increase of 5.6 million people. In the same period, the GDP growth of the state increased from 1.71 trillion USD in 2000 to 2.72 trillion USD in 2020, representing a 60 percent increase. While

[72] CCRS analysis provided by data from Cal Fire. (2023). *Fire Hazard Severity Zones (FHSZ) [GIS dataset]*. California Department of Forestry and Fire Protection. Retrieved May, 2025, European Commission, *Global Human Settlement Layer Data Package 2023,* Publications Office of the European Union, Luxembourg, 2024.

[73] The percentage change in urbanisation for the "moderate" FHSZ over the entire period 2000 to 2020 was 39.97 percent. For the "high" FHSZ, the total growth rate was 32.96 percent. For the "Very high" FHSZ, the growth rate was 46.917 percent.

GDP growth was much faster than population growth in the state, the growth of urbanisation into the three FHSZs is in-between the population and GDP growth rate.

Despite increases in the average level of urbanisation by FHSZ, the observed average levels are fairly low, reflecting the overall low urban density across the state. While the average level of urbanisation has grown in all three FHSZs over the period, all three show similar distributions of urbanisation, illustrated in figure 3.2.2. From the figure, most observations are clustered at the lowest level of urbanisation for all three FHSZs, and higher urbanised areas appear as outliers. This indicates that the average levels of urbanisation in each FHSZ is similarly represented, with distributions.

Analysis on the differences in the distribution shows that the levels of urbanisation are significantly different for each level of fire hazard severity.[74] However, although findings show that urbanisation levels are different in each FHSZ, higher risk levels of FHSZ show significantly higher levels of urbanisation compared to lower risk FHSZ. This indicates that there are significantly higher levels of urbanisation in areas of high wildfire risk compared to areas of lower wildfire risk, suggesting higher risk and greater exposure to wildfires. This is similarly observed from figure 3.2.2, which shows that in 2020, the average level of urbanisation was highest in the highest risk FHSZ, and lowest in the lowest risk FHSZ.[75]

[74] Analysis of differences in distributions is based on the one-sided Mann-Whitney U test, of non-parametric differences in distributions.

[75] Mann-Whitney U test is a rank-sum test of differences in distribution, and does not assume or parametrise the distribution of observations. The one-sided test is used since all levels of urbanisation are positive or > 0. Each FHSZ is compared to the other two. The results of the significance of the p-value are all significant at the 0.05 level. First, "moderate" FHSZ compared to "high" shows that "high" has significantly higher urbanisation with a p-value of 0.041. "Very high" has significantly higher levels of urbanisation than "high" wildfire risk, with a p-value of 0.038. And "Very high" is significantly greater than "moderate" with a p-value of 0.0003.

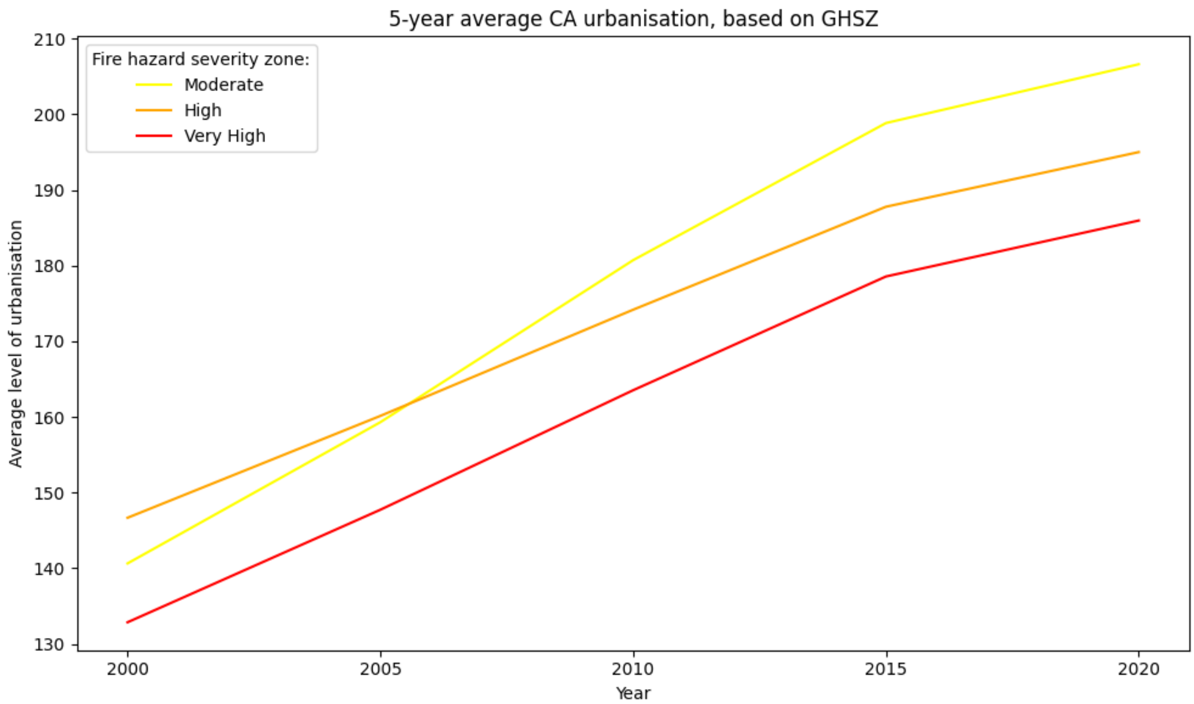

Figure 3.2.1*: Growth trends in the average level of urbanisation in the three FHSZ risk categories, 2000 – 2020.*[76]

Despite the slight difference in the rate of growth at each FHSZ category from previous figure 3.2.1, this growth in urbanisation for each FHSZ category is highly correlated to the overall growth of the population and GDP of the state. For all three risk levels of FHSZs, the rate of growth in urbanisation is highly correlated at greater than 0.99 to the growth in overall population of the state. The correlation between GDP and urbanisation is similarly high at greater than 0.94. Urban development in the lowest risk FHSZ was 40 percent, into the "high" category it was 33 percent, and into the highest risk category the growth was fastest at 47 percent. This means that essentially urban expansion into "high" and "very high" risk wildfire areas accounted for 80 percent of urban growth into the WUI.

[76] CCRS analysis of data provided by European Commission, *Global Human Settlement Layer Data Package 2023,* and the Cal Fire. (2023). *Fire Hazard Severity Zones (FHSZ) [GIS dataset]*.

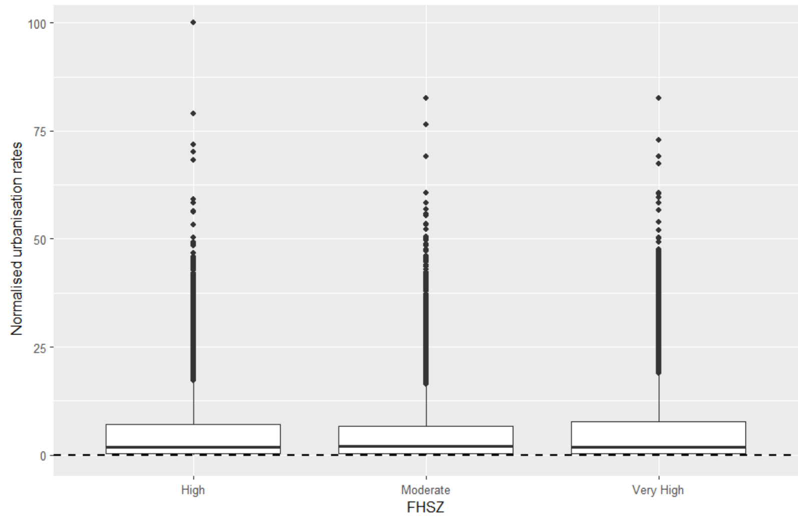

Figure 3.2.2: Distribution of levels of urbanisation in 2020 for each risk level of FHSZs.[77]

Although growth in urbanisation in all three FHSZs are highly correlated with the overall growth across the state, the fastest growth in urbanisation is in the highest risk FHSZ, and the average level of urbanisation across the state is higher in FHSZs of higher risk. This indicates that urban growth along the WUI is expanding most quickly into the most dangerous areas, which is increasing the risk of wildfires caused by human activity, and increasing the exposure of people and property to greater damage from wildfires.

These findings are similar to estimates reported across the US, which have found that the area categorised as WUI expanded over the 20 years from 1990 to 2010, from 581,000 km squared to 770,000 km squared, representing a 33 percent increase.[78] This overall average is broadly consistent with what is observed from figure 3.2.1, showing the urbanisation growth in all three FHSZs ranges from 33 percent to 47 percent.

While several studies have mapped the WUI in the US, and have demonstrated ample evidence that the WUI raises the threat of increased wildfire occurrence, there is less clarity on how fast the WUI is growing, and what is driving growth of the WUI.[79] Fundamentally, there are two processes that could be driving an expansion of the WUI, which is the construction of new homes in or near existing wildland vegetation, as well as an increase or change in the wildland

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[77] CCRS analysis of data provided by European Commission, *Global Human Settlement Layer Data Package 2023,* and the Cal Fire. (2023). *Fire Hazard Severity Zones (FHSZ) [GIS dataset]*.

[78] Volker C. Radeloff, David P. Helmers, H. Anu Kramer, Miranda H. Mockrin, Patricia M. Alexandre, Avi Bar-Massada, Van Butsic, Todd J. Hawbaker, Sebastian Martinuzzi, Alexandra D. Syphard, and Susan I. Stewart, "Rapid growth of the US wildland-urban interface raises wildfire risk", *Proceedings of the National Academy of Sciences* 115, no. 13 (2018), pp. 3314 – 3319.

[79] John T. Abatzoglou and A. Park Williams, "Impact of anthropogenic climate change on wildfire across western US forests," *Proceedings of the National Academy of Science* 113, no. 42 (2016), pp. 11770 – 11775.

vegetation within and near previously developed areas due to changing environment and climate. The prevalence of each process is unclear, which points to gaps in how we might evaluate wildfire management policies and responses.

Our study, which focuses on the expansion of the WUI in the state of California, shows that the expansion of the WUI is strongly related to the growth of urbanisation into areas which are at risk from wildfires, including, most worryingly, some of the highest risk areas. The reasons for urban development expanding high wildfire risk areas is explored in this section.

Section 3.3: Wildfire impacts

Taking the geospatial mapping of FHSZs, this is overlayed onto the observed level of urbanisation according to built-up surface area per 100 metres squared. By mapping this over the period 2000 to 2020, the trend in the growth of urbanisation at each five-year interval shows the rate of urban expansion into each FHSZ. However, since the growth in urbanisation is dependent on the level and sprawl of urbanisation from the previous period, this needs to be accounted for. Additionally, while urban growth was fastest in the highest risk FHSZ, this could still be dependent on previous levels of urbanisation, or in some cases, may not have been avoidable given the designation of some urbanised areas with the highest FSHZ risk.

Hence, to observe the factors driving urban growth in FHSZs, we need to analyse this according to the relative impact of each factor. The results are illustrated in table 3.3.1. The table shows the relative role that each factor has in explaining urban growth in each time period. First, according to the table, the effect of risk levels in FHSZs is negative and significant, indicating that there is a small, but significant attempt for urban development to avoid FHSZs at "high" and "very high" risk levels, based on the negative values, which are estimated relative to the "moderate" FHSZ. However, this effect is small. Second, the table also shows the role of the previous period's level of urbanisation in influencing the current level of urbanisation relative to the risk in different FHSZs. Our results show that the level of urbanisation in the previous period was a much greater determinant of the level of urbanisation in the following period than the level of FHSZ wildfire risk.

		2020	2015	2010	2005
FHSZ	**High**	-0.008***	-0.033***	-0.049***	-0.067***
		(0.0003)	(0.001)	(0.0005)	(0.0003)
	Very high	-0.032***	-0.008***	-0.015***	-0.005***
		(0.0003)	(0.0004)	(0.0006)	(0.0004)
Urbanisation	**2015**	0.786***			
		(0.003)			
	2010		0.906***		
			(0.014)		
	2005			0.854***	
				(0.006)	
	2000				0.812***

*Table 3.3.1: Regression coefficients of the relative factors driving urban development from one period to the next based on previous levels of urbanisation and FHSZs. *, **, ** indicate significance at the 10, 5, and < 1 significance level.*[80]

This reveals that although the process of urban sprawl takes some small consideration of risks associated with building into the WUI, this is not a major factor for developers or house buyers in determining where to build or live, respectively. The primary factor that drives most urban sprawl is the extent of previous urbanisation, indicating that much of urban growth is simply an extension of previous cities and towns, whether or not such extensions push into the WUI.

While urban sprawl into the WUI is mostly determined by the extent of urbanisation in the previous period, it has not considered the degree of urbanisation at different densities. Essentially, table 3.3.1 shows that urban development into "high" and "very high" risk FHSZs has been happening at a slower rate than in moderate risk FHSZs. Building on the analysis and results from table 3.3.1, figure 3.3.1 shows how different levels of urbanisation drive the continued spread of urban sprawl into the WUI at different levels of wildfire risk.

[80] CCRS original analysis.

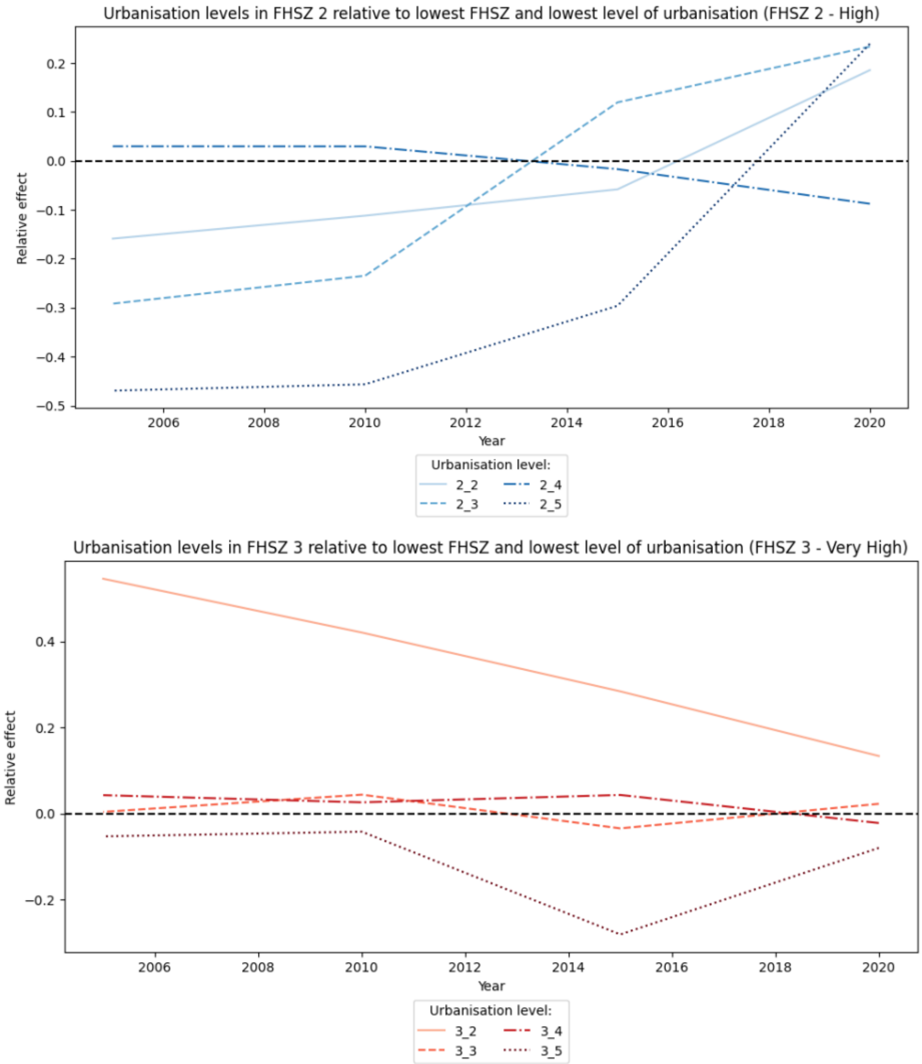

Figure 3.3.1: Relative growth in urbanisation for FHSZ "high" and "very high" risk, 2 and 3, respectively, shown as the difference relative to urbanisation in FHSZs with "moderate" risk, 1. Trends are tagged by 2 numbers: First, FHSZ as 2 or 3, and, second, level of urban density from 2 – 5. Lowest urban density, 1, represented by the horizontal 0 x-axis.[81]

The two plots in figure 3.3.1 distinguishes between five levels of urban density, as well as the three FHSZs. The plot illustrates the relative growth in urbanisation within each urban density group for each FHSZ risk level for each period. Higher urban density is represented by higher grouping values. From the figure, trends are illustrated relative to the baseline, which corresponds to FHSZ "moderate", risk level 1, and the lowest level of urban density 1, represented by the 0 *x*-axis. The figures shows three kinds of urbanisation trends over time: (i) urbanisation starts well below the baseline in 2005 and gradually increases to the baseline by 2020 (from urbanisation trend lines 2_2, 2_3 and 2_5); (ii) urbanisation is roughly equal to the baseline for the whole period (2_4, 3_3, 3_4 and arguably 3_5); and (iii) one case (3_2) where

[81] CCRS analysis of data provided by European Commission, *Global Human Settlement Layer Data Package 2023,* and the Cal Fire. (2023). *Fire Hazard Severity Zones (FHSZ) [GIS dataset]*.

urbanisation starts well above the baseline but decreases to the baseline by 2020 (risk level 3, and urbanisation level 2). The overall message is that urbanisation growth rates seem to converge to the baseline of growth in lower urbanisation areas that have a moderate wildfire risk. In other words, we are confirming our previous finding that urbanisation growth seems largely unaffected by FHSZ ratings.

The figure highlights two additional features to the nature of urban growth into the WUI in California. First, that the level of urban density in the previous period is a significant factor to the extent of urban sprawl into FHSZs in the next period, where trends differ depending on the pre-existing level of urbanisation. It is not the lowest density urban sprawl that is pushing into the highest risk FHSZ, but instead it is growth of areas that already have a higher degree of urbanisation.

Second, since 2005, expansion of urban density seems to be lower in areas of higher fire hazard severity. However, by 2020, these trends converged to a similar, if not opposite effect relative to the lowest density and lowest risk FHSZ. This suggests that cities in California, irrespective of population size or density, may be running out of areas for urban expansion that are not in a high risk FHSZ. As previously established, the extent of urbanisation in the previous period is the biggest determinant of urban growth in the next period. Additionally, overall, small attempts have been made to avoid FHSZs, and although the difference is significant, it is small. The trends from the two plots in figure 3.3.1 further show that urban developers generally made more of an effort to avoid FHSZs in urban planning in earlier periods, but with the trends converging or being higher than the baseline by 2020, they either cared less about warnings from FHSZs or were running out of other areas for urban sprawl, since higher levels of urban density show higher growth trends into increasingly risky FHSZs.

Section 3.4: Wildfire impacts on localised areas

Analysis has looked at statewide trends in the level of urbanisation in FHSZs that is proportionate to and highly correlated with the overall growth rate of the population and GDP, indicating that urban sprawl into the WUI is a part of a larger process of the growing housing demand and economic growth across the state. The level of urbanisation in each FHSZ appears to have converged over time, suggesting that FHSZ risk may not be a very salient factor in growth of urbanisation.

Analysis has so far only observed trends across the entire state, but trends in urban sprawl may be quite different in more localised areas. To observe this, analysis considers localised areas around a wildfire event, and the subsequent growth rate in urbanisation in each of the three FHSZs for the localised areas. For example, figure 3.4.1 plots the overlay of the three factors considered for the localised area. The left panel shows the overlay of the wildfire perimeter, where the mapping of the area beyond the wildfire perimeter includes surrounding towns and cities. It additionally overlays the level of urbanisation, measured according to urban density by built-up surface area per 100 metres squared. This is identified in a colour gradient that clearly distinguishes cities, roads, and the specific variables of interest, which are the buildings themselves. The right panels add the FHSZs, which are overlayed on the wildfire perimeter and the level of urbanisation.

Figure 3.4.1 illustrates the data mapping of two of these fires as examples. First, in the top row is the Valley fire, that occurred from 12 September to 15 October 2015 in the area around Lake County, California. The wildfire significantly damaged the towns of Cobb, Middletown, and Whispering Pines, burning 76,067 acres, and destroying nearly 2,000 buildings, causing at least USD 921 million in insured property damage. At the time, it was considered the third-most destructive wildfire in the state, but this would be surpassed by more recent wildfires.

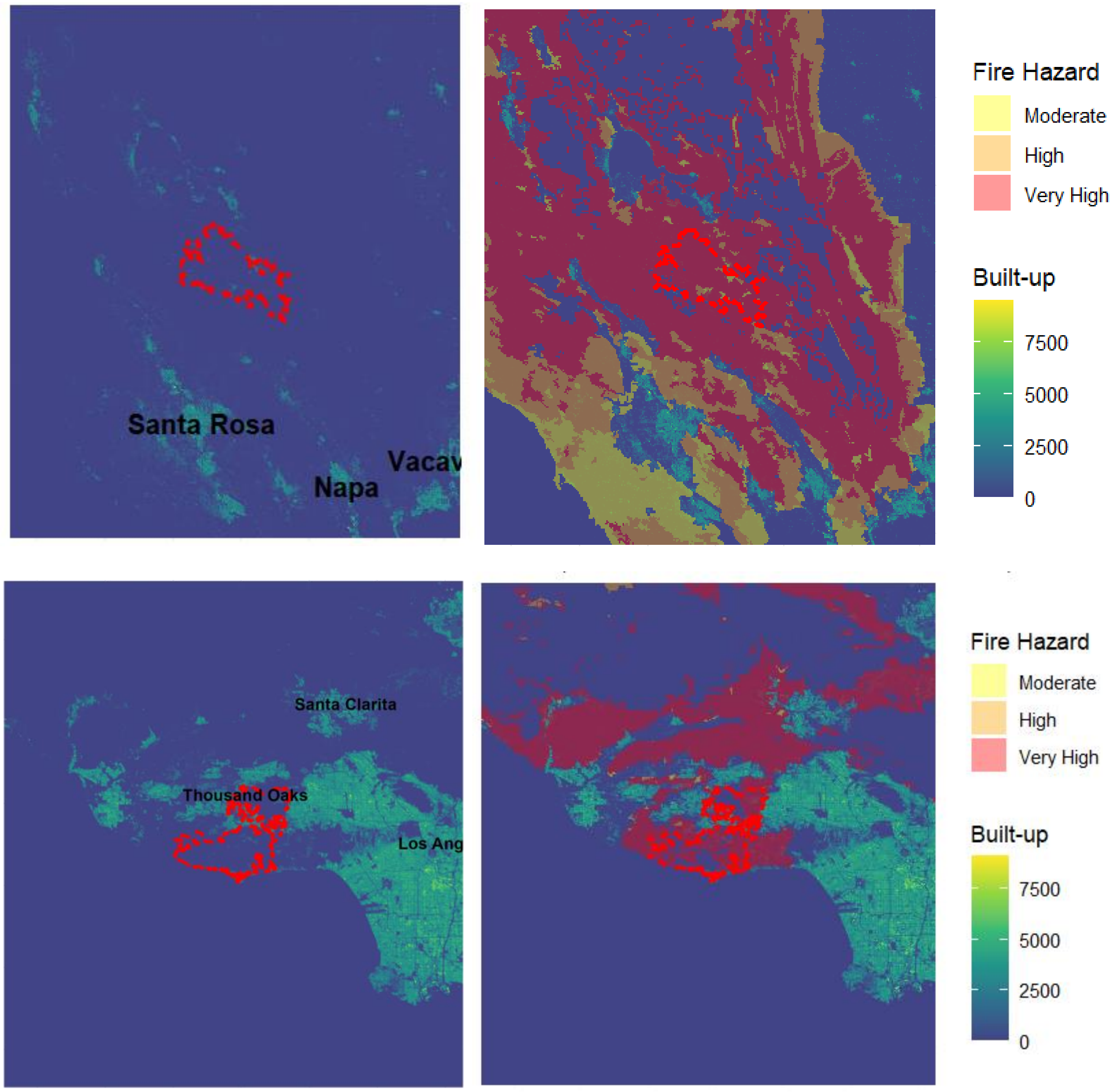

Figure 3.4.1: Data mapping of level of urbanisation showing wildfire perimeter in bright red, and at right adding FHSZs. Panel A (top): Valley Fire, Lake County, 2015. Panel B (bottom): Woolsey Fire, Los Angeles and Ventura Counties, 2018.[82]

The second row illustrates the Woolsey fire in southern California. The wildfire took place from 8 to 21 November 2018, burning 96,949 acres and destroying 1,643 buildings. The wildfire is notable for burning through a highly urbanised part of the Los Angeles metropolitan area, razing several buildings, and leading to the evacuation of more than 295,000 residents from Ventura and LA counties, causing major disruptions to the city.

From the figure, the urban density of Los Angeles can be clearly observed, with a high-level of detail and granular data mapping to highlight the built-up areas of Los Angeles against roads, highways, and mountains. This can further be observed and overlayed with the FHSZ risk levels, which shows that nearly all the surrounding area of Los Angeles in the Santa Monica mountains is designated with the highest fire hazard severity. The FHSZ mapping of Los Angeles indicates that there is essentially no area of urban expansion for Los Angeles that does not push into the highest FHSZ. For other major metropolitan areas of California, the finding is similar, which is that all outlying suburban areas of cities such as San Diego, and to a lesser extent San Francisco, are entirely surrounded by zones designated as “high” or “very high” wildfire risk. This is illustrated in figure 3.4.2, which shows the urbanisation of San Diego and San Francisco with the FHSZ mapping. Hence, although some efforts may have been made to avoid high wildfire risk areas, urban sprawl inevitably ends up expanding into the highest risk areas, since all major cities, such as Los Angeles, have no other areas to expand into. This highlights one of the main dilemmas for urban and economic growth in California; that cities are the main drivers of economic growth for the state, and that people are attracted to moving to these growing cities, but that they have no space to expand to without raising wildfire risk by expanding into the highest FHSZs.

[82] CCRS analysis of data provided by European Commission, *Global Human Settlement Layer Data Package 2023,* and the Cal Fire. (2023). *Fire Hazard Severity Zones (FHSZ) [GIS dataset]*.

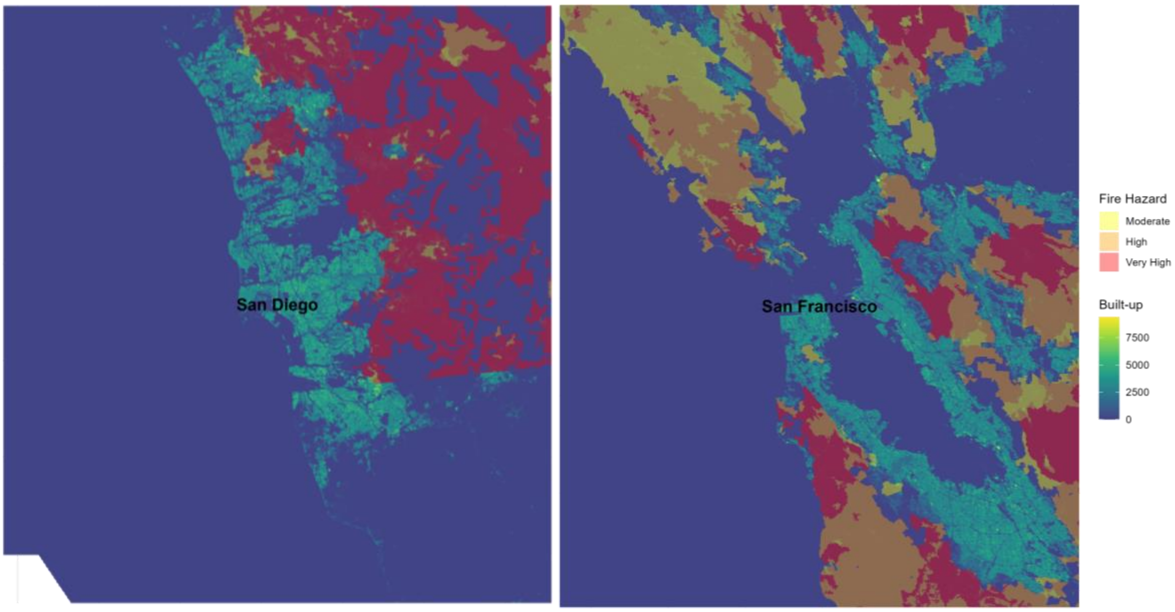

Figure 3.4.2: Data mapping of level of urbanisation in 2020 and FHSZs for major metropolitan areas of California. Left panel: San Diego. Right panel: San Francisco.[83]

Considering the overlay of FHSZ mapping and urbanisation, analysis looks at whether the occurrence of a wildfire affects the subsequent growth in urbanisation. From the Woolsey fire in Los Angeles, the extent of the wildfire was entirely within the highest risk FHSZ. Therefore, it is expected that the local area and community would take FHSZ designations seriously to avoid further urban development into high-risk zones. In order to observe whether the wildfire had an impact on subsequent urban growth and development in the region after the wildfire, figure 3.4.3 plots the growth rate of urbanisation into different levels of FHSZ leading up to and following the Woolsey fire.

[83] CCRS analysis of data provided by European Commission, *Global Human Settlement Layer Data Package 2023,* and the Cal Fire. (2023). *Fire Hazard Severity Zones (FHSZ) [GIS dataset]*.

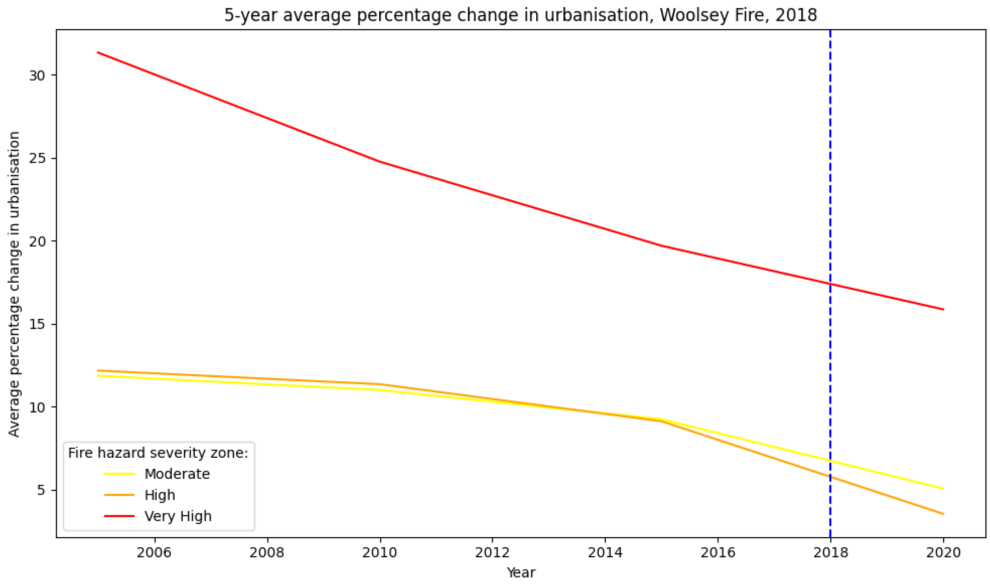

Figure 3.4.3: Average urbanisation growth rate by FHSZ in the Los Angeles area before and after the Woolsey wildfire, designated by the dashed vertical line.[84]

The main insight from figure 3.4.3 is that that in the two periods just before and just after the Woolsey fire, the rate of growth distinctly declined between 2015 and 2020 for the higher risk FHSZs.

The figure also illustrates the average urbanisation growth rate around the Woolsey wildfire over the entire period from 2005 to 2020. The growth rate declines for the area around the Woolsey fire in all three FHSZ, but this rate of decline was the most rapid in the highest FHSZ. This suggests that some effort was made to avoid urban development in higher wildfire risk areas. Despite this, urban growth remained positive for all FHSZ, indicating that urbanisation in the Los Angeles area is expanding overall, and that this expansion inevitably crosses into FHSZs, but that some effort is made to build more in lower FHSZ, rather than in higher risk zones.

Similar trends, of short-term declines in urbanisation after wildfires, are observed for the Cedar fire and the Tubbs fire. These two wildfires cover different areas of California and different events. The Cedar fire occurred in 2016 and affected Kern County in Central California, and the Tubbs fire affected Napa, Sonoma, and Lake counties, occurring in 2017. Figure 3.4.3 shows a distinctive decline in the rate of urbanisation growth in all designated FHSZs following the wildfire event in each area. The figure also highlights the different patterns of urban growth in different areas of California. While some areas show the highest growth rate in the lowest risk FHSZs, some regions show that the highest rate of urban growth was into the highest risk FHSZ, such as the areas of Kern County around the Cedar fire. However, despite differences in

[84] CCRS analysis of data provided by European Commission, *Global Human Settlement Layer Data Package 2023,* and the Cal Fire. (2023). *Fire Hazard Severity Zones (FHSZ) [GIS dataset]*.

the overall growth rate, wildfire events appear to have the same effect on reducing urban growth in any level of FHSZ in the period after the wildfire occurred.

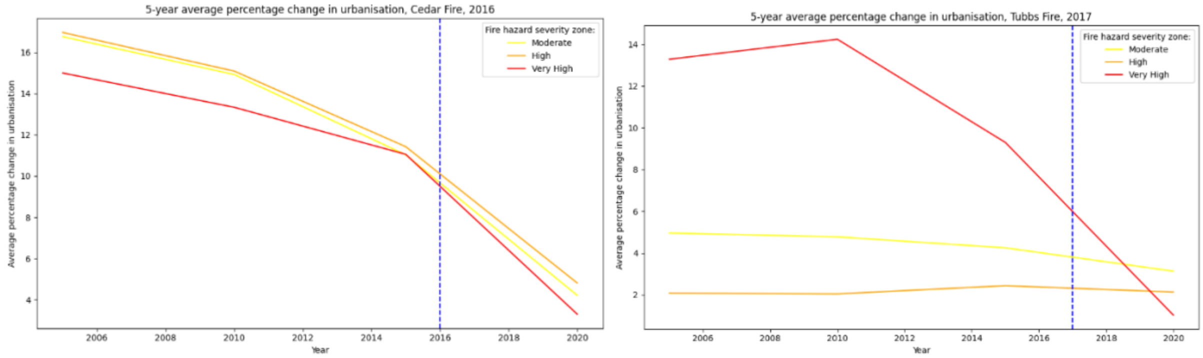

Figure 3.4.4: Average percentage change in urban growth in the metropolitan areas surrounding wildfires. Wildfire event designated by the blue dashed line. Panel A: Cedar Fire, 2018; Panel B: Tubbs Fire, 2017.[85]

Trends in figure 3.4.4 suggest that some effort is made to avoid the highest risk areas, such as in Napa, Sonoma, and Lake Counties, where the urban growth rate was low across the entire period in higher FHSZs. However, in the case of Kern County, urban growth was fastest in the higher risk FHSZs. Comparing trends across all three wildfires, there is urban growth in all three FHSZs, reflecting the overall growth of urbanisation observed previously (in figure 3.2.1) which is highly correlated to population growth and GDP growth in California. We repeat that for some areas, such as the Los Angeles area, urban growth has nowhere to expand into except the highest risk areas.

Despite the overall trend into all FHSZs, evidence from all three wildfires, Woolsey, Cedar, and Tubbs, shows that the rate of growth in the local area distinctly declines in the 5-year period following the wildfire event. This is observed in all three FHSZs in the period following a wildfire, suggesting that urban development appears to respond more to the risk mapping of FHSZs after a wildfire occurs, rather than in any period before. While some attempt at avoiding high risk FHSZs is observed overall and across the state, as shown from table 3.3.1 and from figures 3.2.1, 3.4.2, and 3.4.3, the impact of FHSZ designation on deterring urban development in risky areas is only pronounced after a wildfire has occurred.

[85] CCRS analysis of data provided by European Commission, *Global Human Settlement Layer Data Package 2023,* and the Cal Fire. (2023). *Fire Hazard Severity Zones (FHSZ) [GIS dataset]*.

Section 4: Long-run social and economic impacts of wildfires

Section 4.1: Introduction

Wildfires are a natural occurrence that are part of the natural ecosystem, and are not necessarily positive or negative in their impacts, and have often been utilised to control or modify landscapes, and to support agricultural land development in the fertilization of soils and the control of plant growth.[86] Even when wildfires cause significant destruction to property and the local economy in the short-term to local communities, the long-term effects are less certain. They can create positive effects through demand-side shocks such as increases in fire suppression spending and post-fire recovery, restoration, and rebuilding of damaged areas and lost infrastructure facilities. Alternatively, the long-term negative impacts can also outweigh these benefits, including the direct cost of rebuilding, firefighters, loss of regional income from local production, land and property damages, disconnection of infrastructure networks, and increases in public health and safety costs for emergency services.[87] Conversely, long-run outcomes can also be positive as a result of "creative destruction" from wildfire events or "build back better" scenarios in which economic growth is higher than it would have been.[88]

Several studies have identified contrasting and uncertain evidence on the social and economic impacts of wildfires. In some cases, the added federal and state spending on fire suppression can have a sufficiently large effect relative to the size of the affected to community to generate positive effects on economic growth and employment. While these added spending measures may be small relative to state-level budgets and GDP, in smaller and rural communities that tend to be the most commonly affected by wildfires due to their location on the WUI, they can lead to substantial gains in individual sectors, such as natural resource, mining, and commodities.[89] Similarly, other studies of the economic impacts of wildfires have found that whether or not wildfires have a positive or negative impact depends on the size of the affected community. Smaller towns and communities tend to gain a short-run positive effect on employment and economic growth following a wildfire due to greater investment in reconstruction and redevelopment, but these positive effects largely disappear about four months after the fire. However, larger areas and more high-density cities show no positive or

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[86] Cristina Santin and Stefan H. Doerr, "Fire effects on soils: The human dimension", *Philosophical Transactions B* 371 (2016).

[87] Euijune Kim and Younghyun John Kwon, "Analysing indirect economic impacts of wildfire damages on regional economies", *Risk Analysis* 43, no. 12 (Dec., 2023), pp. 2631 – 2643.

[88] Solomon M. Hsiang and Amir S. Jina, "The causal effect of environmental catastrophe on long-run economic growth: Evidence from 6,700 cyclones", *National Bureau of Economic Research Working Paper Series* 20352 (Jul., 2014).

[89] Max Nielsen-Pincus, Cassandra Moseley, and Krista Gebert, "Job growth and loss across sectors and time in the western US: The impact of large wildfires", *Forest Policy and Economics* 38 (2014), pp. 199 – 206.

negative effects of wildfire events in the short or long-term.[90] In summary, while wildfires can lead to significant destruction and damage to local communities in the short-term, it is the long-term effects of these wildfires that remains uncertain.

Previous analysis has used geospatial data to identify the impacts of wildfires on levels of urbanisation, which has yielded a preliminary indication that wildfires tend to reduce the rate of growth of urbanisation into high wildfire risk areas. This has been observed consistently across several events that have been studied previously, including in the case of the Cedar fire, where the rate of urban growth into FHSZ shows a steep decline from the pre- to post-wildfire periods across all three FHSZ, and the Woolsey fire, where there was already a decline in the rate of urban growth in the highest FHSZ, but this was similarly observed for the “high” and “moderate” risk FHSZs. However, these observed trends have relied on trends over time based on five-year intervals, which does not provide a time series of observations on urbanisation to compare the effect of a wildfire event on the actual change or trend in urbanisation for the affected area. This is because geospatial data on urbanisation is derived from satellite imaging and geospatial data processing, which is provided only at 5-year intervals to map growth or changes in urbanisation according to built-up structural developments. Hence, this type of data cannot be applied to a time series to track actual changes in urbanisation that would be causally linked to a particular wildfire event. This would need to be observed at more consistent time intervals in order to establish that an event was causally linked to the change in trend. Therefore, this section looks more explicitly at the direct long-run effects of wildfire events on social and economic indicators for affected areas over time by using a time series of observations at the county-level, rather than geospatially.

Section 4.2 Methodology

In order to directly estimate the impacts of wildfire events on social and economic changes in California counties, a standard generalised difference-in-difference modelling approach is applied. This method compares the impact of wildfire events occurring in particular counties to a set of counties that did not experience the wildfire. In this sense, the approach sets up a quasi-experiment with a treatment and control group comparison. Specifically, analysis examines the effect of wildfires on a set of key social and economic indicator variables, and observes the long-run effects at 3, 5, and 7 year post-event time intervals. Social and economic trends are compared for the affected county where a wildfire occurred, and trends are compared to all neighbouring counties where the wildfire did not occur. Trends are compared before the wildfire and after, which establishes whether or not the wildfire specifically led to a

[90] Liana Prudencio, Ryan Choi, Emily Esplin, Muyang Ge, Natalie Gillard, Jeffrey Haight, Patrick Belmont, and Courtney Flint, “The impacts of wildfire characteristics and employment on the adaptive management strategies in the intermountain West”, *Fire 1,* no. 3 (2018).

disruption in the trend for the affected county relative to the surrounding counties that were not affected.

An illustrative example of this is shown in figure 4.2.1, which shows the population trend for Butte County, where the Camp fire occurred in 2018, compared to all neighbouring counties around Butte. The Camp Fire has been up until 2024, the deadliest and most destructive wildfire in California's history, leading to 85 deaths, displacing more than 50,000 people, and destroying 18,804 structures, causing an estimated 16.5 billion USD in damages. The wildfire was fuelled by winds that drove through several small towns and communities, largely destroying the towns of Concow, Magalia, Butte Creek Canyon, and Paradise, all in Butte County.[91] From the figure, the population trend of all counties is increasing at a similar rate, if not faster for Butte County compared to neighbouring counties. The vertical line identifies the year 2018 when the Camp fire occurred. Treating this event as a break from the previous trend prior to 2018, there is a clear and distinct decline in population of Butte County, particularly when compared with the trend for neighbouring counties that were not affected by the Camp fire. While this evidence suggests that it was the Camp fire specifically that led to the decline in population, this is more formally established by analysis using the difference-in-difference model.

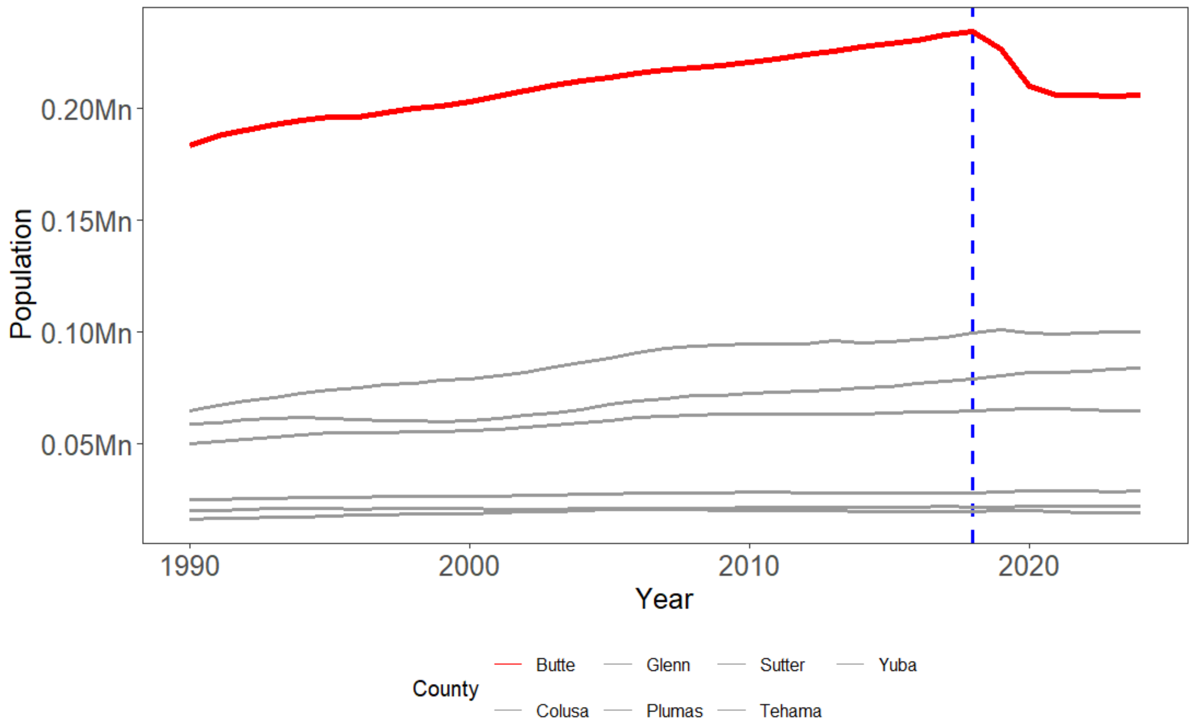

Figure 4.2.1: County-level population trends 1990 – 2023, around Camp Fire, 2018.[92]

[91] Cal Fire, "Watershed Emergency Response Team". Technical report, (2018).

[92] CCRS analysis from data retrieved from the US Census Bureau.

Applying the difference-in-difference analysis to the population trends identifies whether the Camp fire in 2018 was the cause of the population decline. Using the data from figure 4.2.1, this is applied to the difference in population trends for the affected Butte County, relative to the unaffected neighbouring counties.[93] *Treatment* is for the affected county, in this case Butte, for the entire time period, from 1990 to 2024. *Post* represents the post-event trend for all other neighbouring counties to Butte that were not affected by the Campfire in 2018. Finally, the variable determining if the Camp fire represented a significant impact on the population in Butte County is the difference-in-difference coefficient, *difference*

The findings are illustrated in table 4.2.1, which shows the results of the analysis when considering the post wildfire period at 3, 5, or 7 year intervals. Findings from the table confirm what is observed from the county population trends, which is that the population decline in Butte County after 2018 was due to the Camp fire.

Butte, 2018	**3-year**	**5-year**	**7-year**
Difference	-0.046	-0.074**	-0.084**
	(0.049)	(0.040)	(0.037)
Treatment	1.116***	1.124***	1.128***
	(0.021)	(0.021)	(0.021)
Post	0.093***	0.099***	0.103***
	(0.007)	(0.015)	(0.014)

*Table 4.2.1: Difference-indifference results of the impacts of the Camp fire in 2018 on population changes in Butte County compared to surrounding counties for 1990 to 2024 trends. *, **, *** indicate significance at the 0.05, 0.01, and less than 0.01 level.*[94]

The table shows the effect of the wildfires on the population trend for the affected county, in comparison to neighbouring, unaffected counties. *Difference* represents whether the wildfire had a significant impact on changing the trend for the affected county's population. *Treatment* represents the overall trend over the entire pre and post time period for the affected county,

[93] Equation denotes the log of population in each county *i* is taken in year *t*. Indicators are used for time and county to identify pre- and post- event, and affected county and unaffected county. *Treatment* is an indicator for the overall trend of the affected county for the entire period. *Post* is an indicator for the average trend for all other neighbouring counties unaffected by the wildfire. And *difference* is for the trend for the affected county after the wildfire to determine the change in direction of the trend, and if it significantly differs from the trend before the wildfire.

$$log(Population)it = \beta0+\beta1Treati + \beta2Postt + \beta3(Treati\times Postt) + \gamma jCounty\ Fixed\ Effectsj + \varepsilon it$$

[94] CCRS original analysis.

and *post* is the overall trend for neighbouring counties that were not affected by the wildfire. Findings from the table confirm what is observed from the county population trends, which is that the population decline in Butte county after 2018 was due to the Camp fire.

Results from table 4.2.1 are taken at three different post-event time windows. The first column only considers the effects on population 3 years after the Camp fire, which shows a small effect on the post-period population trend for Butte County, based on the coefficient under *difference* in column 1 for the 3-year time window, with a value of -0.046, representing a 5 percent decline in the population change after the wildfire. In the second column, the time window is extended to include 5 years after the event. There is an observable and significant decline in population in Butte, relative to other neighbouring counties that were not affected. The coefficient on the difference in the 5-year period indicates that Butte County experienced a 7.13 percent decline in population 5 years after the Camp fire, while other counties experienced a 10.4 percent growth in population in the same period. Finally, for the 7-year time window, which extends the post-period trend to seven years, the percentage population loss is highest, with the 7-year post-wildfire trend for Butte county's population loss at -8 percent relative to what the population trend would have otherwise been without the wildfire. Butte county, as illustrated in figure 4.2.1, was the largest county by population, which is represented by the population trend for the *treatment* group of Butte county, comparing the county's population trend to all other neighbouring counties. The value 1.128 represents an approximate 208 percent larger population size relative to the average population size of the neighbouring counties prior to the occurrence of the Camp fire. Finally, *Post* represents the average population trend for all other counties that were not affected since the wildfire event, with each column referring to the length of time included in the post-wildfire period. The positive and significant coefficients represent a population increase in the post-wildfire period. Overall, findings illustrate that there was a significant impact of the Camp fire leading to a loss of population that still has not recovered.

Section 4.3: Analysis: Population trends

Findings from Butte County and the Camp fire in 2018 provide an initial indication of the impacts of wildfires on population loss. Similar analysis is extended to other wildfire events, and additional measures of social and economic impacts. Prior to the Camp fire in 2018, the most devastating wildfire in California's history was the Tubbs wildfire that occurred in October 2017, burning over 36,000 acres, and causing extensive property loss and damage in Napa and Sonoma counties. The population trend for Napa County, with the year demarcating the Tubbs fire is illustrated in figure 4.3.1. From the figure, the impact on population following the wildfire is milder than the decline that was observed in the case of the Camp fire in Butte County. The decline is definitively established through the difference-in-difference analysis; see table 4.3.1.

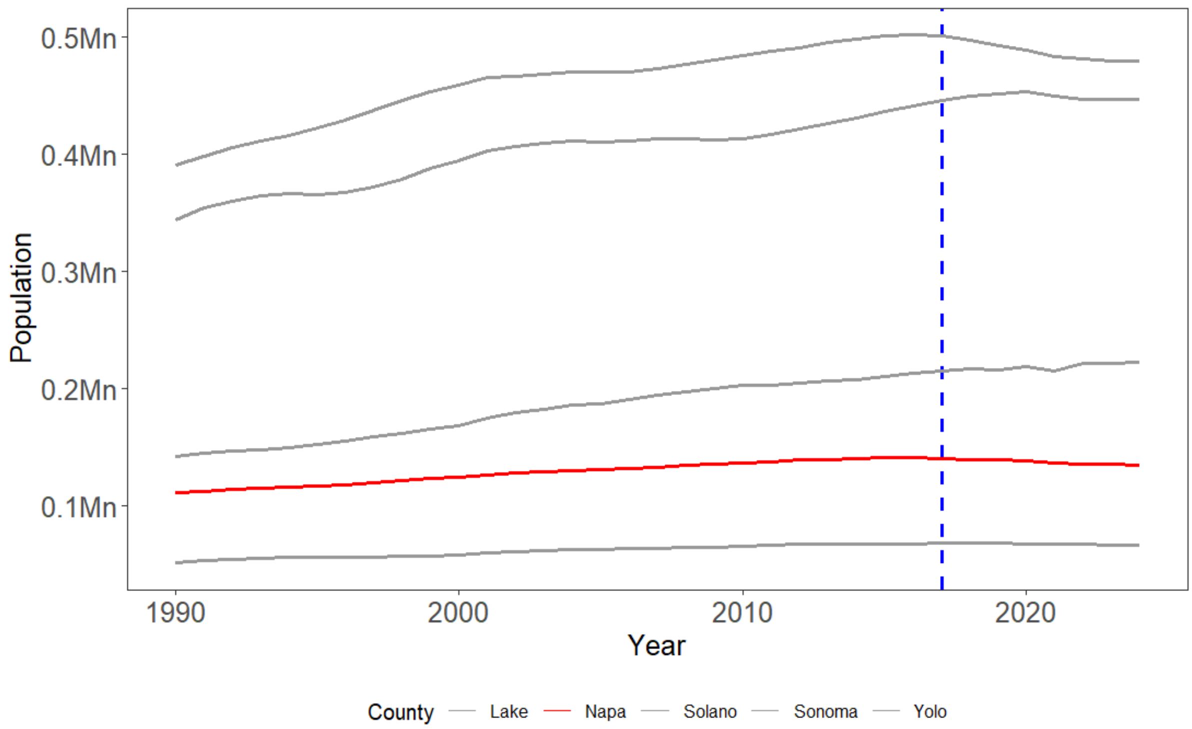

Figure 4.3.1: County-level population trends 1990 – 2023, around Tubbs Fire, October 2017.[95]

The table shows the effects for each of the trends for three wildfires. *Difference* represents whether the wildfire had an impact on the affected county's GDP, *treatment* representing the overall trend of the affected county, and *post* is the overall trend for neighbouring counties that were not affected by the wildfire. From the table, the effect of the Tubbs fire on population change in Napa county amounts to a loss of 4.8 percent, compared to over 8 percent loss in population from the Camp fire. Additionally, the effect took longer to hit Napa county, where there was no distinctive impact on the population trend until more than 5 years after the Tubbs fire.

[95] CCRS analysis from US Census Bureau.

Napa, 2017	3-year	5-year	7-year
Difference	-0.033	-0.041	-0.049*
	(0.054)	(0.043)	(0.037)
Treatment	0.737***	0.740***	0.745***
	(0.022)	(0.022)	(0.021)
Post	0.114***	0.119***	0.126***
	(0.024)	(0.019)	(0.017)

*Table 4.3.1: Difference-indifference results of the impacts of the Tubbs fire in 2017 on population changes in Napa county compared to surrounding counties for 1990 to 2024 trends. *, **, *** indicate significance at the 0.05, 0.01, and less than 0.01 level.*[96]

In order to observe the impact of wildfires across the entire state, this analysis has been extended to look at the impact of the largest wildfire that occurred in each of the 58 counties of California, and the impact that each wildfire had on the county's population up to 7 years since the wildfire event.[97] The impact on each county's population of the largest wildfire to occur in that county is shown across the state in figure 4.3.2.

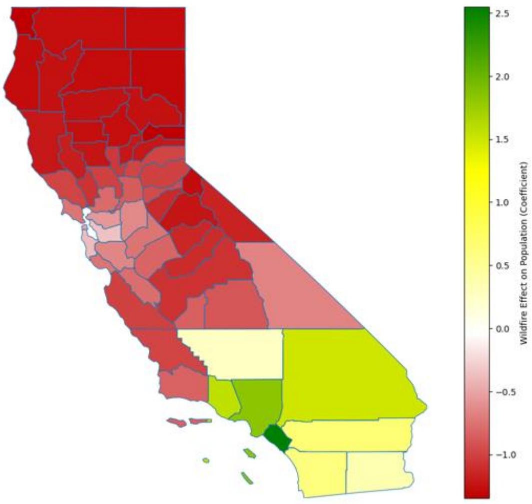

Figure 4.3.2 Impact of the largest wildfire that occurred between the years1990 to 2024 in each California county on the county's population for the following 7 years after the wildfire.

[96] CCRS original analysis.

[97] A rolling time window of 7 years is applied, since the time period for county population trends covers 1990 to 2024. For wildfires that happened relatively early in the period, the wildfire impact is not expected to last more than 5 years, but 7 years is added just to ensure that possible long-term impacts are sufficiently captured.

The figure illustrates the variability in the impact that wildfires can have on populations trends for counties across the state. Counties shown in red experienced more significant population decreases following wildfires than those in yellow or green. The greatest impact is visible in the more rural and less populated counties of Northern California. In contrast, the more urbanised and more populous counties of southern California and the Bay area do not show any distinctive impacts of wildfires on population change. Overall, the figure illustrates the variability in the impact that wildfires can have on the population of counties across the state.

While analysis has highlighted some of the largest wildfires in California's history and shown that they do have a significant impact on long-term reductions in population, this is only for the largest wildfires and, typically, the less populated counties. For example, in counties containing the largest cities and metropolitan areas, such as Los Angeles, San Francisco, or San Diego, there is not much of an impact. This suggests that wildfires have a fairly localised impact on communities, and that this impact is more noticeable in smaller communities, such as those of Northern California, compared to larger ones in Southern California. For communities along the WUI in California, whether impacts are absorbed and lost by the overall population of the county or if they appear to show a significant impact, it is these communities that are most impacted, but their effect is only distinguished if the county is part of the WUI, or if the county is rural.

Section 4.4: Analysis: GDP trends

Several studies have looked at the economic impact of wildfires using a variety of different measures but have primarily focused on estimating the economic damages caused by individual wildfire events. In 2003, there were three different wildfires that broke out around the San Diego area, the largest of which was the Cedar fire. Studies estimating the total direct and indirect damages used a variety of data sources and methods in order to determine the total amount of attributable direct and indirect damages from the wildfires, which amounted to 2.45 billion USD which corresponds to an average of 6,500 USD per acre burned. Of these totals, less than 2 percent of the entire economic impact was from suppression costs once the fire had started.[98] Separately, economic costs of wildfires have also been estimated in terms of specific sectoral costs to local communities, such as medical costs to hospital admissions directly resulting from a wildfire. Kochi et al. (2016) looks at hospitalisations from wildfire smoke exposure in 2007 using a time series count model and a negative binomial model to determine outlying hospitalisations related to wildfire exposures. Findings show that 2007

[98] Matt Rahn, "Wildfire impact analysis", *Fire Impact Analysis,* San Diego State University (Spring, 2009).

wildfire smoke led to a total medical cost of over USD 3.4 million USD; however, these added costs actually appear as increases to GDP via higher expenditure.[99]

Similar studies have focused on economic damages looking at specific types of damages such as the economic costs of the loss of forest timber, the changes in wildfire suppression budgets, and the recovery costs.[100] Other studies have looked at similar types of indirect impacts such as the decrease in production activities, the increase in travel times, and the loss of tangible and intangible assets, such as tourism resources. These studies have emphasised the importance of measuring not only the primary impacts, but also the secondary linkages and damages. In general, economic studies of wildfires have done specific analysis that looks at a variety of different direct and indirect losses and expenditure, which have identified a significant impact on higher costs, but these have remained focused on more specific wildfire events or types of damages. Studies have focused on individual categories of damages, which require extensive data and methodologies to isolate and determine damages that are specifically attributable to wildfires.

In this section, analysis considers instead simply the broader impact of wildfires on the county economy in a similar analytical set up to that used to analyse the population impact of wildfires. While other studies have emphasized the secondary impacts on other sectors such as accommodation, food services, wholesale and retail trades, transportation, and storage, all of these sectors are considered in aggregate in terms of the broader effects on county-level GDP.

GDP values have been collected at the county-level from California for the same period from 1990 to 2024, which are similarly available from the US Census Bureau. Trends in GDP are analysed in the same model framework of a difference-in-difference estimation, which compares the GDP of a county affected by a wildfire in a given year, to the GDP of neighbouring counties that were not affected. Trends in GDP are observed for the Camp fire in Butte County, and for the Tubbs fire in Napa and Sonoma counties, the most damaging and the second most damaging wildfires in California's history in figures 4.4.1 and 4.4.2, respectively.

GDP values have been collected at the county-level from California for the same period from 1990 to 2024, which are similarly available from the US Census Bureau. Trends in GDP are analysed in the same model framework of a difference-in-difference estimation, which compares the GDP of a county affected by a wildfire in a given year, to the GDP of neighbouring counties that were not affected. Trends in GDP are observed for the Camp fire

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99 Leslie Richardson, John B. Loomis, Patricia A. Champ, "Valuing morbidity from wildfire smoke exposure: A comparison of revealed and stated preference techniques", *Land Economics* 89, no. 1 (Feb., 2013), pp. 76 – 100.

100 D. Evan Mercer, John M. Pye, Jeffrey P. Prestemon, David T. Butry, and Thomas P. Holmes, "Economic effects of catastrophic wildfires: Assessing the effectiveness of fuel reduction programs for reducing the economic impacts of catastrophic forest fire events", *US Forest Service, Southern Research Station* (2000).

in Butte County, the Tubbs fire in Napa and Sonoma counties, and the Valley fire in Lake County, the most damaging, the second most damaging, and the third most destructive wildfires in California's history in figures 4.4.1, 4.4.2, and 4.4.3 respectively.

Comparing county-level GDP trends, and highlighting the wildfire event, there is some evidence for an impact of wildfires on GDP. First, the break in the trend is clearer in the case of the Camp fire in Butte County, than in the Tubbs fire on Napa County. In both cases, the GDP trend for the affected county does not grow at the same rate as the trend observed for neighbouring counties. In the case of the Tubbs fire, neighbouring counties such as Solano appear to have more rapid GDP growth following the Tubbs fire compared to before. For the affected Napa County, the trend shows that stagnation or decline is more dominant than growth. While the figures suggest an effect of wildfires on GDP, this is more formally analysed in the difference-in-difference model, which is applied to GDP data, and the results on three wildfires are illustrated in table 4.4.1.

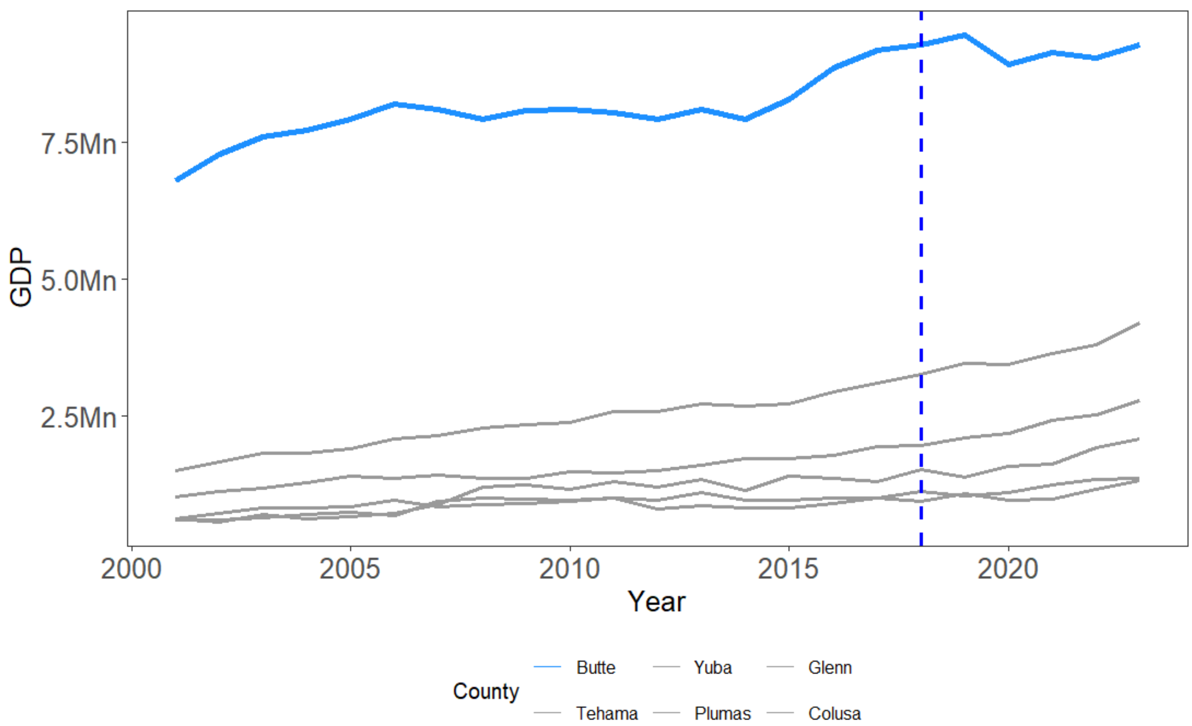


Figure 4.4.1: County-level GDP trends 2000 – 2023, around Camp Fire, November 2018.[101]

[101] CCRS analysis from data provided by the US Census Bureau.

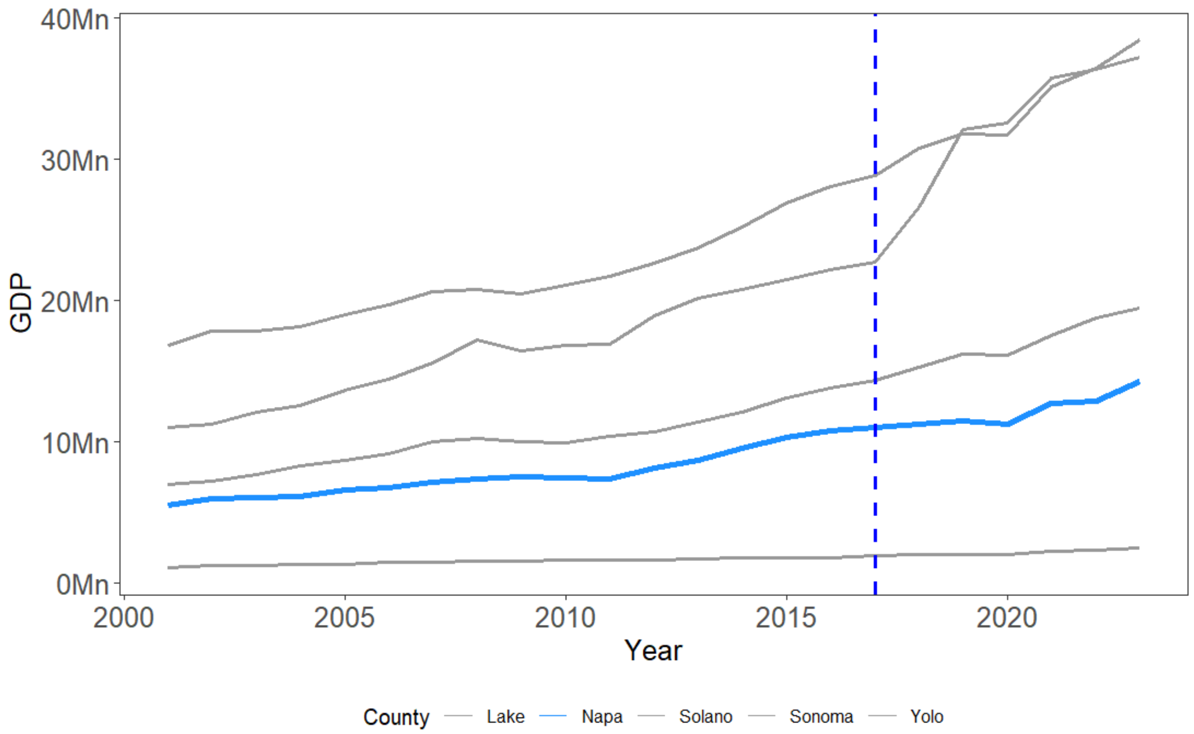
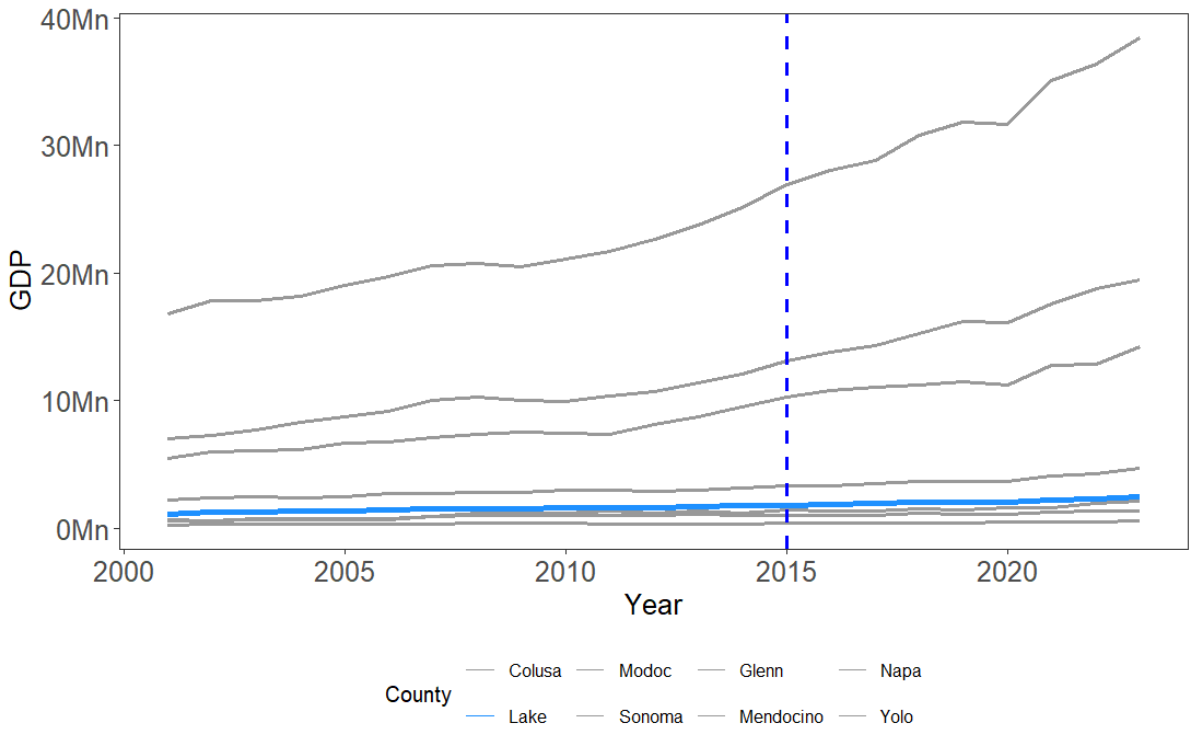


Figure 4.4.2: County-level GDP trends 2000 – 2023, around Tubbs Fire, October 2017.[102]



102 CCRS analysis from data provided by the US Census Bureau.

Figure 4.4.3: County-level GDP trends, 2000 – 2023, around the Valley Fire, September 2015.[103]

From the table, the only wildfire that had a significant impact on GDP was the Camp fire. The significant and negative coefficient indicates that Butte county's GDP trend was approximately 20.1 percent lower than the GDP it would have been were it not for the Camp fire. This is consistent with the decreasing population trend in Butte that has also been observed following the Camp fire.

However, this negative GDP impact does not hold in the case of the other two wildfires included in the table, which are the Tubbs fire in Napa, and the Valley fire in Lake county, which occurred in September 2015. Although the table shows a negative GDP effect following wildfires in both counties, this finding is not statistically significant. This is also illustrated by the much smaller value of the coefficient, which is only 4 percent and 6 percent loss in GDP, respectively. Trends for *treatment* across wildfires shows that the affected county had a significantly higher and growing GDP relative to the other unaffected counties prior to the wildfire. Values for the *post* trend show that GDP for the unaffected counties was also growing significantly, and that over the period the neighbouring counties grew on average at approximately 43.9, 67.7, and 52.35 percent respectively. Hence, in the case of the Camp fire, this represents a significant loss in GDP, whereas for the Tubbs and Valley fire, this does not represent as great of a loss of GDP.

Trends on the GDP impacts of wildfires differ to what has been observed on population. While previous analysis on population has shown a more consistent and significant impact of wildfires in terms of population decline, this is not as consistently observed in the case of GDP. The only case where consistency between population decline and GDP loss is observed is in the case of the Camp fire. Otherwise, previous analysis has shown a significant impact of population loss from the Tubbs fire, but not a similar effect on GDP of Napa County. While Napa is a more populous and higher GDP county compared to Lake County, the Valley fire that affected Lake County also does not appear to have a significant impact on GDP.

Wildfire:	**Camp**	**Tubbs**	**Valley**
Difference	-0.224**	-0.041	-0.062
	(0.053)	(0.099)	(0.087)
Treatment	1.233***	1.657***	0.412***
	(0.059)	(0.061)	(0.059)
Post	0.364***	0.517***	0.421***
	(0.035)	(0.044)	(0.031)

[103] CCRS analysis from data provided by the US Census Bureau.

*Table 4.4.1: Difference-indifference results of the impact of wildfires on GDP changes in affected counties compared to surrounding counties for 2000 to 2024 trends for the 7-year post-wildfire period. The affected county in the Camp fire was Butte, in the Tubbs fire it was Napa, and in the Valley fire it was Lake County. *, **, *** indicate significance at the 0.05, 0.01, and less than 0.01 level.*[104]

The analysis that has been done in table 4.4.1 is similarly extended to all counties of California. For each county, the largest wildfire to hit the county between 2000 to 2024 is analysed according to the impact on GDP in the 7 years after the event. The effect of the *difference* this had on having any effect on the county's GDP following the wildfire is plotted for each county in figure 4.4.4. From the figure a similar pattern of the effects of wildfires on GDP are observed as that for population, as we now explain:

Counties incorporating major metropolitan areas, represented by Southern Californian cities such as Los Angeles, San Francisco, and San Diego, do not show any negative impacts on GDP (or population trends) of wildfires. In contrast, the counties of Northern California experience negative impacts on GDP (and population trends) after wildfires. This is surprising, considering that the counties of Southern California have been exposed to serious wildfires, and are extensively vulnerable due to the climate, so a higher vulnerability risk, but also due to higher exposure risk since Southern California has some of the largest metropolitan areas, as well as extensive urban sprawl from the cities that extend into the WUI. Reports and studies have also demonstrated extensive damages and high economic costs from wildfires occurring across Southern California, including the Cedar fire in San Diego in 2003, the Woolsey fire in Los Angeles and Ventura counties in 2018, and most recently the Palisades fire in Los Angeles county in January 2025. These wildfires are some of the most destructive in the entire state's history, because they destroy so many structures, and cause so much disruption to the economy. Yet these wildfire events do not appear to have significantly or even negatively disrupted the overall economic growth trend of the counties of Southern California in a similar way as they have affected counties of Northern California. This is most likely due to the overall economic size of the counties and cities of Southern California.

[104] CCRS original analysis.

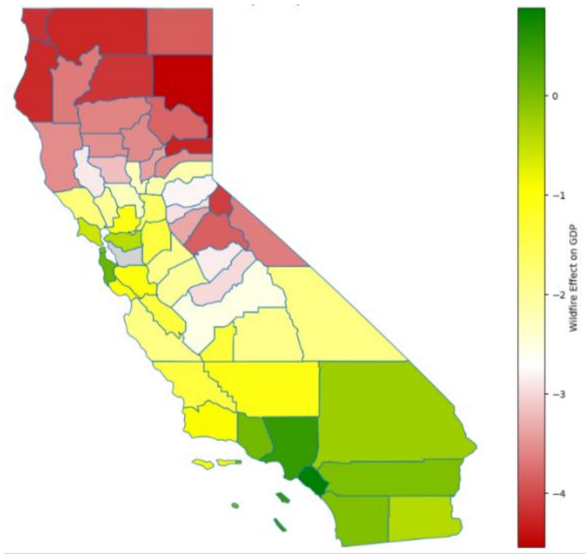


Figure 4.4.4: Impact of the largest wildfire in each county on GDP, 2000 to 2024.

While counties of Northern California show greater negative impacts of population and GDP from wildfires, these counties have much smaller populations and are more rural. Hence, a devastating wildfire represents a much larger impact on the local society and economy as a share of the overall county relative to those of Southern California, since the cities and population is so much larger. While wildfires across the state can be devastating to local communities, even destroying entire towns along the WUI in Southern California, the effects that this loss would have on the population or GDP of counties in Southern California would still be relative small compared to the overall size of the economy or population of somewhere like Los Angeles or San Diego counties. Hence, although there is some evidence that wildfires may have an effect on reducing the rate of population or GDP growth, this effect is not significantly or consistently observed across all counties.

Instead, what is observed is that wildfires can have a significantly negative impact on reducing a county's population and GDP, if the wildfire is large and destructive enough, such as the Camp fire. Moreover, whether wildfires will have more of a long-run impact on a county or state's economy or population, the size of insurance losses to date suggest that the apparent increase in size and frequency of wildfires is an increasing and significant concern to settlements and building stock.

Section 4.5: Analysis: County vulnerabilities

Previous analysis has identified a high variability in the impact of wildfires based on different social and economic characteristics of California counties. In general, more rural and poorer counties of northern California appear to suffer greater losses in terms of both population and GDP compared to southern and more urban counties. These findings have been similarly observed in other studies observing that low-income communities are at a greater risk of suffering effects from wildfires for a variety of reasons, including that these communities are less well-protected from wildfires, and more vulnerable to severe losses.[105]

A study by Reining et al. (2025) looks at 16 California counties with 2.9 million buildings from 2013 to 2021, and found that homes classified as disadvantaged by the US government are 29 percent more likely to be destroyed by wildfires, within 30 years of the homes being built, compared to homes in wealthier communities. The study further concludes that this is largely due to the added costs and expenditure on preventative and protective measures that poorer communities are less likely to implement. For example, roof replacements enable greater resilience for buildings, and the absence of these types of modifications leads to homes and communities being significantly more exposed to wildfire damage. Roof renewal rates increase by 17 percent in wealthier communities following a wildfire event, whereas in poorer communities, the implementation of roof renewal was only 7 percent.[106]

The ability to implement protective measures in the housing stock is ultimately related to costs and discretionary spending of the owners, however it has wider implications for wildfire damage. As individual home owners increase investment in protective and preventative measures for wildfire resistance, each additionally protected home provides collective benefits to the entire community for added resistance.[107] However, the inverse is also true, where the absence of one home's fire protection becomes a greater common threat, as the home provides further fuel for a wildfire to continue burning through the community. When neighbours and communities adopt fire-resistant upgrades, the overall fire resilience of the area improves.[108]

In order to assess the economic discrepancies in wildfire damages and protection, this study compares findings on GDP and population loss effects from wildfires according to the county-level economic inequality based on GDP per capita. While inferences of disparities in wildfire impacts have been suggested based on the greater impacts of wildfires in northern compared to southern counties, this is more formally established by analysing counties according to GDP per capita as a measure of economic inequality between counties. Figure 4.5.1 illustrates the GDP per capita in 2023 of each California county.

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[105] Maria-Luisa Chas-Amil, Emilio Nogueira-Moure, Jeffrey P. Prestemon, and Julia Touza, "Spatial patterns of social vulnerability in relation to wildfire risk and wildland-urban interface presence", *Landscape and Urban Planning* 228 (2022).

[106] Sebastian Reining, Moritz Wussow, Chad Canocco, and Dirk Neumann, "Roof renewal disparities widen the equity gap in residential wildfire protection", *Nature Communications* 16, no. 463 (2025).

[107] Chad Zanocco, "Social and economic disparities impact wildfire protection", *Stanford University Woods Institute for the Environment* (2025).

[108] Eric Steffey, Megha Budruk, and Christine Vogt, "The mitigated neighbourhood: Exploring homeowner association's role in resident wildfire-mitigation actions", *Journal of Forestry* 188, no. 6 (Nov., 2020), pp. 613 – 624.

The figure illustrates the range and distribution of GDP per capita across counties in California. First, the highest GDP per capita counties are concentrated in the Bay Area around San Francisco. Second, counties of the southern California coastline have high GDP per capita, but lower than the Bay Area. Third, counties of the Central Valley and northern California have the lowest GDP per capita. Overall, the distribution reflects a similar urban and rural divide across the state.

Comparing counties by GDP per capita along with the impact of wildfires on population loss, based on previous analysis illustrated in figure 4.3.2, measures the vulnerability of counties based on long-run population loss according to economic disparities. Matching counties according to GDP per capita and the county-level impacts of wildfires on population loss from previous analysis, highlights the relationship between county-level economic disparity and the vulnerability of a county to population loss from wildfires. This is illustrated in figure 4.5.2, which shows that all the values are negative, or below 0 on the *y*-axis, as taken from previous figure 4.3.2 showing the impact of wildfires of long-run population loss by county, indicating that wildfires have a negative effect on population, or population loss. Although as previously discussed, this effect is not always significant for every county. Counties with a high GDP per capita generally show less of an effect on population loss compared to counties with a lower GDP per capita, where there is greater population loss from wildfires.

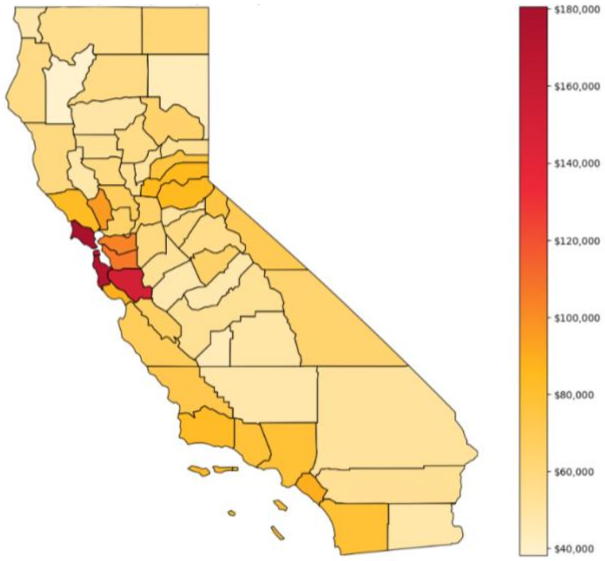

Figure 4.5.1: GDP per capita by county in USD, 2023.[109]

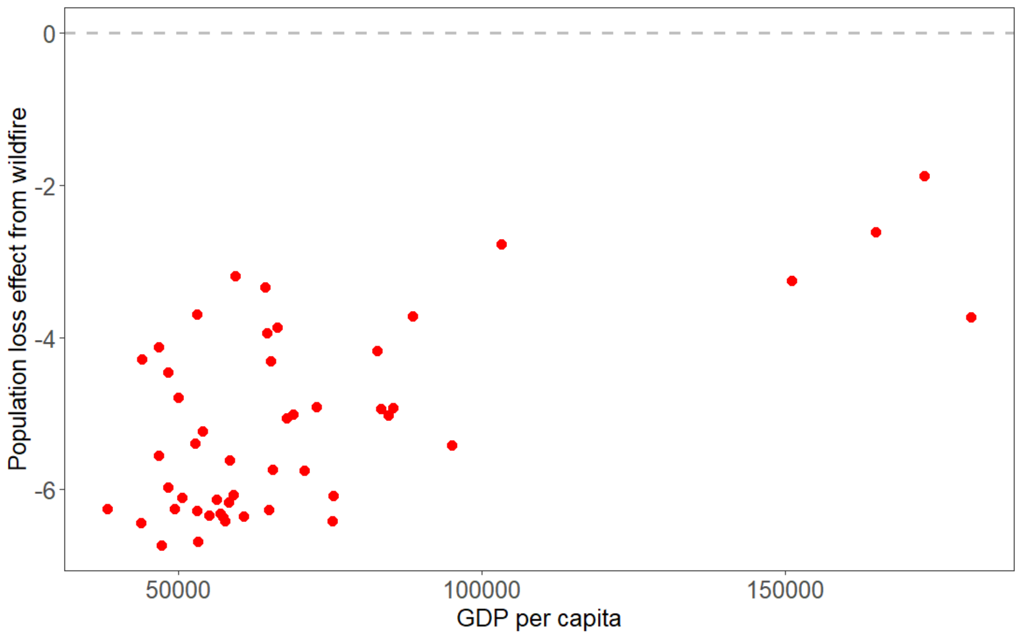

Figure 4.5.2: County-level GDP per capita and population loss effects 7 years after wildfire event.[110]

The correlation of these two variables has a coefficient of 0.62, and is significant at the <1 percent level. This suggests that there is a moderate, but significant positive relationship between GDP per capita and population loss from wildfires. The correlation demonstrates that counties with higher per capita GDP are less likely to see a population loss after a wildfire relative to counties with a lower GDP per capita. This finding is reflective of other studies that have demonstrated that poorer counties are more vulnerable to wildfire damage and impacts compared to wealthier counties.[111]

This analysis is further extended to compare GDP per capita to the wildfire effects on county-level GDP. While our analysis above has demonstrated that the impacts of wildfires on the county-level economy are not large nor generally significant, the impacts for each county have been previously plotted in figure 4.4.4 showing the magnitude of effects for each county, regardless of the significance. Findings suggest that there may be a relationship between the GDP per capita of the county compared to the impacts a wildfire has on economic loss. The relationship between these two variables is similarly plotted in figure 4.5.3.

The figure shows a similar distribution for GDP effects as observed for population effects. Broadly, the higher the county-level GDP per capita moving across the *x*-axis, the lower the GDP loss is as the values approach the zero *y*-axis. For counties at a lower GDP per capita,

[109] CCRS analysis from data provided by US Census Bureau, 2025.
[110] CCRS own analysis.
[111] Sarah E. Anderson, Andrew J. Plantinga, and Matthew Wibbenmeyer, "Inequality in agency response: Evidence from salient wildfire events", *Journal of Politics* 85, no. 2 (Apr., 2023), pp. 625 – 639

there is a wider range of effects, with some showing a significant and large negative impact of wildfires on GDP loss. However, this range is high, since several counties at a lower GDP per capita also show lower loss effects from wildfires. The correlation of these two variables is 0.48, and is significant at the <1 percent level. Similar to the relationship with population, the correlation is significant and positive, where in the case of negative values this indicates that the wealthier the county by higher GDP per capita, the less of an effect from wildfires. In comparison to population loss, the value is lower, indicating that there is a stronger relationship of population loss to GDP per capita, rather than county-level GDP loss to GDP per capita. This is broadly consistent with the overall findings that wildfires have a greater impact on population loss, and less so for GDP loss, since the distribution of population loss effects per county are not as widely distributed, and fit a closer relationship to other county features, rather than the distribution of GDP loss effects which are generally less significant and closer to zero.

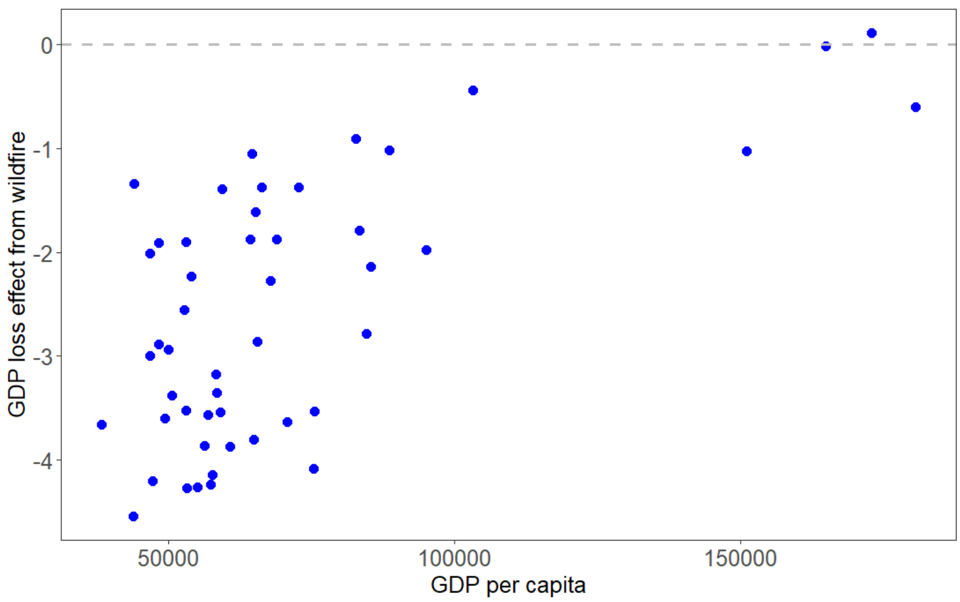

Figure 4.5.3: County-level GDP per capita and GDP loss effect for 7 years after wildfire.[112]

Analysis of the relationship between county-level GDP or population loss effects, in comparison to the overall GDP of the county, confirm findings that wildfires have a disproportionately higher damaging effect on lower GDP per capita areas compared to more productive, and higher GDP per capita ones. This finding is consistent with several other studies showing that lower GDP per capita areas suffer the most structural damage compared to higher GDP per capita areas.[113] Case studies have supported this analysis and have found that there are higher vulnerabilities in poorer communities due to a lack of resources for

[112] CCRS own analysis.

[113] Miyuki Hino and Christopher B. Field, "Fire frequency and vulnerability in California", *PLOS Climate* 2, no. 2 (2023).

effective post-wildfire recovery and rehabilitation. The discrepancy in wildfire damages by GDP per capita may stem from various factors such as differences in public investment in risk reduction projects, unequal firefighting priorities, and the impact of repeated wildfires affecting the same areas, adding to repeated expenses and the loss of accumulated wealth.[114] Conversely, other studies have identified the potential for reverse causality, where social and economic factors contribute to a rise in wildfire incidents due to rural abandonment and subsequent arson.[115] Although this analysis has not attributed particular causality to heightened vulnerability for lower-income areas, it has identified economic disparities and wildfire vulnerability by comparing the differences in effects across California based on county-level information.

While other studies have looked specifically at individual wildfire events, or at particular localised areas in order to compare damages based on highly-granular spatial measures of wealth or income for individual households, property values, or communities affected by wildfires, this study has taken a higher-level approach across California. Despite the result that wildfires do not generally have a significant impact on GDP loss across an entire county, but are more localised to towns or communities, the fact that the difference in the county-level magnitude of GDP or population loss is still significantly correlated with county-level GDP per capita indicates that poorer and lower productivity counties are much more vulnerable to long-run impacts from wildfires in terms of population and GDP loss. These findings support the broader evidence from the distribution of wildfire effects across the state, where counties of northern California are more vulnerable to losses from wildfires compared to more urban and wealthier counties in southern California. This finding supports other studies that have looked at the reasons for this disparity in wildfire damages, with findings focused on costs and expenditure of state, county, and local agencies to adequately allocate fire prevention measures, for individual households to equip structures with fire resistant or preventative material, and for local authorities to manage wildlife and vegetation to prevent wildfires.

Section 4.6 Wildfire effects for disadvantaged communities

The definition of Disadvantaged Communities (DACs) varies by state. Such communities are typically defined as those having median income less than 80% of the State average. In practice this definition can suffer from biases (such as nearby richer areas dragging the median up).[116] The California Environmental Protection Agency have therefore created a more robust

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[114] Andrew J. Plantinga, Randall Walsh, and Matthew Wibbenmeyer, “Priorities and effectiveness in wildfire management: Evidence from fire spread in the Western United States”, *Journal of the Association of Environmental and Resource Economists* 9, no. 4 (Jul., 2022), pp. 603 – 639.

[115] Shahir Masri, Erica Scaduto, Yufang Jin, and Jun Wu, “Disproportionate impacts of wildfires among elderly and low-income communities in California from 2000 – 2020”, *International Journal of Environmental Research and Public Health* 18, no. 3921 (2021).

[116] Bay Area IRWMP. 2024. *Disadvantaged Community Dashboard*.

definition creating an index that considers pollution, and population characteristics. Areas with the top 25% of the index are designated as DACs with some additional areas added, figure 4.6.1 shows the current map of Disadvantaged communities in California.[117]

Figure 4.6.1: Disadvantaged communities in California Source.[118]

Many studies show that disadvantaged communities are more affected by wildfires than average. The number of highly vulnerable people exposed to wildfires in West Coast states increased 2.5x between the first and second decades of this century.[119] It is 29% more likely that a home will be destroyed by wildfires if it is in a DAC and 54% of homes destroyed in Californian wildfires are in low-income homes.[120] There is a clear link between socioeconomic status and the probability of fires starting.[121] One study showed that incomes in high fire hazard areas tend to be 27% higher than average i.e. wealthier than average people tend to live in the WUI, although such regions still contain 12% below poverty levels on average.[122] The same study also found that incomes in communities that had experienced multiple fires were 17% lower than average. Those with lower incomes have less capacity to adapt to growing wildfire risks.[123] Building codes standards chapter 7A recognises the crucial role of fire-resistant roofing to prevent the spread of wildfires yet the rate of roof renewals is 28%

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[117] UC Riverside. 2024. *CalEnviroScreen 4.0 Summary.*

[118] OEHHA. 2024. *CalEnviroScreen SB535 Update.*

[119] Hino, M., and C.B. Field. 2023. "Fire Frequency and Vulnerability in California." *PLOS Climate* 2(2): e0000087.

[120] Reining, S., et al. 2025. "Roof Renewal Disparities Widen Equity Gap in Wildfire Protection." *Nature Communications* 16: 463.

[121] Sultan, V., and T. Kom. 2024. "Socioeconomic Status and Wildfire Risk." *International Journal of Advanced and Applied Sciences.*

[122] Hino, M., and C.B. Field. 2023. "Fire Frequency and Vulnerability in California." *PLOS Climate* 2(2): e0000087.; Wang, Z., et al. 2022. "Cost Allocations for Equitable Wildfire-Resilient Grids." *Nature Energy.*

[123] Auer, M.R. 2021. "Considering Equity in Wildfire Protection." *Sustainability Science* 16: 2163–2169.

lower in DACs than elsewhere.[124] Most of the subsidized housing (75%) in WUI areas are found in Los Angeles, San Diego or San Francisco where residents may have higher than average vulnerability.[125] Black and Native American people often live in counties with higher wildfire risks than other groups.[126] Rural areas are 3x more likely to be exposed to wildfires but typically have a higher proportion of people living in poverty, suffering unemployment and lower than average education levels.[127] A study of the Eaton fire showed that a higher proportion of black residents lived in declining quality property in the fire footprint, that they are more financially burdened so less able to recover after the fire and were 30% more likely to experience major damage in the event.[128]

Combatting wildfires requires substantial resources including firefighting personnel and equipment like aircrafts and ground-based fire engines. Studies have shown that those in poorer communities are allocated few of these resources when wildfires strike.[129]

Overground electricity infrastructure is more susceptible to fires but moving this below ground is costly and tends to occur in more affluent neighbourhoods. In fact, the rate of undergrounding nearly doubles in higher income areas. The electricity infrastructure in poorer regions appears more fire susceptible too, the use of wooden poles compared to concrete, and a higher prevalence of less well controlled tree canopy amplifies the risk in these areas. [130]

In California the Hispanic community has a lower average income level than average.[131] Timely evacuation and other relevant multilingual information is sometimes not made available to them.[132] Limited ability to speak English can also reduce the speed of recovering after a disaster.[133] Evacuation is also a concern for the elderly; the number of fire deaths is 2.5x higher for the over 65s than the younger population rising to 3.5x for the over 85s.[134]

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[124] Reining, S., et al. 2025. "Roof Renewal Disparities Widen Equity Gap in Wildfire Protection." *Nature Communications* 16: 463.

[125] Wang, Z., et al. 2022. "Cost Allocations for Equitable Wildfire-Resilient Grids." *Nature Energy*.

[126] Hwang, E., and A. Meier. 2022. "Wildfire Risk and Socioeconomic Characteristics Using GIS." *Journal of Geographic Information Systems*.

[127] Masri, S., et al. 2021. "Disproportionate Impacts of Wildfires on Elderly and Low-Income Communities." *International Journal of Environmental Research and Public Health* 18(8): 3921.

[128] Ong, P., et al. 2025. "LA Wildfires: Impacts on Altadena's Black Community." UCLA Ralph J. Bunche Center.

[129] Technology Networks. 2024. "Wildfire Rescue Resources Favor Wealthy Communities in California."

[130] Wang, Z., et al. 2022. "Cost Allocations for Equitable Wildfire-Resilient Grids." *Nature Energy*.

[131] Placer County. 2024. *Demographic Dashboard Data*.

[132] Davies, I.P., et al. 2018. "Unequal Vulnerability of Communities of Color to Wildfire." *PLOS ONE* 13(11): e0205825.

[133] Flanagan, B.E., et al. 2011. "A Social Vulnerability Index for Disaster Management." *Journal of Homeland Security and Emergency Management* 8.

[134] FEMA. 2024. *Deaths and Injuries Among Older Adults in Wildfires*.

There is evidence of post-traumatic stress amongst children following wildfires.[135] Adults too can face impaired mental health caused by post wildfire effects such as forced relocation and job losses.[136] There is strong evidence of association between wildfire smoke exposure and adverse respiratory impacts, in particular for those with COPD and asthma, increasing the risk of hospitalisations.[137] The pollutants caused by wildfires including particulates and gases are a risk factor for adverse cardiovascular effects.[138] Such health impacts have been found to be worse for those in areas of high deprivation allowing for education, employment, housing quality and poverty levels.[139]

In summary, poorer residents in California are more likely to see their home destroyed by wildfires and have less capacity to adapt in advance. Deprived areas have electricity infrastructure that is more likely cause a fire. Less firefighting resources are allocated to poorer areas during a fire. Multilingual evacuation advice may not be available affecting some ethnic groups who tend to be less affluent. Those with less financial resources are also less likely to be able to recover after a fire. Health effects from wildfires can affect anyone but vulnerable communities see larger effects and older residents are significantly more likely to die in a fire

[135] McDermott, B.M., et al. 2005. "PTSD in Children Following Wildfire Disasters." *The Canadian Journal of Psychiatry* 50(3): 137–143.

[136] National Academy of Medicine. 2025. *Climate, Health, and Wildfires*.

[137] Reid, C.E., et al. 2016. "Health Impacts of Wildfire Smoke Exposure." *Environmental Health Perspectives* 124: 1334–1343.; Gan, R.W., et al. 2020. "Asthma-Related Medical Use During Oregon's Wildfire Season." *Journal of Exposure Science and Environmental Epidemiology* 30: 618–628.; Rizzo, L.V., and M.C.F.V. Rizzo. 2025. "Wildfire Smoke and Health Impacts: A Narrative Review." *Jornal de Pediatria* 101(Suppl. 1): S56–S64.

[138] Chen, H., et al. 2021. "Cardiovascular Health Impacts of Wildfire Smoke." *Particle and Fibre Toxicology* 18.

[139] Wei, Y., et al. 2025. "PM2.5 Exposure and Hospitalization Risk." *Epidemiology*.

Section 5: Recovery after a wildfire

Section 5.1: Introduction

Previous sections have identified that the number of WUI communities affected by wildfire is increasing, and that wildfires can have significant impacts on the society and economy. Analysis has demonstrated that urban sprawl and development in California over the past 25 years has continued to spread into the WUI, which is at high risk from wildfires, and threatens further potential destruction. Additionally, analysis has illustrated some long-term consequences of wildfires including reducing the rate of GDP and population growth at the county-level, and that the impacts of wildfires vary significantly by county, with poorer and more rural counties of northern California more negatively affected by wildfires than wealthier and more urban counties of southern California.

While analysis has been able to look at long-term trends in increased wildfire exposure through the expanding urban sprawl and growth of the WUI, as well as trends in population and GDP, these trends have been observed at higher levels across the entire state, and at longer time intervals, such as 25 year or 30-year trends. Although wildfires can have significant implications for population loss and GDP for an entire county, the impacts are generally more localised to towns or communities, with shorter term impacts, rather than over decades. However, community-wide studies of structural recovery rates after wildfires vary widely depending on economic conditions, the extent of damage, and whether building codes are improved. Hence, overall rates of rebuilding and the construction of new developments in local communities after wildfires have provided ambiguous evidence of post-fire adaptation. On the one hand, studies have shown that only 25 percent of buildings destroyed by wildfires across the US are rebuilt within 5 years, which may indicate some degree of adaptation as developers try to avoid redevelopment in areas that are highly vulnerable to wildfire risk.[140] On the other hand, studies have shown that rates of construction of new buildings after a wildfire are similar within a previous wildfire perimeter and for the wider county that was not affected by the wildfire. This has been observed in several cases, e.g., a study by Eriksen and Simon (2017) has found that following the 1991 Oakland Hills Fire, which was the most destructive fire in California until 2017, that rebuilding within the wildfire perimeter was common, as were increases in the size of rebuilt houses.[141] This results in a higher likelihood of home-to-home wildfire spread, so increasing wildfire risk in an already vulnerable area. This suggests a lack of adaptation as in some cases of post-wildfire recovery, the occurrence of a wildfire event does not discourage continued re-development into high wildfire risk areas.

[140] Patricia M. Alexandre, Miranda H. Mockrin, Susan I. Stewart, Roger B. Hammer, and Volker C. Radeloff, "Rebuilding and new housing development after wildfire", *International Journal of Wildland Fire* 24 (2015), pp. 138 – 149.

[141] Christine Eriksen and Gregory Simon, "The affluence – vulnerability interface: Intersecting scales of risk, privilege and disaster", *Environmental Planning A* 49, no. 2 (2017), pp. 293 – 313.

Hence, the issue of changing development over time is critical, because risk perception from wildfires diminishes over time as wildfire events fade from collective memory, vegetation regrows, and infrastructure is restored. While the rate of recovery is important in terms of community redevelopment and continued economic growth, so are considerations of adaptive measures, which can be observed both in terms of the extent of redevelopment within the burn area of the wildfire, as well as rate of growth of nearby towns and communities that are not within the wildfire perimeter. While studies have looked at community and building recovery rates after a wildfire with mixed results, there are few studies that have considered the spatial patterns of development relative to wildfire risk based on the rebuild within or adjacent to a wildfire event. Additionally, due to the lack of data availability, particularly when it comes to specific neighbourhoods or properties, as well as the collection of data over time, the time periods for analysis of rebuild and recovery after a wildfire are often on longer-term time scales such as 5 years to 20 years.[142] However, the process of recovery and rebuilding on such long timescales means that other factors become more important to determining redevelopment rather than the effect of the wildfire, such as broader economic growth, urbanisation, property values, interest rates, pre-existing infrastructure, zoning and administrative changes. This is particularly true in California due to its economic size and rate of population and economic growth. Hence, this study looks at the rate of recovery and rebuild for wildfire affected areas both directly destroyed by the wildfire, as well as for the broader adjacent community.

Section 5.2 Methodology

While several studies have looked at the community pattern of rebuild and recovery from wildfires, these studies have been limited in scope due to limited information on the number of structures destroyed by wildfires, as well as the location and type of rebuild following a wildfire.[143] More recently, several studies have taken advantage of satellite imaging in order to use a consistent measure and dataset to observe changes in development over time, with a sufficient granularity to use a monthly time series to observe wildfire affected communities from one month after a wildfire to 3 years. Satellite imagery is used in this analysis to observe rate of recovery in shorter time intervals than what would otherwise be available from satellite imaging and geospatial data.

Studies have used satellite imaging and supplemented images with machine learning techniques to convert image recognition into geospatial data. For example, a recent study uses high-resolution satellite imaging to identify individual buildings within neighbourhoods of

[142] H. Anu Kramer, Van Butsic, Miranda H. Mockrin, Carlos Ramirez-Reyes, Patricia M. Alexandre, and Volker C. Radeloff, "Post-wildfire rebuilding and new development in California indicates minimal adaptation to fire risk", *Land Use Policy* 107 (2021).

[143] Emma E. Sloan, Reem Hajjar, and Emily Jane Davis, "Equity in resilience: A case study of community resilience to wildfire in southwestern Oregon, United States" *Ecology and Society* 30, no. 1 (2025).

towns to determine those that were destroyed by wildfires, and structures that remain standing, in order to observe the rate of recovery, and the types of buildings that are rebuilt.[144] Similarly, satellite imagery is applied to observe recovery and rebuild after a wildfire for several wildfire events across California.

Instead of using highly granular satellite images to identify individual buildings or structures in a neighbourhood that were destroyed by a wildfire, and the observation of individual plot rebuild over time, we use satellite imaging to measure nightlight luminosity data for an entire town or community at a resolution of 500 square metres. In a similar way that satellite images are converted into geospatial data based on machine learning techniques to identify specific features to individual plots of land within a neighbourhood or housing subdivision, measures of nightlight luminosity are also used as geospatial data as a proxy for level of urbanisation or housing development.

Geospatial nightlight luminosity data is taken from the Earth Observation Group, which hosts monthly datasets collected from NASA's Defence Meteorological Satellite Programme satellites.[145] Datasets are processed measures of luminosity that are observed on a geospatial grid, with a granularity of 500 metres squared. Images are collected between the hours of 1.30am and 4.30am local time and are processed to ensure cloud-free coverage. These datasets have been applied for use in several academic and research fields, including for urbanisation and city expansion, social and population research, economic activity and GDP estimation, electricity supply and energy consumption, environmental monitoring and pollution research, as well as disaster emergency and recovery.[146]

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[144] Andres Schmidt, Lisa Ellsworth, Jenna Tilt, Amanda Thiel, Nancy Hiner, "Long-term tracking of recovery of built infrastructure after wildfires with deep network topologies", *Neural Computing and Applications* 37 (2025), pp. 8465 – 8477.

[145] Satellites F15 and F16 of the Block 5D-3 series, designated for meteorological and Earth observation purposes, using Operational Linescan System (OLS) sensors to detect visible and infrared light of nighttime imagery. Also using visible infrared imaging radiometer suite (VIIRS) for acquiring global daily measurements of nocturnal visible and near-infrared light.

[146] Hui Tang, Yongde Zhong, Jinyang Deng, Hongling Xia, and Juan Wei, "Global nighttime light dataset from 1992 to 2022 with focus on low-light areas", *Nature* 12, no. 982 (2025).

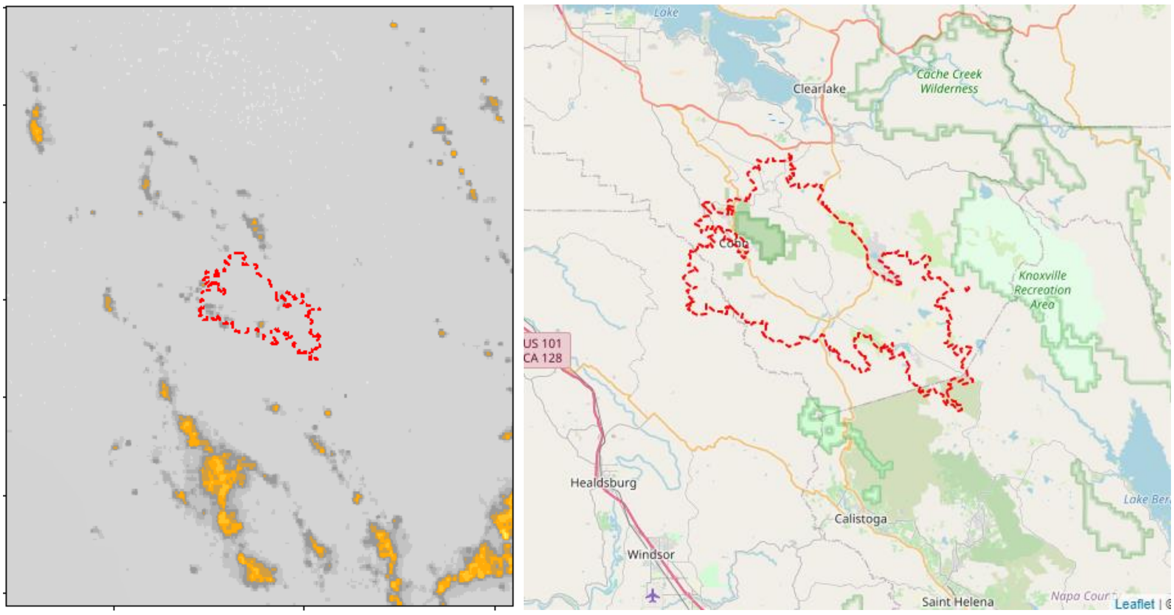


Figure 5.2.1: Wildfire perimeter of the Valley fire, Lake County, 2015. Nightlight luminosity compared to labelled map of cities and towns.[147]

Although measures of nightlight luminosity as a proxy for urban development or built-up development is not granular enough to identify individual buildings, the consistency in the reporting of the data over higher frequency time intervals makes the data source an efficient measure for analysing community and urban recovery after a wildfire event. In order to observe the usefulness of nightlight luminosity as an appropriate proxy for settlement or urban area, figure 5.2.1 compares the cities and towns around the Valley fire, which hit Lake County in September 2015, burning 76,000 acres, destroying nearly 2,000 structures, and causing at least USD 921 million in insured property damage. At the time, it was the third-most destructive fire in California's history based on the total structures burned, and destroying much of the towns of Cobb, Middletown, and Whispering Pines.

From the figure, the use of nightlight luminosity data clearly distinguishes urban areas from the surrounding forests and strongly aligns with the identification of cities and towns. The overlay of the wildfire perimeter shows the towns and surrounding forests that were affected by the wildfire, and the towns and communities that were not affected. By using nightlight luminosity data, a more granular assessment of the different towns affected is used to determine the extent of damage, and the rate of recovery and rebuild over time. As a more granular and consistent measure of urban development and economic activity over time, using nightlight luminosity works as an effective measure of comparing the area and communities

[147] CCRS analysis based on data provided by data from Cal Fire. (2023). *Fire Hazard Severity Zones (FHSZ) [GIS dataset]*.

affected by a wildfire with the areas that were unaffected, to see the rate of recovery in smaller time spans rather than the long-run trends that have previously been studied.

Section 5.3: Analysis

Nightlight luminosity data provides a proxy of geospatial data for measuring urban development at more frequent time intervals than what is otherwise available under different metrics. By applying this data to individual wildfire events, the rate of recovery and rebuild after a wildfire is analysed for localities and towns inside the wildfire perimeter and in close proximity adjacent to it. This can be observed from the data mapping from satellite images of nightlight luminosity. Figure 5.3.1 illustrates the luminosity data of the area around the Valley fire that took place in September 2015 in Lake County, around the towns of Cobb, Middletown, and Whispering Pines. The figure illustrates the data mapping of nightlight luminosity at two intervals, one month before the Valley fire in panel A, and one month after the fire in panel B.

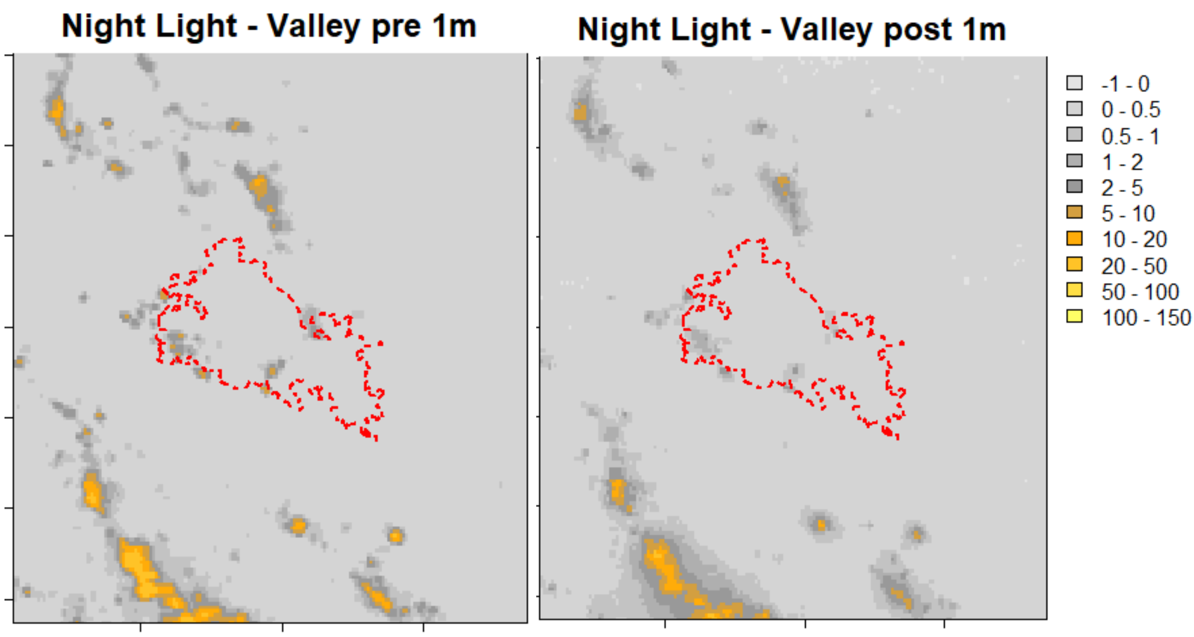


Figure 5.3.1: Intensity of nightlight luminosity for the towns and settlements around the Valley Fire, average of different months, Lake County, including the wildfire perimeter. Panel A: Luminosity around the Valley fire 1 month before the wildfire; Panel B: Luminosity around the Valley fire 1 month after the wildfire.

The image illustrates the luminosity values for each month before and after the actual wildfire event. The wildfire perimeter is also overlayed in the dotted red circle. [148] Luminosity shows the

[148] The luminosity shown in the image is taken as an average of the luminosity across several months prior to the wildfire, since nightlight luminosity data can be noisy with unexpected lights occurring at different places and with varying level of intensity, since the data is extracted from satellite images that

clear distinction between the urbanised areas or towns and the forested area in the region based on the intensity of the luminosity. Additionally, from the figure, there are some noticeable differences in nightlight luminosity for smaller towns and settlements inside the wildfire perimeter, particularly the clustering of luminosity at the western and southern edge of the perimeter. Outside of the perimeter, there are also some visible differences in luminosity, but this is due to the natural variation, such as seasonal, of nightlight luminosity as a proxy measure of human settlement and economic activity. Hence, analysis of time trends is taken at either the average across the area to compare inside versus outside the wildfire perimeter, or is compared for each geospatial data point over time, in order to control for the natural variation in the use of luminosity data for trends over time.

By comparing the luminosity and wildfire perimeter in panel A for the pre-wildfire period to the extent of luminosity in the average of the period in panel B after the wildfire, a measure of damages and recovery can be compared. From the two panels, there are some differences that can be observed in the level of luminosity, particularly within the wildfire perimeter of the Valley fire, which can be compared to other areas further away.

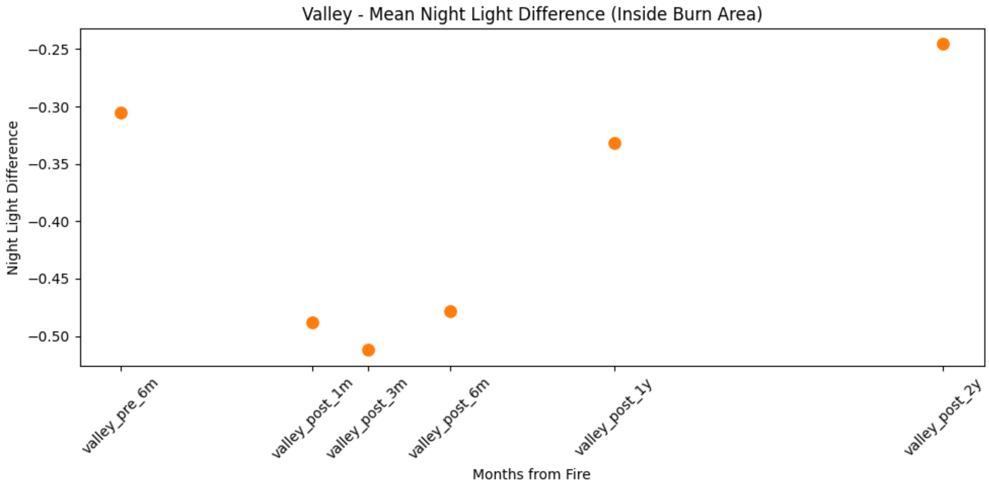
While there are some observable changes in luminosity between the two periods, since luminosity is taken at a lower level granularity, at 500 metres squared, in contrast to the higher granularity of 100 meters squared used for geospatial data on urbanisation from previous section 3, there are some changes in luminosity that are not immediately apparent from the overall data mapping. Instead, differences from one period to another are more clearly distinguished when more formally analysed. Data observations of nightlight luminosity are collected at regular time intervals both before and after a wildfire. This allows the data to track changes over time for the affected area. By analysing geospatial changes in luminosity, analysis more clearly identifies the effect of a wildfire in the loss of combined buildings and infrastructure and allows for a consistent measure of changes over time, at a highly granular monthly level. While previous satellite imaging has been applied to measures of urbanisation by amount of built-up surface area per 100 metres squared, this level of detail is only observed at 5-year intervals, but is more specifically focused on measures of building or structural density. In contrast, nightlight luminosity as a proxy is observed at a lower level of granularity at 500 metres squared to allow for a broader assessment of settlement, infrastructure, and economic activity, rather than only looking at building loss.

Figure 5.3.2 shows two plots for relative average luminosity for the area inside the wildfire perimeter of the Valley and Woolsey wildfires at several points in time, which start 6 months before the wildfire and end 2 years after the event. This is shown as the difference relative to the average across the entire region for which luminosity data is analysed. The difference relative to the mean luminosity for the region is analysed rather than the level of luminosity itself, due to seasonal variations, so that the figure tracks how luminosity inside the perimeter

simply capture the intensity of light observed at nightlight as a proxy for human settlement or urbanisation, rather than explicitly observing the level of urbanisation.

changes due to the wildfire, rather than changes in luminosity that would occur due to seasonal changes common across the entire region.

First, the two plots show a clear decline in the level of luminosity inside the wildfire perimeter from the pre-wildfire period to the post-wildfire period, demonstrating that nightlight luminosity is effectively identifying a loss in building structures and human activity. Second, the trend in luminosity is variable between the two wildfires, and does not show the same pattern, but exhibits similar overall characteristics. In the case of the Valley fire in plot A, the trend shows a decline in the average level of luminosity inside the wildfire perimeter from 6 months before the wildfire hit, to 3 and 6 months after. This indicates that nightlight luminosity data is identifying the property destruction from the wildfire event that is evident in the change in luminosity for the affected area within the wildfire perimeter. As the third most destructive wildfire in California's history at the time it occurred, based on the number of buildings destroyed, the fact that this is observable from the average level of nightlight luminosity inside the wildfire perimeter demonstrates that the use of nightlight luminosity serves as an effective proxy for determining the rate of recovery and rebuild after a wildfire.



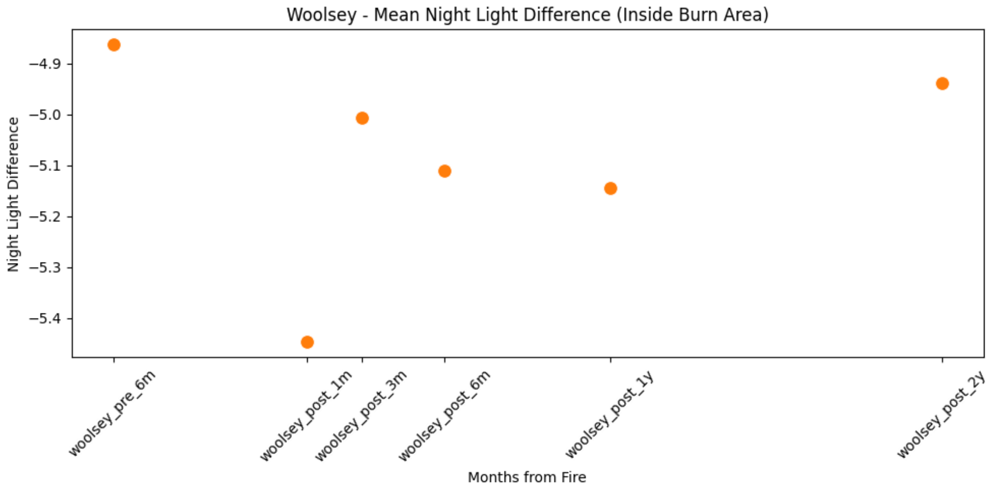


Figure 5.3.2: Average level of luminosity changes within the burn area; Panel A: Valley fire, September 2015; Panel B: Woolsey fire, November 2018.[149]

For the Woolsey fire, the trend is slightly different. It shows a steep decline in the level of luminosity 1 month after the wildfire occurred, demonstrating a significant loss of structures and human or economic activity, but this increases in the subsequent 3 month period after the wildfire. However, over the entire period, the level of luminosity does not return to the level observed in the 6-months prior to the wildfire. While the level of luminosity does recover, it never appears to fully recover to the level it was prior to the wildfire.

Section 5.4 Results

The analysis in section 5.3 is extended here to more specifically identify the rate of recovery that is related directly to the wildfire event. Evidence shows that luminosity declines immediately after a fire, but that there is some variability in the level and rate of recovery after, suggesting a causal relationship. This is more formally established by looking at the relationship of nightlight luminosity in each period directly to the luminosity from the previous period.

In order to look at the causal relationship between the change in nightlight luminosity from the period prior to a wildfire, and rate of recovery in the months and years after, we develop a model that compares the nightlight luminosity at 6 months prior to the wildfire occurring, against the luminosity in different time periods after the wildfire. Hence, measures of luminosity in subsequent periods estimate the relative changes in luminosity compared to the period before the wildfire occurred.[150] Luminosity changes in each wildfire determine how

[149] The results illustrated for the average level of nightlights inside or outside of the wildfire perimeter are mean subtracted over the entire region for which nightlight luminosity has been collected. This is to account for seasonal variation and the natural variability of nightlight luminosity data. Since nightlight luminosity trends are observed at monthly intervals, there is a natural difference in the amount of luminosity across the entire region based on whether nightlights are observed during the winter or summer months, due to longer or shorter nights, respectively. Additionally, there is natural variability due to the occurrence of low-level lighting that could be detected in the data due to human activity that is not actually representative of settlement, building, or urbanisation, but simply nightlights being used. Hence, by subtracting the mean across the whole area, this reduces these types of natural, monthly variation.

[150] The following model is used to analyse the nightlight luminosity data:

$$L_{t-6} = \beta_0 + \beta_n L_{t+n} + \gamma_r + \beta_n L_{t+n} \times \gamma_{r,n} + \delta_{lat} + \theta_{lon} + \epsilon$$

where L_{t-6} is the dependent variable and refers to the nightlight luminosity in the 6 months prior to the wildfire event occurring in time *t;* L_{t+n} are a set of independent variables taken at different intervals after the wildfire event, $t + n$; γ_r is the indicator for whether or not the nightlight luminosity was inside the wildfire perimeter; $L_{t+n} \times \gamma_{r,n}$ is the interaction effect of the luminosity in each time period and whether or not the lights were within the wildfire perimeter, so that the effect of the change in luminosity post-wildfire period luminosity relate to the pre-wildfire period in order to determine the rate of recovery back to the baseline, which is we take to be the luminosity 6 months before the wildfire. The results of this analysis for the Valley fire are illustrated in figure 5.4.1, which shows the relationship of luminosity to the pre-wildfire period for 1, 3, 6, 12 and 24 months after the event.[151]

The figure illustrates the marginal change in luminosity in each period relative to the level of luminosity observed prior to the wildfire. The level of luminosity before the wildfire is represented by the zero *y*-axis. This means that for 1, 3, or 6 months after the wildfire, if the trend is above the zero *y*-axis, then the level of nightlight luminosity is greater than it was relative to 6-months prior to the wildfire, and if the trend is below the zero *y*-axis, then the level of luminosity was lower than the pre-wildfire period. Trends have been separated in a similar way to distinguish between the affected area inside the wildfire in red, and the unaffected area outside the wildfire in blue.

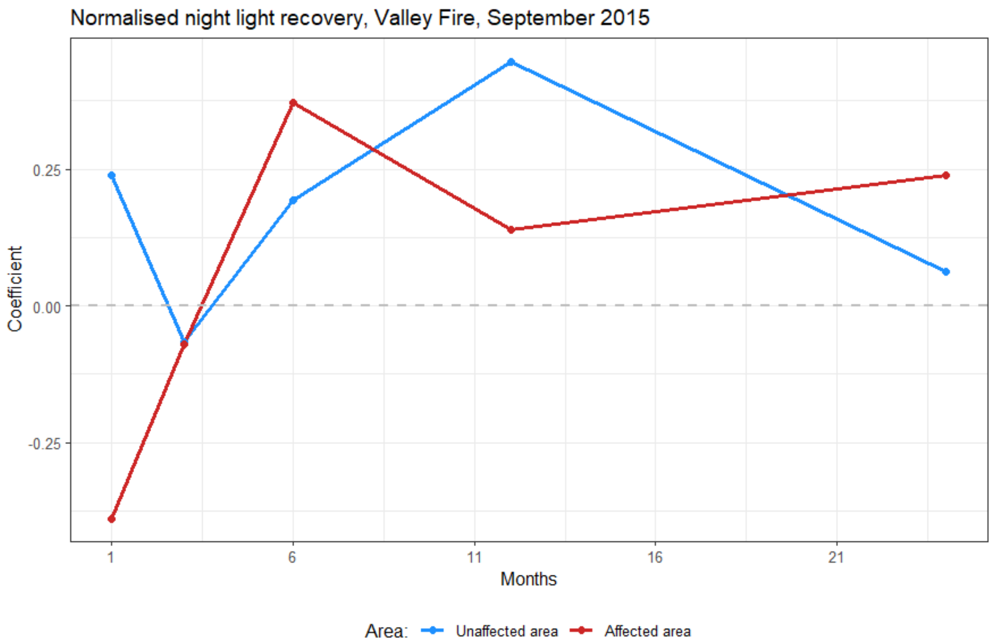


Figure 5.4.1: Nightlight luminosity coefficients (β_n) *for months* n=1,3, 6, 12 and 24 *for the area around the Valley fire, September 2015, in relation to the pre-wildfire luminosity, horizontal y-axis.*[152]

Figure 5.4.1 shows the trend in luminosity for inside and outside the wildfire perimeter for the Valley fire. The sharp negative difference in the first month after the wildfire represents the

is differentiated based on whether or not the nightlight luminosity were affected by the wildfire; $\delta_{lat} + \theta_{lon}$ are a set of controls for latitude and longitude to control for spatial autocorrelation, and ϵ is the error term.

[151] We plot the regression coefficient b_n, where a negative/positive value shows a decrease/increase in luminosity relative to pre-wildfire, for n=1, 3, 6, 12 and 24 months after the wildfire.

[152] CCRS original analysis.

loss in structures. The trend moves closer to the *y*-axis in the third month since the fire, but is still negative, suggesting an increase in luminosity as either construction or rebuild after the fire, but still at a lower level than before the wildfire. By 6 months after the wildfire there is more luminosity in the affected area relative to unaffected areas, suggesting more activity, and potentially more rebuild. 1 and 2 years after the wildfire, the level of luminosity is higher than in the pre-wildfire period, without showing any further decrease below the zero *y*-axis, and showing a slight difference compared to the luminosity effect outside the wildfire perimeter. This suggests that by 1 year after the wildfire, the affected area had redeveloped to a higher level compared to the pre-wildfire period, and that this level of redevelopment remained stable 2 years after the wildfire.

The trend for the unaffected areas is generally above the horizontal *y*-axis, indicating that the level of luminosity was higher in the post-wildfire period relative to 6 months before the wildfire, which illustrates a general growth trend for the surrounding area, broadly consistent with overall growth of the state. The variability in the nightlight luminosity trend outside of the wildfire perimeter in the months following the wildfire could be due to several potential factors. For example, the negative relationship in the 3-month period after the wildfire could be due to a regional evacuation order for surrounding towns that were near the fire, but not ultimately affected, which is why it goes negative at the 3 month interval, and quickly exceeds the pre-6-month period at the post-6-month period. Additionally, the peak difference at 12 months, and then subsequent decline at 24 months could be due to the process of reconstruction and rebuild activity that occurred both inside and outside the wildfire perimeter but could have peaked at 12 months for reconstruction and development, before being completed, after which point activity lowered at the 24-month period.

Although the findings do not necessarily mean that every property or structure that was burnt down by the wildfire was rebuilt, they illustrate that luminosity data works as an effective proxy for observing building loss, and the process of reconstruction. By using luminosity data as a proxy for urban development, it does indicate that the initial impacts in terms of the loss in structures is represented in luminosity, and that there was a period of recovery for the level of urbanisation to return, and subsequently to exceed, the level relative to the pre-wildfire period. In the case of the Valley fire, what is suggested is that there were significant losses between 1 and 3 months after the fire. At approximately 6 months there was greater activity inside the affected area, and that the affected area effectively recovered and exceeded previous levels of activity and development by 1 year after the fire.

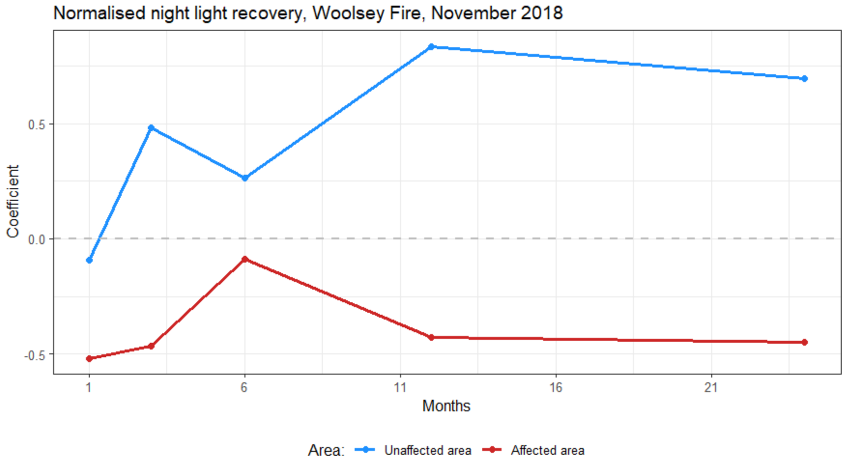


Figure 5.4.2: Nightlight luminosity coefficients (βn) for months n=1, 3, 6, 12 and 24 *for the area around the Woolsey fire, November 2018, in relation to the pre-wildfire luminosity, horizontal y-axis.*[153]

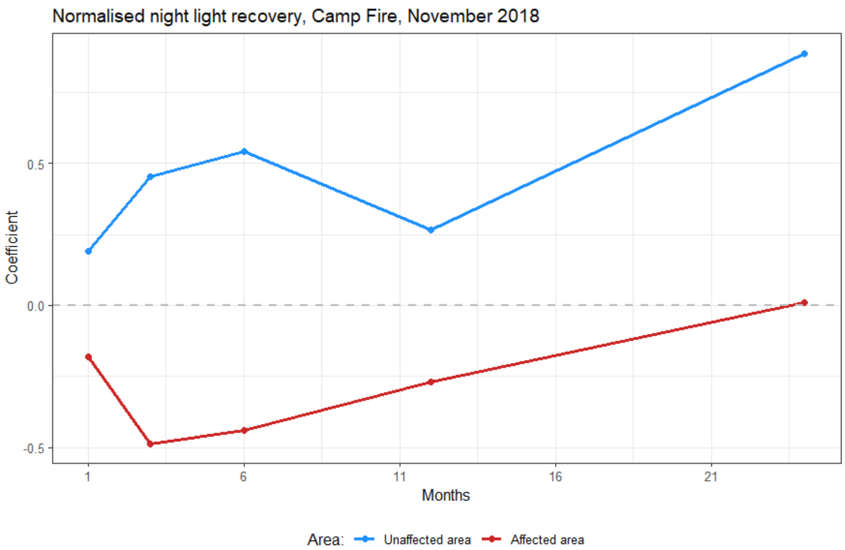


Figure 5.4.3: Nightlight luminosity coefficients (βn) for months n=1, 3, 6, 12 and 24 *for the area around the Camp fire, November 2018, in relation to the pre-wildfire luminosity, horizontal y-axis.*[154]

However, these trends in the rate of recovery are only representative of the Valley fire. In order to compare how recovery and reconstruction went for other wildfires, similar analysis and trends are studied. Figures 5.4.2 and 5.4.3 represent two other wildfires that have been studied in this report. First is the Woolsey fire that took place in Los Angeles and Ventura counties in

[153] CCRS original analysis.
[154] CCRS original analysis.

November 2018. Second is the Camp fire, which took place in more rural Butte County of northern California, and has been studied under different forms of analysis in this report.

In contrast to previous analysis from the Valley fire which showed a period of recovery of between 6 months to 1 year in terms of luminosity, the Woolsey and Camp fires do not show a similar recovery, represented by convergence in trends to either the zero *y*-axis or to the luminosity trend for areas outside of the wildfire perimeter. In both cases, the trends in the relationship between the recovery inside the wildfire area and outside it remain distinct, non-overlapping and non-converging. For both wildfires over the entire period, the relationship between luminosity outside of the wildfire perimeter is above the zero *y*-axis, representing greater luminosity than in the period before the fire. The trend varies slightly at different monthly intervals, which could still be due to seasonal variation within a year. However, the 1- and 2-year trends are more stable and smooth, suggesting a steady growth.

For the luminosity trend within the wildfire perimeter, there are some differences in the trend that demonstrate differences in the rate of recovery. In the case of the Woolsey fire, the luminosity trend for the affected area is below the zero *y*-axis indicating less luminosity than the pre-wildfire period, but this difference does not show any trend of convergence or divergence. This suggests that the affected areas simply did not return or rebuild, and that the overall level of luminosity from the Woolsey fire simply left the area with less development or activity.

In contrast, in the case of the Camp fire, there is significantly less luminosity in the months following the event. This is represented by the negative relationship between the post period luminosity compared to the pre-period luminosity. However, the trend distinctly shows that after a decline from 1 to 6 months after the wildfire, by 2 years after the Camp fire, the area affected by the wildfire appears nearly indistinguishable from the pre-wildfire period. This indicates that in the case of the Camp fire, it took approximately 2 years for the affected area to recover and rebuild to a level similar to what it was in the pre-wildfire period.

This finding for the Camp fire is consistent with what has been observed for the social and economic impacts of the wildfire on Butte County but also highlights some of the differences of what is being measured. Previous analysis has shown that there are significant effects from a wildfire in causing population and GDP loss for several years after the wildfire occurred. Similarly, evidence from figure 5.4.3 shows that the wildfire led to significant destruction for the affected area, and that building structure losses were significantly observed for up to a year after the wildfire. However, the faster rate of recovery that is apparent from nightlight luminosity does not entirely correspond to population or economic recovery in the same way. While previous analysis has looked at county level data for direct measures of population and GDP, the use of luminosity data and trends that has been used as a proxy to measure the rate of recovery after a wildfire on a more granular time scale to look at trends within a year, rather than per year.

As a proxy, luminosity data does not directly correspond to population or economic activity but is a general geospatial proxy for both. This can be a more effective measure in some cases for evaluating the impacts of a wildfire on local communities or areas, especially in cases when a wildfire perimeter is not entirely within a single county, or if the county itself is too large, in which case estimation of the social and economic impacts of a wildfire are diluted due to the larger size of the county, from which social and economic data are typically reported. In these cases, and for this type of analysis, nightlight luminosity data can be a more effective measure of wildfire impacts on local communities and regions, and a better proxy for observing the rate of community recovery and rebuild. Hence, evidence of recovery from the Camp fire from the area directly within the wildfire perimeter is an indication of the recovery of the general economic activity, not a direct measure of the population recovery or the actual recovery of GDP to the pre-wildfire period.

Instead, what is consistent between both approaches to studying the Camp fire is the extent of the devastation by the significant losses observed both in population and GDP at the county-level, and in the loss of activity evident from nightlights, which took nearly two years to recover from. While this does not mean that there was a full return of the population or the GDP to the county-level in the same time frame as the nightlight recovery, it does indicate that it took approximately 2 years for the communities directly impacted by the Camp fire to recover to a level of economic activity from before the wildfire.

Section 5.5: Discussion

This study has analysed nightlights as a proxy for the rate of community rebuild and recovery after a wildfire and has found widely varying results for a set of wildfires. In some cases, such as the Valley fire, the rate of recovery was fairly quick to pre-wildfire levels, which was between 6 months to a year. Yet in other cases, such as the Woolsey fire, there was never a community recovery, where the loss in nightlight luminosity caused by the wildfire simply persisted over the period up to 2 years after it occurred. Still in other cases, such as the Camp fire, community recovery according to nightlight luminosity took approximately 2 years to reach back to similar levels as before the wildfire. The wide-ranging trends based on luminosity suggest that there is no clear or consistent pattern to the rate of community recovery or rebuild after a wildfire, but that it varies based on the individual wildfire or affected community.

While nightlights are used in this case as a proxy to analyse the rate of recovery for a set of wildfires that have affected different communities in California, it does not entirely or precisely reflect actual community rebuild. As previously indicated in the case of the Camp fire, the rate of recovery observed by nightlights shows a general recovery, whereas county-level annual assessments of population or GDP do not show a similar return to pre-wildfire levels. Instead, nightlights show that there was simply a return of economic activity to pre-wildfire levels inside the affected area approximately two years after the event. This relates to broader measures such as the return of shops, the return of residents, and other aspects of daily life, although this does not equate to the entire population returning or that all property or structures in the area were rebuilt.

Other studies that have looked more specifically at actual property rebuild after a wildfire are more focused on a specific wildfire event, rather than an assessment across wildfires, due to the nature of data limitations on such highly detailed information as individual property rebuild. For example, an analysis of the 2010 Fourmile Canyon Fire in Boulder, county found that 3.5 years after the fire, only 30% of lost houses were rebuilt.[155] In a comprehensive study, the rebuilding process of 7,075 buildings after wildfire events in California between 1970 and 2009 was examined, and results show that 58% of the destroyed buildings were rebuilt within three to six years.[156] These studies, while more focused in their analysis either on reconstruction, or on a particular wildfire, demonstrate that the actual reconstruction of a community to fully return to the redevelopment of all properties takes longer than has been indicated by nightlights. While analysis of nightlights illustrates damages and identifies affected areas versus unaffected areas based on the geospatial distribution of nightlight intensity, it conveys more of the rate of community recovery based on activity, rather than by property redevelopment.

Even used as a proxy for activity, recovery, or redevelopment, the analysis shown here serves as an important assessment to determining that sometimes communities never recover after a wildfire but may persist for years as having less residents with less economic activity. Alternatively, even if communities do recover and do rebuild, a localised recovery in the areas destroyed by a wildfire does not also equate to a return to the same population or GDP levels as that observed pre-wildfire. Taking this analysis in section 5 along with previous analysis on county-level effects, shows that wildfires have long-lasting impacts on communities and the wider county. Sometimes locally affected communities never recover, and in other cases, even if there is community recovery back to pre-wildfire levels, this does not necessarily correspond to population or GDP recovery at the county-level.

[155] Miranda H. Mockrin, Susan I. Stewart, Volker C. Radeloff, Roger B. Hammer, and Patricia M. Alexandre, “Adapting to wildfire: Rebuilding after home loss”, *Society and Natural Resources* 28 (2015), pp. 839 – 856.

[156] H. Anu Kramer, Van Butsic, Miranda H. Mockrin, Carlos Ramirez-Reyes, Patricia M. Alexandre, and Volker C. Radeloff, “Post-wildfire rebuilding and new development in California indicates minimal adaptation to fire risk”, *Land Use Policy* 107 (2021).

Section 6: Building codes

Section 6.1 The Wildland Urban Interface

The WUI is where human habitation mixes with untamed vegetation such as forests, shrublands and grasslands. Such regions are highly prone to wildfires. The WUI has witnessed a material increase in human presence since the 1940s for a variety of reasons including: overcrowding in cities, cheaper land, reduction in transport costs, and a general aspiration from some to live amongst nature.[157] The public did not seem concerned by wildfires in the 1980s and much of the 1990s and indeed budgets for fire management were cut severely in the mid-1980s. Despite this, the US Department of Agriculture highlighted the term Wildland Urban Interface in their budget request in 1988 and stated their intention to focus on this as a key research area. [158]

For many years the WUI did not have an agreed definition, and this ambiguity was formally rectified only in 2007 using photo and satellite digital imagery.[159] The key terms underlying the definition are:

Interface communities: where urban structures directly abut wildland fuels

Intermix communities: where structures are dispersed throughout wildlands

Census block: the smallest geographical unit used by the U.S Census bureau for displaying census data

Human presence: deemed to occur when housing density exceeds 1 housing unit per 40 acres.

Wildland vegetation: Any type of vegetation except those that are "clearly not wild" such as urban grass, orchards, agricultural crops.

High wildland area: covers more than 5km^2 and has more than 75% of wildland pixels

WUI intermix: There is human presence in the census block and wildland vegetation pixels exceed 50% of the total.

WUI interface: Census blocks that are: (i) not WUI intermix and (ii) within 1.5 miles[160] of a high wildland area.

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[157] Stewart, S.I., V.C. Radeloff, R.B. Hammer, and T.J. Hawbaker. 2007. "Defining the Wildland Urban Interface." *Journal of Forestry* 105: 201–207.

[158] Sommers, W. 2008. "The Emergence of the Wildland-Urban Interface Concept." *Forest History Today*.

[159] Stewart, S.I., V.C. Radeloff, R.B. Hammer, and T.J. Hawbaker. 2007. "Defining the Wildland Urban Interface." *Journal of Forestry* 105: 201–207.

[160] Chosen as the typical distance an ember can travel on the wind

The current definition is chosen to allow tracking of WUI growth over time and to compare regions. Cal Fire agencies may still use their own definitions for fire management as they can take account of other features that may not be ubiquitous across the U.S. Around 80% of the WUI is intermix. Interface regions typically form the periphery around urban centres.[161]

The WUI expanded rapidly by 33% to 190m acres from 1990 to 2010 and over this period the number of homes within increased by some 41% to 43.4m and still continues to grow by around two million acres per year.[162] The WUI represents around 10% of the total land area but contains one-third of homes in the United States some 39% of all houses with an estimated value of around USD 1.3 trillion.[163] The East Coast has a greater proportion of WUI regions but California has the largest number of homes within it.[164] Around 1 in 3 Californians (14m) live in the WUI and nearly 45% of new build has occurred in this region since 1990 and 2020.[165]

Across the US, but in California in particular, we therefore see a growing probability of hazard due to climate change and an increasing level of exposure due to the expansion of the WUI. To counter this several regulations have come into force.

Section 6.2 Building codes

The following section restricts attention to California which has the strongest wildfire building codes in the world.[166] The region is subdivided into three areas:

State responsibility areas: where Cal Fire is legally required to provide fire protection. It usually excludes land within city boundaries and federal lands (some counties have negotiated exceptions). The boundaries are reviewed every five years, with the potential for annual adjustments.

Local Responsibility areas: Urban and Suburban areas where local agencies handle wildfire protection. Incudes city and county fire departments.

Federal responsibility area: land over which the federal government has responsibility.

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161 Radeloff, V.C., et al. 2005. "The Wildland–Urban Interface in the United States." *Ecological Applications* 15: 799–805.

162 USDA Forest Service. 2018. "Rapid Wildland-Urban Interface Growth Increases Wildfire Challenges."; International Code Council. 2024. *Wildland-Urban Interface Resources.*

163 Radeloff, V.C., et al. 2018. "Rapid Growth of the US Wildland-Urban Interface Raises Wildfire Risk." *Proceedings of the National Academy of Sciences* 115 (13): 3314–3319.; USDA Forest Service. 2018. "Rapid Wildland-Urban Interface Growth Increases Wildfire Challenges."

164 Radeloff, V.C., et al. 2005. "The Wildland–Urban Interface in the United States." *Ecological Applications* 15: 799–805.

165 CalMatters. 2025. "LA County Fires and the Wildland-Urban Interface."

166 Baylis, P., and B. Boomhower. 2021. *Mandated vs. Voluntary Adaptation to Natural Disasters: The Case of U.S. Wildfires.* NBER.

Since the 1960s California state has required property owners to create a defensible space around buildings of around 10 meters.

From 19-20 October 1991 following 5 years of drought a large wildfire raged in California in the city of Oakland in Alameda County. Known by several names: the Tunnel fire, Oakland hills firestorm or East Bays hill fire, this devastating fire claimed 25 lives and destroyed over 3000 properties. Damages exceeded USD 1.5 billion (1991 dollars) making it the largest ever dollar lost from a wildfire up to that point in time.[167] This wildfire led to several new pieces of legislation relating to building codes or hazard mapping. According to Baylis and Boomhower the Bates Bill (1992) required the production of maps showing very high fire severity zones.[168] The Assembly Bill 3189 (1994) set standards for ignition resistant roofs – requiring (from 1995) a medium standard (class B) for new construction in regulated areas and (from 1997) a very high standard (class A) on buildings in high hazard areas. A further Assembly Bill 423 (1999) removed the option to use unrated building materials. This marked a step change in fire safety for new buildings from around 1998.

The intention to develop stronger and more complete building codes and behaviours may have arisen after the Tunnel fire, but it was not until 2005 that the next major building code change occurred. Causes of the delay included: the time taken to produce fire hazard severity maps, the effort required to carry out research into fire resistant building materials and the political delays to achieve consensus. Arguably the devastating Cedar fire in 2003 which destroyed nearly 3000 buildings and led to 15 deaths in San Diego County, costing USD 1.3 billion, contributed to the political momentum. Chapter 7A was added to the California Building code in 2005, with mandatory compliance required for all new buildings after 2008.

Chapter 7A applies to homes built in very high fire hazard severity zones and requires fire resistant roofing and sidings, tempered windows to prevent shattering under high radiant heat, vents and protection for eaves and soffits that prevent the intrusion of embers and fire-resistant decking materials. The act requires vegetation management and a defensible space of at least 100 feet (or to the property line if less) around structures to reduce available fuel.

The high fire severity region maps determine which properties are required to comply. In 2025 new maps were issued by Cal Fire which increase the area designated as high and very high risk by 168% now affecting 1 in 10 people in the State.[169]

The destructive Eaton and Palisades fires in January 2025 have, likely, expedited further and stronger regulations and codes. On 26th February 2026 the State of California adopted the 2024 International Wildland-Urban Interface Code® which give further clarity on ignition resistant construction and defensible spaces but also describe emergency vehicle access

[167] Routley, J. 1992. *The East Bay Hills Fire, Oakland-Berkeley, California.* FEMA.
[168] Baylis, P., and B. Boomhower. 2021. *Mandated vs. Voluntary Adaptation to Natural Disasters: The Case of U.S. Wildfires.* NBER.
[169] CalMatters. 2025. "CAL FIRE Maps Hazard Zones in California."

requirements, water supplies, and the maximum housing density in some regions.[170] In 2020 California legislation required the Board of Forestry and Fire Protection to create regulations for a new "Zone 0" (the region within 5ft of a property) but has not yet been put into force. In 2025 Governor Newsom's Executive Order N-18-25 set a deadline of December 31, 2025, for the Board to complete rulemaking for Zone 0 which will be enforceable from 1 January 2026. Although there are many causes of property damage such as direct flame contact from nearby structures or trees and radiant heat, which can shatter glass, most structures are ignited by embers which can travel for miles on the wind ahead of the fire.[171] Learning this lesson, Zone 0 aims to create an ember-resistant defensible area around a property. This new requirement applies to houses built within State responsibility areas and very high fire hazard zones of local responsibility areas and notably to *both* new build from 2026, and existing properties from 2029.[172] Regulations affecting existing properties are rare though Assembly bill 38 requires sellers of buildings to provide a certificate to show which if any retrofits have been undertaken.[173]

The Insurance Institute for Business & Home Safety (IBHS) has created the Wildfire Prepared Home project to help homeowners better protect their homes.[174] It is voluntary but creates a list of actionable steps to reduce risk. Eligible homeowners can apply for two levels of accreditation. The standard level has 10 key criteria covering building features such as roofing, gutters, air vents and fencing. The higher "plus" version requires a further 10 steps to meet the standard including fire resistant wall covers, heat-resistant windows and non-combustible decking. To become accredited homeowners must apply for a designation, and have an inspection, they must then certify annually that necessary ongoing maintenance has been carried out. The designation lasts for 3 years after which they must re-apply. The town of Paradise was an early adopter and all homes built after 2022 were required to comply with the standards. The standards have recently been updated by the IBHS including what steps to take during red flag warning days such as moving vehicles and any other combustible items away from the home.[175]

[170] International Code Council. 2024. "California Strengthens Resiliency with Adoption of 2024 Wildland-Urban Interface Code."

[171] CAL FIRE. 2025. *Defensible Space Zones 0, 1, and 2.*

[172] Ibid.

[173] California Land Title Association. 2024. *Point-of-Sale Retrofit for Wildfire Protection.*

[174] Insurance Institute for Business & Home Safety (IBHS). (2025). *Wildfire Prepared Home Guide Brochure*.

[175] Insurance Institute for Business & Home Safety (IBHS). (2025). *Wildfire Prepared Home Technical Standard*.

Section 6.3: Stronger codes reduce risk

Based on 5000 responses to a UC Berkely survey some 80% of Californians would support stronger building regulations, even if they increased building costs.[176] Research suggests that they would be wise to do so as there is clear evidence that strong codes reduce damages. It is notable that 70% also support greater restrictions on building homes in high-risk areas, although only 55% support building more homes in highly urbanised existing areas rather than the WUI.

A case study from FEMA suggests that in the Thomas fire of 2017 the Montecito coastal district in California witnessed minimal damages due to the adoption of building codes which banned fire risky materials and provided funding for specialists to advise homeowners on risk reduction.[177] As second FEMA study suggests that adoption of Chapter 7A will save the state USD 24 billion over the next 75 years due to reduced damages and lives saved.[178] Knapp et al. found that "Homes built prior to 1997 fared poorly, with only 11.5% surviving, compared with 38.5% survival for homes built in 1997 and after".[179] A case study exploring the Camp Fire of 2018 found that 51% of houses built to Chapter 7A standards survived whereas only 18% built prior to 2008 survived the fire.[180]

A study by Baylis and Boomhower shows a statistically significant finding that homes built after 2008 (where Chapter 7A applies) are 40% less likely to be destroyed than homes built in 1990 facing identical exposure.[181] Homes built from 1998 following the Bates and Assembly bills show a 25% reduction indicating the earlier rule changes in the 1990s also had a significant effect in reducing risk, consistent with the findings from Knapp et al. Reinforcing this message, figure 6.3.1 shows a clear reduction in the share of buildings destroyed for newer properties. Neighbours' homes within 10 meters that are built to the latest code confer around 6% reduction in destruction probability to nearby homes suggesting that free riding confers some but only a small benefit.

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[176] UC Berkeley Institute of Governmental Studies. 2024. *Survey on Wildfire Adaptation.*

[177] FEMA. 2024. *Building Codes Strategy.*

[178] FEMA. 2024. *Building Codes Save Study.*

[179] Knapp, E.E., et al. 2021. "Housing Arrangement and Vegetation Factors Associated with Home Survival in the 2018 Camp Fire." *Fire Ecology.*

[180] PreventionWeb. 2024. "Analysis: Safety Rules Give Homes a Better Chance in Wildfires."

[181] Baylis, P., and B. Boomhower. 2021. *Mandated vs. Voluntary Adaptation to Natural Disasters: The Case of U.S. Wildfires.* NBER.

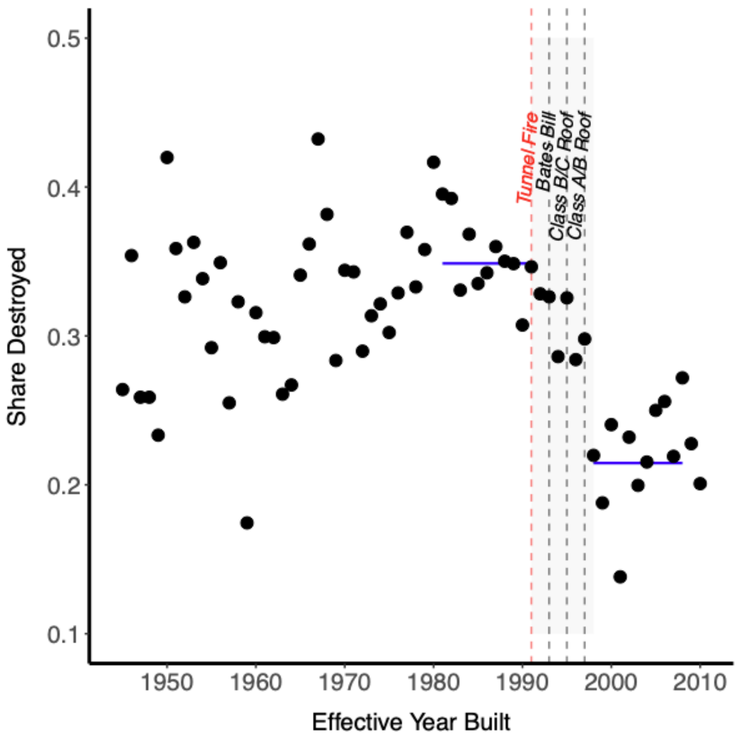


Figure 6.3.1: Share of buildings destroyed in wildfires by year built.[182]

Baylis and Boomhower carried out an economic cost benefit study and note that strong building codes are "unambiguously positive" for fire prone areas but that retrofits are only worthwhile in areas of extreme wildfire hazard.[183]

In summary, a number of tragic fires since the 1990s have led to a series of building code changes that have been shown to be cost effective in reducing the probability of building destruction.

[182] Ibid.

[183] Ibid.

Section 7: Insurance industry impacts and responses

This section explores how levels of insurance have varied over time (penetration), how the insurance industry and regulators have responded to the growing wildfire threat and how the insurer of last resort (FAIR plan) has responded in recent years.

Section 7.1 Penetration levels

Insurance penetration is defined as the insurance premiums written in a region as a ratio of its GDP. Whilst the GDP of California has soared so that it now has the 4th largest economy of any country in the world, its spending on insurance has increased faster.[184] The rise in insurance penetration may be due to several factors such as an increase in property prices, increases in risk levels that were permitted to be included in premium rate filings and increases in the number of policies bought. The latter would suggest an increased desire for protection within society. Figure 7.1.1 shows that penetration was falling 2013-2017 and then began rising; it seems notable that growth in penetration started after the major Tubbs (2017) and Camp (2018) wildfires.

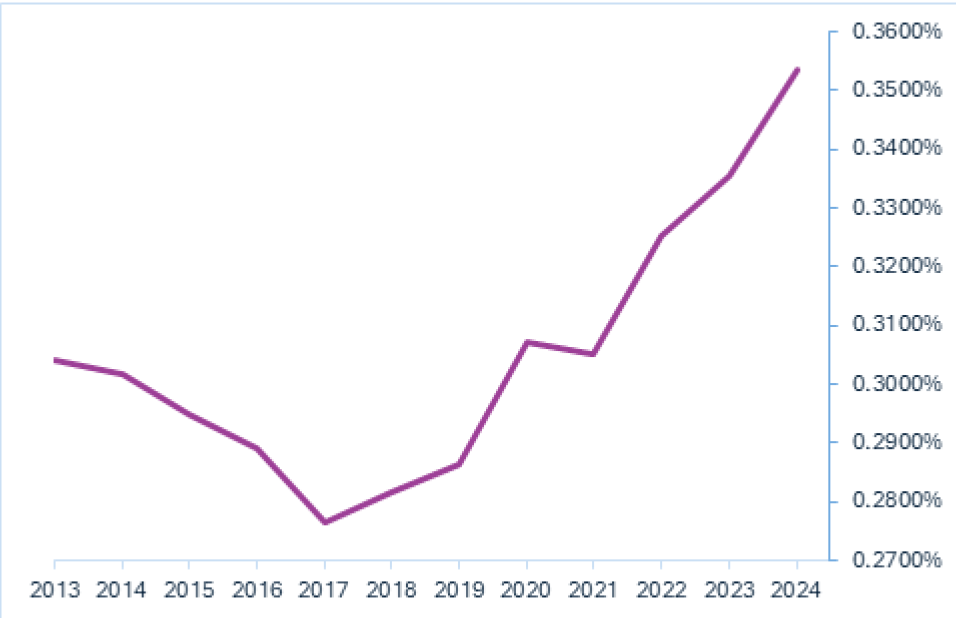


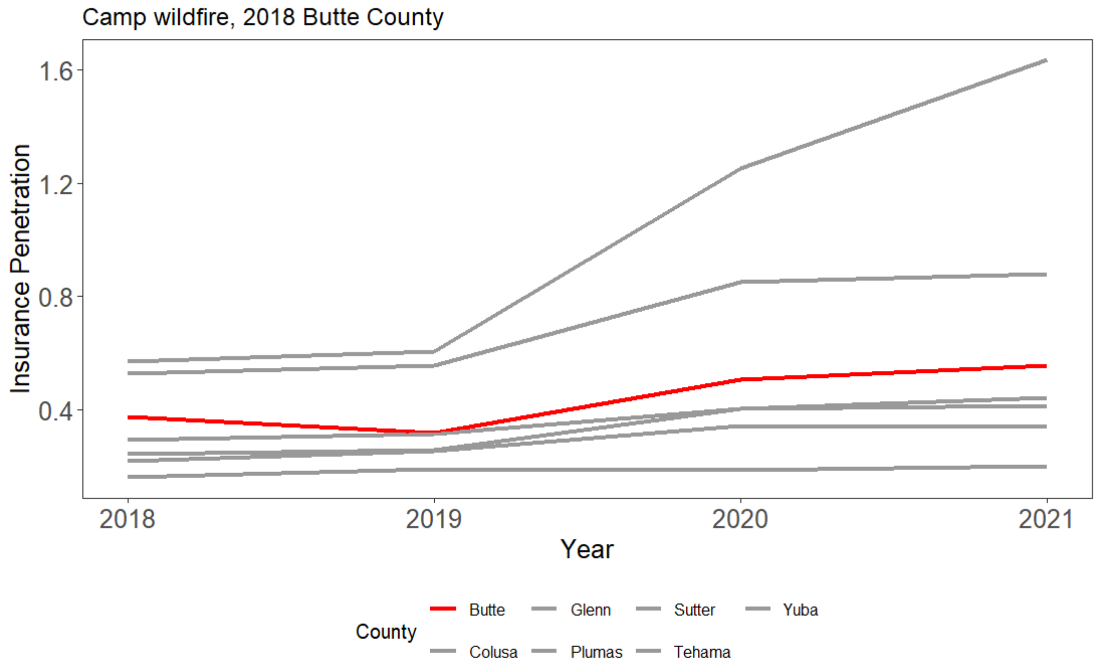
Figure 7.1.1: Statewide insurance penetration in California.[185]

We have analysed four major fires the Bond fire in Orange County 2020, Camp fire in Butte County 2018, Oak fire in Mendocino 2020 and Carr in Shasta County 2018. We find that there are strong increases in penetration from 2020 likely following the large increases in premium rates in that period. The largest increases appear to be neighbouring unaffected counties

[184] Office of the Governor. 2025. California Is Now the 4th Largest Economy in the World.; California Department of Insurance. 2024. Market Share Data.

[185] CCRS analysis from data provided by California Department of Insurance. 2024. Market share data.

where penetration was already high (Figure 7.1.2), suggesting that people are more likely to respond to risks that are "close to home".



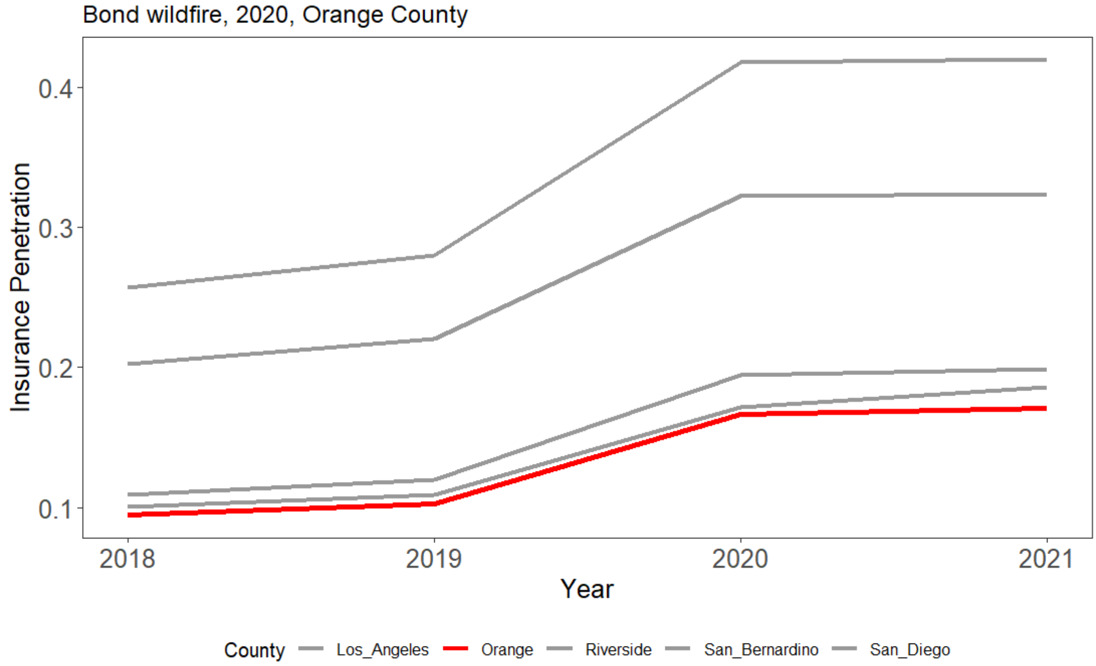


Figure 7.1.2: Insurance penetration trends for counties affected by wildfires between 2018 to 2021, compared to neighbouring, unaffected counties. Red line highlights the affected county insurance penetration trend compared to all other neighbouring county trends. Panel A: Camp fire, Butte county, November, 2018; Panel B: Bond fire, Orange county, December 2020.[186]

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[186] CCRS analysis from data provided by California Department of Insurance. 2023.

Section 7.2: Insurance response

According to Marsh US, composite residential and commercial property insurance rates declined by 9% in Q1 2025 following a 4% decline in Q4 2024 driven, they say, by increased insurer competition and decreasing reinsurance costs.[187] This trend is not observed in California due in part to the cost of wildfires in the region.

Figure 7.2.1 shows the loss ratio (insurance claims divided by premiums) across California.[188] It shows a significantly higher loss ratio in the years of 2017 and 2018. The major wildfires in 2020 did not lead to such high loss ratios due to increases in premium rates, higher deductibles and high-risk properties moving to the FAIR plan (see below). Insurance industry sources have noted that around two thirds of the loss will be covered by local carriers, and the final third by reinsurers.[189]

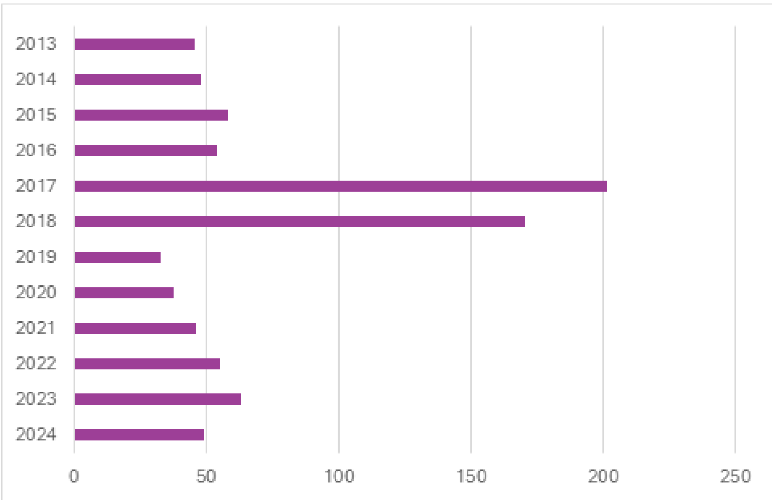

Figure 7.2.1: Statewide California insurance loss ratio by year.[190]

Insurers have reacted to the wildfires in several ways, including:

- Withdrawing cover from certain Zip codes.[191]
- Exiting certain lines of business such as products aimed at small to medium businesses.[192]

[187] Marsh. 2025. U.S. Insurance Rates. Updated Insights.
[188] California Department of Insurance. 2024. Market Share Data.
[189] Swiss Re Institute. 2025. *Natural Catastrophes in 2024: Sigma Report 1/2025.*
[190] California Department of Insurance. 2024. Market Share Data.
[191] Merlin Law Group. 2023. "Insurance Companies Cancel Fire Insurance."
[192] Insurance Journal. 2024. "State Farm Will Not Renew California Property Insurance Policies."; Reuters. 2023. "Liberty Mutual to Stop Offering Business Owners Policy in California."

- Withdrawal from the region entirely.[193]
- Increasing premium rates.[194]
- Increasing deductibles.[195]

From 2019 to 2024 inclusive more than 100,000 homeowners saw their policies non-renewed in many cases in high fire risk and rural areas.[196] Some Zip codes saw more than 10% of homes face non-renewal.[197] This has prompted a strong regulatory response including seeking a commitment from insurers to raise their exposures in fire distressed regions to 85% of their statewide market share and including targets to reduce exposure to the FAIR plan.[198] In addition, regulators have clarified that as a state of emergency has been declared following the 2025 wildfires cancellation or non-renewal is not permissible for one year from 7 January 2025 for any ZIP codes in affected regions.[199]

For most hazards and in most states, insurers must demonstrate their premium rates are backed by data and are actuarial sound.[200] This is often appropriate for high frequency risks (where many claims arise permitting statistically justified frequency and severity analysis), and for stationary risk types (where the underlying risk is arguably not changing much from year to year). It is less appropriate when risks are changing quickly such as wildfire risks where this report has shown that climate change is materially amplifying hazard levels. Some risks are very rare, such as the loss from a very large wildfire at a particular location. They might be observed only every few decades or even centuries. But when they occur, they can be enormous, dominating long run average losses for many years. Such risks are called "heavy tailed risks", and they are not amenable to statistical insurance rating as they will be either over-represented if they have recently occurred or significantly underrepresented if they have not occurred. For this reason, the insurance industry has developed Catastrophe models which simulate risks based on scientific, engineering and statistical data. These models fill in the blanks where claims data is missing and can materially change the view of risk compared to past observed claims. As part of the sustainable insurance initiative from 2 January 2025 insurers will finally be able to use catastrophe models to assess risk levels.[201] This will permit

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[193] Extruct.ai. 2025. Data Room: Insurance Companies Leaving California.

[194] CBS News. 2023. "California Wildfires: Home Insurers Dropping Homeowners."

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[196] Pauls, Brenna. 2024. *California's Homeowners Insurance Crisis.* UCLA Luskin School of Public Affairs.

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[198] California Department of Insurance. 2025. *Sustainable Insurance Strategy*.

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[200] National Association of Insurance Commissioners. 2024. *PFR-24.*

[201] Willkie Farr & Gallagher LLP. 2024. *California's Proposed Regulations to Enable Catastrophe Modelling and Expand Wildfire Protection.;* California Department of Insurance. 2024. Press Release on New Wildfire Regulation, December 13.

insurers to better assess risks but also to project the impact of fire mitigation and to create a more robust risk-based pricing view of the exposure.

It is hoped that these insurance reforms will gradually transfer business back to the insurance industry. In the meantime, customers in very high-risk areas are still relying on the FAIR plan.

Section 7.3 FAIR plan

The Fair Access to Insurance Requirements Plan (FAIR plan) was set up in August 1968 to assist homeowners to obtain insurance when unavailable from traditional markets.[202] It is not funded by taxpayers and, in addition to premiums paid by customers, obtains funding from all insurers that are licenced to write property insurance in California. Insurers share in the profits and expenses of the plan in proportion to their market share in the state. The plan is described as an "Insurer of Last Resort" and aims to be a temporary solution until market rates become available. The Plan was set up during a period of civil unrest and was not originally set up in response to wildfire losses but in recent times these have been a major fraction of the claims arising under the plan. Figure 7.3.1 shows the rapid growth in FAIR plan policies starting from the wildfires in 2018 and accelerating again after 2022.

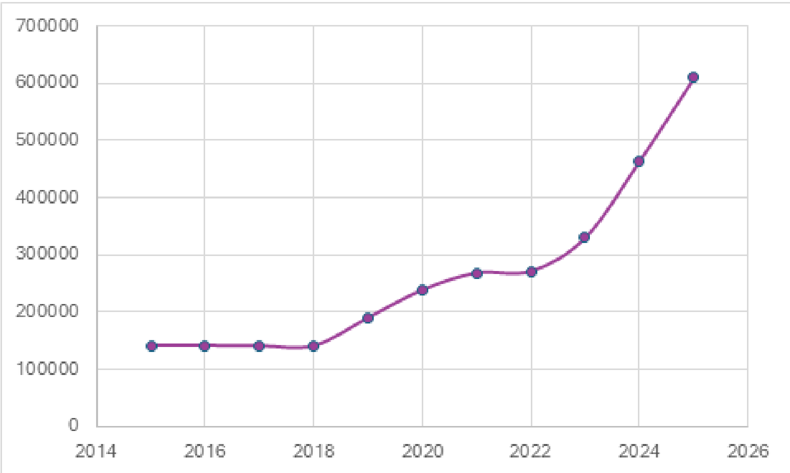

Figure 7.3.1: FAIR plan number of policies in force.[203]

The FAIR plan purchases reinsurance which attaches at USD 900 million. The first layer of USD 350 million is Excess of Loss and is fully supported by reinsurers. After this, losses are shared between the direct writers and the reinsurers. The total reinsurance payment is capped at USD 2.63 billion deemed to equate to an experience of a 1 in 100-year loss.[204]

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[202] California FAIR Plan. 2025. About the FAIR Plan.

[203] CCRS analysis from data provided by California FAIR Plan. 2025. Key Statistics and Data, and California Department of Insurance. 2022. Insurance Policy Count Data 2015–2021. Fact Sheet.

[204] Kennedys Law. 2025. Structure of the California FAIR Plan and the Financial Challenges.

The FAIR plan has the right to request funds from licenced insurers to pay for claims if it cannot afford the payments from its own funds. On 11 February 2025, in Order No. 2025-1 Commissioner Lara ordered USD 1billion be collected in this way for the first time since 1994.[205] The order noted that the FAIR plan would otherwise not be able to meet upcoming claims payments, having then already paid USD 914m in claims with a further USD 3.251 billion reserved, notwithstanding the USD 1.45 billion they expected to receive from reinsurance. The USD 1 billion assessment will be collected from licenced insurers who are permitted to pass 50% of this to their customers. Once an assessment goes above USD 1 billion in a year the insurers may recoup 100% of the excess above this.[206]

The California Department of insurance noted that the FAIR plan represented 3.0% of insurance market in 2021.[207] If the total market size has not changed materially over this period, this figure would now have risen to 6.8%. In the same report the Department also noted that the FAIR plan share in regions of high risk of fire was over 20%.

FAIR plan average premium rates have risen by 13% p.a. since 2021 far outstripping inflation of just under 4.5% p.a. Coverage limits for residential properties were doubled in 2019, the first rise in decades and in March 2025 a large increase in limit was approved for commercial properties.[208] Discounts of up to 20% of the wildfire element of cover are now offered to policyholders who have strengthened their property.[209]

In summary, insurance penetration rates were falling prior to the major fires but have risen steadily in California. Huge losses in 2017, 2018, and 2020 led many insurers to raise premium rates and some to exit the state. Many of the non-renewed policies have moved to the FAIR plan which has seen significant growth in exposure. Recent regulatory responses have sought to limit further non-renewals and to encourage a transfer back to the insurance industry through the introduction of risk-based pricing. Time will tell whether such pricing remains affordable in an era of climate change.

[205] California Department of Insurance. 2025. Order No. 2025-1 Approving the California FAIR Plan Association's Request.

[206] Perr & Knight. 2025. California FAIR Plan Assessments Are Real.

[207] California Department of Insurance. 2022. Insurance Policy Count Data 2015–2021. Fact Sheet.

[208] California Department of Insurance. 2025. Press Release No. 028-2025.

[209] Ibid.

Conclusion

This report has studied the rising social and economic impacts of wildfires by looking at the state of California. The risks from wildfires have been highlighted by the insurance industry for many years, but in the last 10 years the financial effects of this threat have accelerated.[210] This report has shown that in recent years there has been a secular increase in the size of wildfires in California in terms of acres burned, the number of structures destroyed, and the costs in terms of economic damages and insurance losses. The 2025 wildfires affecting the Palisades and Eaton are likely to see the largest financial loss to date from this cause approaching the cost of a major hurricane. With 30,000 people under evacuation orders, the near miss in the Hughes fire could have made costs even higher had the winds not died, allowing the valiant firefighters to control the blaze.[211] Impacts from wildfires are likely to get worse over time with climate change increasing the probability of fire weather and increasing the length of the season over which fires can occur in some locations.

The past 35 years has seen substantial expansion into the WUI, in the US as a whole, and California in particular, despite warnings about the fire risks in those zones from the late 1980s. Satellite imaging and geospatial data trends over time have shown that urban sprawl has pushed cities into higher wildfire risk areas, and increasingly pushing settlements into the WUI. Building codes have strengthened over this period, in response to the growing threat, and enabled by some major fires which solidified public opinion to act. New buildings in high-risk locations must now be built from a range of fire-resistant materials and have a wide exclusion zone separating them from vegetation. There remains a large inventory of older buildings which are still at high risk of destruction, however, so we can expect material losses from wildfires for many years to come.

Our report has carried out a structured literature review of this topic from a multidisciplinary perspective including climate science, economics, statistical analysis and insurance. We have found that the fastest growth in urban development has been into the highest fire risk areas, that wildfires represent significant long-run social and economic losses to counties, and that this impact is particularly pronounced for poorer and more rural counties of Northern California compared to wealthier and more urban counties of Southern California. These GDP and population loss effects from wildfires have a higher magnitude impact for counties with lower GDP per capita, and are less significant for counties with a higher GDP per capita. From nightlight luminosity analysis of three major wildfires, this report finds variability in the rate of recovery for local communities after a wildfire. In some cases, there is no recovery back to pre-wildfire levels 2 years after a wildfire. In other cases, recovery of social and economic activity in the affected area can appear as quickly as 1 year after a wildfire, and in others, analysis shows it can take longer for activity to return to pre-wildfire levels of around 2 years after a wildfire. We note the perversity of the GDP measure which will see rebuilding costs as positive addition, without fully recognising the destruction of property.

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[210] Lloyd's. (2013*). Wildfire: a burning issue for insurers?* Lloyd's PDF Risk Reports.

[211] Keri Blakinger, *"A 'Brush with Catastrophe': Close Call with Hughes Fire Stirs Concerns About Jail Safety,"* Los Angeles Times, February 12, 2025.; *LA's Hughes Fire Shows New Risks of Super-Fast Suburban Blazes,* Bloomberg, March 19, 2025.

The opportunity costs for education, health, or other foregone human welfare projects are not recognised – but they are real.

Data suggests that insurance penetration was falling statewide up to 2017/18 when some major fires may have changed public attitudes. Since then, penetration has risen sharply. This may be partly due to increasing premium rates which reflect the growing risks but may also reflect more people purchasing cover. The FAIR, plan known as the insurer of last resort, has seen a substantial rise in the number of policyholders and now represent a significant percentage of those covered in high fire risk regions. In 2025 plan has had to request USD 1 billion funding from insurers for the first time in 30 years and it seems likely that more will be requested to cover the ultimate cost of the 2025 fires.

In summary, wildfires globally and for California in particular, are a spreading risk which will continue to grow, in number, size, frequency and financial cost for the foreseeable future. They represent a major catastrophe risk for insurers and a mixture of strong building codes, careful planning decisions, public support and risk-priced pooling of risks locally and globally through reinsurance will be needed to mitigate the threat.

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