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Research Note

Long-term trends in wildfire damages in California

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Abstract. In 2017 and 2018, wildfires in California burned millions of hectares and caused billions of dollars in structure damages. This paper puts these recent fires in a long-term historical context by assembling four decades of data on wildfires in California. We combine administrative data of structure loss due to wildfire with economic data on replacement costs and spatial data on fire locations and sizes. We find that over the period 1979–2018, wildfires in California have been getting larger and that the trend is accelerating. This same trend is seen in the wildland–urban interface. As well, total structure damage from wildfires has grown steadily during the past four decades. Our conclusion is that the recent California fires are not an anomaly, but rather part of a trend towards larger and increasingly destructive wildfires.

Keywords: California, economics, historical data, spatial analysis, structure damage, temporal trends, wildfire, wildland urban interface.

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Introduction

Wildfires in California in 2017 and 2018 destroyed thousands of homes, burned over 2 million acres (0.8 million hectares), and dominated headlines across the country. Although 2019 saw significantly less structure damage, fires in 2020 burned over 4 million acres (1.6 million hectares) and destroyed over 10 000 structures (Cal Fire 2020). With climate change increasing fire activity in the western USA and given the current pace of housing development of the wildland–urban interface (WUI), California is bracing for more destructive wildfires in the future (Westerling *et al.* 2006; Moritz *et al.* 2014; Radeloff *et al.* 2018; Williams *et al.* 2019).

Diverse vegetation, climate and human settlement patterns have spatially heterogeneous and complex effects on wildfires within California (Williams *et al.* 2019). Keeley and Syphard (2019) characterise California's wildfires as either fuel-dominated or wind-dominated. Fuel-dominated fires tend to occur in interior conifer forests in the central and northern parts of the state, where fire exclusion has resulted in anomalous fuel loads that can produce unusually severe and large fires. Fuel-dominated fires tend to occur in summer when lightning strikes are most common, and to burn in areas with low populations. Thus, structure damages from fuel-dominated fires are relatively low. Wind-dominated fires tend to occur in western parts of the state from north of San Francisco to the southern border. These fires mostly happen during the fall (autumn) when extreme offshore wind events are common. In contrast to fuel-dominated fires, wind-dominated fires tend to be human-caused and to burn in highly populated areas, often causing substantial structure damage.

Previous authors have assembled data on long-term trends in ignitions and area burned in California. Keeley and Syphard (2018) document fire-ignition patterns by source (e.g. lightning, powerlines) in California since the early 1900s, finding that in all regions of the state, fire frequency increased up until 1980, but has displayed the opposite pattern since then. Fewer ignitions do not mean smaller fires, however, as Williams *et al.* (2019) find a positive trend in the annual area burned over the period 1972–2018. The positive relationship is significantly different from zero for the whole state and the North Coast and Sierra Nevada regions, but insignificant for the Central and South Coast regions. While informative, these studies provide an incomplete picture of the damages from wildfire. Besides the unclear relationship between fire frequency and area burned (Keeley and Syphard 2018), large fires do not always cause a lot of structure damage. One of the most destructive wildfires in California history (US$1.1 billion in losses) was the small (1520 acre; 615 hectare) Tunnel fire.

Previous studies of property damages from wildfires focused on buildings damaged or destroyed. Using data on fire perimeters and Google Earth satellite imagery, Alexandre *et al.*

(2015) identified all burned and rebuilt buildings for large fires in the USA over the period 2000–2005. Kramer *et al.* (2018) extended this study to cover the period 2000–2013, and identified the percentages of threatened and destroyed buildings within the WUI (59 and 69%, respectively). In a study focused on California, Syphard *et al.* (2012) identified all structures damaged or destroyed in two fire-prone regions of the State over the period 2001–2010. In another California study, Kramer *et al.* (2019) analysed building losses from large fires over the period 1985–2013. Finally, Blanchi *et al.* (2010) documented structures destroyed by 54 Australian bushfires over the period 1957–2009, and related these losses to meteorological conditions.

The current report presents data on wildfire damages to structures in California over the period 1979–2018. We expand on earlier studies by documenting trends over a longer (40-year) period, including a larger set of fires, and estimating monetary losses rather than just structure loss. In contrast to previous studies that analyse satellite imagery to determine structure loss, we merge administrative data from Annual Wildfire Activity Statistics Reports (commonly known as 'Red Books'), available from the California Department of Forestry and Fire Protection (Cal Fire), with spatial data on fire perimeters and locations. This allows us to consider a longer time span compared with studies that rely on satellite imagery and a larger range of fire sizes. Many previous studies identify fire perimeters with the Monitoring Trends in Burn Severity data, which only includes fires over 1000 acres (405 hectares) in size (Alexandre *et al.* 2015; Kramer *et al.* 2018, 2019).

We explore several questions that have not been addressed in the literature. First, what are the trends in wildfire structure damages in California over the past four decades? Are the recent destructive fires an anomaly or part of a longer-term trend? Second, how do wildfire structure damages vary across different regions in California? Third, what is the relationship between area burned and structure damages from wildfire?

Methods

To build our database, we started with fire perimeter data from Cal Fire's Fire and Resource Assessment Program (FRAP), which includes most fires over 10 acres (4 hectares; brush fires and grass fires have greater reporting minimum areas) reported by Cal Fire and the US Forest Service (USFS). These data provide geo-referenced fire perimeters dating back to the 19th century, although we use perimeters since 1979 for this study. These data allow us to determine fire counts and area burned for all fires in California (as reported by FRAP) from 1979 to 2018.

One way to characterise hazardous fires is to examine ones that burned in the WUI since these are areas with a mix of houses and wildland vegetation. We combined intermix and interface WUI (see Radeloff *et al.* 2005) into a single category and overlaid the fire perimeters onto geo-spatial data from Radeloff *et al.* (2017) delineating the WUI. We grouped fire years to match one of the three available WUI layers: 1979–1995 (WUI 1990), 1996–2006 (WUI 2000), and 2007–2017 (WUI 2010). These data identify the WUI area burned for California fires over the 1979–2018 period.

We use the Red Books to document wildfire structure damages for the subset of fires that occur within State Responsibility Areas (SRAs). SRAs are those lands for which the State of California has financial responsibility for prevention and suppression of wildfires. This excludes federal lands and lands within incorporated city boundaries. The Red Books track the number of structures, including residences, commercial buildings and outbuildings, damaged or destroyed by wildfires 300 acres (121 hectares) or greater occurring in SRAs. (Wildland Fire Annual Reports from the National Interagency Coordination Center report a breakdown of structures destroyed by California wildfires for the years 2013–2018; https://www.predictiveservices.nifc.gov/intelligence/intelligence.htm. On average, residences accounted for 70% of structures destroyed.) If some portion of a fire occurs in an SRA, the Red Books report total damaged or destroyed structures for the fire (i.e. structures on non-SRA lands are included). Structure damage reports from the Red Books are available back to 1943, but the damages have only been reported separately by fire since 1979. For this study, we digitised the annual structure damage data from the Red Books from 1979 to 2017. Because the 2018 Red Book was not published when this analysis took place, we used the Cal Fire Damage Inspection database to count damaged structures in 2018 wildfires. The analysis does not include years after 2018; however, we reference some post-2018 data in the *Discussion* section.

The number of structures damaged is converted to dollar losses with estimates of average replacement cost for structures (excluding contents). These estimates are developed from the National Structure Inventory v2 (NSI) for 2018 (US Army Corps of Engineers 2019). For each county, we used the NSI to identify all structures (residential, commercial, industrial, public) within SRAs and to compute a county average replacement cost. We limited our attention to SRAs to avoid inflating estimates with urban structure values. Because we apply replacement cost estimates from a single year (2018) to structure losses in previous years (1979–2018), we are assuming that the average replacement cost for a structure in a county (in real, inflation-adjusted terms) does not change over time. Replacement cost depends on the cost of building materials and labour, but not on the cost of land, which is the main driver of real increases in home prices in California during the study period. The Census Bureau's Construction Price Index shows that nominal housing construction costs rose by virtually the same amount as the Consumer Price Index between 1979 and 2018, justifying our assumption (these two indices can be found at https://www.census.gov/construction/cpi/ and https://www.bls.gov/data/inflation_calculator.htm).

Our approach accounts for variation among counties in construction costs, but for a given county, changes over time in inflation-adjusted structure losses are due solely to changes in the number of structures damaged and destroyed. Structures reported as damaged are estimated at half the value of a structure. We are unable to distinguish between structures damaged or destroyed for years before 1991; for these early years, all structures are assumed to be destroyed, which means that loss estimates are potentially overestimated for years before 1991.

Results

Fig. 1 shows the cumulative area burned over time for all fires and WUI fires. The superimposed trend line indicates that, for all fires,

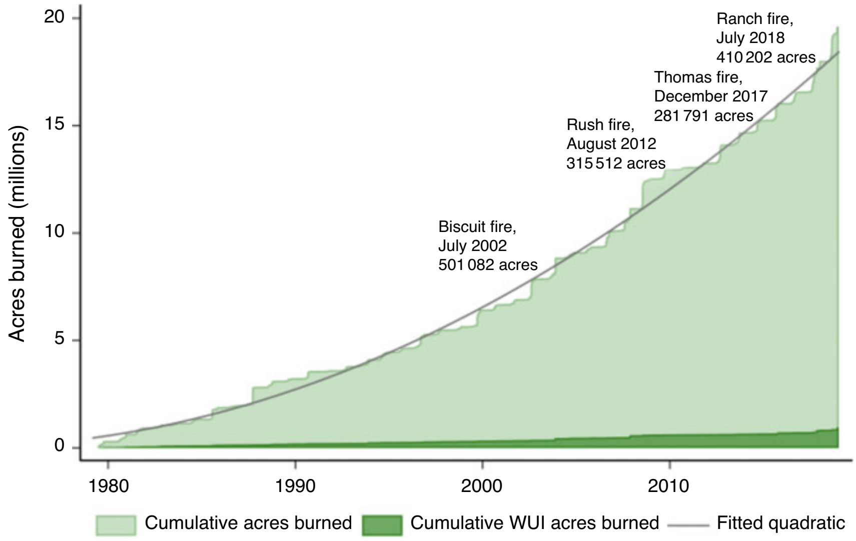

Fig. 1. Cumulative acres burned and WUI acres burned, 1979–2018, for all fires in California. Selected fires labelled for reference. One acre is equal to 0.405 hectares.

area burned has been increasing at an increasing rate, consistent with Williams *et al.* (2019). Twenty million acres (8 million hectares) experienced wildfire during the 1979–2018 period for an annual average rate of 500 000 acres (202 000 hectares). However, the annual rate during the 2009–2018 decade was 708 000 acres (287 000 hectares), compared with 337 000 acres (136 000 hectares) between 1979 and 1988. The fires noted in Fig. 1 are the largest in their respective years according to our data.

The area of WUI burned was, on average, ~5% of the total burn area across the decades (Fig. 1). Similarly to the pattern for all fires, cumulative WUI area increased at an increasing rate (see Supplementary material Fig. S1). The average annual WUI area burned was close to 32 000 acres (13 000 hectares) during the 2009–2018 decade compared with ~22 000 acres (8900 hectares) for the 1979–1988 decade. Thus, although the area of WUI burned is increasing every year on average, the rate of increase is lower than for all fires.

The area burned in the WUI reflects threats to structures, whereas the Red Books allow us to estimate actual structure losses for the subset of SRA fires, after we have converted the number of structures damaged and destroyed to replacement costs in dollar terms. The structure damage reports over the 1979–2018 study period were provided for 1567 fires, or 14.7% of all fires in California as reported in FRAP. However, the fires included in the Red Books represent 62% of the total area within the FRAP fire perimeters. Moreover, because many non-SRA fires are in areas without significant development, the Red Books are likely to account for almost all structure losses. National Fire and Aviation Management reports on total structures destroyed by wildfire in California for the period 2006–2018 reveal that SRA fires account for 94% of all structures destroyed over that period. (These data are summarised by Headwaters Economics and available at https://headwaterseconomics.org/natural-hazards/structures-destroyed-by-wildfire/.)

Monetary losses from SRA fires in California have been increasing over time (Fig. 2). The average annual loss during the 2009–2018 decade was almost US$1 billion, compared with

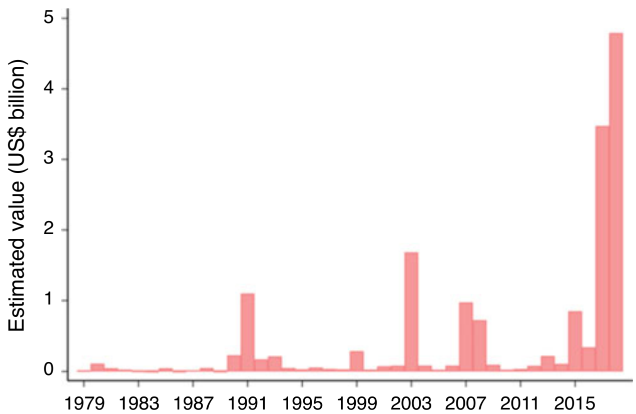

Fig. 2. Estimated value of structure losses (in 2018 US dollars) for SRA fire, by year, 1979–2018.

US$0.40 billion from 1999 to 2008, US$0.19 billion from 1989 to 1998, and US$0.03 billion from 1979 to 1988 (all values in constant 2018 US dollars). Monetary losses per area burned (Supplementary material Fig. S2) follow a similar pattern, revealing that wildfires in California have become increasingly destructive over time. Although a complete set of data for 2019 and 2020 was not available to include in the analysis, structure damage estimates from Headwaters Economics (see above) show that few structures were destroyed in 2019, whereas in 2020 the losses were comparable with 2017.

The map in Fig. 3 provides detail on where structure damages from SRA fires are occurring. Areas near San Diego and north of Los Angeles, San Francisco and Sacramento stand out as having particularly destructive fires in terms of the value of structures lost. These are also locations where the WUI has been expanding and structures are at greater risk of destruction from wildfires (Westerling and Bryant 2008; Radeloff *et al.* 2018; Kramer *et al.*

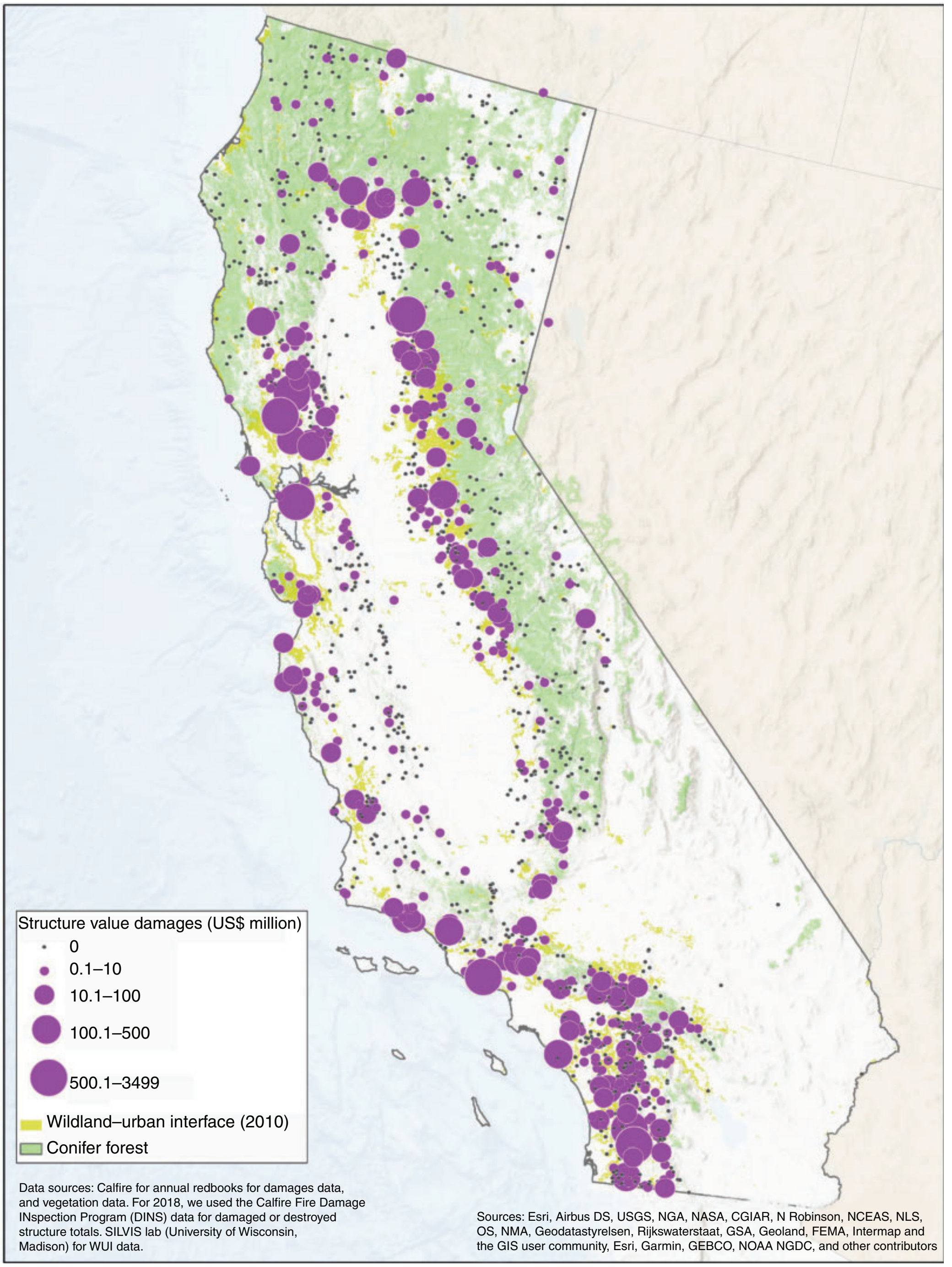

Fig. 3. Map of structure damages and fire perimeters for SRA fires, 1979–2018.

2019). Areas with conifer forest tend to have fewer destructive fires, with the exception of the west slope of the Sierra Mountains. In part, this is because these areas are within federally managed forests with little development.

Discussion

The data presented in this report provide a longer-term historical context for recent destructive fires in California. While wildfire is a natural process in many parts of California, our data show clearly increasing trends between 1979 and 2018 in the area burned overall, the area burned within the WUI, and damages to structures. We did not detect a clear north–south pattern in our results. The top 10 counties in terms of wildfire structure damages in each of the four 10-year periods we considered were just as often northern counties as southern counties, although total damages for northern counties were somewhat higher.

Our main conclusion is that the fires in 2017 and 2018 were not outlier events, but rather part of a long-term trend in California towards larger and more destructive fires, in terms of both area burned and structure loss. What can explain this pattern? One driver appears to be climate. In a retrospective analysis, Williams *et al.* (2019) found a clear link between increases in summer forest-fire extent in California and warming-driven increases in atmospheric aridity. Goss *et al.* (2020) find that the frequency of fall days with extreme weather conditions has more than doubled since the early 1980s. Expansion of the WUI is another possibility, as the majority of buildings destroyed in California wildfires are found in these areas (Kramer *et al.* 2019). Although ignitions have declined for most sources in recent decades, an exception is power lines (Keeley and Syphard 2018), which have been the cause of several recent and highly destructive fires in California.

Beyond property destruction, wildfires are a significant source of local air pollution, especially particulate matter (Clay and Muller 2019). As well, wildfires have the potential to reduce the value of unburned homes if they alert homeowners to the risk of future fires and decrease amenities. This can result in further reductions in the area's property tax base. A study in Colorado found, however, that the effects of wildfires on housing prices were fairly short-lived (McCoy and Walsh 2018).

The wildfires of the late 2010s prompted calls to change how and where to build in the future. However, these warnings are not new and there has been much discussion throughout the decade on learning how to coexist with wildfires (Moritz *et al.* 2014). In order to make smart policy changes, it is important to understand historical trends and their drivers. We find an increase in wildfire area and structure damage per area burned, as well as evidence that these trends are accelerating. Moreover, development continues to increase in the WUI (Radeloff *et al.* 2018), and the same trend in increasing structure damages is seen in the WUI as throughout California. Against this backdrop, policies that affect insurance rates for high-risk homes, building codes and the funding mechanisms for firefighting services require careful scrutiny (Plantinga 2018). More broadly, policies that promote adaptive resilience to wildfire can play an important role (Schoennagel *et al.* 2017), and California has recently devoted significant resources to this effort (see https://www.gov.ca.gov/2021/04/13/governor-newsom-signs-landmark-536-million-wildfire-package-accelerating-projects-to-protect-high-risk-communities/).

Data availability

The data are available at https://ucsb.box.com/s/f4cewdf1kap8dj1fk600qrmt1d7zjv8k.

Conflict of interest

The authors declare no conflicts of interest.

Declaration of funding

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