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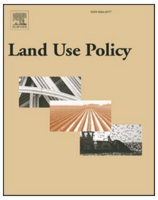

# Post-wildfire rebuilding and new development in California indicates minimal adaptation to fire risk

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## ABSTRACT

Every year, wildfires destroy thousands of buildings in the United States, especially in the rapidly growing wildland-urban interface, where homes and wildland vegetation meet or intermingle. After a wildfire there is a window of opportunity for residents and public agencies to re-shape patterns of development, and avoid development in locations that are inherently at higher risk of wildfire destruction. We examined 28 of the most destructive wildfires in California, the state where most buildings are destroyed by wildfires, to evaluate whether locations of rebuilt and newly constructed buildings were adaptive (i.e., if building occurred in lower risk areas). In total, these fires burned 7,075 buildings from 1970 to 2009. We found minimal evidence for adaptation both in the number and placement of buildings post-fire. Rebuilding was common: 58% of the destroyed buildings were rebuilt within three to six years, and 94% within thirteen to twenty-five years after the fire. Similarly, we found minimal trends toward lower risk areas in the placement of 2,793 rebuilt and 23,404 newly constructed buildings over the course of 13–25 yr. In fact, long-term data revealed that relative risk of new construction either did not change significantly over time or increased. A destructive wildfire could provide an opportunity to assess and change building practices, yet our results show that such change is largely not occurring. As wildfires increasingly threaten communities, this lack of change could result in growing rates of destruction and loss of life.

## 1. Introduction

Globally, wildfire losses have increased dramatically over the past several decades, with record setting events in Australia, Europe, Chile, Canada, and the United States (Bowman et al., 2019; Cruz et al., 2012; Gómez-González et al., 2018; Tymstra et al., 2020). Losses are a result of complex interplay of biophysical and social factors, including climate change driven increases in wildfire frequency and size, and an expanding wildland-urban interface (WUI) where people live in close proximity to wildland vegetation (Abatzoglou and Williams, 2016; Abatzoglou et al., 2018; Fischer et al., 2016). In the United States, housing development in areas with native vegetation is the primary force driving WUI expansion. The WUI grew by >30% in number of houses and area from 1990 to 2010, putting more homes at risk from wildfire (Radeloff et al., 2018; Kramer et al., 2018). WUI housing growth also increases the likelihood of wildfires because fire ignitions are primarily associated with humans (Balch et al., 2017; Nagy et al., 2018). This increase in ignitions, combined with vegetation changes (Collins et al., 2017; Sugihara et al., 2006) and climate change (Abatzoglou and Williams, 2016; Schoennagel et al., 2017), is driving increases in wildfire activity across the western U.S., leading to more frequent, intense, and larger wildfires (Abatzoglou and Williams, 2016; Westerling, 2016). The result has been increasing loss of property due to wildfires (Schumann et al., 2020), despite soaring wildfire suppression expenditures (USDA, 2015). All of these trends are poised to worsen in the future (Syphard et al., 2019), raising the question of how homeowners and communities can meaningfully reduce wildfire risk.

One potential way to reduce wildfire exposure is to change the extent and configuration of built development. The location and arrangement of buildings, especially their topographic position and distance from

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other buildings, plays a critical role in determining wildfire loss (Alexandre et al., 2016b; Syphard et al., 2012) in combination with vegetation, accessibility for fire fighters, building materials, and distance from the fire perimeter (Carmel et al., 2009; Gibbons et al., 2012; Syphard et al., 2012). Only a small proportion of buildings are lost in most fires (6% on average), emphasizing the importance of understanding and minimizing the factors that contribute to wildfire risk (Alexandre et al., 2015).

The time after a wildfire may present a unique window of opportunity to change building patterns as owners and communities take stock of their post-fire environment and make decisions about rebuilding destroyed buildings and constructing new buildings in wildfire-prone areas (Mockrin et al., 2016; Schumann et al., 2020). At the broadest level, any rebuilding and new construction within fire perimeters signals investment in these hazardous areas and a willingness to live with wildfire risk. However, more nuanced evaluations of adaptation can also evaluate and compare the level of wildfire risk to individual buildings. When building does occur within these fire perimeters, building decisions can be adaptive if people i) choose not to rebuild in locations where the probability of destruction is highest, and ii) place new construction in locations with lower probability of destruction by wildfire (Fig. 1). In this way the wildfire itself provides strong, direct evidence regarding the likelihood of wildfire, and where risk is highest, if residents are willing to act on such evidence.

Wildfires, similar to other disasters, often prompt minimal changes in policy and the built environment (Greenberg et al., 2014; Mockrin et al., 2016, 2018; Solecki and Michaels, 1994). After disaster, people often rebuild in the same location, for multiple reasons, despite continued vulnerability to future hazards (Simon and Dooling, 2013). Relocating after disaster is costly and psychologically difficult (Barile et al., 2019). Existing infrastructure facilitates rebuilding in much the same way, and local governments often encourage rebuilding and new construction to promote economic recovery (Mockrin et al., 2016; Pais and Elliott, 2008; Simon and Dooling, 2013). Indeed, post-disaster building may even result in an expanded human footprint in hazard-prone locations, in part because residents rebuild larger homes, capitalizing on insurance payments and disaster relief initiatives (Klomp, 2016; Lazarus et al., 2018). In other words, there are powerful reasons why adaptation in the form of change in building locations may not occur at the individual and community level.

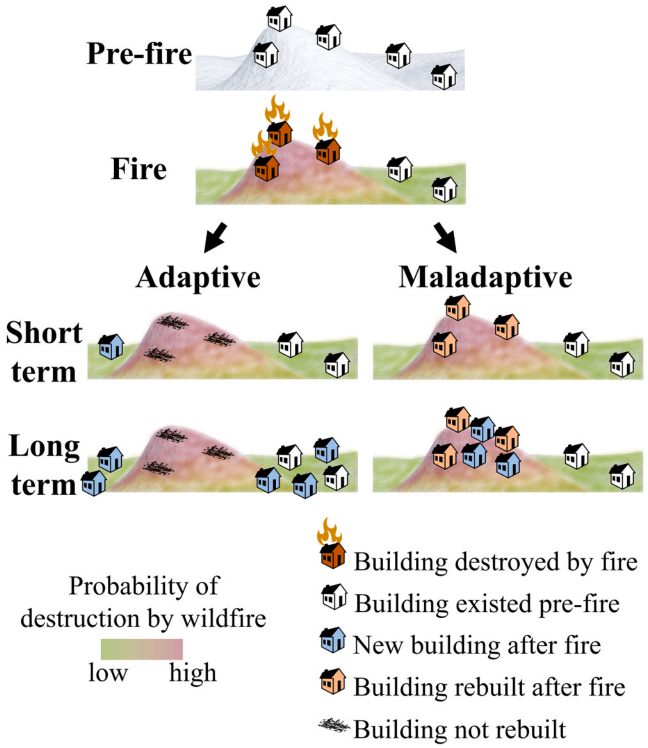

**Fig. 1.** Conceptual model shows how derived probability of destruction can be used to determine whether rebuilding and new construction within wildfire perimeters is adaptive (with rebuilding and new construction primarily in lower risk areas) or maladaptive (with rebuilding and new construction primarily in higher risk areas).

Overall rates of rebuilding and of new development after wildfires thus far provide ambiguous evidence of post-fire adaption. On one hand, only 25% of buildings destroyed by wildfires across the conterminous US are rebuilt within five years (Alexandre et al., 2015), which may indicate adaption. On the other hand, rates of new development are similar within wildfire perimeters and the larger counties where fires occurred (Alexandre et al., 2015), which suggests that wildfire does not discourage building within fire perimeters (lack of adaptation). In the case of the 1991 Oakland Hills Fire, the most destructive fire in California until 2017, rebuilding was common, as were increases in the size of rebuilt houses (Eriksen and Simon, 2017; Simon, 2014), resulting in a higher likelihood of home-to-home wildfire spread (Eriksen and Simon, 2017; Simon, 2014) and higher overall fire risk for the area. However, the Oakland Hills Fire was (at the time) a uniquely destructive fire in a densely developed area, and is one of few fires where development was assessed long-term. The issue of changing development over time is critical because risk perception diminishes for residents and community leaders alike as wildfire events fade from collective memory over time, vegetation regrows, and infrastructure is restored (McCaffrey et al., 2013; Paveglio et al., 2016). Finally, studies thus far have rarely considered the spatial patterns of development relative to wildfire risk, that is, going beyond rebuilding and new development totals (Alexandre et al., 2015; Kramer et al., 2018), to consider future potential wildfire risk at the level of individual buildings, though see Galiana-Martín (2017) and Gonzalez-Mathiesen et al. (2021).

Our goal was hence to identify whether the locations of rebuilding and new construction after wildfire were adaptive, over both short and long time frames, using a record of destructive wildfires over four decades in California. Specifically, we determined (1) rates of rebuilding and new construction both in the short-term (3–6 yr) and the long-term (13–25 yr) and (2) if rebuilding and new construction was less likely in higher risk locations, both in the short-term and the long-term. We defined and modeled risk as the probability that a house is destroyed if a wildfire occurs, based on landscape characteristics. We expected to find less evidence for adaptation in rebuilding, because existing infrastructure provides a strong incentive to rebuild in the same location, but more evidence for adaptation in newly constructed buildings because they can be more easily placed in less-risky locations. Furthermore, we expected building locations for new construction to be most adaptive shortly after the fire and to diminish over time as local memory of the wildfire event fades.

## 2. Materials and methods

We analyzed 28 California wildfires that burned between 1970 and 2009. Using historic aerial imagery, we digitized the location of all buildings within their perimeters over time, gathering data on building losses, rebuilding, and new construction, for up to 25 yr after the wildfire (Fig. 1). Our study was the first to examine long-term rates of rebuilding and new development. California is an apt study area because it has the highest number of buildings lost to wildfire in the conterminous United States (Kramer et al., 2018) despite huge investment in wildfire suppression (Ingalsbee and Raja, 2015), coupled with regulations and land use planning targeting reduced fire risk (Plevel, 1997). We quantified rebuilding and growth rate within each fire over time. We defined and modeled risk as the probability that a house is destroyed if a wildfire occurs, and we modeled this risk based on landscape characteristics associated with fire risk such as land cover, elevation, slope, ruggedness, topographic position, and distance to nearest town, major road, fire perimeter, and other buildings, as well as the observed destruction during the given wildfire. We derived models of the relative risk of building locations in each fire based on the pattern of destruction in that fire and checked for model robustness (Appendix A). We compared the relative risk of the locations of i) rebuilt buildings versus those that were not rebuilt and ii) buildings present before the fire versus those newly constructed after the fire.

### 2.1. Study area

The state of California experiences numerous destructive wildfires each year, and has the most building destruction due to wildfire in the conterminous United States, more than the other 47 states combined, between 2000 and 2013 (Kramer et al., 2018). As a result of these high wildfire impacts, California conducts extensive outreach and education via programs such as Firewise (National Fire Protection Association, 2016), the California Fire Safe Council (Everett and Fuller, 2011), University of California Center for Fire Research and Outreach, University of California Cooperative Extension fire and forestry specialists, California Fire Science Consortium (Kocher et al., 2012), Fire Adapted Communities (Fire Adapted Communities), and Fire Learning Network (Fire Learning Network, 2015).

California is a diverse state, with a wide range of natural systems and human communities that capture a variety of potential circumstances that influence post-fire recovery. California has a range of ecosystems and vegetation types, ranging from chaparral in the South to mixed conifer in the Sierras, oak woodland in the Sierra foothills, and redwood on the northern coast (Sugihara et al., 2006). Much of California is flammable, and over half of the state is covered by vegetation that depends on wildfire to reproduce and flourish (Barbour and Major, 1995). These conditions make wildfire suppression difficult and wildfires destructive where buildings are also present (Sugihara et al., 2006). In addition to diversity in vegetation, California has a diverse population of residents in fire-prone areas, including a diversity of incomes, ages, race/ethnicities, and built environments (home values, home and building density, and proximity to open space).

### 2.2. Data

California has reliable historic wildfire records and copious historic aerial photos, which allowed us to collect detailed data on destruction, rebuilding, and new construction in 28 wildfires that burned between 1970 and 2009. Before 1970, aerial photography was too scarce, and we bounded our study at 2009 to allow time for rebuilding to occur. For our 28 study wildfires, 11 occurred between 1970 and 1999 (data collection described below), and the remaining 17 burned after 1999 and were derived from an existing dataset (Alexandre et al., 2015).

To assess destruction and new construction in wildfires that burned between 1970 and 1999, we searched numerous databases for reports of wildfires that destroyed at least 50 buildings, including assorted newspaper archives, CAL FIRE's list of the top 20 most destructive wildfires (CAL FIRE, 2018), the USDA Forest Service national database of destructive wildfires (Short, 2014), Incident Command Status (ICS-209) reports, which compile daily records of building damage for wildfires where these reports are generated (National Wildfire Coordinating Group, 2016), and National Interagency Fire Center historically significant wildland fires (National Interagency Fire Center, 2016). Based on these databases, we identified 45 candidate wildfires (Table B1), and searched for their wildfire perimeters from the Fire and Resource Assessment Program (FRAP) records (CAL FIRE, 2012) and the Monitoring Trends in Burn Severity dataset (MTBS) (Monitoring Trends in Burn Severity, 2017) or, when these were not present, other online data sources. We found perimeters for 29 of the 45 candidate wildfires.

We searched for aerial photographs and high-resolution satellite images that covered each wildfire area for several time steps: (1) before the wildfire (up to five years before), (2) immediately after the wildfire (zero to two years), (3) shortly after the wildfire (three to six years), (4) medium-time after wildfire (eight to twelve years), (5) long-time after wildfire (13–17 years), and (6) very-long-time after the wildfire (18–25 yr). Although we grouped long- and very-long groups for final reporting, these subcategories were necessary for modeling. We used imagery from a variety of sources including Google Earth (Google Inc., 2016), UC Santa Barbara's aerial photo library, the Aerial Imagery Research Service (UC Santa Barbara Library), the Nationwide Environmental Title Research group (NETR) – a national database of aerial images (Nationwide Environmental Title Research LLC.), and library archives at *removed for blinded review*.

Ultimately, 12 wildfires had sufficient imagery coverage over time. We georeferenced the images and digitized the location of every building within the wildfire perimeter and up to 500 m outside of it to account for potential inaccuracies in perimeter mapping and the chance of spot-fire ignitions outside the mapped perimeter that may have destroyed buildings. Furthermore, we determined whether each building was (a) destroyed by the wildfire and never rebuilt, (b) destroyed by the wildfire and rebuilt (noting the image year of rebuilding), (c) survived the wildfire, or (d) was newly built after the wildfire (noting the image year that the new construction appeared). We defined rebuilding as another building appearing in the same location, but we did not have information on building type or owner (e.g., a home replaced by a commercial building would count as "rebuilt" in this work). We only included wildfires where we could identify at least 20 destroyed buildings, which reduced the sample size to 11 (see Appendix B for detailed descriptions of each of these wildfires). The 11 wildfires were located in both Northern and Southern California, spanning multiple ecological and socioeconomic zones, and representing a range of destruction rates (Fig. 3).

We augmented these wildfires with 17 additional wildfires from a dataset of 250 wildfires that burned between 2000 and 2013 in California, described by Alexandre et al. (2015) and (Kramer et al. (2018)). Only 69 of these wildfires had sufficient destruction, and only 17 of those met the criteria for imagery for time steps one, two, and three above, accounting for rebuilding and new construction between three and six years after the wildfire. Thus, our final dataset included 28 wildfires that burned between 1970 and 2009 (Fig. 3).

For each building in our dataset, we calculated multiple landscape characteristics to parameterize a risk model for each wildfire. We derived (1) land cover type in 1980, 1992, 2001, and 2011 from the National Land Cover Database, (2) distance to the nearest incorporated town or urban area using the US Census Bureau's incorporated places and urban areas, (3) distance to public land using the Protected Areas Database of the United States, (4) elevation and slope, (5) landscape ruggedness (Riley et al., 1999) at 10-m resolution and for a three by three cell neighborhood, (6) topographic position index (Jenness et al., 2013), (7) distance to the nearest primary and secondary roads from the Census Bureau's Tiger roads, (8) distance to the wildfire perimeter (Monitoring Trends in Burn Severity, 2017), (9) distance to the nearest destroyed and surviving building, and (10) the number of other buildings present within 100 m just before the wildfire (see Table A5 for metric description, source, and summary).

### 2.3. Data analysis

To better understand whether building behavior is adaptive to future wildfire risk, we asked (1) what are the rates of rebuilding and new construction both in the short-term (3–6 yr) and the long-term (13–25 yr) after a wildfire, and (2) is rebuilding of destroyed buildings and new construction less likely in higher risk locations, both in the near-term and the long-term?

We calculated the rebuilding rate within three to six and 13–25 yr after the wildfire for each wildfire, and for all 7,075 buildings destroyed by wildfire in our sample. We also calculated the growth rate due to new construction after the wildfire. For the rebuilding rate ($R$) $R = 100 \times (r/d)$ where $r$ is the number of rebuilt buildings, and $d$ is the number of destroyed buildings. Growth rate ($G$) was calculated as $G = 100 \times ((n + s)/s) - 100$ where $n$ represents the number of new buildings built after the fire, and $s$ represents the number of buildings that survived the fire.

To identify whether rebuilding and new construction took place in locations with higher risk, and if this changed over time, we constructed risk models for each of the 28 wildfires in the dataset, and calculated risk using a probit specification (StataCorp, 2017; Wooldridge, 2011). We derived models of the relative risk of building locations in each fire based on the pattern of destruction in that fire and checked for model robustness (Appendix A). We compared the relative risk of the locations of i) rebuilt buildings versus those that were not rebuilt and ii) buildings present before the fire versus those newly constructed after the fire. The probit model is well-suited for cases where the dependent variable can take on only two values (i.e., rebuilt or not rebuilt; destroyed or not destroyed). The unit of analysis was the individual building, and the dependent variable was equal to one if a building was destroyed and zero if not. We parameterized the probit model using a host of variables that have been found to influence wildfire risk to buildings in other settings (detailed above and in Table A5). The output of the probit model was the predicted probability of a building being destroyed by wildfire, given its set of covariates (StataCorp, 2017).

Using these wildfire risk models, we predicted, for each building in each wildfire, the probability that the building would be destroyed. We then compared, for each wildfire, the predicted wildfire destruction probability of buildings that were rebuilt versus those that were destroyed but not rebuilt, applied a two-sample $t$-test to identify significant differences in the mean wildfire risk between rebuilt and not rebuilt buildings in each wildfire, and counted the number of wildfires where there were significant differences. Thus, we identified if, on average, buildings that were rebuilt were in higher or lower risk locations than those that were destroyed but not rebuilt. If one variable perfectly predicted the likelihood of a building being destroyed (for instance, if all destroyed buildings and no surviving buildings were located in one land cover type), we did not model risk for that wildfire, because such a model would not provide any additional information.

Using the same wildfire risk models, we compared the wildfire risk of new construction that was built within three to six years of the wildfire to all buildings present at the time of the wildfire. There were 17 wildfires for which data three to six years after the wildfire was available and where new construction occurred. To compare wildfire risk between new and original (present before the wildfire) buildings, we applied the coefficients from the risk models to make out-of-sample predictions of the wildfire risk of the locations of newly constructed buildings. We then compared the predicted risk to the wildfire risk of all buildings present at the time of the wildfire. Once again, we applied a two sample $t$-test to test for statistically significant differences, and counted the number of wildfires with significant differences between new and original buildings, as well as the average difference in means for significant observations.

We investigated how building patterns changed after a destructive wildfire for rebuilding and new construction separately. In an ideal case, we would have information on the exact time from fire to building for each observation and with such data, we could use survival analysis techniques to understand the building process relative to fire risk. However, in our case, limits in photo availability resulted in imprecise data on timing of building activities, and this influenced the statistical techniques we chose. To examine the effect of time-since-fire on locational risk of rebuilt buildings, we regressed the predicted wildfire destruction probability of rebuilt buildings on the number of years that passed between the building being destroyed and rebuilt. We conducted this linear regression for each wildfire individually. The components of the model were the number of years between a wildfire destroying the building and when that building was rebuilt (as the dependent variable), the predicted wildfire destruction probability (as the independent variable), and an intercept term. A positive and statistically significant coefficient would indicate that buildings with lower wildfire risk were rebuilt more quickly than buildings with high risk. A negative and statistically significant coefficient would indicate that buildings with high wildfire risk were rebuilt before buildings with lower wildfire risk. We ran these regressions for 11 wildfires for which we had 13–25 yr of rebuilding data. We conducted an analogous analysis for new construction to test whether buildings built soon after a wildfire had higher or lower wildfire probability than those built longer after it.

### *2.4. Robustness checks*

While probit models were better suited for out-of-sample prediction, we also explored logit models and predictions based on boosted regressions (Cameron and Trivedi, 2005). Boosting can produce precise predictions, so we ran boosted models for each of the 28 wildfires to predict wildfire risk. We compared measures of goodness of fit between the boosted and non-boosted models using pseudo $R^2$ comparison to test for the advantage of using a model other than probit (StataCorp, 2017; Wooldridge, 2011). The probit model was an effective method for predicting risk probabilities. Overall, our measures of goodness of fit between the boosted and non-boosted models were very similar, so we completed our analyses using standard probit models, which were easier to use for out-of-sample prediction (StataCorp, 2017).

## 3. Results

In total, we found 7,075 buildings destroyed by 28 wildfires (2% of all buildings within those fire perimeters; Table A1). Over half of those destroyed buildings (58%) were rebuilt within 3–6 yr, and nearly all buildings were rebuilt within 13–25 yr (94% of 2,985, Table A1, Fig. 2). Fire variability was high, however, with rebuilding rates 13–25 yr after wildfire ranging from 13% to 100% (Table A1, Figs. 2 and 3). Newly constructed building rates after wildfires were as high as 205%, and new construction was common in all but the 1991 Oakland Hills and 1985 Baldwin Hills Fires, where already dense development prior to the wildfire meant that there was little undeveloped land available for new construction (Figs. 2 and 3; Appendix A).

We found no consistent trend of reduced risk of wildfire loss for either rebuilt or newly constructed buildings in the short-term (3–6 yr). Rebuilt buildings were in significantly lower risk locations in six out of 28 wildfires, but in higher risk locations in five wildfires (Fig. 4; Tables A2 and A3), with no significant difference in the remaining 17 wildfires (Fig. 4; Table A3). The plentiful new construction after a wildfire also showed no consistent trends toward lower-risk locations short-term. Of the 17 wildfires where new construction occurred within three to six years of the wildfire, new buildings were located in significantly lower risk areas in eight wildfires, but significantly higher risk areas in four wildfires (Fig. 4; Tables A2 and A3), and for the remaining five wildfires, there was no statistically significant difference (Fig. 4; Table A3). Across California, these differences in rebuilding and new construction, as well as changes over time meant that there were no consistent trends of reduced wildfire risk for buildings at the individual fire level over both the short-term and long-term time periods. Two fires had consistently lower risk in rebuilt and newly constructed buildings short-term (1993 Laguna Fire and 1977 Sycamore Fire), while another two had consistently higher risk in rebuilt and newly constructed buildings short-term (1980 Panorama Fire and 2008 Sayre Fire) (Table A2).

Long-term (13–25 yr after wildfire), rebuilding did not result in a different landscape post-fire compared to pre-fire, and new construction often occurred in higher risk areas longer after the fire. Of nine fires for which we had long-term data, the location of rebuilt buildings became higher risk over time in a single wildfire, and the opposite was true for two wildfires (Fig. 4; Tables A3 and A4). The remaining six wildfires showed no significant difference between the building location and the

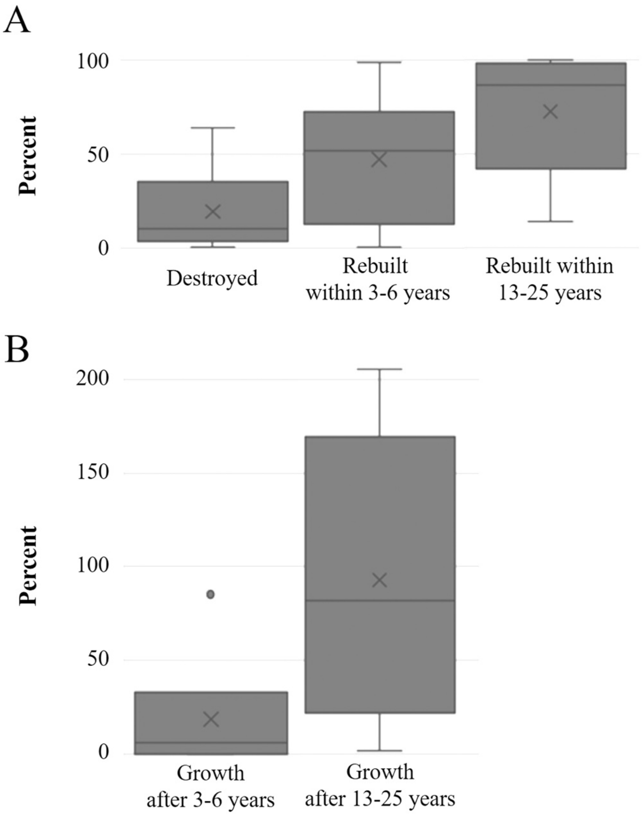

**Fig. 2.** Boxplots showing the distribution of values among fires for a) building destruction, short-term rebuilding rate, and long-term rebuilding rate and b) short-term growth and long-term growth. Median and quartile values are shown as horizontal lines around the gray box (using proportions in each wildfire as input). Minimum and maximum values are shown as the whisker lines above and below each box, or as a single dot for outliers. The overall proportion in each category, shown as an "X," is calculated from all buildings in our dataset. Growth was measured as growth from new construction: [100 × (buildings newly constructed + buildings that survived the fire)/buildings that survived the fire] – 100. See Table A1 for exact numbers.

timing of rebuilding (Fig. 4; Tables A3 and A4). For new construction, four wildfires showed increasing risk over time for building locations, while the remaining five wildfires showed no significant trend (Fig. 4; Tables A3 and A4). Although more wildfires showed significant reductions in wildfire risk for new construction than for rebuilding, it was still uncommon, occurring in less than half of the fires examined. Wildfire risk for new buildings also increased as time passed, suggesting that lessons learned from wildfires may fade over time.

## 4. Discussion

California has a long history of destructive wildfires, most recently with notably large and destructive wildfires in 2017 and 2018 leading to the loss of over 25,000 homes (National Interagency Coordination Center, 2017, 2018). Tens of thousands of homeowners and in some cases, entire cities and communities, are now facing complex and challenging decisions about rebuilding and recovery, in an era when global climate change is poised to intensify wildfire hazards (Abatzoglou and Williams, 2016; Schoennagel et al., 2017; Williams et al., 2019). Indeed, since the early 1970s, California's annual wildfire extent has increased fivefold (Williams et al., 2019). Yet, our comprehensive survey of post-fire development during the same time period showed that destructive wildfire resulted in few buildings being permanently removed from the landscape. Long-term, only 6% of buildings lost to fire were not yet rebuilt. New development far outpaced rebuilding in contributing to the built environment post-fire. In addition, the location of these buildings—both rebuilt and newly constructed—showed no consistent adaptation by reducing wildfire risk. For most fires, rebuilding did not result in a different landscape post-fire compared to pre-fire, and new construction often occurred in higher risk areas longer after the fire. None of the fires studied had consistent reduction in wildfire risk for rebuilds and new construction over short- and long-term.

This lack of change in building pattern, i.e., the lack of evidence for adaption, had no clear geographic or temporal pattern, and suggests that local governments did not restrict or guide building based on wildfire risk after these fires. Since the early 1990s, there have been state-mandated requirements for defensible space and fire-resistant materials (new/rebuilding) in certain areas of higher wildfire risk (Kocher and Butsic, 2017), and individuals can always voluntarily choose such building materials or landscaping. Although we do not have such data on *how* people build, we found a consistent lack of adaption in *where* people build, similar to other disasters which also did not result in major changes in building pattern (Birkland, 2006; Solecki and Michaels, 1994). Although the notion of building back better forms a hallmark of disaster recovery, from global frameworks to individual jurisdictions, in reality, recovery often prioritizes rebuilding and de-emphasizes risk (Kim and Olshansky, 2014; McCaughey et al., 2018). Post-disaster, government financial assistance and homeowners insurance also help facilitate rebuilding without requiring or promoting changes in building location (Becker, 2009; Mockrin et al., 2015). California's land use policies make no restrictions on residential development because of wildfire risk, although we have found instances where complying with access and water supply standards were so costly they slowed or discouraged rebuilding (after 2009′s Station fire in Los Angeles County; (Mockrin et al., in review)). It was also unclear from our data if individuals built larger homes, which has been documented after wildfires in Colorado and California, and poses additional risk of increasing house-to-house fire spread (Mockrin et al., 2016; Pais and Elliott, 2008; Simon and Dooling, 2013). In response, some jurisdictions purposefully facilitate rebuilding if houses are rebuilt to similar size (City of Malibu, 2020; Mockrin et al., 2016). For example, those rebuilding after 2018′s Woolsey fire in Malibu can choose to rebuild a home of similar size for a building permit of less than $200 and same-day approval, while expanding a home in size or height can cost thousands of dollars more, with a months- to years-long permitting approval process (City of Malibu, 2020).

Development decisions could also indicate a lack of knowledge about landscape factors that influence wildfire risk. Destroyed buildings provide evidence of substantial risk (Brenkert-Smith et al., 2013; Meldrum et al., 2015) but residents may decline to rebuild or live in burned areas long-term, and newer residents will lack first-hand experience with wildfire events. In addition, owners may be resistant to taking mitigation actions, such as using fire resistant building materials or maintaining defensible space, even after destructive wildfire (Cohen, 2000; Manzello et al., 2009; Syphard et al., 2017). Property owners may assume that fire risk is diminished after wildfire because there is less available fuel, they may be in denial or fatalistic about the likelihood of a second wildfire, or they may opt against mitigation actions due to financial or esthetic reasons (McCaffrey et al., 2013; McGee et al., 2009; Mockrin et al., 2015).

Our analyses demonstrate considerable rebuilding and new development within wildfire perimeters, at the same time that ecological changes have drastically altered wildfire regimes in California (Safford and Van de Water, 2014; Sugihara et al., 2006). In particular, fire frequency in the chaparral systems in Southern California has increased rapidly, so that fires are now recurring in some areas within 10 yr (CAL FIRE, 2012; Safford and Van de Water, 2014; Zedler et al., 1983). The increase of wildfires is due to a combination of fast regeneration of a flammable fuelbed, often exacerbated by invasive non-native grasses (Keeley and Zedler, 2009), and a lengthening of the wildfire season due

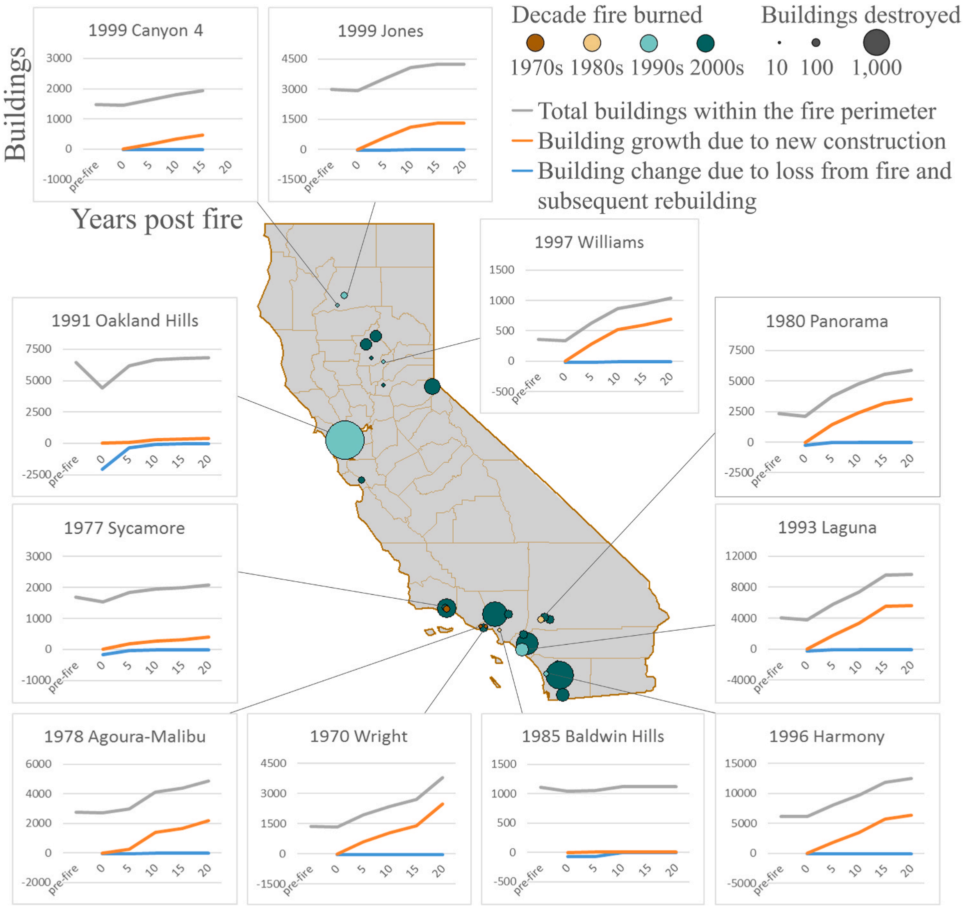

**Fig. 3.** Trends in rebuilding, new construction, and overall buildings within the perimeters of 11 California wildfires from pre-fire to 13–25 yr after the wildfire burned. Note that building loss due to wildfire is reflected by a negative building change, which approaches zero as buildings are rebuilt.

to changes in climate (Balch et al., 2017). These factors, as well as increased homes and people in these areas causing more ignitions (Nagy et al., 2018), are likely to continue into the future, intensifying the frequency and intensity of wildfires in Southern California, and throughout the state (Radeloff et al., 2018). Indeed, 6 of the 10 most destructive fires (in terms of building destruction) in California history have occurred in Northern California and in the last 17 yr (since 2004; (CAL FIRE, 2020)).

Despite these challenges, we suggest that altering the locations of future development could reduce the overall wildfire risk to the built environment and alleviate the mitigation and fire protection burdens of buildings in fire prone areas. However, our results show that thus far individuals and local governments are not choosing to reduce wildfire risk by adaptively locating buildings on the landscape. We came to these conclusions by taking a decades-long retrospective approach and using a thorough modeling framework which examined building-specific wildfire risk for each of these wildfires and buildings over time. Enhancing similar analyses and sharing outcomes (losses, rebuilding data, subsequent exposure) across jurisdictions will be vital to help inform local development decisions. After the devastating losses of the 2017–2020 wildfire seasons, California now has multiple, legislatively-mandated changes to WUI regulations pending, including changing Fire Safe Regulations that determine road and water access and updating regulations for subdivision planning, defensible space, and infrastructure, as well as increasing assistance for land use planners at local jurisdictions from the state and CAL FIRE (Governor's Office of Planning and Research, 2020; Mowery and Punchard, 2021). At the same time, there are also many competing demands for housing access and affordability throughout the state (State of California, 2018). Our work suggests additional landscape factors, considered at the level of the building site, can be valuable ways to consider and assess wildfire risk. Additional research into landscape factors will be required to ensure that maps of fire risk are as accurate as possible, and can be provided for meaningful consideration in land use policy and development decisions such as buyouts or road infrastructure improvements for areas of greatest risk.

### 4.1. *Limitations*

While our results showed some clear and unambiguous patterns, our study also had a number of limitations that need to be considered when interpreting our results. First, we did not have information on building materials or defensible space maintenance, so could only draw conclusions based on rates of building and building locations. Specifically, we did not assess the buildings affected by the 1992 Bates Bill that required new defensible space and building material for some California residents, and may have influenced home survival. Second, our sample size of wildfires was small due to limited availability of historic aerial imagery. Third, models were based on vegetation at the time of the wildfire, and only considered development within the wildfire perimeter. It would also be valuable to examine how vegetation, and hence fuels, change after fires, but this was outside the scope of our study. Fourth, there was high variability between wildfires, consistent with numerous other studies (Alexandre et al., 2015; Mockrin et al., 2018). Therefore, the outcome associated with a specific wildfire may differ from our general results. Fifth, estimates of risk were based on characteristics of landscape position, land cover, and surrounding buildings, and were modeled after each wildfire for the time series available for that fire. Similar characteristics have been considered by other studies examining

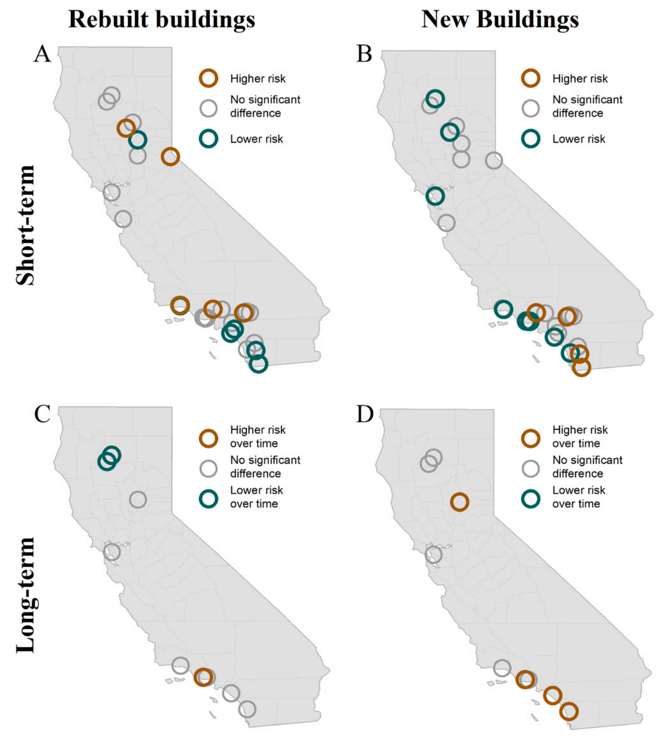

**Fig. 4.** Map of significant trends by fire of a) rebuild locational risk and b) new building locational risk, 3–6 yr after fire, as well as c) rebuild locational risk and d) new building locational risk, over time (comparing risk of building 13–25 yr post-fire to 3–6 yr post-fire). Each fire used in each of the four models is represented by a hollow circle. Generally, brown represents a lack of adaptation, (building in higher risk areas in the short term or building in riskier areas through time), and teal represents adaptive building in lower risk areas in the short term and through time.

building risk to wildfire (Alexandre et al., 2016a, 2016b; Syphard et al., 2012). Our predictions of landscape wildfire risk should not be used to predict universal wildfire risk, nor should they be used to predict the actual risk to a building in a subsequent wildfire. Subsequent wildfires may occur under different weather conditions and different fuel loads. However, additional research into these areas would be highly informative.

## 5. Conclusion

Climate change, invasive grasses, fuel accumulation due to wildfire suppression, and an expanding WUI—with development often located in high-risk locations—put increasing numbers of buildings at risk to destruction by wildfire, and make it likely that highly destructive wildfires will continue to occur. Additionally, our results show that there is little adaptation to wildfire risk, even after wildfires have occurred. Indeed, new construction within wildfire perimeters often occurs in higher-risk areas as more time passes after a fire, which means that more buildings will require protection from future wildfires over time. With a tight budget, and billions of dollars spent each year on wildfire suppression in the United States, policymakers and planners aim to reduce the risk of wildfire on the landscape. In this regard, placing buildings where fire risk is lowest is an obvious solution, but one that our results indicate has not been embraced in practice.

## Author contributions

**H.A.K.**, **V.C.R.**, **V.B**, **M.H.M.**, and **P.M.A.** designed research; **H.A.K.**, **C.R.**, and **V.C.R.** performed research; **H.A.K.**, **V.B.**, **V.C.R.**, and **C.R.** analyzed data; and **H.A.K.**, **V.B.**, **V.C.R.**, **M.H.M.**, **P.M.A.**, and **C.R.** wrote the paper.

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### *Conflicts of interest*

The authors declare no conflicts of interest.

## Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.landusepol.2021.105502.

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