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November 12, 2020

San Diego County Planning & Development Services
Attn: Mark Wardlaw, Director of Planning & Development Services
5510 Overland Avenue, Suite 310
San Diego, CA 92123
By email: Mark.Wardlaw@sdcounty.ca.gov

RE: Otay Ranch Resort Village—Village 13 Final Environmental Impact Report; Otay Ranch Resort Village, Project Nos. GPA04-003, REZ04-009, TM-5361, SP04-002, and ER LOG04-19-005

Dear Mr. Wardlaw:

We appreciate your preparation of a Final Environmental Impact Report (FEIR) responding to public comments on the Draft Environmental Impact Report (DEIR), including the comments we submitted on December 27, 2019, regarding wildfire risks associated with the proposed Otay Ranch Resort Village—Village 13 Development (Project). After reviewing the FEIR, we acknowledge and appreciate that you have provided more information regarding wildfire risks associated with the Project. We believe, however, that the FEIR's discussion of these risks remains inadequate.[1]

I. THE FEIR FAILS TO ADEQUATELY ADDRESS THE INCREASED WILDFIRE RISK THAT WILL RESULT FROM THE PROJECT

In our comment letter, we explained that locating new development in a very high fire hazard severity zone will itself increase the risk of fire and, as a result, increase the risk of exposing residents, employees, and visitors to that enhanced risk. We further explained that the DEIR fails to analyze the increased risk of wildfire that will result from siting the Project within a such a zone.

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[1] This letter is not intended, and should not be construed, as an exhaustive discussion of the FEIR's compliance with the California Environmental Quality Act (CEQA) or the Project's compliance with other applicable legal requirements.

The County's response to our letter incorrectly denies that an increased risk exists. According to the County, "there is no evidence that higher density residential development in San Diego County—including development in the wildland-urban interface—has increased fire-ignition frequency. In fact, research suggests the opposite . . . ." (Response RA-5-7; see also *ibid.* ["there is no data available that links increases in wildfires with the development of higher density ignition resistant communities"]; RA-5-8 [denying knowledge of "any study . . . that establishes a causal link between development of higher density, planned communities in wildland areas and increases in fire-ignition"].) This is inaccurate. Indeed, a recent report prepared for the San Diego County Fire Authority regarding this Project reaches the conclusion that the County now rejects. The study, which analyzes wildfire risks associated with the Project, states: "Numerous studies have identified that human wildfire ignition is directly tied to population growth (CAL FIRE, Keeley, et. al.) *and is an inescapable result of any development in the Wildland-Urban Interface*." (Rohde & Associates, Fire Services Operational Assessment for Otay Ranch Village Resort, Village 13 (Feb. 1, 2020) ("Rohde Report"), p. 11, emphasis added.)[2]

Notably, the studies documenting the association between population in the wildland-urban interface and increased fire risk include reports by leading experts Jon Keeley and Alexandra Syphard—experts upon whom the County relies heavily in its response to our comment letter (see RA 5-7). (See, e.g., Ex. B, Keeley and Syphard et al., *The 2003 and 2007 Wildfires in Southern California* in Natural Disasters and Adaptation to Climate Change (Boulter et al., edits., 2013), p. 44 ["The massive losses of property and lives in recent fires are the result of human population growth and expansion into these fire prone landscapes."]; Ex. C, Keeley and Syphard, *Nexus Between Wildfire, Climate Change and Population Growth in California* (March 2020) Fremontia, Vol. 47, No. 2, p. 26 ["More people translates into a greater probability of an ignition during a severe wind event, and more development in highly fire pone landscapes inevitably results in greater losses of lives and homes."]; Ex. A, email from A. Syphard dated May 29, 2020, p. 1.) According to Mr. Keeley and Ms. Syphard, the County's response does not accurately describe their work. (See Ex. A, p. 1.) While they are not accusing the County of intentional mischaracterization, they make clear that the County's analysis misses the bigger picture and thus excludes critical detail about wildfire risk.

The County's response seems to rely largely on the notion that the Project is "higher density" and, therefore, not likely to increase the potential for wildfire to occur. That notion, however, obscures the nuanced relationship that exists between housing patterns—including density *and* other variables—and fire risk. (See Ex. A, p. 1.) While Mr. Keeley and Ms. Syphard's work has shown that low- and intermediate-density housing is most at risk, density is not the only relevant factor; location within the larger landscape and within an individual development are also relevant. (See *ibid.*; see also Ex. D, Syphard and Keeley, *Why Are So*

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[2] While this is correct, the Rohde Report also contains numerous flaws, as set forth in the November 11, 2020 letter from the Endangered Habitats League (EHL), the July 3, 2020 letter from Griffin Cove Transportation Consulting, PLLC (Ex. S to EHL letter), and the September 11, 2020 letter from Reax Engineering (Ex. P to EHL letter).

Many Structures Burning in California? (March 2020) Fremontia, Vol. 47, No. 2; Ex. E, Syphard and Keeley et al., *Land Use Planning and Wildfire: Development Policies Influence Future Probability of Housing Loss* (Aug. 2013) PLOS ONE, Vol. 8, Issue 8.)

In addition, and perhaps more importantly here, while low-density housing might be most at risk, that does not mean high-density housing is free of risk. Mr. Keeley and Ms. Syphard explain that, contrary to the County's claim, their "research does not support the notion that high density housing is not at high risk . . . ." (Ex. A, p. 1.) This is "particularly" true "if the high density housing is in close proximity to any significant area of undeveloped wildland vegetation." (*Ibid.*) By "focusing on the area **just within the development instead of the development within the larger landscape context**," the County misses the larger picture. (*Ibid.*, emphasis in original.) "If high-density development is located within a matrix of wildland vegetation, that is actually the most dangerous housing pattern you could have!" (*Ibid.*) This combination is "particularly dangerous . . . because there is exposure to fire hazard AND the possibility for structure-to-structure spread." (*Ibid.*) In other words, Mr. Keeley and Ms. Syphard's research supports the *opposite* of what the County claims; if the Project truly is "higher density" development, given its proximity to wildland vegetation it may actually be the most dangerous housing pattern possible.

As this makes clear, density is relevant to loss, but location and housing patterns are also highly relevant. For example, Mr. Keeley and Ms. Syphard published a 2013 paper analyzing the risk associated with three different housing patterns: (1) infill, "characterized by development of vacant land surrounded by existing development, typically in built-up areas"; (2) expansion, which "occurs along the edges of existing development"; and (3) leapfrog growth, meaning development "beyond existing urban areas such that the [development] is surrounded by undeveloped land." (Ex. E, p. 2.) The authors found that leapfrog development presented the greatest risk and infill development the least. (*Id.*, p. 8.) By focusing on density, the County downplays the other attributes of the Project, such as the fact that a significant portion of the Project is bordered by wildlands and that the development sits among more than 1,100 acres of open space (FEIR 4-3), which will contribute to the wildfire risk. The County's analysis of the wildfire risks associated with the Project should account for these other variables.

Mr. Keeley and Ms. Syphard also believe that the County misconstrues their 2015 paper on ignition patterns. (Ex. A, p. 1; see RA-5-7.) Pointing to the paper's finding that equipment caused the most wildfires in San Diego County and accounted for the greatest area burned, the County speculates that such fires are "associated with lower density housing," and thus higher-density housing carries less fire risk. (RA-5-7.) As Mr. Keeley and Ms. Syphard explain, however, "[t]he main point found by our research is that humans cause 95% of fires, and as humans move farther east and into wildlands the likelihood of ignitions moving into those areas also increases. That is how humans alter the spatial pattern of fires, regardless of ignition source." (Ex. A, p. 1.) Further, while some sources, like equipment, may be more numerous, they do not necessarily result in the largest fires. "It is more about the timing and pattern of the ignition relative to wind corridors and during severe fire weather." (*Ibid.*)

The experts also take issue with the County's argument that development in the wildland-urban "*interface*" carries a lower risk than development in the wildland-urban "*intermix*." (RA-5-7.) Mr. Keeley and Ms. Syphard make clear that development in both locations is "very dangerous." (Ex. A, p. 1.)

Finally, Mr. Keeley and Ms. Syphard's work refutes the County's claim that the Project will be adequately protected because its structures and design make it "ignition resistant" (RA-5-7). In their paper entitled "Factors Associated with Structure Loss in the 2013-2018 California Wildfires," Mr. Keeley and Ms. Syphard found that "MANY of the houses destroyed were newly built. Newer construction definitely may help *but is not a panacea by any means*. That also goes for defensible space." (Ex. A, p. 1, emphasis added; see Ex. F, Syphard and Keeley, *Factors Associated with Structure Loss in the 2013-2018 California Wildfires* (Sept. 2019) Fire, 2, 49.) Their work also shows that fuel breaks have a "limited effectiveness at preventing fire spread during severe wind conditions when 99% of the structure loss occurs." (Ex. A, p. 1.) In other words, "[t]hose measures in a new development do not mean those homes are safe from fire." (*Ibid.*)

In sum, the County's assertion that the Project will not exacerbate wildfire risk is over-simplified and relies on sources that, in fact, prove the opposite. These critical flaws in the County's analysis cannot be overlooked. The County must not certify the FEIR and approve the Project until it adequately addresses the increased risk of wildfire that the Project will create. (See CEQA Guidelines, § 15126.2(a) [requiring the evaluation of potentially significant environmental impacts of locating development in areas susceptible to hazardous conditions such as wildfire risk areas, especially as identified in hazard maps and risk assessments].)

II. THE FEIR FAILS TO ADEQUATELY ADDRESS THE CUMULATIVE WILDFIRE RISK POSED BY ALL NEW OTAY RANCH DEVELOPMENT

Our comment letter also states that the Project is one of a number of large new developments in the same area, and that the DEIR fails to adequately assess the cumulative impact on fire risk posed by siting these developments in this very high fire hazard severity zone. For the same reasons the FEIR does not sufficiently address the increased wildfire risk resulting from the Project, it likewise fails to sufficiently address the cumulative risk posed by all new development in Otay Ranch.

III. THE FEIR FAILS TO ADEQUATELY ADDRESS EVACUATION IN THE EVENT OF FIRE

In our comment letter, we state that the DEIR needs to include a robust evacuation plan. This remains true. Because the Project increases the risk of wildfire, it must also contain a plan for safe evacuation. The FEIR neither acknowledges that added risk nor assures that the community can be evacuated safely. It also fails to address the Project's impact on the evacuation of nearby communities that use the same roads, and the impact on firefighters and emergency responders who must access the site and prevent the spread of a wildfire while the Project and neighboring areas are evacuating. The FEIR needs to rectify these failures.

The County essentially responds that a project- or community-specific evacuation plan would be useless for two main reasons: (1) because fire evacuations are managed by law enforcement and fire agencies that rely on their own plans, and (2) because evacuation events are too fluid and variable to allow for pre-emergency planning. (RA-5-12, RA-5-13.) This response misses the point. We are not asking the County to interfere with law enforcement or to prepare for every possible scenario. Rather, we are asking the County to analyze, with adequate detail, whether the Project and its surrounding residents can be evacuated safely. This is not only possible but required to address the increased risk of wildfire that will result from the Project. The County's response and the FEIR, including but not limited to the County's Global Response R5, its "Conceptual Wildland Fire Evacuation Program," and the Rohde Report, fail to provide this critical analysis. The November 11, 2020 letter from EHL, and its attached July 3, 2020 letter from Griffin Cove Transportation Consulting, PLLC (Ex. S to EHL letter), and September 11, 2020 letter from Reax Engineering (Ex. P to EHL letter), explain the shortcomings of this analysis in detail. The County must adequately consider the safe evacuation of residents before certifying the FEIR and approving the Project.

IV. The FEIR Should Prohibit Certain Vegetation on Private Lots

Our comment letter also states that the DEIR's recommendation "that none of the plant materials listed in the 'Prohibited Plant List' . . . or otherwise known to be especially flammable be planted on private lots" (DEIR, Appx. C-21 p. 28) should be changed to a requirement. While we appreciate the County's response that it would "consider" this request, the FEIR does not make the requested change. For the safety of the Project's residents, the FEIR should change the recommendation regarding prohibited and flammable plants to a requirement.

We appreciate your consideration of our comments and respectfully request that you refrain from certifying the FEIR and approving the Project until the FEIR is revised accordingly. If you have any questions or would like to discuss our comments, please feel free to contact us.

Sincerely,

Kimberly Gosling

KIMBERLY R. GOSLING
Deputy Attorney General

For XAVIER BECERRA
Attorney General

Attachments

cc: Greg Mattson, Project Manager (*by email:* Gregory.Mattson@sdcounty.ca.gov)

SA2019102285

Exhibit A

From:	Alexandra Syphard
To:	Nicole Rinke; Keeley, Jon
Cc:	Kimberly Gosling
Subject:	Re: Wildfire expertise/question re. ignition risks
Date:	Friday, May 29, 2020 1:55 51 PM

Dear Nichole and Kim,

This claim made by SD County mischaracterizes our work We had previously written a letter to Dan Silver saying as much, and the text we wrote to him is copied below Please let me know if this helps

Best,
Alexandra

Dear Dan:

Jon Keeley and I have reviewed the materials you sent and we would like to clarify that our research does not support the notion that high density housing is not at high risk, particularly if the high density housing is in close proximity to any significant area of undeveloped wildland vegetation. t is true that our papers have consistently shown that low-density housing is most at risk when you look at a full gradient of housing density across a region. However, in all of our papers - and those of others as well - we find that the relationship with housing patterns and fire risk are nuanced and include more variables than just density. In particular, we find that the riskiest patterns are small to medium-sized clusters of development within a larger landscape of wildland vegetation, in addition to low-to-intermediate housing density and proximity to the edge of development.

In other words, I would say the materials are only getting part of the picture. That is because they are focusing on the area **just within the development instead of the development within the larger landscape context**. If a high-density development is located within a matrix of wildland vegetation, that is actually the most dangerous housing pattern you could have! That's because at very high densities, the relationship can switch to where houses closer than 50m to each other are more likely to have structure to structure spread (of course, depending on the building materials). In other words, there is significance to the location and size of high density development. This has been explained clearly in additional papers by Alexandre et al. 2015a and b. For example, in the Cedar Fire, we found that high-density structures in smaller clusters of development in Julian were the larger risk factor, and I think that is the same thing going on here in the newly proposed developments. Large wildland surrounding high-density areas is a particularly dangerous combination because there is exposure to fire hazard AND the possibility for structure-to-structure spread.

I also think the discussion about our paper on ignition patterns is a bit misconstrued. The main point found by our research is that humans cause 95% of fires, and as humans move farther east and into wildlands the likelihood of ignitions moving into those areas also increases. That is how humans alter the spatial pattern of fires, regardless of ignition source. Some sources are more numerous than others (like equipment), but those aren't necessarily the ones that result in the largest fires. It is more about the timing and pattern of the ignition relative to wind corridors and during severe fire weather.

In the article I wrote for an upcoming Fremontia issue (attached, Jon has one too), I have synthesized all of our work on structure loss, so some of the references in there may be helpful. Also see the attached paper by Anu Kramer finding interface communities in CA being dangerous, which runs contrary to some of the language in the materials you shared. True, intermix WUI is also very dangerous, but so is the interface.

I might add that in the paper Jon and I published in Fire, Factors Associated with Structure Loss in the 2013–2018 California Wildfires, MANY of the houses destroyed were newly built. Newer construction definitely may help but is not a panacea by any means. That also goes for defensible space. Also recall the work that we have done on fuel breaks and their limited effectiveness at preventing fire spread during severe wind conditions when 99% of the structure loss occurs. Those measures in a new development do not mean those homes are safe from fire. The Australians are a great example of never saying anything is fire-proof. It isn't.

I hope that is helpful. Please let me know if we can clarify anything further.

Alexandra Syphard and Jon Keeley

> On 5/28/2020 6:31:03 PM, Nicole Rinke <nicole rinke@doj ca gov> wrote:
>
> Hello Jon and Alexandra,
>
> My colleague, Kim (cc'd here) and I are with the California Attorney General's office. Our office is reviewing and commenting, as appropriate, on proposed projects in wildland areas throughout the state to make sure that wildfire risks/issues are being adequately disclosed and considered during CEQA review for various land use approval processes at the local level. So far, we have commented on the Paraiso Springs Project in Monterey County and the Otay Village 13 Project in San Diego County.
>
> You are both prolific in your research and writing on topics that relate directly to the work we are doing and we are interested in talking with you. On the Otay Village 13 Project, in particular, San Diego County has cited your work as support for its position that the project does not present a significant fire risk, based in large part on its characterization of the project as "higher density" housing. (See page 4-5 of the pdf response to our comments, https://www.sandiegocounty.gov/content/dam/sdc/pds/ceqa/OtayRanchVillage13Resort/PrePC/2019Comments/Responses/RA-5_AttorneyGeneral_Response_2.27.2020%20(rrs).pdf; our comment letter can be found here: https://www.sandiegocounty.gov/content/dam/sdc/pds/ceqa/OtayRanchVillage13Resort/PrePC/2019Comments/Comments/RA-5_AttorneyGeneral.pdf).
>
> We are curious to hear your perspective on the County's response to our comments - would you be open to talking with us? We might

also be interested in working with you more broadly and would like to discuss that with you too.

Thank you for your important work in this area and for your time. We look forward to hearing from you.

Best, Nicole

Nicole Rinke / Deputy Attorney General / (916) 210-7797 / Nicole.Rinke@doj.ca.gov
Office of the Attorney General / Public Rights Division/ Land Law
1300 I Street/ P.O. Box 944255/ Sacramento, CA 94224-2550

Exhibit B

The 2003 and 2007 wildfires in Southern California

Chapter January 2013

DOI: 10.1017/CBO9780511845710.007

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Frontmatter
More information

NATURAL DISASTERS AND ADAPTATION TO CLIMATE CHANGE

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5

The 2003 and 2007 Wildfires in Southern California

JON E. KEELEY, ALEXANDRA D. SYPHARD AND C. J. FOTHERINGHAM

Although many residents of southern California have long recognised that wildfires in the region are an ongoing, constant risk to lives and property, the enormity of the regional fire hazard caught the world's attention during the southern California firestorms of 2003 (Figure 5.1). Beginning on 21 October, a series of fourteen wildfires broke out across the five-county region under severe Santa Ana winds, and within two weeks, more than 300,000 ha had burned (Keeley et al., 2004). The event was one of the costliest in the state's history, with more than 3,600 homes damaged or destroyed and twenty-four fatalities. Suppression costs for the 12,000 firefighters have been estimated at US$120 million, and the total response and damage cost has been estimated at more than US$3 billion (COES, 2004).

Just four years later, almost to the day, this event was repeated. Beginning on 22 October 2007, thirteen wildfires broke out across the same region, and under similar Santa Ana winds, consuming more than 175,000 ha, destroying more than 3,300 structures and killing seven people (Keeley et al., 2009). The 2003 and the 2007 wildfires were remarkably similar in their causes, impacts and the human responses they elicited. Particularly alarming is the observation that these fire events are not new to the region, as large fire events have occurred historically.

5.1 Prior Condition

Essentially every year, in all counties in the southern California region, there are fires that range in size from 1,000 to 10,000 ha (Keeley et al., 1999). This regional history of wildfires is largely a result of the Mediterranean-type climate, with winter rain growing conditions sufficient to produce dense vegetation and a long summer drought that converts this biomass into highly flammable fuels. Although these conditions occur periodically under other climatic regimes, the Mediterranean-type climate results in such conditions annually. Massive fires more than 50,000 ha, similar to the 2003 and 2007 fires, have occurred nine times since the earliest date for which we have records,

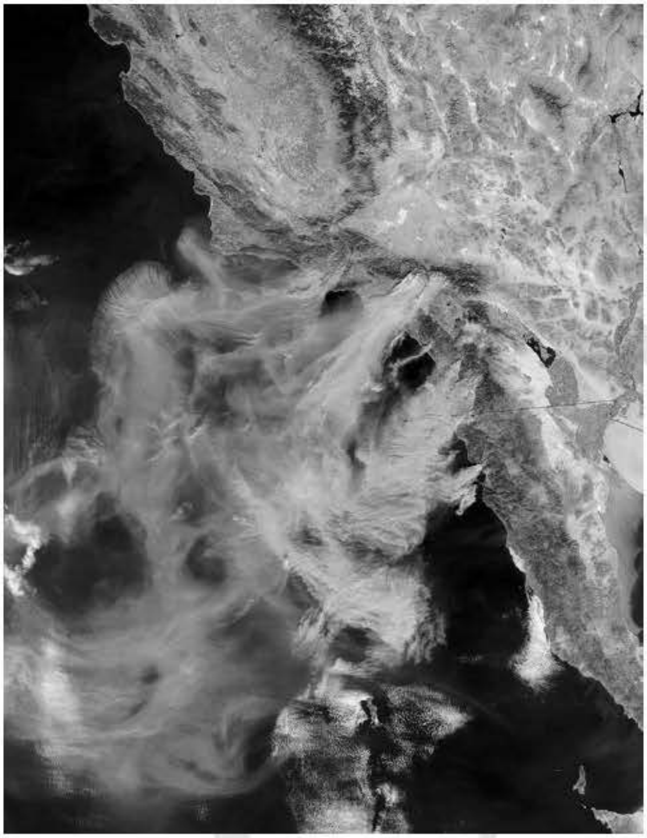

Figure 5.1 Smoke plumes blown by offshore Santa Ana winds during the 2003 firestorm in southern California, 24 October 2003. These winds occur every autumn after the summer drought with gusts $>$100 km hr^{-1} and relative humidity $<$ 5%. Panel covers an area of $\sim$350 $\times$ 600 km; US–Mexico border indicated by thin line about mid-frame (http://earthobservatory.nasa.gov/).

beginning with the 24 to 28 September 1889 Santiago fire (Keeley and Zedler, 2009). These large fire events span the period from before active fire suppression to the present, when active fire suppression is practiced. This illustrates that large wildfires are a natural feature of this landscape and that, despite the best intentions, firefighters are unable to suppress all fires. Although firefighters often contain most fires at much smaller sizes than would be the case in the absence of fire suppression activities, the potential still persists for some fires to escape control, particularly under extreme weather conditions.

Although one major aspect of the prior condition is the regional propensity for large, high-intensity wildfires owing to the Mediterranean-type climate and regular Santa Ana wind conditions, the other major condition that contributed to the impact of the 2003 and 2007 wildfires is the distribution of human settlements relative to fire-prone wildland vegetation. The 1889 Santiago fire is estimated to have been the largest recorded fire in the region, yet no one died and no homes were destroyed. Since 1889, however, human population and the area of urban development have grown by orders of magnitude. In the last fifty years, the region has, on average, lost 500 homes a year to wildfires (Cal Fire, 2000). The massive losses of property and lives in recent fires are the result of human population growth and expansion into these fire-prone landscapes.

5.2 Vulnerability

In general, urban environments in southern California are particularly vulnerable to wildfires because of the hot Santa Ana winds, which last several days and have gusts exceeding 100 km/h and relative humidity under 5 per cent. These winds blow from the interior toward the coast, and there are one or more such events every year in the autumn (Raphael, 2003), when vegetation is at its driest. Although the 2003 and 2007 fires were driven by Santa Ana winds, these winds were not outside the normal range of variability in duration or intensity (Keeley et al., 2004; 2009), so it is apparent that winds alone cannot account for why these fires were particularly destructive.

One reason the southern California region was especially vulnerable to massive fire events in 2003 and 2007 is the extraordinarily long antecedent droughts. Annually, the region is subject to an intense summer drought of little or no rainfall for four to six months; however, prior to the 2007 fires, there had been seventeen months of drought with an average Palmer Drought Severity Index (PDSI) of –3.62, and prior to the 2003 fires, there were fifty-four months of drought (Keeley and Zedler, 2009).

Although drought typically affects fire behaviour by decreasing fuel moisture, this was not likely the main reason these droughts contributed to the extraordinary size of these fires. Nearly every autumn, there are Santa Ana wind-driven fires, and the fuel moisture of these shrublands is typically at the lowest level of physiological tolerance. At the time of the 2007 fires, live fuel moisture for the most common chaparral shrub, *Adenostoma fasciculatum*, was no different than in other years (Keeley and Zedler, 2009). It is hypothesised that the primary effect of the drought was to produce significant amounts of dieback in the vegetation, and this contributed to fire spread by increasing the incidence of spot-fires ahead of the fire front (Keeley and Zedler, 2009). This resulted in extraordinarily rapid fire spread that in many cases exceeded firefighters' capacity for defending homes.

5.3 Resilience

The resilience of urban communities to the wildfires of 2003 and 2007 was largely a function of their location and spatial arrangement, as well as the specific properties of home construction and landscaping. Santa Ana wind-driven fires follow specific topographic corridors (Moritz et al., 2010), and at a landscape scale, homes that burned in the 2003 and 2007 fires were distributed in areas that have been historically fire prone and in areas that were located farther inland, closer to the points of fire origin (Syphard et al., 2012). Homes at low to intermediate densities and in smaller, isolated neighbourhoods were also more likely to be burned (Syphard et al., 2012). This could be because of the spatial relationship between homes and wildland vegetation as well as the more limited accessibility of homes to firefighters, as neighbourhoods with fewer roads were also more likely to be burned. Those homes on the interior of developments or on the leeward side (i.e. southern and western perimeters) largely survived untouched (C. J. Fotheringham, US Geological Survey, Western Ecological Research Center, unpublished data).

Homes in the direct path of these fires were the most vulnerable, but housing construction also plays a role. Building ordinances have increased the resilience of homes to burning through structural changes that make homes more resistant to ignition, and as a result, new homes are often more resilient to burning (Quarles et al., 2010). However, another factor is that landscaping age affects the level of plant biomass in close proximity to the homes, and many of these landscaping choices pose significant threats as they age. In a study of 2003 and 2007 fires, the age of homes was significantly correlated with the total tree cover within a 22 m radius of the house ($r^2 = 0.244$, $p < 0.001$, $n = 310$; C. J. Fotheringham, unpublished data), and as discussed below, this may contribute to structural losses. Thus, it will require some work to parse out the relative role of improved construction techniques from increased landscaping fuels.

5.4 Physical Characteristics of the Event

There is evidence that most of the homes lost in these 2003 and 2007 fires ignited from embers blown from the wildland to the urban environment. An in-depth case study of a neighbourhood that experienced substantial home losses in 2007 showed that two out of every three homes were ignited either directly or indirectly from embers, as opposed to uninterrupted fire spread from the wildland to the structure (Maranghides and Mell, 2010). Another reflection of the importance of embers is the observation that for houses on the perimeter of developments, the amount of clearance around homes had no significant effect on whether a home burned (Table 5.1). These patterns fit a widely held generalisation that most homes are not destroyed by direct heating from the fire front but rather from embers that ignite fine fuels in, on or around the house (Cohen, 2000; Koo et al., 2010). Such embers or firebrands are often carried from fuels several kilometres away, and no reasonable amount of clearance around the home can protect against this threat. The extent to which embers create a hazard is a function of them landing on a suitable fine fuel on or adjacent to the home.

Urban landscaping played a significant role in property losses during the 2003 and 2007 fires (Table 5.1). Homes that burned had significantly greater ground surface

Table 5.1. *Comparison of characteristics of burned and unburned houses in a portion of the 2003 and 2007 fires. Clearance is for a subset of homes on the periphery of urban development.* P *values for Mann-Whitney test (C. J Fotheringham and J. E. Keeley, unpublished data)*

	Burned		Unburned		
	Mean (S.E.)	N	Mean (S.E.)	N	*p*-value
Clearance width (m)	9.38 (1.27)	83	12.45 (1.41)	82	0.115
Tree canopy overlap (m)	10.79 (1.01)	150	5.37 (0.81)	160	0.00001
Tree ground surface cover (m^2)	146.74 (13.43)	150	97.75 (9.22)	160	0.021
Patio (m)	4.82 (0.45)	150	3.59 (0.35)	160	0.051
Deck windward side (m)	0.87 (0.20)	150	0.383 (0.10)	160	0.069

cover (GSC) of trees in the yard, and the amount of tree canopy that overlapped the house was greater than for unburned homes. It is hypothesised that tree canopies that shade homes drop highly flammable litter on and around the structure that contributes to ignitions from embers. Burned homes also had more patio and decking than unburned homes, and these too potentially contributed to ignition (Table 5.1).

Other landscaping choices that can affect structure loss are the planting of drought-tolerant species by home owners and landscape specialists. Many of these species come from other fire-prone regions and share characteristics with fire-prone native species, including retention of dead fuels in the canopy and increased flammability. In addition, it is commonly believed that ornamental vegetation is resistant to fire because of regular irrigation; however, no systematic studies have been conducted to determine the effects of the extreme Santa Ana conditions on ornamental plant moisture content.

5.5 Emergency Management

In 2007, roughly a half million residents were evacuated, with major disruptions in personal and professional lives. There are numerous ways to calculate the costs of such an event, and estimates range from hundreds of millions to billions of dollars. There are many indirect economic costs that are more difficult to estimate, for example, the displacement of the San Diego Chargers football game to Arizona because of occupation of their stadium by evacuees. Calculating the net economic impact is made even more complicated by the fact that there were huge offsets in the damage from wildfires by insurance payments that amounted to billions of additional dollars to the California economy (Hartwig, 2007).

The massive evacuation from homes in the path of the 2003 and 2007 fires would seem to have been the prudent thing to do, although, despite stern warnings from the media, most agencies involved in this evacuation contend that it was not mandatory. After the 2007 fires, it was advocated that one of the communities that suffered major home losses consider encouraging residents during the next fire to stay with their homes in order to assist firefighters (Paveglio et al., 2010). In southern California, this is referred to as 'shelter-in-place' and is fashioned after a program in Australia known as the 'go early or stay and defend' policy (Mutch et al., 2010). Key to this idea is that it requires pre-planning and decision making long before a fire incident occurs (see further discussion of this policy in Chapter 8).

5.6 Post–Event Adaptation

Understandably, after the enormous impact of the 2003 and 2007 fires, there has been strong public sentiment to try to prevent such losses from occurring again. For example, there was renewed interest in promoting community involvement in fire protection. The federal government has made large sums of money available to community groups such as Fire Safe Councils, whose objectives are to promote fire-safety education for homeowners and to encourage pre-fire management. One of the primary objectives of pre-fire management has been to increase efforts to reduce hazardous fuels. As a result, wildland fuel treatments in southern California U.S. Forest Service (USFS) forests have increased in the years following these 2003 and 2007 fires. In particular, the trend has been to broaden the areal extent of treatments beyond the traditional practice of creating long, linear breaks in vegetation to provide firefighter access for suppression.

Despite these efforts to reduce broad swaths of fuel across the landscape, recent research demonstrates that fuel breaks are most effective where they provide access for fire-fighting activities (Syphard et al., 2011a; 2011b). Therefore, some managers are also starting to recognise that strategically located fuel modification zones around the urban interface are likely to provide better community protection with fewer resource impacts to natural ecosystems (Witter and Taylor, 2005). In addition to strategically located fuel breaks, creating defensible space around homes is now widely embraced in the fire management, policy and scientific communities and strongly promoted in Fire Safe Councils. Defensible space is also likely to be more instrumental in community protection than remotely located fuel breaks.

Despite a legal mandate in California for 30 m clearance around homes, there has been increasing sentiment after the 2003 and 2007 fires that more clearance is always better (e.g. Figure 5.2). Therefore, in many communities, home owners are now requested to clear up to 90 m by the local fire department. In some cases, insurance companies require 120 m. It is increasingly evident from field inspections as well as from aerial imagery that many homeowners at the wildland-urban interface are clearing in excess of 30 m, and some in excess of 90 m.

Figure 5.2 Clearance around a rural home in San Diego County, California, that exceeds state requirements (photo by J. E. Keeley).

A common misunderstanding regarding defensible space is that the words 'vegetation clearance' confuse people into thinking that they need to clear all fuel within the safety zone, that is, to bare ground (e.g. Figure 5.2), instead of simply reducing concentrated fuel around the home. Complete removal of fuel may actually create more problems than it solves; it encourages growth of highly combustible grasses, with a substantially longer fire season; it is aesthetically less pleasing (e.g. Figure 5.2); it degrades the water-holding capacity of the soil, promoting erosion; and it destroys important wildlife habitat essential to birds and small mammals that add to the rural lifestyle (Halsey, 2005).

The current lack of a clear science-based system for determining appropriate clearance size potentially has huge impacts on the landscape. In other words, although the mandate is to create 30 m of defensible space, empirical evidence is still lacking on whether more area will provide more protection. We conducted a rough experiment to estimate approximately how much vegetation removal would occur if defensible space guidelines were strictly adhered to, at both 30 m or increased to 90 m, by residential property owners in San Diego County that owned sufficient land to comply with these guidelines. Using a parcel boundary map and a digitised map of residential structures, we calculated the number of properties that were large enough to accommodate defensible space clearing requirements and multiplied these by the area of the

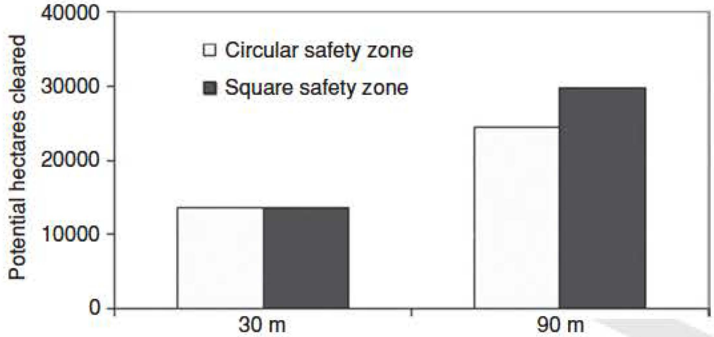

Figure 5.3 Potential area of vegetation clearance that would occur if San Diego County, California, property owners with large-enough properties adhered to 30 m vs. 90 m defensible space requirements. Circular and square safety zones refer to the shape of the clearance around all sides of an occupied structure.

circle that would account for defensible space around all sides of a house located in the centre of the property.

If all property owners on sufficiently sized parcels cleared a 30 m radius around their property, 13,722 ha of vegetation would be removed (Figure 5.3). If those property owners with parcels large enough, that is, a subset of the 30 m parcels, extended clearance to a 90 m radius, this would potentially bring the total vegetation loss to a figure equalling two-thirds the size of the region's largest habitat conservation area, the San Diego Multiple Species Conservation Plan. Of course, many of these parcels already have thinned the vegetation on their property, and not all properties are compliant or will be required to clear the full 90 m around their property. But the numbers do provide a perspective on the importance of understanding the benefits of increasing clearance from 30 to 90 m, which would represent a major loss of natural resources.

5.7 Climate Change Impacts on Southern California Fire Regimes

Southern California is recognised as one of the most fire-prone environments on earth because of its location, climate and vegetation. There is widespread concern that global warming will result in more frequent and more intense fires (Running, 2006). While some landscapes may experience more frequent fires and others more intense fires, it is of course unlikely both will occur in the same ecosystem since they are generally inversely related – that is, intensity is heavily dependent on duration of fuel accumulation.

It is our view that most of the published forecasts of climate change impacts on fire regimes are rather speculative at this point. Predictions are largely based on increasing temperatures affecting fire activity by reducing fuel moisture, which often is tied to increased probability of ignitions and fire spread. There are several considerations that need to be looked at before accepting this causal relationship. (1) Global warming is driven by increased partial pressure of CO_2, and there are direct effects of increased CO_2 on plant physiology that will act to produce opposite effects on fuel moisture. In short, as CO_2 goes up, water use efficiency goes up, and for chaparral, this has been estimated to be as much as 35 per cent with a doubling of CO_2 (Chang, 2003). (2) Fire regimes of different vegetation types will not likely respond the same to increased temperatures and increased CO_2, and since fire regime changes have the potential for type conversion of vegetation, predictions of future fire activity cannot be made without serious consideration of vegetation changes. (3) Climate change is only one of a multitude of global changes. In southern California, models predict a 3 to 5 per cent increase in temperature but more than a 50 per cent increase in population by 2040. Since humans are responsible for more than 95 per cent of all fire ignitions, and expansion of urban development into wildlands sets the stage for catastrophic wildfire outcomes, predictions about future fire impacts that fail to include human demographic changes are of questionable value for this region.

Changes in winds have the potential for substantial changes in future fire regimes, but we have even less certainty as to what to expect with winds. Some models of future changes in Santa Ana winds suggest a shift to later in the autumn, and Miller and Schlegel (2006) predict that this will result in increased area burned in coastal California. However, one could predict the opposite effect because later winds will increase the probability of Santa Ana winds being preceded by autumn rains, and historically, when winds have been preceded by precipitation, it has had a negative effect on area burned (Keeley, 2004). In a different modelling framework, Hughes, Hall and Kim (2009) predicted a dramatic drop in Santa Ana winds in the coming years, which of course would suggest we have a rosy future in terms of reduced fire hazard. In short, the models we have for predicting the future are often contradictory, which is to be expected because they are in a rudimentary stage of development. However, as a consequence, they are not presently useful for most of the decision making required to deal with future fire hazards in the region.

5.8 What Are the Lessons Learned?

The 2003 and 2007 wildfires remind us that large fire events are an inevitable and inescapable part of living in southern California. Despite decades of fuel break construction, improvements in fire-safe codes and building regulations and thousands of firefighters, homes continue to be lost nearly every year. The predominant viewpoint has been that government is responsible for protecting homes during fires; but as scattered patterns of development continue to extend into the most flammable parts of the landscape, it becomes more and more difficult for firefighters to defend every home. Thus, many victims blame government officials for not having cleared more fuel, or they accuse firefighters of not protecting their homes (Kumagai et al., 2004).

Perhaps because most fire management has been focused on wildlands, there has been relatively little effort towards learning from other hazard sciences. For example, flood hazard science has made great strides in reducing losses through better land planning (Abt et al., 1989). The potential is immense for fire scientists and emergency mangers to learn from these hazard sciences, as altered land planning is very likely one of the more important avenues for reducing losses from wildfires as well. This is because the location and pattern of housing significantly influence where fires occur and, in turn, where fires are most likely to result in losses.

Earthquake science has never taken the approach of trying to eliminate the hazard but rather alters human infrastructure to make living in this environment much safer. Fire scientists are gradually coming around to the idea of infrastructure hardening, but most information on the types of construction and landscaping necessary to fireproof a house are of an anecdotal nature, and there is an urgent need for science-based approaches. We suggest a change in perspective that acknowledges fire risk as an inevitable component of the landscape and that we prepare as we would for other hazards.

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Exhibit C

NEXUS BETWEEN WILDFIRE, CLIMATE CHANGE AND POPULATION GROWTH IN CALIFORNIA

Jon E. Keeley and Alexandra D. Syphard

Since the year 2000 California has experienced a remarkable upsurge in wildfires. Over five million hectares have burned in the last 20 years, which is double the area burned in the previous two decades. Much of this increase has been driven by large fires of more than 50,000 hectares that cause catastrophic losses of lives and property (Keeley and Syphard 2019). This increased fire activity has been correlated with an increase in average temperature over this same period, leading many observers to assert that global climate change must be playing a major role. Climate models forecast continued warming and thus some have suggested these catastrophic fires are the "new normal" or the "new *ab*normal," (Birnbaum 2018). In contrast, others have declared that these fires are the result of "forest mismanagement" (Cranley 2018) and this has stimulated renewed interest in fuel reduction (Office of Governor 2019). It's almost as though these opinions aren't even in reference to the same fires, and as described below, there is some validity to this assertion.

Sorting out the factors driving this rise in fire activity requires an appreciation for the diversity of landscapes and fire regimes in the state. After all, California has the largest latitudinal range of any western state, comparable to that from southern New Mexico to Wyoming, and the largest altitudinal range (containing both the lowest and highest points in the lower 48 states). California also is the most populous state in the union: One out of eight Americans live here. And most live within dense metropolitan areas juxtaposed with fire-prone wildlands, while a great many more live widely dispersed in rural settings.

A key to sorting out the factors behind increased fire activity is understanding that we are looking at two very different types of fires: fuel-dominated vs wind-dominated fires. And each of these is controlled by different environmental and historical factors (Table 1). Understanding the differences between these two types of wildfires is helpful for navigating the confusing array of opinions expressed in the media as well as determining the appropriate management responses to reduce future fire impacts.

Above: Aerial retardant drop on a chaparral wildfire in coastal southern California, taken July 5, 2008, in the foothills of the Los Padres National Forest. *[Dan Lindsay]*

FUEL-DOMINATED FIRES

Many of the forest fires of the past two of decades have grown out of control due to anomalous fuel loads resulting from 20th century management practices. In the early 1900s increasing state and federal interest in timber resources led to vigorous suppression of natural fires in forests that historically had burned at decadal frequency (McKelvey and Busse 1996) (Fig. 1). In the moderately productive mid-elevation conifer forests of the Sierra Nevada there is typically a vertical separation between dead branches and other litter on the ground and the living tree canopies above, and thus frequent lightning-ignited fires were commonly restricted to low intensity surface fires (Fig. 2). As a result such fires were relatively easy to extinguish and thus many forests in the western U.S. have experienced over a century of near total fire exclusion.

One consequence is that some of these forests have accumulated understory surface fuels that represent fuel loads an order of magnitude greater than historical levels (Keifer et al. 2006), made even worse by the massive ingrowth of new saplings that not only further increase the fuel load but also act as ladder fuels carrying fire from the surface to the canopy. A century without fire has made these forests susceptible to high intensity crown fires, a fire pattern evident in many recent Sierra Nevada fires (Fig. 3). These types of fires are best described as fuel-dominated fires (Table 1).

To be sure, some fuel-dominated fires can produce their own extreme winds (e.g., the 2010 Station Fire in Los Angeles County or the 2018 Carr Fire in Shasta County), resulting from the high intensity burning of heavy fuel loads. The extreme heat produces pyrocumulonimbus clouds and are often described as plume-driven fires that can collapse, producing extreme wind events (Clements et al. 2018). However, such winds are internally generated, a phenomenon that could be altered by undertaking fuel treatments prior to fire events.

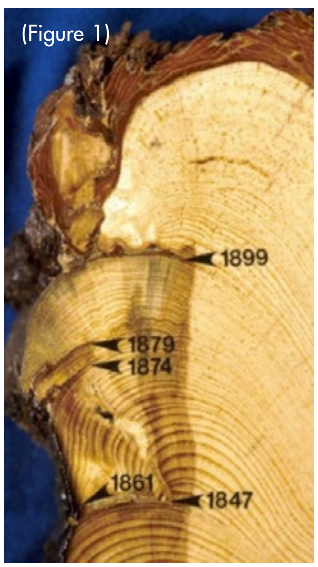


Figure 1. Cross section of ponderosa pine, upper edge is the outer bark, pith is towards the bottom. Dates indicate previous fires and none since active fire suppression in the early 1900s *(section from Bruce Kilgore, photo by Jon Keeley, USGS)*

Figure 2. Low intensity surface fire typical of historical fires in many western forests *(Rim Fire burning in Yosemite National Park, photo by Jon Keeley, USGS)*

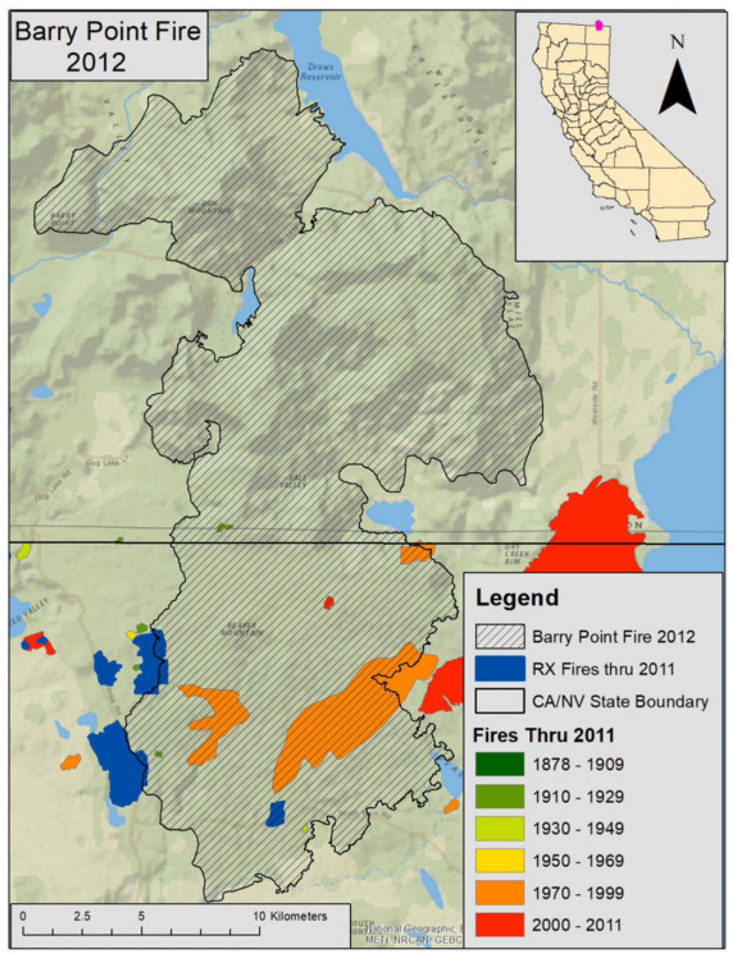


Figure 3. Fire perimeter for the 2012 Barry Point Fire, hatched area indicates no previous recorded fire from 1910 to 2012, roughly 90% of area burned in 2012, legend indicates other historical fire dates *(data from the State of California Fire and Resource Assessment Program, FRAP Fire History Database, https://frap.fire.ca.gov/mapping/gis-data/; accessed Jan 2020).*

WIND-DOMINATED FIRES

Figure 4. Offshore dispersion of smoke from a) North Wind driven fires in northern California, 2017, and b) Santa Ana Wind driven fires in southern California, 2003.

On the other hand, wind-dominated fires are those controlled by external weather events. This is an important distinction, as we have no ability to alter such weather-driven wind events. Our most catastrophic fires of the past few decades have been just such wind-dominated fires. They typically occur in the western portions of California and burn over non-forested landscapes of shrubs, grasses, and woodlands. These fires grow rapidly due to extreme wind events and, as a result, pose severe challenges to fire suppression efforts. Readers will be familiar with several of these recent "firestorms," including the 2017 Napa-Sonoma "Wine Country" fires and the 2018 Camp Fire driven by North winds in northern California. (Historically this is the appropriate term; however, such winds are sometimes referred to as Diablo winds, a term spawned by a newspaper reporter who noted that the 1991 Oakland Hills Tunnel Fire was driven by winds coming from the direction of Mount Diablo, thus the term is less appropriate for wind-driven fires throughout the region.) Other such "firestorms" include the 2017 Thomas Fire and the 2018 Woolsey Fire driven by Santa Ana winds in southern California. While these winds may occur in both the spring and autumn (Fig.5a) they are most problematic in the autumn, following the three to six months of drought typical of our Mediterranean climate (Fig. 5b), leaving natural vegetation at its lowest moisture level. It is these autumn Santa Ana wind and North wind fires that account for the most catastrophic fires in the state (Table 1).

TABLE 1. Selected fires representing fuel-dominated and wind-dominated fires.

Year	Fire	County	Mon. (days)*	Hectares	Cause	Lives	Structures
			Fuel-Dominated Fires:				
2007	Marble C	Monterey	July -	71,980	Lightning	0	0
2012	Barry Point	Modoc	Aug -	37,630	Lightning	0	3
2012	Rush	Lassen	Aug -	110,080	Lightning	0	1
2013	Rim	Stanislaus	Aug -	104,220	Campfire	0	112
2014	King	El Dorado	Sept -	39,260	Arson	0	80
2015	Rough	Fresno	July -	61,360	Lightning	0	4
			Wind-Dominated Fires:				
1889	Santiago	Orange	Sept (3)	125,000	Campfire	0	0
1970	Laguna	San Diego	Sept (3)	70,500	Powerline	5	382
2003	Cedar	San Diego	Oct (3)	109,500	Flares	15	2,820
2007	Witch	San Diego	Oct (2)	80,200	Powerline	2	1,265
2017	Tubbs	Sonoma	Oct (2)	14,900	Powerline	22	5,643
2017	Thomas	Ventura	Dec (10)	114,080	Powerline	2	1,063
2018	Camp	Butte	Nov (2)	62,060	Powerline	88	18,804
2018	Woolsey	Ventura	Nov (3)	39,335	Powerline	3	1,643
2019	Kincade	Sonoma	Nov (5)	31,470	Powerline	0	374

*indicates days of Santa Ana or North winds *[data from the State of California Fire and Resource Assessment Program, FRAP Fire History Database, https://frap.fire.ca.gov/mapping/gis-data/; accessed Jan 2020].*

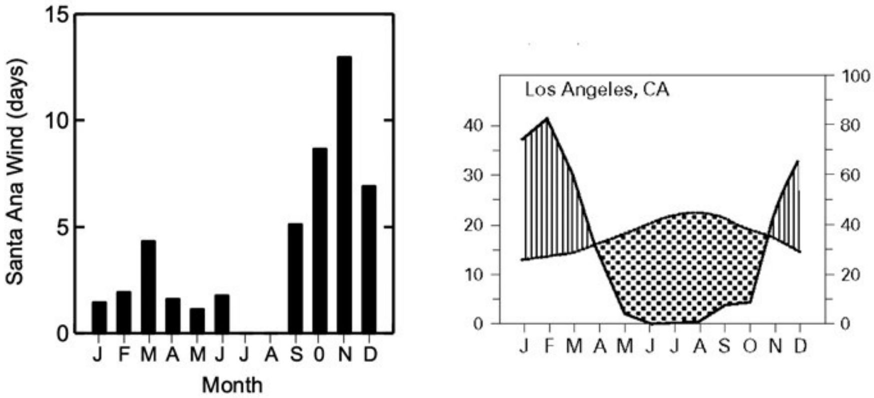


Figure 5. a) Days of Santa Ana winds and b) temperature and precipitation in Los Angeles illustrating typical Mediterranean climate of winter rains and summer droughts *(from Keeley et al. 2012).*

Historically these landscapes have not experienced the fire exclusion seen in many Sierra Nevada landscapes, despite being managed by the same fire suppression policy (Fig. 6). This is due to the fact that essentially all are caused by human ignitions, which are relatively common due to the high population density in the western portion of California (Keeley and Syphard 2018). As a consequence, there has not been any lack of fire and most large fire events burn across landscapes with an extensive fire history and no anomalous fuel accumulation. Indeed, some of these large fires—e.g., the Thomas Fire (Keeley and Syphard 2019)—have burned across areas where extensive prescription burning had occurred in recent years, pointing to the conclusion that prior fuel treatments are having limited effect on the spread of these fires. Even landscapes not experiencing high fire frequencies, such as the San Francisco Bay Area, are not outside their range of natural fire frequencies and so fuels have not accumulated due to fire suppression (Keeley 2005). To be sure, some communities in this region have dangerous fuels but these are often the result of urban plantings of *Acacia, Eucalyptus* and *Pinus* and not so much due to accumulation of wildland fuels from elimination of natural fires.

Every year there are many Santa Ana wind events but most years we don't see major wind-driven fires because they are entirely dependent on a human ignition happening during an extreme wind event. Indeed, only about five percent of the Santa Ana wind days are accompanied by a large fire event (Rolinski et al. 2019). Some have suggested that these Santa Ana winds are increasing in frequency, duration, and intensity, but records do not show a change in the character of these winds since the mid-1900s (Williams et al. 2019). Rolinksi et al. (2016) found that fires during extreme weather events are larger than ones in less extreme Santa Ana conditions, and some have interpreted this to mean that fires are becoming worse because Santa Ana winds are becoming more extreme. However, this study only considered Santa Ana winds after an ignition had occurred, thus ignition sources are critically important. It's important to recognize that Rolinksi's Santa Ana Wind Threat Index is not an indication of when an extreme fire will occur but only how bad the fire will be once ignited. What determines an extreme fire year is the untimely human ignition during an extreme wind event. This is illustrated by the fact that the frequency of these wind events is not correlated with area burned (Keeley and Syphard 2018) and our largest fire years occur in high as well as low Santa Ana wind intensity years

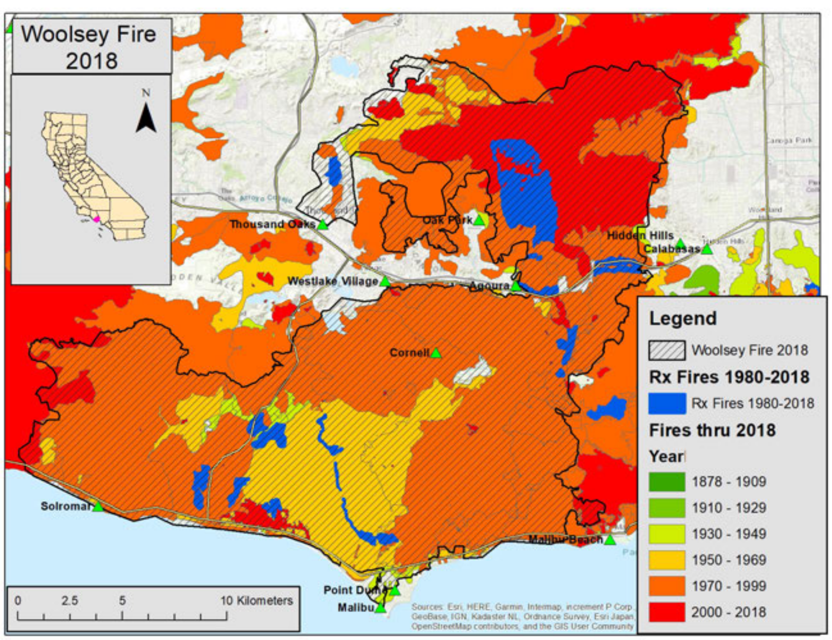


Figure 6. Fire history within the perimeter of the 2018 Woolsey Fire. Hatched area indicates less than 1% of the area unburned prior to 2018, legend indicates other fire dates *(data from the State of California Fire and Resource Assessment Program, FRAP Fire History Database, https://frap.fire.ca.gov/mapping/gis-data/; accessed Jan 2020).*

(Fig. 7). Ultimately it is all determined by an untimely human ignition event. Of course climate is peripherally related as it has been found that these fires are less likely to occur when relative humidity is high (Jin et al. 2014) and this most certainly is tied to decreased probability of such fires after early autumn precipitation (Keeley and Syphard 2017).

Indeed, Santa Ana wind events occur multiple times every year, yet during most such wind events there is no human ignition and thus no fire (Keeley and Syphard 2017). There is little evidence that the increase in the number of catastrophic fires is the result of increased intensity of Santa Ana wind events. For example Guzman-et al (2016) mapped the annual intensity of Santa Ana wind events (Fig. 7) yet when we overlaid extreme fire years of over 100,000 hectares burned in southern California (Fig. 7), we find that such extreme fire years are associated with low as well as high intensity Santa Ana wind years; e.g., the catastrophic 2003 Cedar Fire (Table 1) occurred during a year with low intensity Santa Ana winds.

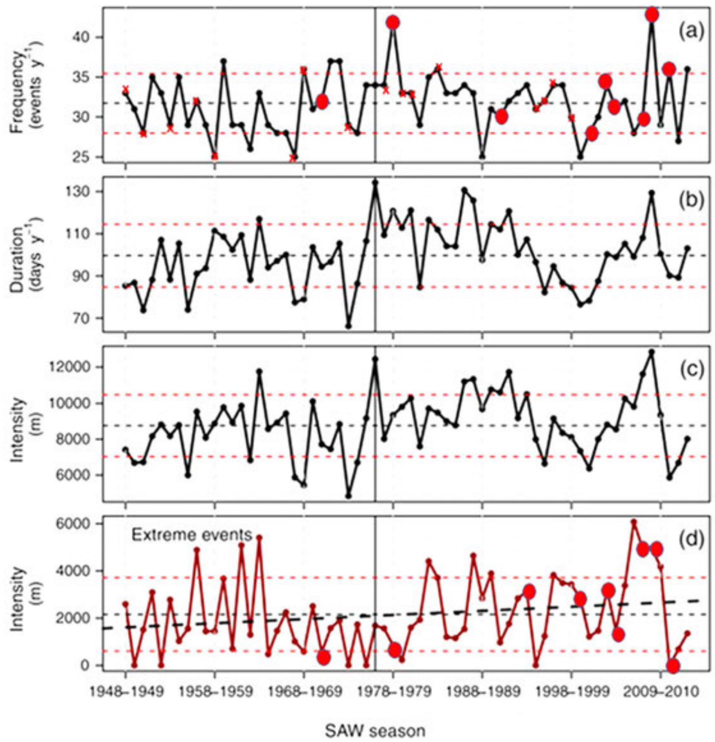


Figure 7. Pattern of Santa Ana Wind (SAW) characteristics from Guzman-Morales et al. 2017 and with red dots indicating very high fire years exceeding a hundred thousand hectares burned *(from Keeley and Syphard 2017)*. Correlation analysis between frequency of Santa Ana Wind events or the intensity of extreme Santa Ana Wind events with area burned there is no significant relationship in southern California (R2=0.01 and R2=0.00, respectively).

CHANGING IGNITION SOURCES

Lightning is a common ignition source in forests of the Sierra Nevada and northeastern California and thus accounts for many fuel-dominated fires (Table 1). However, lightning is relatively uncommon in coastal regions (Keeley and Syphard 2018) and does not occur under the synoptic conditions that create extreme Santa Ana and North wind events. Thus, these wind-dominated fires are ~ 100% human-ignited fires (either from intentional causes, such as arson, or accidental causes, such as sparks from equipment).

In the last decade, the majority of these large fires—including some of the biggest fires in 2017, 2018, and 2019—have been ignited by powerline failures during extreme wind events. Indeed, since the year 2000 over half a million acres have burned due to powerline failures, which is five times more than in the prior two decades (Keeley unpublished data). The increased impact of powerline-ignited fires is not the result of increased frequency or intensity of extreme wind events. There are two likely explanations for this increase in powerline-ignited fires: 1) expansion of the electrical grid due to increased development, which provides more opportunities for powerline ignited fires, and/or 2) deteriorating powerline equipment resulting from age and inadequate maintenance (one California regulator contends that electrical grid equipment is being run to the point of failure (Penn et al. 2019)).

GLOBAL CLIMATE CHANGE

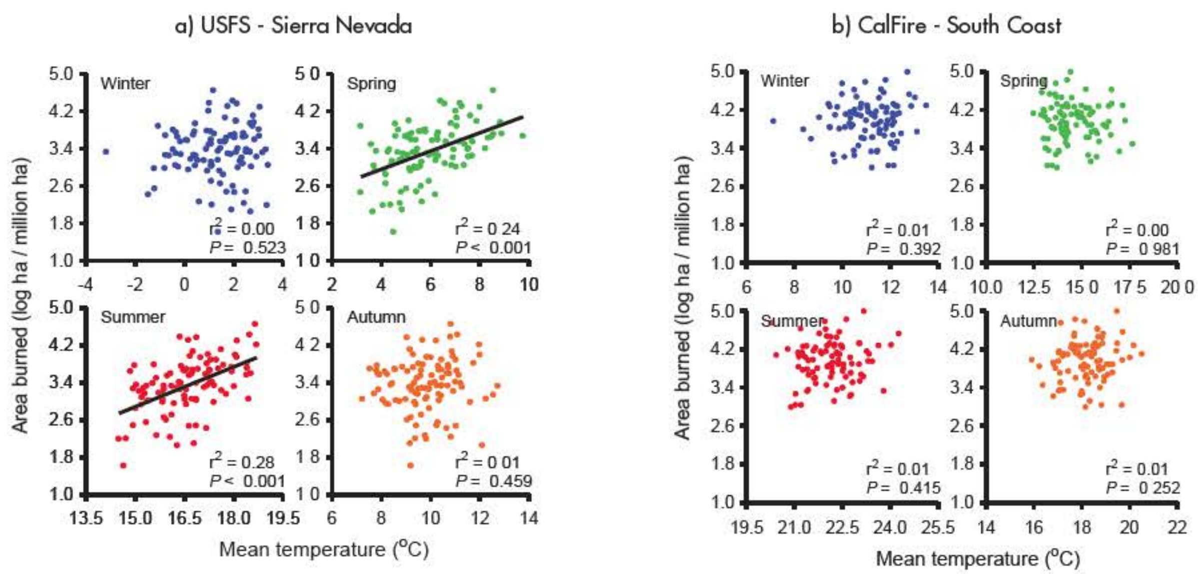
Some forecasts of future fire regimes based on different climate change simulations predict huge increases in California wildfires (Westerling 2018). These models need to be viewed in light of the fact that they are driven by untested assumptions, they don't adequately account for the complexity of fire driven changes in vegetation (Syphard et al. 2018b), and they don't consider changes in fire-climate relationships over time, as well as changes in human-ignition patterns.

An alternative approach to future modeling is retrospective studies. Confucius stated "If one wants to define the future, they must study the past" (Castro 2012). We recently conducted a study that took an empirical approach and asked how seasonal variation in temperature and precipitation has correlated with area burned, year to year, in the past. This investigation, which differs from those using algorithms of future fire-climate relationships, covered much of the last 100 years and separated out the effect of different seasonal temperatures (Keeley and Syphard 2017).

One interesting finding is that in no region of the state did winter temperature play a role in determining subsequent fire activity. This may be important since some climate models predict the greatest global warming to occur in the winter in the northern hemisphere. So perhaps this type of warming might not translate into changes in fire severity and frequency in California.

We can summarize our findings by contrasting U.S. Forest Service lands in the Sierra Nevada (Fig. 8a) with the lower elevation California Department of Forestry and Fire Protection responsibility lands in southern California (Fig. 8b). In Sierra Nevada forests there is a significant relationship between higher spring and summer temperatures and area burned; indeed, in the last 50 years, the combination of these two climate variables (spring and summer temperature) could explain over 50% of the year-to-year variation in area burned (Keeley and Syphard 2017). This is consistent with claims that global warming has played a role in increased burning in western forests in recent decades (Abatzoglou and Williams 2016).

In contrast, on non-forested landscapes in southern California we found little correlation between seasonal temperatures and area burned (Fig. 8b), a pattern consistent with other recent studies (Williams et al. 2019). We surmise that this is likely due to the fact that in southern California it is hot and dry enough every year to support large fires. (Note that maximum summer temperatures in the Sierra Nevada, when fires are most extensive, are similar to the lowest temperatures observed in southern California in the summer, Fig. 8a&b). The lack of a strong annual climate relationship with fires in southern California is due to climate being overridden by other factors, such as extreme wind events, increasing human ignitions during severe wind events, and long-term drought. Interestingly, while there has been an effect in the last 50 years of prior year precipitation on fires in southern California, this effect is well known in grasslands and savannas throughout the southwest and is tied to elevated grass fuel loads following high rainfall years (Keeley and Syphard 2017). We believe the reason this relationship showed up for southern California in the last half of the long-term record (Fig. 8b) is due to the well-documented increase in type conversion from shrublands to grasslands in the region (Syphard et al. 2018a).



Akaike IC regression models

Sierra Nevada (USFS)	r2	
1910 - 2013	0.39	Temp spr+Temp sum-Ppt spr
1910 – 1959	0.42	- Ppt spr - Ppt win
1960 - 2013	0.52	Temp spr + Temp sum

South Coast (CalFire)	r2	
1919 - 2013	0.00	
1919 - 1959	0.00	
1960 - 2013	0.25	Prior ppt-Ppt aut -Ppt sum

Figure 8. a) annual area burned from 1910 – 2013 for USFS lands in the Sierra Nevada plotted against winter, spring, summer, autumn temperatures and multiple regression models using all temperature and precipitation data for these four seasons, and b) annual area burned from 1919 – 2013 on CalFire lands in southern California and multiple regression analysis *(from Keeley and Syphard 2017)*.

One climate factor not considered when investigating annual climates is the impact of long-term droughts; i.e., those that last for multiple years. Recently California experienced an intense drought that began in 2012 and lasted for three years in the Sierra Nevada and eight years in southern California (Jacobsen and Pratt 2018). It was accompanied by an immense dieback of trees in the Sierra Nevada (Stephens et al. 2018) and of shrublands in southern California (Keeley and Syphard 2019). This creation of massive dead fuel loads represents a legacy on the landscape that may persist through subsequent years of higher rainfall. If drought-induced dieback proves to have been a critical factor in making the 2017 and 2018 fire years so extreme it raises doubts as to whether these fire years represent a new normal for California, since although droughts are expected to be more severe under climate change, there is no evidence that such extreme droughts will be a normal feature going forward.

What can we conclude about how climate change may impact these coastal wind-driven fires? Global warming may reduce grass growth leading to reduced fire frequency in these grass-dominated landscapes. On the other hand, higher temperatures have the potential for increasing the intensity of plant stress during droughts, perhaps elevating dieback of woody plants that would exacerbate fire spread and intensity; a study by Williams et al. (2015) concluded that the last severe drought in the Sierra Nevada increased the stress by ~10-15 percent. A further impact of global warming is that it will likely alter postfire recovery of shrublands by changing the competitive balance to favor alien grasses, increasing type conversion to highly flammable herbaceous fuels, leading perhaps to increased fire frequency (Syphard et al. 2018a, 2019, Park et al. 2018).

In summary, there is good reason to conclude that global warming is affecting Sierra Nevada forest fires. In montane forests with fuel-dominated fires, summer temperatures—although fluctuating greatly from year to year—have been on an upward trajectory for many decades and it is reasonable to assume a causal relationship between increased fire activity and global warming. However, over this same period there has been a steady increase in understory fuels. This raises an interesting question: Would the strength of the observed climate impact (Fig. 8a) have been as strong in the absence of this anomalous fuel accumulation due to fire suppression? In contrast, in the coastal regions there is limited evidence that climate change is impacting wind-dominated fires (Fig. 8b). However, global warming has the potential for a number of indirect impacts on vegetation that may alter fire regimes.

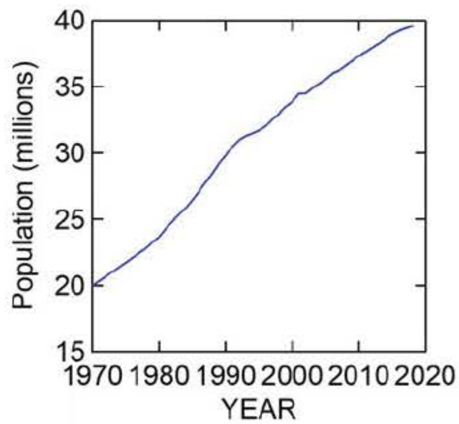


Figure 9. California population from Census Bureau *(https://www.census.gov/data; accessed June 2019)*

POPULATION GROWTH

Roger Kennedy, a former National Park Service director, was one of the first to bring attention to the role of population growth in raising the threat of wildfire (Kennedy 2006). It is true that since 2000 California has experienced a highly variable and subtle rise in temperature. However, less noticed is that there has also been a steep rise in population, adding about six million people (Fig. 9) over the last two decades. Since ~100% of the wind-dominated fires are ignited by humans or human infrastructure, there is likely a causal relationship between this population growth and the increased incidence of catastrophic wind-dominated wildfires.

Although local, state, and federal agencies have made significant progress in reducing the overall number of fires in the state over the last several decades (Keeley and Syphard 2018), there has been an increase in ignitions during extreme wind events. Thus, the real driver of wind-dominated fires is not the extreme wind events per se, but rather untimely human ignitions during such extreme wind events. And, of course, the addition of 300,000 more people every year in the state increases the probability of such an ignition event; moreover, urban sprawl into wildland areas increases the probability of losses of lives and property. An illustration of this is the 2017 Tubbs Fire that roared through sections of Santa Rosa, Sonoma County (Fig. 10b) causing the deaths of 22 people and destroying more than 5500 structures. Fifty years earlier the Hanly Fire had burned through

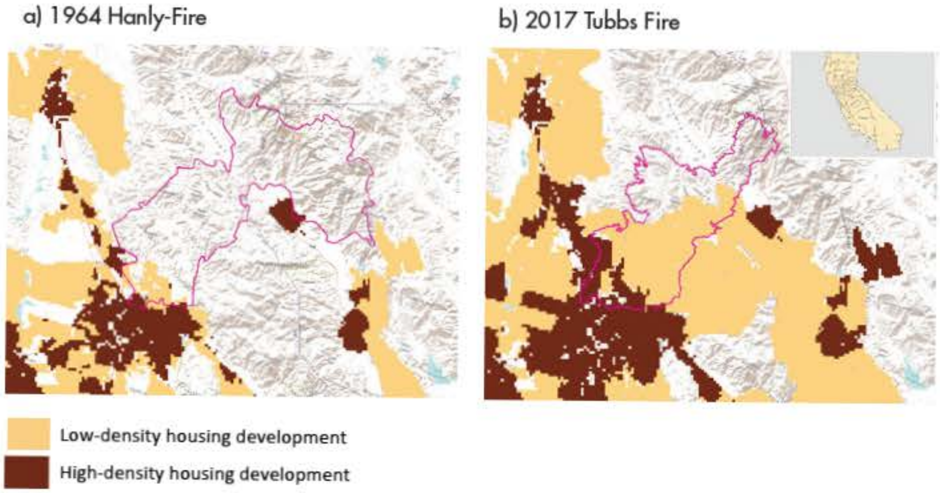


Figure 10. a) 1964 Hanly Fire perimeter in pink, and b) 2017 Tubbs Fire perimeter in pink, with changes in low density and high density housing *(from Keeley and Syphard 2019).*

much of the same landscape during a North wind event (Fig. 10a), yet no one died and only about 100 structures were lost. Some researchers have discounted this comparison because the Hanly Fire burned over a longer period of time and therefore it is assumed it was not driven by severe winds. However, that fire burned for a longer duration because it was was nearly three times the size of the Tubbs Fire and when it made its run towards Santa Rosa (overlapping with the perimeter of the much later Tubbs Fire) it was driven by extreme dry winds (*The Press Democrat*, September 26, 1964, front page), suggesting fire behavior similar to the 2017 Tubbs Fire. The difference in impact of these two fires is likely due to the fact that during this 50-year period Santa Rosa's population grew from 30,000 to 170,000 people and the urban footprint had expanded such that in 2017 development had expanded so that two thirds of the area burned by the Tubbs Fire was low density housing (Fig. 10b). This urban expansion was accompanied by expansion of the electric power grid, increasing the chances of a powerline failure during North wind events that drove both the Hanly and Tubbs fires.

MANAGEMENT CONSIDERATIONS

Fuel-dominated and wind-dominated fires exhibit important differences (Table 1) that inform how to manage these events. First, the fuel-dominated fires are largely forest fires in lightly populated regions such as the Sierra Nevada. In contrast, most wind-dominated fires occur in non-forested ecosystems in the western half of the state, though they may also occasionally occur in more interior sites, such as the 2018 Camp Fire that burned in Paradise. Wind-dominated fires occur in densely populated landscapes and these fires are responsible for the greatest loss of lives and property.

MANAGEMENT CONSIDERATIONS—FUEL-DOMINATED FIRES

Montane forests have an anomalous accumulation of fuels due to more than a century of fire suppression and logging and therefore require concerted efforts at reducing the present fuel load (North et al. 2012). In the late 1960s, staff at Sequoia National Park began prescription (Rx) burning and soon after the other national parks in the Sierra Nevada followed suit (Keeley and Syphard 2019). Over time these parks greatly exceeded the area burned by adjacent forests. In recent years the USFS lands have accelerated the amount of Rx burning. However, all Sierra Nevada lands are a long way from burning at a rate sufficient to restore natural historical fire frequencies. There are many limitations, including funding, air quality restrictions, diversion of personnel from Rx burns due to wildfires, among others.

MANAGEMENT CONSIDERATIONS—WIND-DOMINATED FIRES: THE 5 P'S

The distinction between fuel-dominated and wind-dominated fires is similar to the dichotomy between katabatic and non-katabatic wind-driven fires made by Kolden and Abatzoglou (2018). They point out that in southern California there are summer "fuel-dominated fires" and autumn "wind-dominated fires." While both types of fires occur in the region, it is the latter type that account for the vast amount of acreage burned, loss of lives and destruction of property. While management needs to be cognizant of both types of fire, it needs to be appreciated that summer fires are the least threatening fires and we should put our greatest effort toward autumn wind-dominated fires. Although all fires are a threat if fuels around homes have not been reduced, there are five points to consider with respect to the catastrophic wind-dominated fires:

1) ***People:*** On these landscapes, fire is more of a people problem than a fuel problem. More people translates into a greater probability of an ignition during a severe wind event, and more development in highly fire prone landscapes inevitably results in greater losses of lives and homes.

2) ***Prevention:*** Rather than focusing on fuel treatments the scientific evidence clearly points to a need for a much greater emphasis on fire prevention. Although progress has been made in reducing the number of fires, the area burned has increased (Keeley and Syphard 2018). Powerline failures are a major cause of large fires and solutions to this increasing threat remain elusive. As widely reported in the media, three major utility companies in the state have implemented plans to monitor winds and shut down the power grid during extreme wind events. Such so-called Public Safety Power Shutdowns (PSPS) have the potential to decrease fire starts and limit damage (and, as a by-product, raise public awareness of fire threats). But there are many accompanying problems, as became evident during the recent Kincade Fire (Table 1) in October 2019, which was started by an electric failure, despite widespread power outages at the time. Such shutdowns impacted a multitude of vital services, including medical equipment, water pumps, traffic signals, communication equipment etc. One solution might be undergrounding the power lines in areas known to be corridors for extreme winds (Keeley et al. 2009). However, this would be much more expensive for the utilities to install and maintain. In addition, in areas where sensitive natural resources are present, overhead power lines may be less destructive. Nonetheless, San Diego Gas & Electric, which has led the way with responding to powerline-ignited wildfires, reports that 60% of its distribution lines are currently underground (Joe Vaccaro, Fire Mitigation & Climate Adaptation Manager, San Diego Gas & Electric Company, personal communication, 5 Dec 2019).

3) ***Planning:*** Community planning needs to devote similar attention and resources to fire as to other hazards. Since we have limited ability to control earthquakes and floods, some urban planners have utilized zoning restrictions to reduce impacts of these hazards. Yet, zoning restrictions are largely lacking when it comes to fire hazards, in large part because fires have been perceived as controllable. However it is increasingly obvious that this is not always the case and many communities are currently very vulnerable. Fire-zoning (Kennedy 2006) needs to be given more consideration as well as urban planning that insures adequate ingress for fire fighters and egress for residents during extreme fire events. Perhaps replacing community planning with a more regional approach might contribute to these efforts.

4) ***Protection:*** High intensity fires generally do not directly ignite homes when separated from vegetation by 30 meters (Cohen 2000). Home ignitions are usually the result of embers blown onto the structure and this is particularly true under extreme wind conditions. Ember cast firebrands often travel over a distance of half a mile or more. Embers ignite only under specific circumstances and this is most likely when they land on dead fuels (Zhou et al. 2019). Homeowners can diminish the probability of damage by addressing those factors that affect embers igniting their home, such as reducing plant litter on roofs and gutters, enclosing eves so that vent orientation is less susceptible to ember entry, closing open eves, placing fine mesh screens on vents, and installing double-pane windows and appropriate siding (Syphard and Keeley 2019). Well-watered trees with significant foliage can provide protection from ember cast onto a home (Keeley and Syphard 2019). In fact, watered trees with green foliage may not be susceptible to ignitions by embers, but rather could serve to extinguish them and deprive them of dry fuels. While the notion of trees as "ember catchers" is appealing it is a largely untested idea.

   Roof top sprinklers may provide an added measure of protection and may be justified by the observation that trees adjacent to destroyed homes often survive because their foliage is moist, whereas combustible materials in homes represent dead fuels that are likely at equilibrium with ambient relative humidity of 10 percent or less. However, such sprinklers would need to address a number of issues. For example, metropolitan water lines and water supplies are sometimes compromised during fire events and thus there would need to be a stand-alone water tank. Also, shutting down the power grid is happening more often and thus solar or other alternative power would need to be available to pump water. In addition, there is the need for further research on how to engineer such a system in order to prevent the water spray from being dissipated to the atmosphere due to the high winds. Incorporating a system like this would likely be a significant expenditure that may not be possible for many home owners.

Fuel treatment around homes is critical but needs to be focused on the 'house out', i.e., putting the greatest effort into the area nearest the home and less as one moves further into the wildlands. Reducing fuels within 30 meters of the house is generally sufficient and further clearance beyond that is of doubtful value (Syphard et al. 2012).

5) ***Prediction:*** There is an urgent need for improved meteorological and fire behavior models that can provide real time prediction of wind patterns and fire spread during these extreme events, coupled with improvements in communication systems for providing that information to agencies and homeowners.

Acknowledgments

We thank Marti Witter and David Loeb for very constructive suggestions on this manuscript and Anne Pfaff for preparing the fire history maps. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

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Exhibit D

WHY ARE SO MANY STRUCTURES BURNING IN CALIFORNIA?

Alexandra D. Syphard and Jon E. Keeley

California has earned a reputation for wildfires that inflict serious damage on human infrastructure, dating back to images of Richard Nixon hosing down the roof of his house in the 1961 Bel-Air fire, and of the famous "fireproof" home of grocery store entrepreneur Fred Roberts burning to the ground in 1982. In recent years, this notoriety has been transformed into public alarm, reflected in the apocalyptic headlines of recent newspaper articles suggesting the "end of California" (*New York Times*, 30 October 2019) and that "California is becoming unlivable" (*The Atlantic,* 30 October 2019). Now the phrase "the new normal" has worked its way into the lexicon, sustained by record-breaking structure loss numbers in 2017 and 2018 despite significantly lower structure losses in 2019.

It remains to be seen whether or not those two recent years were back-to-back one-in-a-hundred-year events, or if the trend has crossed some kind of tipping point, but data do show a long-term trend of significant increase in structures lost to wildfires since the beginning of the 20th century (Fig. 1). What was an average of ~500 homes lost per year in Southern California from about 1950–2000 (CalFire 2000) has recently climbed to ~2700 structures per year statewide from 2000–2018 (Syphard and Keeley 2019). California is not alone in the U.S., or in the world, in suffering increasing impacts from wildfires (e.g., Blanchi et al. 2012, Haynes 2015, Viegas 2018). Impacts so far in the current Australian bushfire season have been record-breaking, with several thousand structures lost, more than 25 fatalities, and unthinkable losses to wildlife. The question that follows, then, is why?

Although trends vary from region to region, one clear reason for increasing wildfire-related losses is the overall

Above: A home burned by the Thomas Fire in 2017. *U.S. Air Force Photo, Master Sgt. Brian Ferguson]*

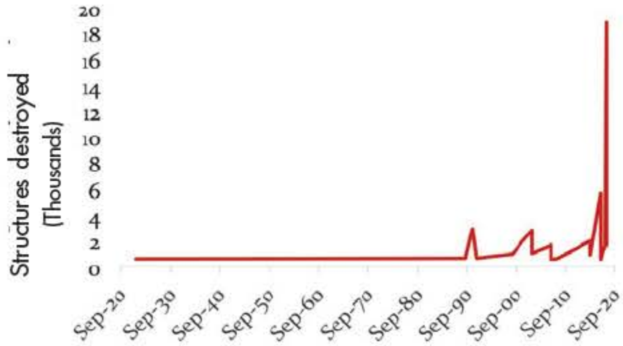

Figure 1. Annual number of structures destroyed in wildfires in California from 1920 to 2018. Source: California Department of Forestry & Fire Protection

increase in wildfire activity. Although, counter to intuition, the number of wildfires has declined in the last several decades, area burned has either remained constant or increased, with substantially higher frequency of large wildfires (Keeley and Syphard 2018), and as discussed further in Keeley and Syphard (this issue). Perhaps an even stronger explanation for increased wildfire-related structure loss is the rapid development of the wildland-urban interface (WUI), which not only exposes more structures to wildland fire, but also increases the likelihood for more human-ignited fires (Radeloff et al. 2018). Despite these trends, however, not all fires result in structure loss, and not all structures are impacted by wildfires they are exposed to. Thus, it is essential to study the factors that are most strongly related to structure exposure and resilience to wildfire, which could then lead to better adaptation and coexistence with wildfire in this era of the "new normal."

In response to this need, a growing number of scientists are conducting empirical research studies to answer the question of why some structures are lost in wildfires and others aren't. Results so far show that the answer to that question is complicated. That is, structure loss results from the confluence of multiple interacting factors across different temporal and spatial scales, which all vary by ecosystem. Given this complexity, misunderstandings and disagreements have arisen over the cause and direction of trends in wildfire activity (Doerr and Santín 2016), fire risk and structure loss (Mccaffrey et al. 2019), and thus, the most effective approach for prioritizing fire management decisions (Moritz et al. 2014). In fact, management techniques appropriate for one region are commonly applied inappropriately to other regions (Noss et al. 2006).

One way that this conflict over priorities can be reduced is through better information and understanding of the similarities and differences that contribute to structure loss among wildfire ecoregions. As data accumulate about the range of conditions under which losses occur, it will be increasingly possible to sort out which risk management techniques are most appropriate for different regions. Wildfire structure losses in the last several decades have already provided a wealth of data for studies comparing factors associated with structures that survived or were destroyed. Most of this work has been done in California (Maranghides and Mell 2009, Syphard et al. 2012a, 2014, 2017, 2019c, Miner 2014, Alexandre et al. 2015, Kramer et al. 2019, Syphard and Keeley 2019) and Australia (Leonard 2009, Blanchi et al. 2010, 2012, Gibbons et al. 2012, 2018, Price and Bradstock 2013, Penman et al. 2019); but some work has also been done in other parts of the continental United States (Alexandre et al. 2016, Kramer et al. 2019).

Combined, the results of this research show clear roles for both local, house-level factors (e.g., structural characteristics of a particular house and property-level landscaping) and broader, landscape-level factors (e.g., housing pattern and location, topography, fuel, and fire characteristics) in explaining why some structures survive wildfires and others don't. This is consistent with the natural hazards literature that theoretically places vulnerability within the intersection of "exposure," that is, potential contact with a hazard; and "sensitivity," or the degree to which the hazard can cause harm (Birkmann 2006). Vulnerability to wildfire is a combination of exposure and sensitivity such that vulnerability results in loss when sensitive characteristics of structures are exposed to hazard events (e.g., the wildfire) (Cutter 1996, Schumann et al. 2019). Thus, exposure is the part of vulnerability related to characteristics of a location, and sensitivity is the risk of loss due to intrinsic physical or social characteristics.

EXPOSURE

Coincidence of fires and houses

A structure's wildfire hazard exposure ultimately lies at the spatial intersection of a wildfire event and the location of the property. The probability of structure loss thus depends on the relative likelihood that a fire ignition results in a fire within the geographical range of structures in the wildland-urban interface (WUI). In turn, this depends on the location and timing of a fire ignition, which varies depending on cause and biophysical characteristics (Syphard and Keeley 2015) relative to other determinants of fire size, including

Caption here. *[Rick Halsey]*

topographic conditions; fuel amount, moisture, and spatial continuity; and weather (Faivre et al. 2016). Large fires tend to be either primarily fuel-dominated or wind-dominated (Keeley and Syphard 2019), with most damage and economic loss occurring from wind-driven fire events (Jin et al. 2015, Keeley and Syphard this issue).

Large fire probability increases with the co-occurrence of human-caused ignitions and severe wind conditions (Abatzoglou et al. 2018). This means that, as population increases and development further encroaches into wildland vegetation, there is an increased risk that a human-caused ignition will coincide in place and time with hot, dry weather; flammable vegetation; and severe wind conditions. Data show that fires tend to be most frequent at low to intermediate housing and population densities (Syphard et al. 2009, Bistinas et al. 2013). Thus, the rapid increase in the spread of exurban development like that occurring now in California (Radeloff et al. 2018), has the potential to both increase the number of ignitions and decrease the overall distance between wildlands and housing.

As the distance between wildland vegetation and housing development decreases across a landscape, the overall exposure of houses to wildfire increases. This helps to explain research that shows the arrangement and location of housing development to be a top-ranked predictor of whether a structure survives or is destroyed by wildfire (e.g., Syphard et al. 2012b, Alexandre et al. 2016, Kramer et al. 2019). In terms of arrangement, data consistently show that loss to wildfire is highest at relatively low housing density (Kramer et al. 2018, Syphard et al. 2019c) and at the interface between wildlands and development (Kramer et al. 2019), regardless of the geographic region in which a structure is located.

Other housing patterns, such as the way housing is dispersed, or the size of housing clusters, are also influential, although their relative importance in explaining structure loss varies from region to region (Alexandre et al. 2015, 2016). Topography is an additional exposure-related factor significantly related to structure loss, as fire tends to spread quickly upslope, meaning that houses on ridgetops are particularly vulnerable. An important caveat to the relationship between low structure density and structure loss is that, once a fire reaches a development, structure-to-structure spread is possible if adjacent houses are highly flammable and spaced within at least 50 meters of one another (Price and Bradstock (2013). In these circumstances, high housing density can be a significant risk factor (Maranghides and Mell 2009).

Fire patterns, altered fire regimes, and vegetation management

In addition to housing arrangement, housing location affects the potential exposure of a structure to wildfire because some areas are inherently more fire-prone than others (Syphard et al. 2012b). Certain parts of the landscape tend to burn repeatedly while others do not, and this reflects the wide variation in fire regimes across California (Syphard and Keeley in press). During the last century, fire regimes in California have been altered due to a range of factors including climate change, land use change, and legacies of fire management. However, the cause of fire regime changes, and their relative effects, have been nearly opposite in the northern and southern-coastal parts of the state (Safford and Water 2014). As described in Keeley and Syphard (this issue), a history of successful fire exclusion in dry, mixed-conifer forests contributed to an alteration of what had been a low-intensity surface fire regime that typically burned back the understory plants without reaching into the canopy and burning the large trees. The subsequent increase in the density of surface litter and the unchecked ingrowth of young trees that serve as ladder fuels now facilitate uncharacteristically severe crown fires. In contrast, in the native shrublands of southern and central coastal California, increased human-caused ignitions have resulted in unnaturally high fire frequency, with increases in wildfire further promoted by ongoing conversion of shrublands to more flammable invasive grasses (Fusco et al. 2019, Syphard et al. 2019b, 2019a).

These differences in the two fire regimes, and how they have been altered, have led to substantial controversy regarding wildfire exposure and the effects and effectiveness of vegetation management (Keeley et al. 2009, Halsey and Syphard 2015). In both northern and southern California, changes in fire regimes could lead to more dangerous or frequent wildfires, thereby increasing structure exposure to hazard. Mechanical treatments and prescribed fire in dry, mixed-conifer forests that reduce the understory and decrease small diameter tree density may help return these forests to a more resilient condition, and thereby potentially reduce exposure of structures to high fire hazard (Knapp et al. 2017).

On the other hand, in the non-forested landscapes that dominate the coastal central and southern parts of the state, vegetation management is primarily focused on reducing the extent of woody vegetation. That is, mechanical treatments are typically designed to remove and reduce the cover of native shrublands and increase the cover of herbaceous vegetation. Prescribed fire in this region *increases* the amount of uncharacteristically frequent fire, putting additional stress on native chaparral and shrublands. Therefore, in non-forested ecosystems vegetation management is inconsistent with ecological integrity and, in addition, has minimal efficacy in the wind-driven fires that result in the most structure loss (Keeley and Syphard this issue).

Access as a risk factor

While vegetation management may control fire behavior by slowing wildfire spread, wildfires during extreme wind conditions typically generate embers and burning debris that can fly kilometers ahead of the fire front. Therefore, fuels management in remote landscapes, even if it does alter fire behavior, has little possibility of preventing wind-driven fires from spreading and expanding if there are no firefighters present to control the fire. This is the likely explanation for why Penman et al. (2014) found that fire size and exposure of property to wildfire in Southern California are primarily controlled by fire weather and characteristics of the built environment, with fuel treatments or fuel load management having minimal influence. Fuel load is less likely to be limiting during wind-driven wildfires and reduction of fuel load in remote areas is unlikely to affect fire outcomes (Keeley et al. 2004, Schoennagel et al. 2004).

On the other hand, strategic placement of fuel breaks near communities may be more effective at reducing exposure because firefighters can use these for safe access to perform suppression activities (Syphard et al. 2011). In addition to strategically placed fuel breaks near communities, the road network surrounding a structure is also important for minimizing exposure from an access perspective. Wide roads and multiple access points can facilitate the transport of firefighting resources to properties within a community; in addition, a good road network provides faster and more efficient evacuation alternatives (Mangan 2000).

SENSITIVITY

Community sensitivity to wildfire, and the capacity to recover from wildfire losses, is related to the social and demographic characteristics of a region (Schumann et al. 2019). In terms of the physical nature of structure loss, however, the primary determinants of sensitivity include defensible space and home structure characteristics as well as firefighter accessibility.

Defensible space

There is certainly a degree of confusion regarding defensible space. A common sentiment is that the larger the defensible space, the better protected the home. Thus, clearance far in excess of legal requirements is

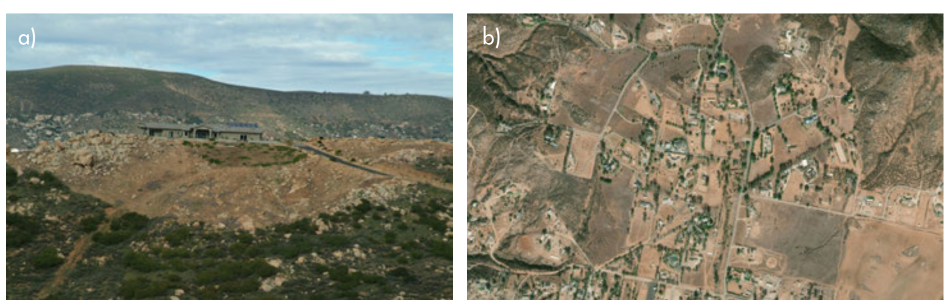

Figure 3. Local (a) and landscape-scale (b) examples of defensible space being performed beyond legal requirements or scientific evidence for protection

increasingly being carried out (Fig. 3a), sometimes at a broad scale (Fig 3b). This is not necessarily helpful or effective. At the same time, many homeowners fail to create sufficient defensible space to improve structure survival.

What does the evidence show about the effectiveness of defensible space? The state of California requires homeowners in state-defined hazardous areas to provide 30 meters (100 feet) of defensible space around their home, which involves the maintenance of specific horizontal and vertical distances of spacing between patches of woody vegetation. Empirical studies in two Southern California areas found that defensible space of approximately 5-20 meters (16-66 feet) provided significant protection, with additional distance providing little or no significant benefit, even on steep slopes (Miner 2014, Syphard et al. 2014). Empirical research looking at structure loss in Australia also found that vegetation reduction and defensible space were most effective at close proximity to the structure (Gibbons et al. 2012, Penman et al. 2019), and that regular irrigation and proper spacing could be as just as effective as clearing woody vegetation (Gibbons et al. 2018).

The largest empirical study of home survival published to date, which included more than 40,000 structures subjected to wildfires over a five year period (Syphard and Keeley 2019), showed that defensible space distance explained little or none of the variance in structure survival. Instead, characteristics of the structure itself were far more significant (Fig. 4). These results should not be interpreted to mean defensible space is not important. But they do suggest that the most important component of defensible space may be the characteristics of vegetation closest to the house. For example, vegetation touching the structure and trees overhanging the roof were highly significant in the two empirical examples from Southern California.

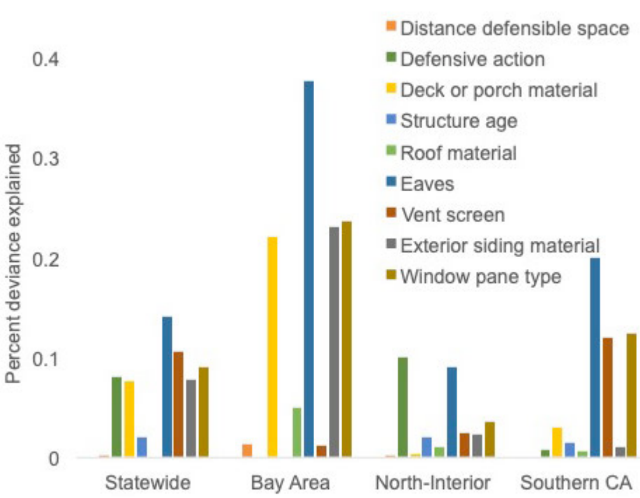

Figure 4. Relative importance (percent deviance explained) of defensible space distance and structural characteristics explaining structure loss to California wildfires from 2013–2018 for the entire state and broken into three broad regions. *Figure modified from Syphard and Keeley (2019).*

Figure 5. Image of flammable debris on a roof that could ignite from wind-blown embers, reflecting how vegetation near or overhanging structures could increase the likelihood of structure loss.

Ember cast

It needs to be appreciated that, particularly during extreme wind-driven fires, most homes do not burn from direct flame contact, but rather from embers blown from the fire front, even from a kilometer or more away. Thus, the material that embers land on, be it vegetation or the structure itself, is key to whether the structure ignites or not. In some cases, the effect of overhanging trees or nearby vegetation is mostly related to the dead plant material or debris that is close to the structure (Fig.5). Likewise, many of the structural characteristics found to be most important in this recent study (Syphard and Keeley 2019) were related to the prevention of ember penetration, such as vent screens and eaves. Open eaves (Fig. 6a) are much more vulnerable to fires than closed eves (Fig. 6b). Open eaves have vents that are arranged perpendicular to the ground and thus in direct line of oncoming wind-driven ember cast. Closed eaves have vents facing down towards the ground and perhaps less prone to embers entering the vents.

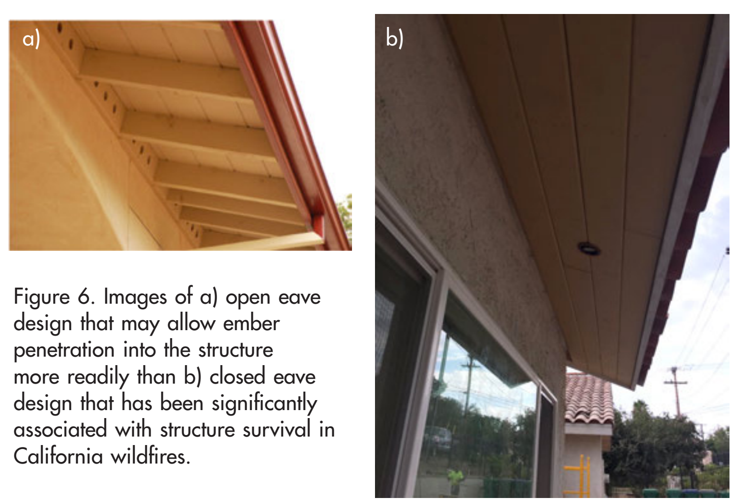

Figure 6. Images of a) open eave design that may allow ember penetration into the structure more readily than b) closed eave design that has been significantly associated with structure survival in California wildfires.

CONCLUSION

The studies described above illustrate that some structures are destroyed in wildfires and others are not because of multiple, often interacting, factors that variably influence the exposure and sensitivity of a property to wildfire. In an ideal world, strategies to increase community resilience to wildfire would be ranked and prioritized according to their relative potential for success in preventing structure loss in any given ecosystem. Of course, an ideal world would also not have to account for factors such as cost, effort, and feasibility, which add to the complexity of decision-making in the real world.

While most empirical research on structure loss has so far focused on either exposure or sensitivity factors independently, an integrated analysis in Southern California provided a comparison of the relative importance of different exposure-related and sensitivity-related variables (Syphard et al. 2017, Fig. 7) in distinguishing destroyed from surviving structures. Study results suggested that exposure (when measured by structure density) was the most important factor overall that distinguished destroyed from surviving structures. The relative importance of different sensitivity variables (e.g., structure age or landscaping characteristics) varied depending upon whether the structure was highly exposed (i.e., at low housing density) or less exposed (i.e., at high housing density) (Fig. 7).

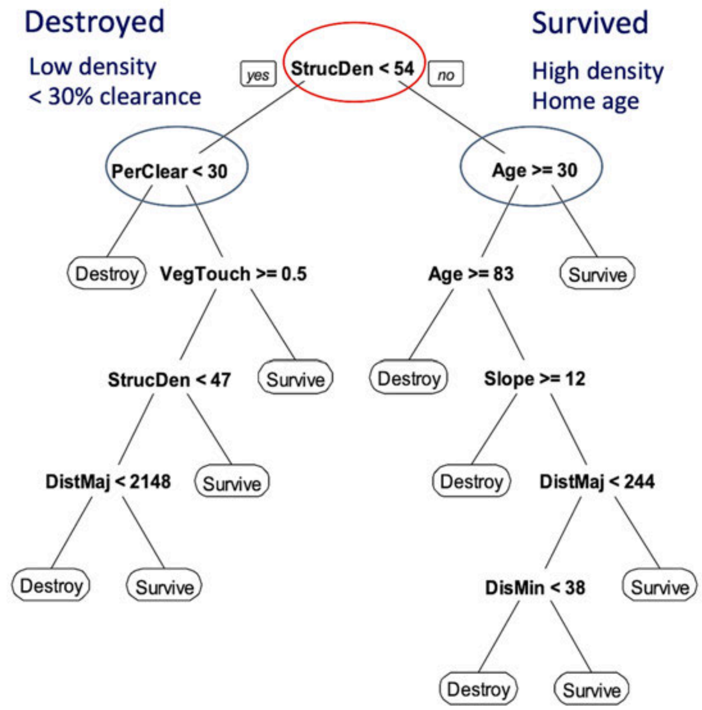

Figure 7. Classification tree showing the hierarchy of factors that best distinguished destroyed from survived structures in Southern California wildfires. Abbreviations are: StrucDen = structure density; PerClear = percentage woody vegetation clearance on property; Age = age of structure; VegTouch = number of sides of structure with vegetation touching; Slope = percentage slope on property; DistMaj = distance in meters to a major road; DisMin = distance in meters to a minor road. *Modified from Syphard et al. 2017.*

These results suggest that, in an ideal world, the most effective strategy at reducing future structure loss would focus on reducing the extent of low-density housing via careful land planning decisions. This conclusion is rather obvious given that reducing exposure reduces the chance that a wildfire could reach a structure in the first place. In the real world, regardless of land use planning decisions for future development, there is extensive existing development that may be exposed to future wildfires. Therefore, strategies like ignition prevention and strategic vegetation management could potentially reduce the exposure of these houses by focusing on the initiation or spread of the wildfire.

Once a fire reaches a property, structure sensitivity then becomes the key determinant for survival. In many areas, effective efforts to minimize sensitivity to wildfire include education and increased awareness of appropriate defensible space practices, development of Firewise Communities (Jakes et al. 2007), and improvement in building codes. Nonetheless, some communities underinvest in defensible space (Taylor et al. 2019), while in others, homeowners create excessive clearance (Fig. 3) that may increase the extent of invasive grass on the property. Conversion of native woody vegetation into grass in the non-forested landscapes of Southern California, for example, could increase the flammability of the property (Fusco et al. 2019), particularly if the grass is not irrigated regularly (Gibbons et al. 2018).

Given the importance of structural characteristics in home survival in recent California wildfires (Syphard and Keeley 2019), the improvement of building codes has been a positive development overall. However, there is already extensive existing residential development in fire-prone areas that was built prior to the adoption of new building codes. Reducing the fire sensitivity of these homes generally entails retrofits and modifications, which can be expensive (Quarles and Pohl 2018). However, some of the most effective actions, such as eave coverings and vent screens, are generally less expensive than replacing roofing or exterior siding, although window replacement can also be expensive (Quarles and Pohl 2018).

one, from the individual homeowner, to local planning and permitting officials, to state and federal government authorities, will need to be involved in instituting preventive measures. Management appropriately informed by science and data analysis can reduce future structure losses and minimize ecological impacts to assure a more sustainable future. While these efforts may seem expensive in the present, it is much less expensive than paying for losses in the future.

The 2017 Thomas Fire. *[Stuart Palley, U.S. Forest Service]*

It would appear, given recent improvements in adapting structures to withstand fire, that the increase in the numbers of houses burned in wildfire is not a matter of increased sensitivity. Instead, the answer lies somewhere in the combination of factors that govern exposure, including changes to wildfire behavior and activity, as well as exurban development that places structures in the path of these wildfires. Climate and vegetation change may increase the probability of large wildfires in some regions, such as the northern parts of California (Syphard et al. 2019c); but in other regions, like Southern California, climate change is likely to manifest differently, most likely indirectly, via factors such as long-term drought and vegetation change.

While the effects of climate change on wildfire vary from region to region, housing pattern variables have consistently been the most important factors explaining structure loss across California and elsewhere. This suggests that much of the increase in structure loss in California may be attributable to increases in this type of exposure—and that planning decisions could have broad-scale benefits in the future. Also consistent across regions is the potential for homeowner mitigation measures to provide significant improvement in structure survival probability. Those measures that focus on reduction of ember impact and penetration are most important.

Despite these overall consistencies, there is variation in the nature and strength of relationships in all of these factors. Wildfire frequency and behavior, and fuel characteristics, vary widely by ecosystem; thus, vegetation management efforts differ greatly in effects and effectiveness and should be implemented appropriately. Regardless of regional variations, every-

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Exhibit E

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Land Use Planning and Wildfire: Development Policies Influence Future Probability of Housing Loss

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Abstract

Increasing numbers of homes are being destroyed by wildfire in the wildland-urban interface. With projections of climate change and housing growth potentially exacerbating the threat of wildfire to homes and property, effective fire-risk reduction alternatives are needed as part of a comprehensive fire management plan. Land use planning represents a shift in traditional thinking from trying to eliminate wildfires, or even increasing resilience to them, toward avoiding exposure to them through the informed placement of new residential structures. For land use planning to be effective, it needs to be based on solid understanding of where and how to locate and arrange new homes. We simulated three scenarios of future residential development and projected landscape-level wildfire risk to residential structures in a rapidly urbanizing, fire-prone region in southern California. We based all future development on an econometric subdivision model, but we varied the emphasis of subdivision decision-making based on three broad and common growth types: infill, expansion, and leapfrog. Simulation results showed that decision-making based on these growth types, when applied locally for subdivision of individual parcels, produced substantial landscape-level differences in pattern, location, and extent of development. These differences in development, in turn, affected the area and proportion of structures at risk from burning in wildfires. Scenarios with lower housing density and larger numbers of small, isolated clusters of development, i.e., resulting from leapfrog development, were generally predicted to have the highest predicted fire risk to the largest proportion of structures in the study area, and infill development was predicted to have the lowest risk. These results suggest that land use planning should be considered an important component to fire risk management and that consistently applied policies based on residential pattern may provide substantial benefits for future risk reduction.

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Introduction

The recognition that homes are vulnerable to wildfire in the wildland urban interface (WUI) has been established for decades [e.g., 1,2]; but with a recent surge in structures burning, this issue is now receiving widespread attention in policy, the media, and the scientific literature. Single fire events, like those in Greece, Australia, southern California, and Colorado have resulted in scores of lost lives, thousands of structures burned, and billions of dollars in expenditures [3 6]. With the potential for increasingly severe fire conditions under climate change [7] and projections of continued housing development [8], it is becoming clear that more effective fire risk reduction solutions are needed. "Fire risk" here refers to the probability of a structure burning in a wildfire within a given time period.

Traditional fire risk reduction focuses heavily on fire suppres sion and manipulation of wildland vegetation to reduce hazardous fuels [9]. Enormous resources are invested in vegetation manage ment [10], but as increasing numbers of homes burn down despite this massive investment, the "business as usual" approach to fire management is undergoing reevaluation. One issue is that fuel treatments may not be located in the most strategic positions, i.e., in the wildland urban interface [11]. Yet, even if treatments surrounded all communities, scattered development patterns are difficult for firefighters to reach [12 14], and fuel treatments do little to protect homes without firefighter access [15 16]. Fuel treatments may also be ineffective against embers or flaming materials that blow ahead of the fire front [17].

One alternative to traditional fire management that is receiving widespread attention is to prepare communities through the use of fire safe building materials or creating defensible space around structures [17 18]. These actions represent an important shift in emphasis from trying to prevent wildfires in fire prone areas to better anticipating fires that are ultimately inevitable. Neverthe less, the cost of building and retrofitting homes to be fire safe can be prohibitive, and these actions do not guarantee immunity from fire [19].

Land use planning is an alternative that represents a further shift in thinking, beyond the preparation of communities to withstand an inevitable fire, to preventing new residential structures from being exposed to fire in the first place. The reason homes are vulnerable to fires at the wildland urban interface is a function of its very definition: "where homes meet or intermingle with wildland vegetation" [20]. In other words, the location and pattern of homes influence their fire risk, and past land use decision making has allowed homes to be constructed in highly flammable areas [21]. Land use planning for fire safety is beginning to receive some attention in the literature [22 23], and there is growing recognition of the potential benefits of directing development outside of the most hazardous locations [8,19,24].

Despite recent attention in the literature, land use planning for wildfire has yet to gain traction in practice, particularly in the United States. However, fire history has been used to help define land zoning for fire planning in Italy [22], and bushfire hazard maps are integrated into planning policy in Victoria, Australia [25]. Although some inertia inevitably arises from complications with existing policy and plans, a primary impediment to the design and implementation of fire smart land use planning is lack of guidance about specific locations, patterns of development, or appropriate methodology to direct the placement of new development. Without a solid knowledge base to draw from, planners will be misinformed about which planning decisions may result in the greatest overall reduction of residential landscape risk. Even worse, poor science could result in placement of homes in areas that actually have high fire hazard.

Research on how planning decisions contributed to structures burning in the past provides some guidance about what actions may work in the future. Analysis of hundreds of homes that burned in southern California the last decade showed that housing arrangement and location strongly influence fire risk, particularly through housing density and spacing, location along the perimeter of development, slope, and fire history [26]. Although high density structure to structure loss can occur [27 28], structures in areas with low to intermediate housing density were most likely to burn, potentially due to intermingling with wildland vegetation or difficulty of firefighter access. Fire frequency also tends to be highest at low to intermediate housing density, at least in regions where humans are the primary cause of ignitions [29 30].

These results suggest, for example, that placing new residential development within the boundaries of existing high density developments or in areas of low relief may reduce fire risk. However, it is difficult to know whether broad scale planning policies would actually result in the intended housing arrangement and pattern at the landscape scale, and whether those patterns would result in lower fire risk. Our objective here was to simulate three scenarios of future residential development, and to project wildfire risk, in a rapidly urbanizing and fire prone region where we have studied past structure loss [25]. We based all future development on an econometric subdivision model, but we varied the emphasis of subdivision decision making based on three broad and common growth types.

Although cities vary in extent, fragmentation, and residential density [31 32], urban form typically adheres to a set of common patterns [33 34], and we based our development scenarios on the three primary means by which residential development typically occurs: infill, expansion, or leapfrog [34]. Infill is characterized by development of vacant land surrounded by existing development, typically in built up areas where public facilities already exist. [35 36], and should result in higher structure density rather than increased urban extent. Expansion growth occurs along the edge of existing development, extends the size of the urban patch to which it is adjacent, and may have variable influence on structure density. Leapfrog growth occurs when development occurs beyond existing urban areas such that the new structure is surrounded by undeveloped land. This type of growth would expand the urban extent and initially result in lower structure density; but these areas may eventually become centers of growth from which infill or expansion can occur. We asked:

1) Do residential development policies reflecting broad growth types affect the resulting pattern and footprint of development across the landscape?
2) Do differences in extent, location, and pattern of residential development translate into differences in wildfire risk, based on the current configuration of structures?
3) Which development process, infill, expansion, or leapfrog, results in the lowest projected fire risk across the landscape?

Methods

Study Area

The study area included all land within the South Coast Ecoregion of San Diego County, California, US, encompassing an area of 8312 km^2. The region is topographically diverse with high levels of biodiversity, and urban development has been the primary cause of natural habitat loss and species extinction [37]. Owing to the Mediterranean climate, with mild, wet winters and long summer droughts, the native shrublands dominating the landscape are extremely fire prone. San Diego County was the site of major wildfire losses in 2003 and 2007 [38], although large wildfire events have occurred in the county since record keeping began, and are expected to continue, as fire frequency has steadily increased in recent decades [29,39]. The county is home to more than three million residents, and approximately one million more people are expected by 2030 [40]. Although most residential development has been concentrated along the coast, expansion of housing is expected in the eastern, unincorporated part of the county.

Econometric Subdivision Model

A host of alternative modeling approaches exist to simulate future land use scenarios [41], including a cellular automaton model that we previously applied to the study area [42]. We chose to use an econometric modelling approach for this study because we wanted to capture fine scale, structure level patterns and processes that are correlated with housing loss to wildfire [26]; and econometric models may perform better at the scale of individual parcels [43].

Although we based the three development scenarios on generalized planning policies, we also wanted to ensure that the residential projections were realistic and adhered to current planning regulations. The objective of the econometric modeling was to estimate the likelihood that residential parcels will subdivide in the future. Therefore, we used a probit model to estimate the transition probability of each parcel based on a range of potential explanatory variables typically associated with parcel subdivision and housing development [44 45].

To develop the model of subdivision probability, we acquired GIS data of the county's parcel boundaries in years 2005 and 2009 from the San Diego Association of Governments (SANDAG). The dependent variable was equal to 1 if a parcel subdivided between 2005 and 2009, and zero otherwise. Using these data layers we first determined which parcels were legally able to subdivide given current land use regulations. Minimum lot size restrictions are typically considered the most import restriction for determining future land use. We deemed a parcel eligible for subdivision if the current lot size was greater than twice the minimum legal size given the land class. To determine which parcels subdivided between 2005 and 2009, we queried parcel IDs where the total area was reduced by at least the minimum lot size between the two time periods. Finally, we were able to generate a suite of variables that determine the likelihood of a parcel developing in the future (Table S1).

We overlaid the parcel boundaries over a range of GIS layers representing our explanatory variables. These data are available to download at (http://www.sandag.org/index.asp?subclassid 100&fuseaction home.subclasshome). Our ex planatory variables included: parcel size, parcel size squared, six dummy variables which capture non linear effects of parcel size, distance to the coast, distance to the coast squared; distance to city center and its square, current zoning, slope, land use, roads, if the parcel is in a protected area, if the parcel is in a development area, if the parcel is in the redevelopment area (Table 1).

Spatial Model of Future Development under Planning Alternatives

The outcome of the land use change econometric model is the subdivision probability for each parcel for a five year time step. Based on these probabilities, we developed a GIS spatial simulation model of future land use under three distinct planning scenarios: infill (development in open or low density parcels within already developed areas), expansion (development on the fringe of developed areas), and leapfrog (development in open areas). The model runs in four 5 year time steps from 2010 to 2030, and generates the spatial locations of new housing units in the county.

Although development decisions could feasibly depend on fire risk, we did not model that here. There is no evidence that fire has influenced past regional planning decisions, so it was not used as an explanatory variable in the econometric model. Although we could have evaluated the potential for future development decisions to be based in part on fire risk, this would have required simulation of feedbacks between fires and probability of develop ment. Because our objective in this study was to isolate the effects of the three distinct growth types, we modeled fire risk only as a function of development pattern and not vice versa.

We constructed a complete spatial database of existing residential structures in the study area [26]. These structures and their corresponding parcel boundaries served as the initial conditions for all three scenarios of the spatial simulation model. The current and projected future GIS layers of structures were also subsequently used in the fire risk model (see below). The

Table 1. Variables and results from the probit regression model of parcel subdivision in San Diego County.

Subdivided (1 = yes, 0 = no)	Coefficient	Std. Err.	z	P>|z|	[95% Conf. Interval]	
Acres of lot	0.0026342	0.00075	3.51	0	0.001164	0.004105
Acres of lot ^{2}	3.02E 06	1.29E 06	2.34	0.019	5.55E 06	4.93E 07
Distance to ocean	7.42E 06	1.33E 06	5.59	0	0.00001	4.82E 06
Distance to ocean ^{2}	2.33E 11	8.28E 12	2.82	0.005	7.11E 12	3.96E 11
Distance to major road	2.17E 07	2.74E 06	0.08	0.937	5.16E 06	5.59E 06
Distance to major road ^{2}	1.94E 11	1.70E 11	1.14	0.252	5.27E 11	1.38E 11
Distance to nearest city center	0.0000115	1.70E 06	6.76	0	1.5E 05	8.16E 06
Distance to nearest city center ^{2}	2.89E 11	9.70E 12	2.98	0.003	9.91E 12	4.79E 11
Slope between 0–5%	0.6211289	0.211761	2.93	0.003	0.206085	1.036173
Slope between 5–10%	0.3911427	0.210684	1.86	0.063	0.02179	0.804076
Slope between 10–25%	0.0716669	0.212725	0.34	0.736	0.34527	0.4886
Rural Residential	0.3563149	0.071512	4.98	0	0.49648	0.21615
Single Family	0.1361149	0.068678	1.98	0.047	0.001509	0.270721
Multi-Family	0.2505093	0.151486	1.65	0.098	0.54742	0.046397
Road	0.015329	0.086094	0.18	0.859	0.15341	0.184069
Open Space	0.7440933	0.099145	7.51	0	0.93841	0.54977
Orchard/Vineyard	0.5813305	0.097867	5.94	0	0.77315	0.38951
Agriculture	0.9785208	0.132734	7.37	0	1.23867	0.71837
Vacant Land	0.5222501	0.074586	7	0	0.66844	0.37606
Zoned protected	0.253769	0.076881	3.3	0.001	0.103086	0.404452
Area marked for redevelopment	0.2680261	0.14069	1.91	0.057	0.54377	0.007722
Area marked for development	0.5780101	0.064103	9.02	0	0.452371	0.703649
Parcel between 10–20 acres	0.3379532	0.065899	5.13	0	0.46711	0.20879
Parcel between 5–10 acres	0.6119036	0.067012	9.13	0	0.74325	0.48056
Parcel between 2–5 acres	1.16297	0.07062	16.47	0	1.30138	1.02456
Parcel between 1–2 acres	1.563956	0.090286	17.32	0	1.74091	1.387
Parcel between.5–1 acres	1.999939	0.099893	20.02	0	2.19573	1.80415
Parcel between.25–.5 acres	2.178273	0.117101	18.6	0	2.40779	1.94876
Constant	1.397931	0.227467	6.15	0	1.84376	0.9521

Sample size 113 001, LR Chi^2 1535.23, pro>chi 0, pseudo R^2 0.22. Further description of the variables is provided in Table S1.
doi:10.1371/journal.pone.0071708.t001

dataset of existing housing includes locations of 687,869 structures, of which 4% were located within the perimeter of one of 40 fires that burned since 2001. During these fires, 4315 structures were completely destroyed, and another 935 were damaged.

For future development scenarios, we wanted to allocate an equal number of new structures to the landscape. This was to ensure that any predicted difference in fire risk was a function of the arrangement and location of structures, not the total number of structures. Nevertheless, differences in the total number of structures were simulated with each of the 5 year time steps. We determined the number of housing units to add during the simulations based on projections made by San Diego County [46]. Using factors such as development proposals, general plan densities, and information from jurisdictions, the county estimated that between 331,378 units and 486,336 units could be supported within the developable residential land by 2030. Because the eastern, desert portion of the county was not included in our study area, we used a conservative approach and simulated the addition of 331,378 new dwelling units. We divided this number by four to define the number of new dwelling units to add at each time step, assuming a linear growth rate.

One output of the econometric model was the prediction of the maximum number of new dwelling units that could be added to each parcel. However, dwelling units may consist of apartments as well as single family homes. The mix of single and multifamily units in the region has remained relatively constant over time, and the overall trend has been a mix of roughly 1/3 multifamily and 2/3 single family units. Because the fire risk model is based on points representing structure locations across the landscape, regardless of the number of dwelling units per structure, we needed to generate a conversion factor from dwelling units to structures. We therefore defined a minimum lot size of 0.25 acre on which no more than a single structure could be built, regardless of the number of dwelling units in it (i.e., a single family home or apartment complex). Then, once a parcel was selected for development by the model (see details below), we divided its total area by the maximum number of dwelling units to be added, according to the econometric model. If the result was larger than 0.25, we subdivided parcels according to the result. If not, we quantified how many 0.25 acre parcels fit into the original parcel, and generated the new parcel boundaries accordingly.

Using the initial map of parcels (year 2010), we classified each parcel that was defined as eligible for development (in the previous stage) as suitable for one of the three planning scenarios described above, according to the number of developed parcels in its immediate neighborhood (i.e., those parcels that share a boundary with the focal parcel). We defined 'developed parcels' as ones that had more than one house per 20 acres (8.09 ha). Therefore, according to these density thresholds, we allowed some parcels with nonzero housing density to be considered as 'undeveloped' because these large, rural parcels might contain a single or a handful of houses but they exist within a large open area. In other words, the overall land cover of these parcels was effectively undeveloped, and we therefore assumed that development in adjacent parcels would be akin to development in open areas.

We defined infill parcels as those that were completely surrounded by developed parcels. Expansion parcels had at least one neighboring parcel that was undeveloped; and leapfrog parcels were those with no developed parcels in their immediate surroundings. We reclassified the type of each available parcel in the same manner after each time step, to account for changing dynamics in the development map of the county.

We conducted three simulations, one for each development scenario (infill, expansion, and leapfrog). In each simulation, all parcels were eligible to subdivide, regardless of their class. Therefore, to build a simulation for a specific scenario, we increased the development probability of parcels of the selected scenario by 20%, to favor their development compared to the other types of parcels, without prohibiting development in the other parcel types. This approach was necessary because the projected number of dwelling units was much larger than it would be possible to fit in infill and leapfrog class parcels solely. For example, as the spatial coverage of developed parcel expands, there is less contiguous area that is undevelopable and suitable for leapfrog development. Therefore, the scenarios are not exclusive, but rather a mixture of the three development types. Yet, in each scenario, there is one main type of development, and smaller amounts of development events of the other two types.

Due to the immense computational demand of the simulations, we adopted a deterministic, rather than a stochastic approach to decide on which parcels were subdivided. After enhancing the transition probability according to the corresponding scenario, we ranked and then sorted all parcels according to their probability of subdivision. We then sequentially selected parcels, while simulta neously tallying the number of dwelling units in them, until the development target in that time step (one fourth of the total number of dwelling units to be added: 82,795) was reached. Once the development target was reached, we moved to the next time step. After each time step, the remaining parcels that were still eligible for development were re classified to development types according to the new spatial configuration of the landscape.

Once a parcel was selected for subdivision, and the number of new parcels to develop in it was calculated (as detailed above), an equal area spatial splitting model was employed to split the parent parcel to the predefined number of equal area child parcels. We developed a simple splitting model which is based on iterative splitting of larger parcels into two smaller parcels using a straight line splitting boundary. Once the parcel was fully split into the needed number of sub parcels, we allocated a new structure inside each new parcel by generating a point at its centroid (center of gravity). The point datasets of all structure locations per time step per scenario were passed over to the fire risk model, which is described below.

Fire Risk Modeling and Analysis

To project the distribution of fire risk under alternative scenarios, we used MaxEnt [47 48], a map based modeling software used primarily for species distribution modeling [48], but we have used it successfully for ignition modeling [50] and for projecting current fire risk in the study area [26]. For this study, we slightly modified the model from Syphard et al. [26]. The dependent variable was the location of structures destroyed by fire between 2001 and 2010. Although inclusion of damaged structures in the data set does not significantly affect results [26], we only included completely destroyed structures to avoid the introduction of any uncertainty.

The MaxEnt software uses a machine learning algorithm that iteratively evaluates contrasts among values of predictor values at locations where structures burned versus values distributed across the entire study area. The model assumes that the best approximation of an unknown distribution (i.e., structure destruc tion) is the one with maximum entropy. The output is an exponential function that assigns a probability to every cell of a map. Thus, the resulting continuous maps of fire risk represented the probability of a structure being destroyed by fire. In these output maps, areas of predicted high fire risk that did not have structures on them represented environmental conditions similar to those in which structures have actually burned.

We based the explanatory variables on those that were significantly related to burned structures in Syphard et al. [26], including maps depicting housing arrangement and pattern, housing location, and biophysical factors. Housing pattern variables reflected individual structure locations as well as the arrangement of structures within housing clusters. We calculated housing clusters, defined as groups of structures located within a maximum of 100 m from each other, by creating 100 m buffers around all structures and dissolving the overlapping boundaries [51].

Because burned structures were significantly related to small housing clusters [26], we calculated the area of every cluster as an attribute, and then created raster grids based on that attribute. Low to intermediate housing density and distance to the edge of the cluster were also significant explanatory variables relative to housing pattern and location [26], so we also created raster grids for those. GIS buffer measures at 1 km have been found to explain approximately 90% of the variation in rural residential density [52], so we developed density grids using simple density interpolation based on a 1 km search radius, with area determined through square map units. To create grids representing distance to the edge of clusters, we first collapsed the cluster polygons into vector polyline files, and then created grids of interpolated Euclidean Distance to the edge within each cluster.

Because the MaxEnt model randomly selects background samples in the map to compare with locations of destroyed structures, we used a mask to restrict sampling to the developed environment within cluster boundaries; the distance to the edge of the cluster would represent a different relationship inside a cluster boundary versus outside in the wildland. We also modified the grids to ensure that any random sample located within the 100m buffer zone would receive a value of 100m; thus, all points within the buffer were considered "the edge of the development".

After creating the grids representing housing pattern and arrangement of the current configuration of structures, we applied the same algorithms to the maps of simulated future structure locations. We thus generated grids representing future housing pattern and arrangement under alternative development scenarios. The other explanatory variables, including fire history, slope, fuel type, southwest aspect, and distance to coast [26] remained constant through time for current and future scenarios. Although historic fire frequency and fuel type typically change through time, we did not simulate their dynamics here because we wanted to isolate the effect of planning decisions on housing pattern and arrangement while holding everything else constant.

We conditioned the MaxEnt model on present distributions of housing using ten thousand random background points and destroyed structures located no closer than 500 m to minimize any effect of spatial autocorrelation. We used 80% (260 records) of these data for model training, and 20% [66 records) for testing. We repeated the process using cross validation with five replicates and used the average of these five models for analyses. For smoother functions of the explanatory variables, we used hinge features, linear, and quadratic with an increase in regularization of beta set at 2.5, based on Elith et al. [48]. The smoother response curves minimize over fitting of the model. We conducted jackknife tests of explanatory variable importance.

We first developed the model using mapped explanatory variables derived from the current configuration of structures. To project fire risk under the different time steps of the alternative development scenarios, projected the model conditioned upon current conditions onto maps representing future conditions by substituting the grids representing future housing pattern and arrangement. This is similar to how potential future distributions of species are projected under climate change scenarios [49].

To quantify differences among current and future alternative scenarios, we calculated metrics representing housing density, pattern, and footprint to determine the extent to which the planning policies produced differences in housing pattern and location. We compared the modeled structure fire risk of the scenarios by overlaying all maps of structure locations with their respective mapped output grids from the MaxEnt models and calculating probability of burning for every structure point. We also calculated total area of risk by selecting three threshold criteria [53]. These criteria, at 0.05, 0.25, and 0.5 represented three different degrees of risk, and we calculated the proportion of structures that were located in risk areas for every time step in all scenarios.

Results

The probit econometric model, run on 113 001 observations, showed that larger parcels were most likely to subdivide, although the relationship between parcel size and subdivision probability was non linear (Table 1). Parcels closer to existing roads, the ocean, those with lower slopes, and those designated as fit for development were all most likely to develop. Parcels designated in redevelopment areas were less likely to develop. Overall, the model had a pseudo r squared of 0.22.

The land use simulation model, based on a combination of the econometric subdivision model and three different growth policies, resulted in substantial differences in the extent and pattern of housing of the three scenarios. The total area of housing development, or the housing footprint, was largest for simulations where leapfrog growth dominated, followed by expansion type development, and then infill (Figure 1a). The differences in the housing footprint became larger among the scenarios over time, but the largest difference was between infill and the other two development types. As the housing footprint expanded in the three scenarios, the corresponding housing density declined, so that leapfrog growth resulted in the lowest housing density per 1 km, followed by expansion and then infill (Figure 2b). Despite the near inverse of this relationship, there was generally a larger separation among scenarios with regard to housing density. With larger housing footprints and lower housing density, the number of separate housing clusters increased while their size decreased (Figure 2c).

In the first two time steps of the model (2015 and 2020), the simulated development pattern closely followed the desired pattern in the scenario, although some of the growth in the infill scenario ended up becoming expansion or leapfrog (Table 2). In the last two time steps (2025 and 2030), there were not enough infill parcels left, and thus, the majority of growth in these simulations became expansion, followed by infill, and then leapfrog. In the last time step, there were not enough isolated parcels in the leapfrog scenario and thus, the majority of development became expansion. Thus in general, as more development occurred in the simulations by the year 2030, the majority took the form of expansion.

The area under the curve (AUC) of receiver operating characteristic (ROC) plots, indicating the ability of the MaxEnt model to discriminate between burned and unburned structures, averaged across five cross validated replicate runs was 0.91. The AUC represents the probability that, for a randomly selected set of observations, the model prediction was higher for a burned structure than for an unburned structure [49].The two most important variables in the model according to the internal jackknife tests in MaxEnt [47] were related to housing pattern:

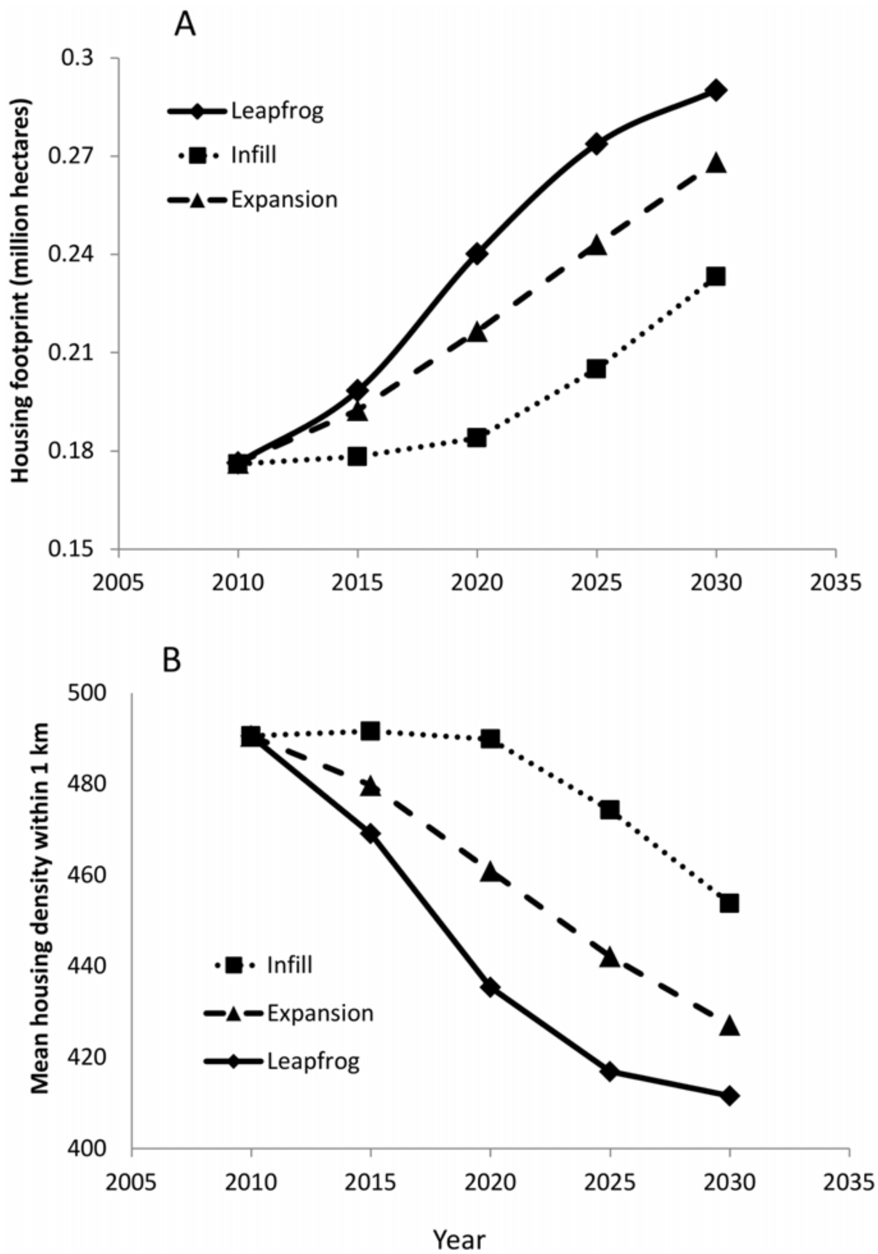

Figure 1. Trends of development extent and pattern for three planning policy simulations from 2010 2030, including A) total housing footprint representing the area of land within all housing clusters, and B) mean housing density averaged across all housing clusters.
doi:10.1371/journal.pone.0071708.g001

low to intermediate housing density and small cluster size and housing density (Figure 3). The distance to the edge of housing cluster was a less important contribution.

Maps showing the probability of a structure being destroyed in a wildfire, displayed as a gradient from low to high risk, show broad agreement relative to the general areas of the landscape that are riskiest, with correlation coefficients ranging from 0.85 0.91 (Figure 4). Nevertheless, subtle differences are apparent in the three development scenario maps by year 2030, with the highest risk areas in the expansion scenario located farther east than infill, and the highest risk areas in leapfrog occupying a wider extent than either of the other two scenarios.

Differences among current housing and the three development scenarios are clearly illustrated through the mean landscape risk, or total probability of all structures burning (Figure 5). All three development scenarios were predicted to experience an increase in mean landscape risk over the duration of the simulations, except for infill at year 2015. The highest landscape risk to structures was predicted for the leapfrog scenario, followed by expansion, and then infill. The increase in risk over time is more gradual for the infill scenario than the other two scenarios.

The ranking of scenarios varied according to the proportion of structures located within different levels of risk defined through binary thresholding (Figure 6). When the continuous risk maps were thresholded at the lowest number of 0.05, a large proportion

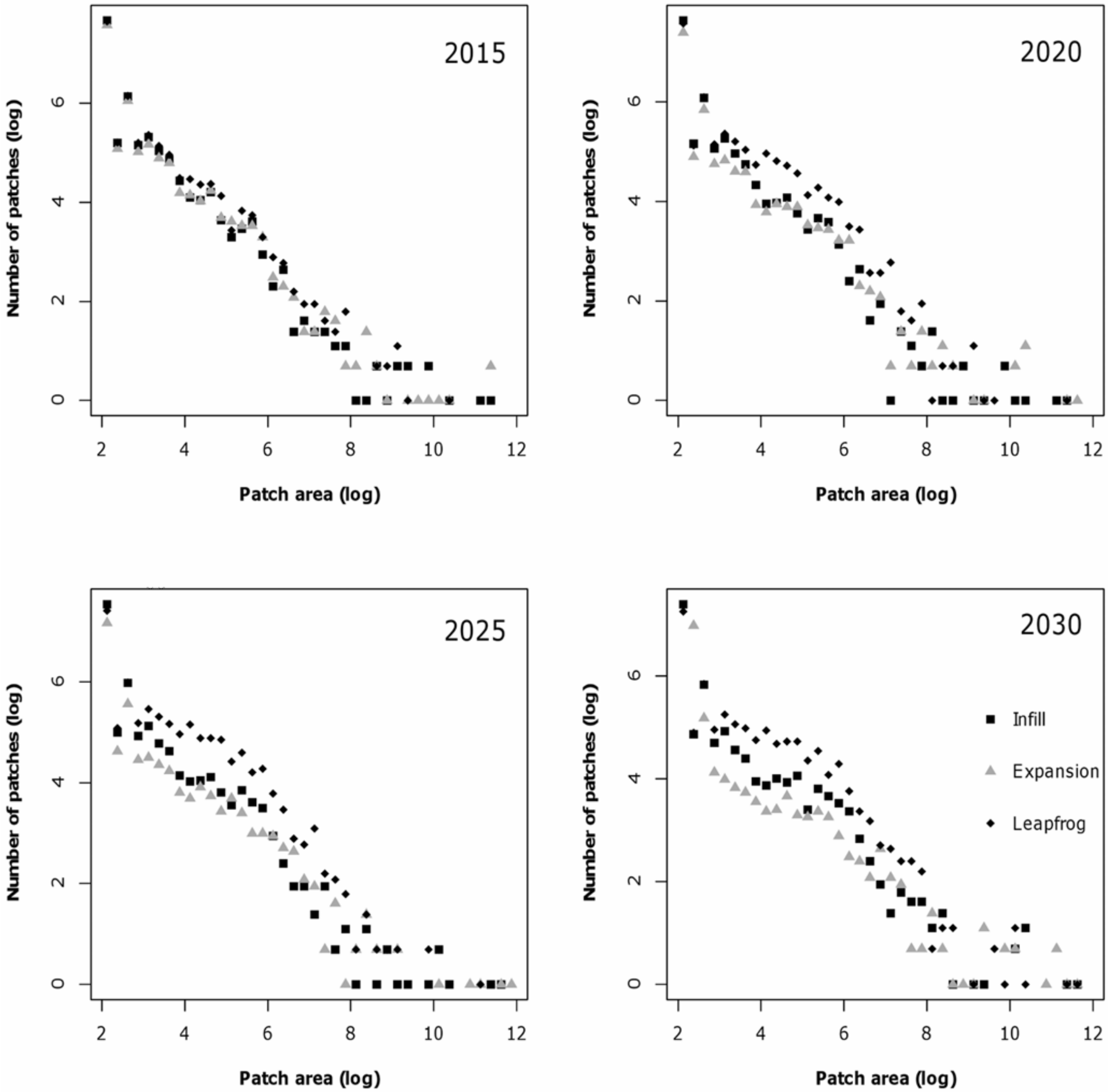

Figure 2. Trends in number of patches and patch area for three planning policy simulations from 2010 2030. Numbers were log transformed for better visual representation of the scenarios.
doi:10.1371/journal.pone.0071708.g002

of structures in all scenarios fell within areas defined as risky according to this criterion. At this threshold, the proportion of structures in high risk areas increased linearly for the expansion and leapfrog development scenarios while the proportion of infill homes increased more gradually. When risk was defined more conservatively at 0.25, temporal trends for the leapfrog and infill scenarios were similar to the 0.05 threshold. However, the proportion of structures at risk in the expansion scenario initially increased to 2020, but this proportion leveled off and declined by 2030. When the threshold was highest at 0.50, a very low proportion of structures in any scenario were located in areas at risk. But in these high risk areas, the expansion scenario switched places with infill to have the lowest proportion of structures at risk in all time steps. Leapfrog had the largest proportion of homes at risk. This proportion of homes located in areas at risk with a threshold at 0.5 declined over time for all three scenarios.

Discussion

Our simulations of residential development showed that planning policies based on different growth types, applied locally for subdivision of individual parcels, will likely produce substantial and cumulative landscape level differences in pattern, location, and extent of development. These differences in development pattern, in turn, will likely affect the area and proportion of

Table 2. Pattern of simulated development under infill, expansion, and leapfrog growth policies.

		Actual development		
Development scenario	**year**	***Infill***	***Expansion***	***Leapfrog***
Infill	2015	9450	18	6
	2020	11787	153	29
	2025	236	624	144
	2030	325	890	179
Expansion	2015	0	772	0
	2020	0	1243	2
	2025	0	1871	1
	2030	0	2662	0
Leapfrog	2015	0	10	408
	2020	0	5	1132
	2025	1	83	3563
	2030	34	917	0

The numbers in the table denote the numbers of patches of a given development type.
doi:10.1371/journal.pone.0071708.t002

structures at risk from burning in wildfires. In particular, the scenarios with lower housing density and larger numbers of small, isolated clusters of development, i.e., leapfrog followed by expansion and infill, were generally predicted to have the highest predicted fire risk to the largest proportion of structures in the study area. Nevertheless, rankings of scenarios were affected by the definition of risk.

Theoretically, it makes sense that leapfrog development produced fragmented development with larger numbers of small patches, lower housing density, and a larger housing footprint; and that infill resulted in the opposite, with expansion in the middle. By definition, leapfrog development requires open space around all sides of the newly developed parcel, whereas infill requires development on all sides, and expansion requires development on one side and open space on another. Implementing these planning policies on real landscapes, however, can be complex if there are more houses to build than there are parcels that meet the definitions of the three planning rules, and thus not all development conforms strictly to the policy [54]. In our simulations, parcels meeting the definition of each growth type had a higher probability of subdividing; yet, as we were simulating a real landscape, many newly developed parcels did not meet the scenario criteria. That the three scenarios nevertheless produced substantial differences in landscape level development patterns shows that decision making at the individual level can lead to meaningful broad scale effects.

The objective of the econometric model was to provide a baseline probability to predict which parcels were most likely to subdivide; thus, the econometric model itself provides no explanation of how a given policy affects likelihood of subdivision, although it does indicate the correlation between the policy and the outcome. In our setting, which areas are protected, marked for redevelopment, or marked for development may be endogenous to the land owner decision to subdivide. In the case of these variables especially, our results should not be interpreted as causal predictors. Likewise, we use data only from 2005 2009 to predict changes to 2030. If major changes in the land market take place

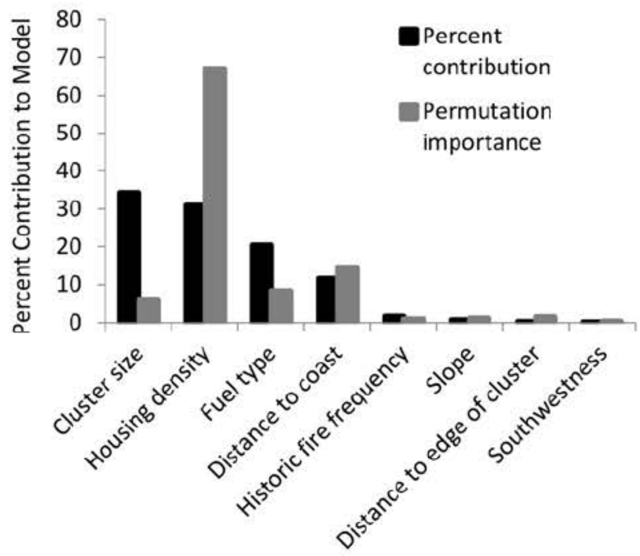

Figure 3. The importance of explanatory variables averaged across five cross validated replications in the MaxEnt fire risk model. Percent contribution is determined as a function of the information gain from each environmental variable throughout the MaxEnt model iterations. Permutation importance reflects the drop in model accuracy that results from random permutations of each environmental variable, normalized to percentages.
doi:10.1371/journal.pone.0071708.g003

over this time horizon our model will not be able to take this into account.

Although some differences in predicted fire risk among the three scenarios likely stemmed from location of new structures relative to variables such as distance to coast, fuel type, or slope, the most important variables in the fire risk model were housing density and cluster size, with most structure loss historically occurring in areas with low housing density and in small, isolated housing clusters. Thus, leapfrog development was generally the riskiest scenario and infill the least risky. The most surprising result was the variation in predicted risk for the expansion scenario over time and at different thresholds. While leapfrog and infill showed similar trajectories across thresholds, expansion went from being the highest risk scenario at the low threshold to being the lowest risk scenario at the highest threshold. Because the threshold is merely a way to group structures into a binary classification, this means that, while the average risk calculated across all homes shows expansion to rank in the middle of infill and leapfrog throughout the simulation (Figure 5), the other two scenarios have a relatively larger proportion of homes that are modeled to be at a very high risk (i.e., 0.25 or 0.5), particularly by the end of the simulations. Because the total number of structures with a risk greater than 0.25 or 0.5 is relatively low in all scenarios, this difference in distribution of homes at the highest risk is not reflected in the mean. Another reason for the shift in rank of expansion over time is that, as more development occupied the landscape, there were fewer parcels remaining to accomplish infill or leapfrog type growth in the other scenarios. Thus, by the end of the simulations in year 2030, the majority of growth in all scenarios was expansion, and there was some convergence between scenarios. Finally, the change in risk of expansion growth over time may reflect that, despite the relatively low importance of distance to edge of cluster as an explanatory variable, expansion growth is characterized as having an initially fragmented landscape pattern that eventually merges into large patches with low edge.

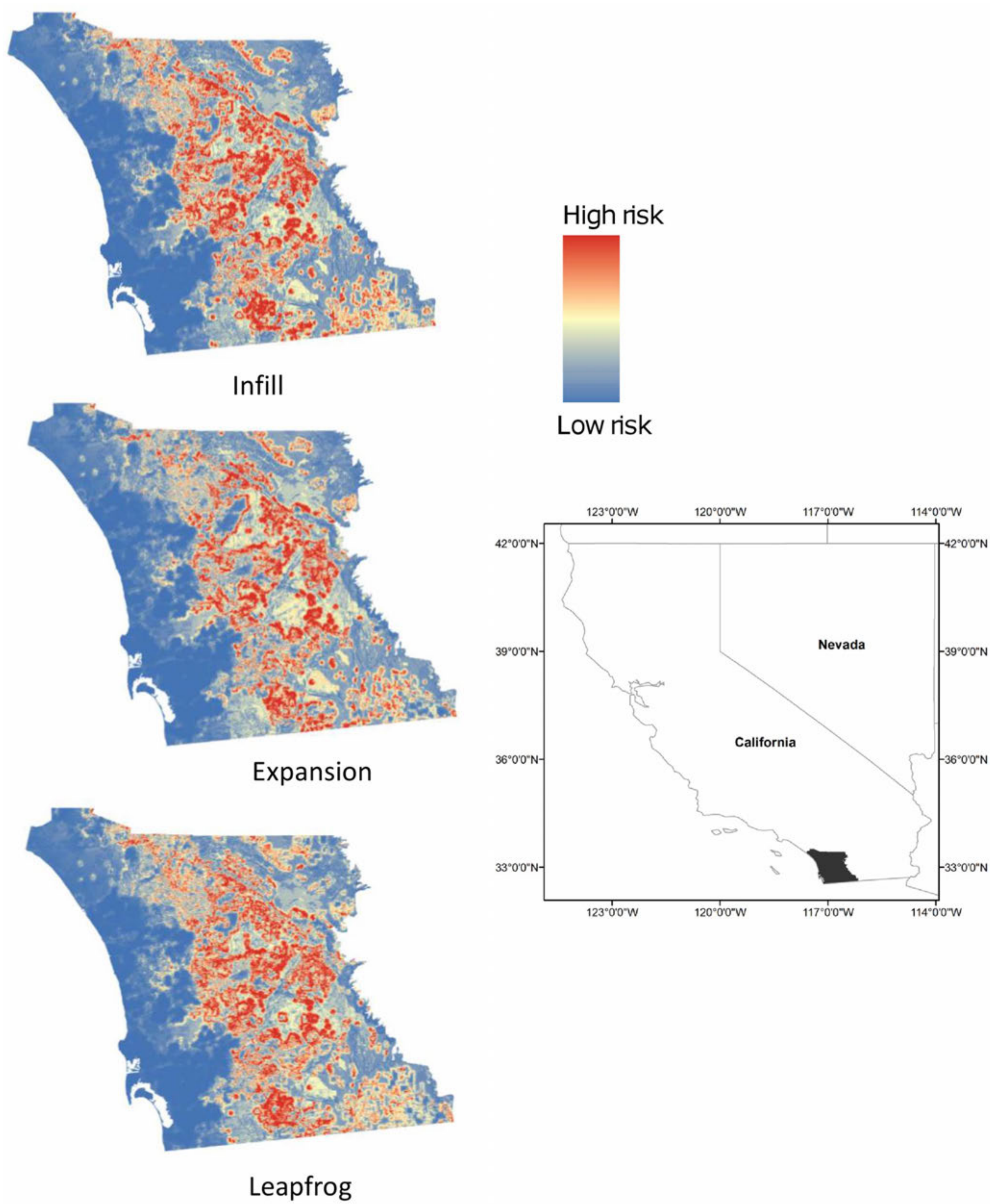

Figure 4. Maps of the study area showing projected wildfire risk at year 2030 for simulations of residential development under policies emphasizing infill, expansion, or leapfrog growth.
doi:10.1371/journal.pone.0071708.g004

Although leapfrog development clearly ranked highest in terms of fire risk, the interpretation of which planning policy is best may depend on fire management objectives and resources, as well as other considerations such as biodiversity or ecological impacts.

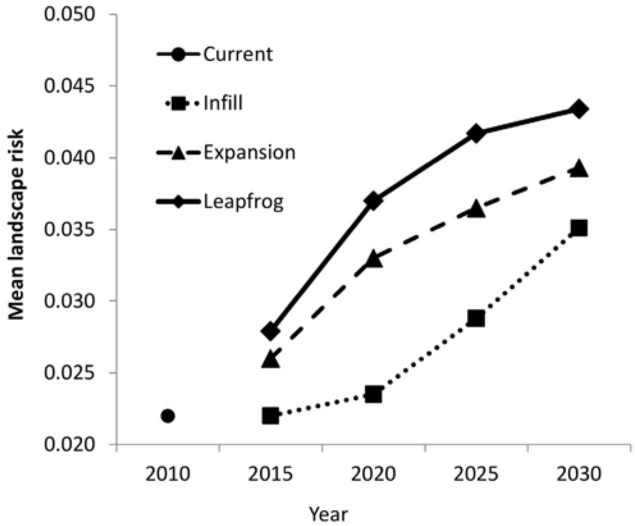

Figure 5. Projected landscape fire risk, reflecting the proba bility of burning in a wildfire averaged across all residential structures on the current landscape and in three development scenarios of infill, expansion, and leapfrog for year 2030.
doi:10.1371/journal.pone.0071708.g005

The spatial pattern of development affects multiple ecological functions and services [55], with potentially varying conservation implications; both leapfrog and expansion development consumed more land than infill, which would likely lead to more ecological degradation [56]; nevertheless, higher density clustered develop ment may be dominated by more invasive species [57]. Trade offs between fire protection and conservation are common, but techniques are available for identifying mutually beneficial solutions [58].

Different perceptions of the fire risk results could also potentially translate into different planning priorities for management. For example, if the priority is to plan for the lowest overall risk to structures, then the mean landscape risk clearly delineates the rankings of options, with infill being the winner. However, if the objective is to reduce the number of structures at the highest risk threshold, i.e., > 0.5, then expansion is the best option, at least by 2030. An important consideration for fire management is the total area that needs to be protected, as well as the length of wildland urban interface [8,13]. Therefore, despite the lower number of structures at the highest risk thresholds, expansion creates more edge than infill and may translate into greater challenges for firefighter protection.

Although we did not create separate scenarios for high or low growth, the results at different time steps can be substituted to envision the potential outcome of developing more or fewer houses. In the short term, the total fire risk is projected to increase proportionately as more land is developed. However, given the inverse relationship between housing density and fire risk, it is possible that this trend could reverse if housing growth eventually resulted in expansive high density development.

Land use planning is one of a range of options available for reducing fire risk, and the best outcome will likely be achieved through a combination of strategies that include homeowner actions, improvements in fire safe building codes, and advanced fire suppression tactics. Although we isolated the effect of land use planning policy in the three development scenarios, the fire risk model nevertheless showed that the pattern and location of structures in this study area were the most important out of a suite of factors influencing structure loss. We used a correlative approach that did not incorporate mechanisms or feedbacks, but our models clearly illustrated differences in the cumulative effects of individual planning decisions. The relationship between spatial pattern of development and fire risk is likely related to the intermixing of development and wildland vegetation [29,59]; thus, these results likely apply to a wide range of fire prone ecosystems with large proportions of human caused ignitions. Nevertheless, because fire risk is highly variable over space and time, and due to a range of human and biophysical variables [60], we recommend planners develop their own models for the best understanding of where the most fire prone areas are in their region [19].

With projections of substantial global change in climate and human development, we recommend that land use planning should be considered as an important component to fire risk management, potentially to become as successful as the prevention of building on flood plains [61]. History has shown us that preventing fires is impossible in areas where large wildfires are a natural ecological process [4,9]. As Roger Kennedy put it, "the

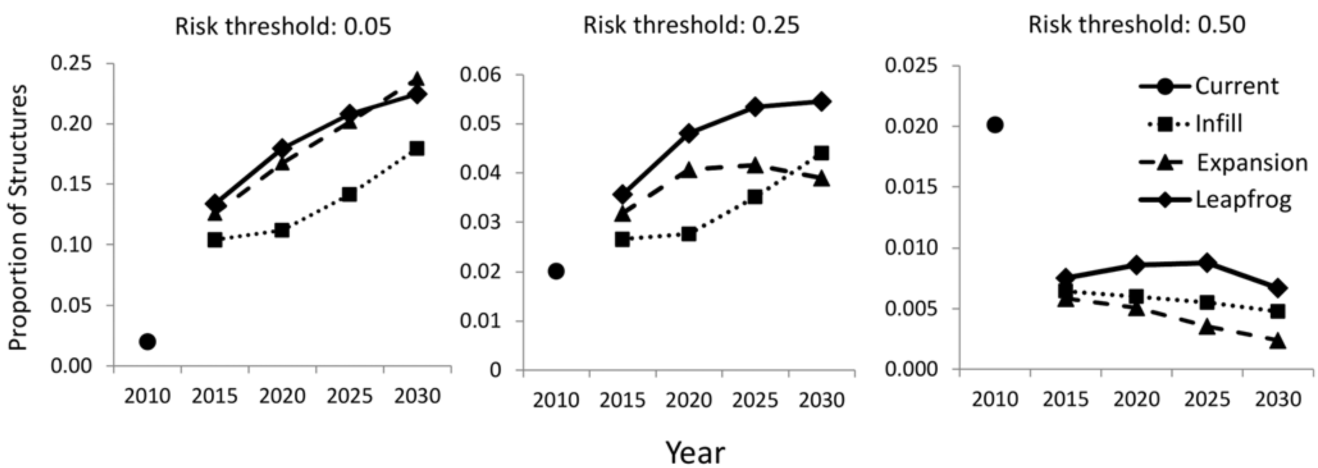

Figure 6. Proportion of residential structures that are located in areas of high fire risk defined using thresholds from the fire risk model of 0.05, 0.25, and 0.5 for current structures and for structures simulated under infill, expansion, and leapfrog growth policies.
doi:10.1371/journal.pone.0071708.g006

problem isn't fires; the problem is people in the wrong places [62]."

Supporting Information

Table S1 Definitions and summary statistics for variables used in the probit model.
(DOCX)

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Author Contributions

Conceived and designed the experiments: ADS JEK ABM VB. Performed the experiments: ADS ABM VB. Analyzed the data: ADS ABM VB. Wrote the paper: ADS JEK ABM VB.

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Exhibit F

fire

MDPI

Article

Factors Associated with Structure Loss in the 2013–2018 California Wildfires

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Abstract: Tens of thousands of structures and hundreds of human lives have been lost in recent fire events throughout California. Given the potential for these types of wildfires to continue, the need to understand why and how structures are being destroyed has taken on a new level of urgency. We compiled and analyzed an extensive dataset of building inspectors' reports documenting homeowner mitigation practices for more than 40,000 wildfire-exposed structures from 2013–2018. Comparing homes that survived fires to homes that were destroyed, we investigated the role of defensible space distance, defensive actions, and building structural characteristics, statewide and parsed into three broad regions. Overall, structural characteristics explained more of a difference between survived and destroyed structures than defensible space distance. The most consistently important structural characteristics—having enclosed eaves, vent screens, and multi-pane windows—were those that potentially prevented wind-born ember penetration into structures, although multi-pane windows are also known to protect against radiant heat. In the North-Interior part of the state, active firefighting was the most important reason for structure survival. Overall, the deviance explained for any given variable was relatively low, suggesting that other factors need to be accounted for to understand the full spectrum of structure loss contributors. Furthermore, while destroyed homes were preferentially included in the study, many "fire-safe" structures, having > 30 m defensible space or fire-resistant building materials, were destroyed. Thus, while mitigation may play an important role in structure survival, additional strategies should be considered to reduce future structure loss.

Keywords: defensible space; building construction; homeowner mitigation; firefighting; defensive actions; fire safety

1. Introduction

California has long been recognized for its fire-prone ecosystems and fire-related losses to human lives and property [1]. In the last several years, however, this recognition has turned into bewilderment and terror as tens of thousands of structures and hundreds of human lives have been lost in fire events throughout the state [2]. Deadly and destructive wildfires have been occurring in other regions across the globe as well, such as Portugal [3], Australia [4], and Southern Europe [5]. The increased frequency and magnitude of these fire events have contributed to the recent claim that we are entering a "new normal" phase of wildfires [6]. Most of these catastrophic fires are started by humans, so as populations steadily increase and people are pushed farther into hazardous wildlands, the problem could get even worse. Thus, the need to understand why and how structures are being destroyed during wildfires has taken on a new level of urgency.

Fully understanding why recent California wildfires were so destructive will likely require many years of research focusing on a range of factors at different scales, from fire behavior and climatology to fire management and land development. Answering questions pertaining to fire behavior will require different data and methodological approaches, compared to answering the questions related to why homes were destroyed, although the actual outcome will be a combination of the two.

In California, there has been a long-standing interest in understanding how local and regional responses are needed to reduce damage from wildfires [7,8]. In terms of understanding why homes are destroyed, there is an emerging literature that includes studies focused on local, property-level factors as well as studies on landscape-scale factors such as vegetation management and fuel characteristics, fire suppression, topography, and housing development patterns (e.g., [9,10]). These studies have significantly advanced our understanding of home safety, but the majority have been conducted through computer simulations and laboratory experiments, and thus, there remains a need for pre- and post-fire empirical data to document and validate what happens under actual wildfire conditions [11]. Recent fire events have generated more data on structure losses, and the number of empirical studies is increasing, particularly relative to understanding spatial patterns of structure loss at a landscape scale [12–15].

In terms of defensible space, the state of California requires fire-exposed homeowners to create a minimum of 30 m (100 ft) of defensible space around structures, and some localities are beginning to require at least 60 m (200 ft) in certain circumstances (e.g., [16]). Of the few studies that have empirically tested the relative benefits of defensible space, the authors demonstrated that up to 30 m (100 ft) of vegetation reduction around a structure can significantly increase the chance of structure survival (e.g., [17–20]). However, in these case studies, the most effective distance of defensible space was much less than regulations require (e.g., [19,21,22]), and other factors, such as housing density, landscape position, proximity of vegetation to the house, irrigation and water bodies, and building construction materials, were equally or more important [20,23,24].

Regarding fire safety in building construction materials, there have been many detailed studies conducted via carefully designed laboratory experiments [25–27]; and recent building codes in California have been designed to reflect these studies. Despite the solid laboratory evidence, few empirical studies have documented building characteristics associated with structure loss in real wildfire situations. In one study, Syphard et al. [23] found several significant relationships among building construction materials and structure loss in San Diego County, CA, USA, with window framing material and number of windowpanes being more protective than roofing or exterior siding material, and year of construction also being a significant proxy for building characteristics. The sample size in this study was somewhat limited, however, and other factors like structure density and vegetation characteristics were found to be equally or more important, depending on the location of the structure.

In addition to knowing whether certain mitigation actions can be statistically significantly associated with structure destruction, it is important to understand how often these homeowner 'best practices' actually translate into structure survival. Statistical significance is not a safety guarantee and does not necessarily translate into probability. While it is important for homeowners to have the best protection available, it is also important for them to understand the extent to which these actions tend to result in a positive outcome. Without large datasets of actual structure losses, it has until now been impossible to know the frequency at which best practices translate into structure survival, and whether those results are generalizable across different landscapes.

As of now, most guidance on homeowner 'best practices' is derived from limited empirical studies and assumptions based on fire behavior, and thus, the relative efficacy of these practices remains largely theoretical. Empirical studies on the effects of local homeowner mitigation practices, including defensible space or building materials, have been mostly in the form of case studies for a selection of wildfires on specific landscapes (e.g., [19,23,28,29]). Although these studies provide insights, we need a broader understanding across multiple fire events, and thus we need a database that captures characteristics of structures exposed to many fires across a variety of ecosystems.

The California Department of Forestry and Fire Protection (Cal Fire) began a statewide building inspection program in the late 1980s that has been continually upgraded and improved over time, and recent large catastrophic wildfires have added enormously to the amount of data available. The Cal Fire Damage INSpection Program (DINS) was founded with the goal to collect data on damaged, destroyed, and unburned structures during and immediately after fire events to assist in the recovery process, to validate defensible space regulations, and to provide local governments and scientists information for analyzing why some structures burned and why some survived [30]. For all fire events in the state that involve the damage or destruction of buildings worth $10,000 or more, a team of trained inspectors visit during and immediately after the wildfire to collect, for all structures exposed to the fire, a range of information including the extent of damage, defensible space before the fire, building characteristics, and other items.

Through a public records request, we acquired DINS data for more than 40,000 structures that survived, were damaged, or were destroyed across all California wildfires from 2013–2018, making this potentially the largest combined dataset of its sort. Our objective was to summarize these data statewide and across three broad California regions (San Francisco Bay Area, Northern Interior forests and foothills, and Southern California) to a develop a more generalized understanding of local-scale factors characterizing and differentiating destroyed or majorly damaged structures ("destroyed") from those that survived or only had minor damage ("survived") during wildfires. Although other studies have shown landscape-scale and other spatial factors such as topography, fuels, and housing arrangement to significantly affect structure loss probability, we focused here exclusively on the homeowner mitigation practices quantified by the building inspectors to answer:

1. How important was the extent of defensible space in distinguishing destroyed and survived structures?
2. What structural characteristics of homes were associated with increased susceptibility to destruction?
3. Did these patterns vary by region?

2. Materials and Methods

2.1. Data and Summary Statistics

The Cal Fire DINS data were collected for all wildfires, of any size, that resulted in structure damage or destruction. Once building inspection teams arrived at a fire, they recorded information on every exposed structure, including damaged, destroyed, and unburned homes, valued at a minimum of $10,000 or greater than 120 square feet (11 square meters), which is the size at which a permit is required for building. The inspection process occurred by dividing active wildfires into geographical zones as the fire was burning, then a designated number of two-person teams of trained inspectors were assigned to the zone and went to the field to record data. Data were collected for surviving structures in addition to damaged and destroyed structures, and the level of structural damage was recorded in different percentage classes.

Given that most recent structure losses in California have occurred in three distinct regions of the state [2], with most losses occurring within single fire events, we divided the dataset into three regions to compare potential regional differences. Thus, we assigned each county with structure loss to either the "Bay Area", which included counties surrounding the San Francisco Bay; the "North-Interior", which included primarily the northern Sierra Nevada but also other northern coastal and interior counties; and "Southern CA", including coastal counties south of San Luis Obispo County (Table 1).

Building inspectors grouped the structures into classes of damage corresponding to unburned; minor (cosmetic or nonstructural damage); moderate (partial to complete failure of structural building elements); and destroyed. The vast majority of structures were in either the minor or destroyed classes (94% in the Bay Area, 99% in the North-Interior, and 95% in Southern CA), so we lumped unburned with minor and called them "survived," and lumped moderate with destroyed and called those "destroyed."

The types of data collected included features of the property and vegetation, and inspectors also started to use pre-fire ancillary data, such as assessors' parcel information, to add details for badly damaged or destroyed structures. Most data fields were categorical to ensure consistency in recording, and the teams used phone applications and GPS data to enter information in the field. For this study, we summarized data for most categories in the inspection report, including distance of defensible space, roof type, exterior siding, eaves, windowpanes, vent screens, and deck or porch material.

The distance of defensible space around structures was recorded as one of several ordinal categories, including 0; 0–9 m (0–30 ft); 9–18 m (30–60 ft); 9–30 m (30–100 ft); 18–30 m (60–100 ft); and >30 m (100 ft). We therefore labeled defensible space into four classes in which 5 m (15 ft) were added to the lowest number of each class and used as the label. We merged the class 9–30 m (30–100 ft) with the 18–30 m (60–100 ft) class. Therefore, 0 or 0–9 m were labeled as "5 m", 9–18 m was labeled "14 m," 9–30 m or 18–30 m were labeled "22 m," and >30 m was labeled "35 m." We also used these numeric values to calculate average defensible space distances.

In the 2018 fires (including the Camp Fire and Woolsey Fire in the North-Interior and Southern CA regions, respectively), some new variables were added, including defensive action taken and home age. For defensive action, the inspectors recorded whether it was firefighters, civilians, or both who protected the structures during the wildfires, or, they recorded when the information was unknown. For all years, roof type was most frequently recorded as either "combustible" or "resistant" in the Bay Area, but it was broken into different material classes in the other two regions, so for each region we analyzed data according to the most commonly used classification for that variable. Vent screens were also characterized differently for different fires in which the "screened" class was broken into "fine" or "mesh > 1/8" in some cases, and "unscreened" was referred to as "no" or "none" in some cases. We lumped these together into "screened" and "unscreened".

Building data were collected for different occupancy types (e.g., single- and multi-family residences, outbuildings, commercial buildings, and barns), so we conducted an initial sensitivity analysis using the full dataset comparing rankings of proportions using all structures versus single-family residential structures only, and we found similar rankings for most variables. The variables in which the ranking between single-family residential and other buildings was different were those which would likely characterize non-residential structures (e.g., buildings having no windowpanes, vents, or eaves). Therefore, to preserve the integrity of these classes and for a more robust dataset we used all structures for our analyses in the different regions.

For all variables, there were a substantial number of blank fields where no data were recorded, so there are unequal numbers of data points in all data categories (Table S1). Therefore, we summarized and analyzed all data fields based only on the data that were available for those fields. For comparison purposes we calculated two types of proportions for different perspectives. First, we determined the proportion of the category in each burn class (i.e., for both survived and destroyed structures, what proportion belonged to each category of the variable); and second, we determined the proportion of burn class within each category (i.e., for each category in the variable, what proportion survived or were destroyed) (Figures S1–S8).

2.2. Analysis

To assess the relative importance of each variable, we developed simple generalized linear regression models (GLMs) [31] using defensible space or building characteristics as single predictor variables and survived versus destroyed structures as the bivariate dependent variable. For each model, we used a logit link and specified a binomial response, then calculated and compared the deviance explained (D^2), which is analogous to R-squared in linear regression for each variable. For the statewide analyses of defensive action and structure age, we used the combined data for the North-Interior and Southern CA regions only. We did not model roof type statewide (i.e., only ran models for individual regions) because the classification system varied from region to region. For these regions, we used data from whichever classification was most common in each region (roof type 1 for North-Interior and Southern CA and roof type 2 for the Bay Area, Table 1). Given the large amount of missing data in the different explanatory variables, we did not perform multiple regression, as our objective was to create a relative importance ranking of the variables using only the data available.

Table 1. Number of destroyed and survived structures from 2013–2018 by county and region in California. Dash marks indicate no structure outcomes recorded. The bold totals report the sums of destroyed and survived structures for each region.

Region	County	Number Destroyed	Number Survived
Bay Area	Contra Costa	1	–
	Lake	2588	89
	Mendocino	566	32
	Monterey	88	4
	Napa	1123	587
	Santa Clara	29	700
	Santa Cruz	6	19
	Solano	11	56
	Sonoma	6764	470
	Yolo	24	88
	Total	**11,200**	**2045**
North-Interior	Amador	1	
	Butte	19,061	740
	Calaveras	936	31
	Fresno	10	2
	Humboldt	5	–
	Inyo	2	–
	Lassen	4	1
	Madera	16	4
	Mariposa	142	20
	Mono	58	6
	Nevada	63	4
	Shasta	1889	260
	Siskiyou	339	18
	Tehama	26	4
	Trinity	142	7
	Tuolumne	1	–
	Yuba	274	8
	Total	**22,969**	**1105**
Southern	Kern	398	21
	Kings	1	–
	Los Angeles	1667	339
	Orange	38	43
	Riverside	53	10
	San Diego	246	67
	San Luis Obispo	81	7
	Santa Barbara	110	42
	Ventura	1075	200
	Total	**3669**	**729**

Because defensible space distance classes can be hypothetically considered as progressively protective against harm (i.e., that more defensible space is more protective), we used a calculation common in medical research, the relative risk [32], to compare adjacent pairs of shorter and longer distance classes of defensible space in addition to comparing the protective effect of the shortest versus longest distance classes (0–30 ft vs. >100 ft). Relative risk is a ratio between proportions of classes having a good outcome (here, structure survived wildfire) versus proportions of classes having a bad outcome (here, structure was destroyed) and indicates whether there is either no relationship (a value of 1) or if the exposed group (structures with shorter distances of defensible space) has either a significantly higher (values >1) or significantly lower (with values <1) risk of surviving the fire given the data available.

We also calculated the relative risk for most of the building inspection variables. For those with more than one independent category, we calculated the relative risk based on the proportion of survived structures in each category relative to the combined proportion of survived structures in all other categories. For variables with binary classes of "combustible" or "resistant", (Table 1), we calculated the relative risk using the combustible class as the exposure group.

3. Results

From 2013 to 2018, building inspectors examined 41,717 structures, with 37,838 (~90%) damaged or destroyed by fires in 36 California counties, with the largest number destroyed in Butte County in the North-Interior Region, followed by the Bay Area, then Southern California (Table 1). Of the total number of structures inspected, 18% (n = 2045) in the Bay Area, 5% (n = 1105) in the North-Interior, and 20% (n = 729) in Southern CA survived the fires.

3.1. Defensible Space and Defensive Actions

The relative importance of defensible space, as quantified by deviance explained in the regression models, was virtually nil statewide, and the only region in which defensible space had a deviance explained of at least 1% was the Bay Area (Figure 1). Statewide, home survival was associated with slightly longer average distances of defensible space, and this distinction was more pronounced for the Bay Area (Figure 2). On the other hand, when averaging mean values of defensible space classes across survived and destroyed homes, there was a slightly higher mean defensible space distance for destroyed structures in the North-Interior, and virtually no difference in Southern CA (Figure 2).

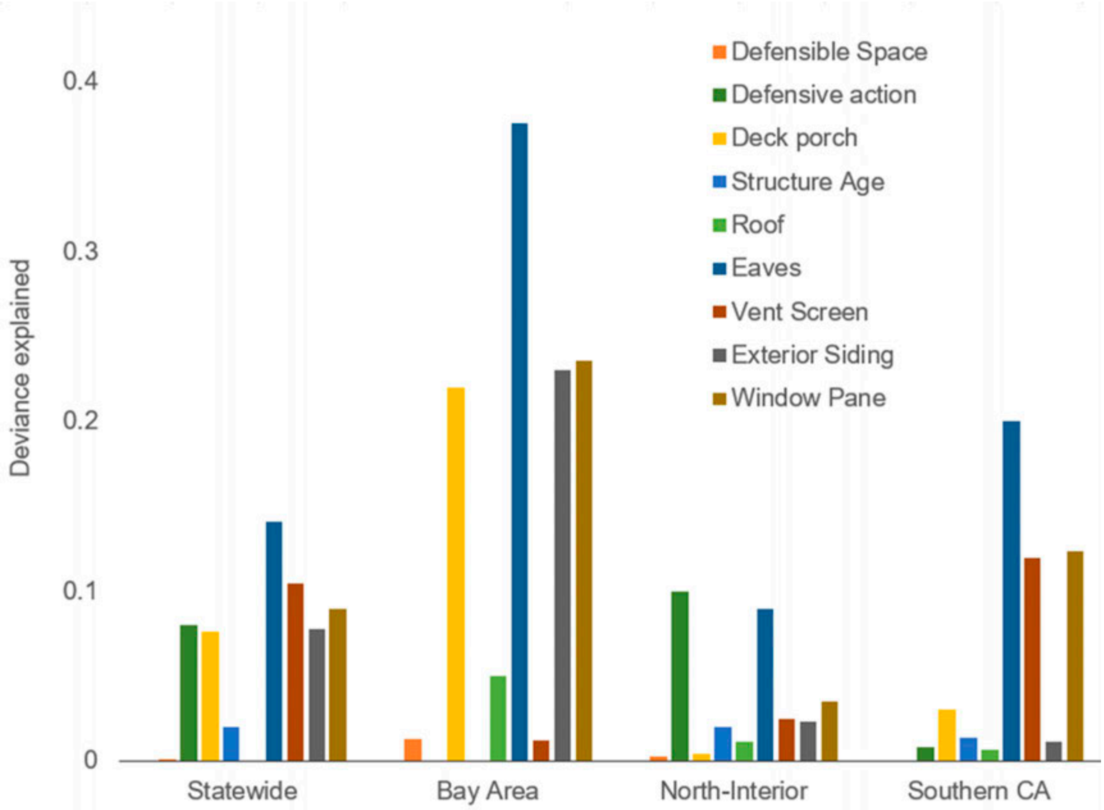

Figure 1. Deviance explained for building inspection variables statewide in three California regions. Defensive action and structure age were only available for North-Interior and Southern CA.

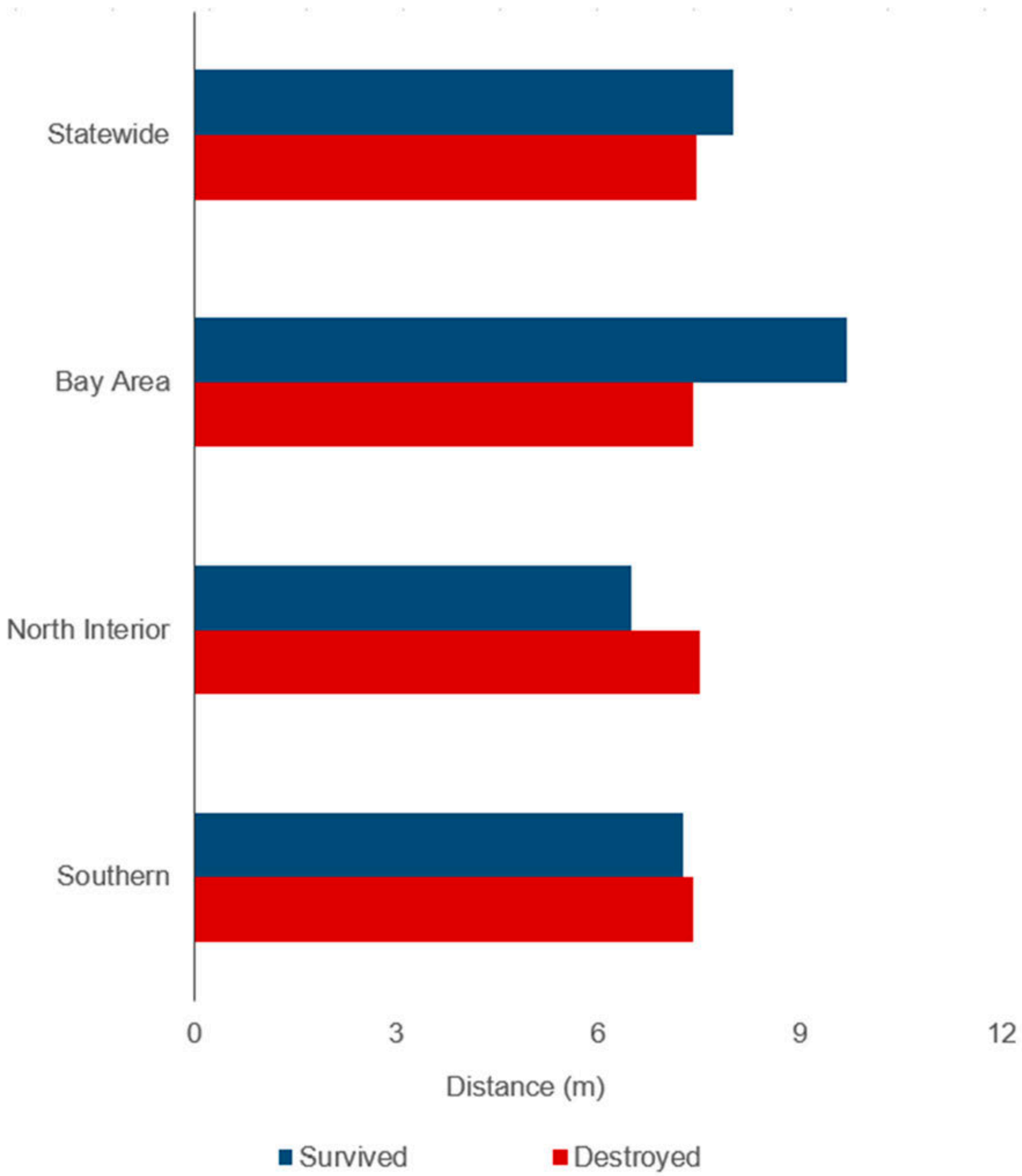

Figure 2. Average distance of defensible space for survived and destroyed structures statewide and in three California regions.

Except for the comparison between 22 m (75 f) vs. 14 m (45 ft) of defensible space statewide, the relative risk ratios for the statewide and Bay Area data showed consistently lower relative risk when comparing classes of longer distance intervals with shorter distance intervals (Table 2). In the North-Interior, there was a higher relative risk of destruction with more defensible space when comparing 22 m (75 f) vs. 14 m (45 ft), but there was a significantly lower relative risk when comparing 35 m (115 ft) vs. 22 m (75 ft) (Table 2). There were no significant differences in relative risk among any defensible space distance classes in Southern California (Table 2).

Although defensive action was only recorded in the 2018 fires in the North-Interior and Southern CA regions, it was more important than any other variable for North-Interior, and it was less important in the Southern California data (Figure 1). Statewide (using these two regions and comparing the importance to other variables), it had a medium-high relative importance (Figure 1). The relative risk ratios for both regions showed that civilian, fire department, and both types of defensive actions were significantly more protective than unknown action (Table 2). In the North-Interior, the fire department providing defensive action provided better protection than civilian actions, but either both or civilian defensive actions provided a slightly better relative risk ratio for Southern CA.

Table 2. Relative risk (RR) among building inspection variables statewide and for three California regions. A relative risk of 1 indicates no difference between classes; >1 means the relative risk of destruction is higher in the first category listed; <1 means the relative risk of destruction is lower than in the other classes. Dashes indicate where no data were available for certain categories.

Variable	Statewide		Bay Area		North-Interior		Southern	
Defensible Space	**RR**	***p*-Value**	**RR**	***p*-Value**	**RR**	***p*-Value**	**RR**	***p*-Value**
14 m (45 ft) vs. 5 m (15 ft)	0.95	0.0001	0.98	0.06	0.97	0.09	0.97	0.24
22 m (75 ft) vs. 14 m (45 ft)	1.08	0.0001	0.98	0.19	1.07	0.003	1.07	0.06
35 m (15 ft) vs. 22 m (75 ft)	0.88	0.0001	0.79	0.0001	0.95	0.0001	0.98	0.61
35 m (15 ft) vs. 5 m (15 ft)	0.91	0.0001	0.76	0.0001	0.98	0.09	1	0.89
Defensive Action								
Both vs. others	0.95	0.0001	–	–	0.68	0.004	0.69	0.04
Civilian vs. others	1.08	0.0001	–	–	0.81	0.0001	0.68	0.04
Fire Department vs. others	0.88	0.0001	–	–	0.44	0.0001	0.81	0.03
Unknown vs. defensive action	0.91	0.0001	–	–	1.02	0.0001	1.01	0.39
Deck, Porch Material								
Composite vs. others	0.85	0.0001	0.93	0.007	0.92	0.03	0.78	0.04
Masonry vs. others	1.002	0.48	1.17	0.0001	0.99	0.03	1	0.78
Wood vs. others	0.98	0.01	1	0.6	1.01	0.002	0.97	0.27
None	1.01	0.10	0.35	0.0001	1	0.24	1.02	0.25
Roof Type								
Asphalt vs. others	1.05	0.0001	–	–	1.03	0.0001	1.02	0.4
Concrete vs. others	0.89	0.0007	–	–	0.94	0.05	0.82	0.04
Metal vs. others	0.97	0.0001	–	–	0.98	0.001	1.04	0.14
Tile vs. others	0.88	0.0001	–	–	0.89	0.0001	0.97	0.25
Wood vs. others	1	0.84			0.99	0.96	1.06	0.38
Combustible vs. resistant	–	–	1	0.75	–	–	–	–
Eaves								
Enclosed vs. others	0.79	0.0001	0.88	0.0001	0.95	0.0001	0.83	0.0001
None vs. others	1.06	0.0001	0.49	0.0001	1.02	0.004	1.35	0.0001
Unenclosed vs. others	1.04	0.0001	1.15	0.0001	1.5	0.0001	0.99	0.86
Vent Screen								
Screened vs. unscreened	0.94	0.0001	0.76	0.0001	0.97	0.0001	0.95	0.23
Exterior Siding								
Combustible vs. resistant	1.05	0.0001	1.03	0.0002	1.04	0.0001	1.07	0.0001
Window Panes								
Multi vs. others	0.94	0.0001	0.94	0.0001	0.97	0.0001	0.74	0.0001
None vs. others	1.01	0.12	0.25	0.0001	0.98	0.04	1.14	0.01
Unenclosed vs. others	1.06	0.0001	1.05	0.0001	1.02	0.0001	1.12	0.0001

3.2. Building Inspection Characteristics

Home construction materials explained a substantial amount of variation in housing losses statewide and across regions (Figure 1). Overall, eaves consistently explained more than any other structural parameters, and having enclosed eaves versus no eaves or unenclosed eaves had a highly significant protective effect as seen in the relative risk ratios (Table 2). The structural variable with the second highest deviance explained across all regions was windowpanes (Figure 1), although statewide this variable was ranked slightly lower than vent screens, and vent screens were also nearly as important as windowpanes in Southern California (Figure 1). The relative risk of having single pane windows was consistently and significantly higher than having multiple pane windows statewide and across all areas (Table 2). Structures that had no windows were not significantly different in relative risk compared to structures with windows statewide, but they had a lower relative risk than structures with windowpanes in the Bay Area and North-Interior, and this was reversed in Southern CA (Table 2). There was a consistent and significantly lower relative risk for structures with screened versus unscreened vents across the state and regions (Table 2).

Aside from eaves, windowpanes, and vent screens, the importance and relative risk of structural parameters associated with structure survival varied across the state and regions. Statewide and in the Bay Area, fire-resistant exterior siding material and deck or porch material were nearly as important as windowpanes (Figure 1), with consistently lower relative risk ratios for fire-resistant siding material (Table 2). In terms of deck or porch material, the most consistently significant effect was the significantly lower relative risk of having composite decking material versus other materials (Table 2). Although roofing material did not explain substantial variation in any of the regions (Figure 1), for the North-Interior and Southern CA regions, where the material types were broken out, concrete and tile both had lower relative risk ratios, although tile was not significant for Southern CA (Table 2). In the North-Interior, metal roofs also had slightly lower significant relative risk (Table 2).

Although structure age, a proxy for all building construction materials, was only recorded for the North-Interior and Southern CA regions, it did not explain substantial variation in structure survival relative to individual building characteristics (Figure 1). On average, however, older homes were consistently more likely to be destroyed than younger homes (Figure 3).

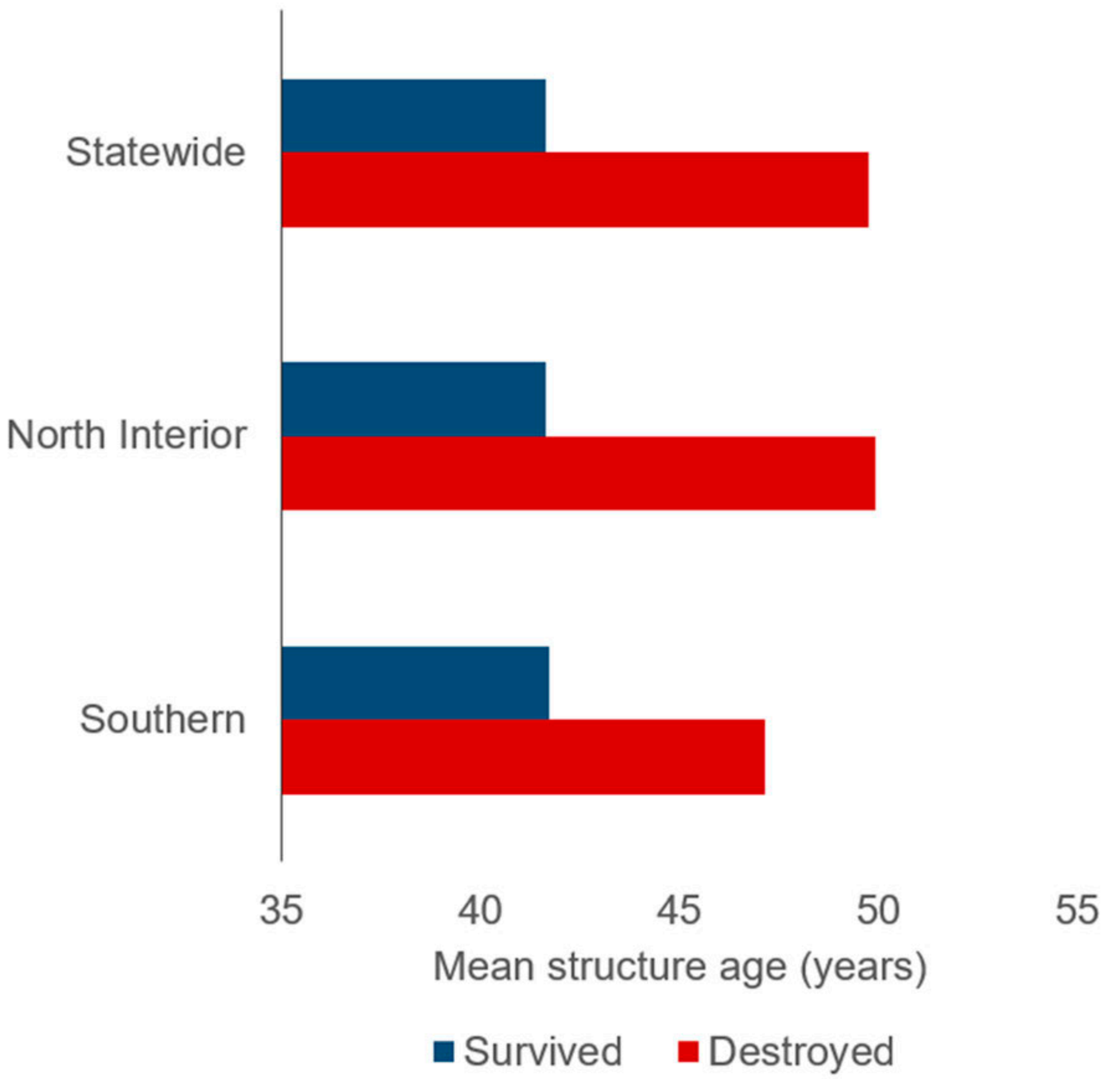

Figure 3. Mean age of structure for survived and destroyed homes in two California regions. The statewide calculations are based on combined totals of both regions (i.e., the Bay Area did not include this variable).

4. Discussion

In terms of mitigation practices for protecting homes against wildfire, perhaps the most widely recognized and regarded action that homeowners can take is to create defensible space around structures [20,33]. In fact, defensible space and "hardening homes" via building construction practices or structure retrofits, collectively referred to as the home ignition zone (HIZ), have often been considered the primary factors that matter in terms of structures surviving wildfire [34,35]. Despite the widespread advocacy of these practices, there has been little empirical study of their effectiveness under actual wildfires, and there is still debate on how much defensible space is critical to home survival despite the regulated distance of 30 m (100 ft).

In this study based on more than 40 k records of structures exposed to wildfires from 2013 to 2018, we found that, overall, defensible space distance explained very little variation in home survival and that structural characteristics were generally more important. Although the relative importance and relative risk ratios of different factors recorded by building inspectors varied slightly from region to region, there were also general similarities, particularly in that structure survival was highest when homes had enclosed or no eaves; multiple-pane windows, and screened vents.

The only region in which defensible space distance explained at least 1% variation in structure survival was the Bay Area, where survived structures had an average of 9.7 m (~32 ft) of defensible space versus 7.4 m (~24 ft) for destroyed structures. Although there were significant differences in relative risk between most pairs of distance classes of defensible space statewide and for the North-Interior, there were some conflicting patterns in the Bay Area and North-Interior, and there was no significant effect of defensible space distance for any comparison in Southern California. The other surprising finding was that, of the structures that did have more than 30 m of defensible space, the vast majority were destroyed in these fires (Figures S1–S8). This of course reflects the large proportion of destroyed structures in the dataset, but it also suggests that structures with greater amounts of defensible space are often still vulnerable.

One potential explanation for the limited importance of defensible space in these data may be that the defensible space distance classes were defined rather broadly, too broad to discern critical details that may have a much bigger impact. Of the few studies quantifying the most effective distance of defensible space for making a significant difference in structure survival probability, Syphard et al. and Miner [19,21] both found the optimum distance to be much shorter than the required 30 m, with the ideal range between 5–22 m. Distances longer than that provided no additional significant protection. Furthermore, these and other studies have shown that more nuanced characteristics of landscaping are most critical for structure protection, including vegetation touching the structure or trees overhanging the roof [36]. The arrangement of vegetation and irrigation are also important factors not accounted for [20]. In fact, despite defensible space traditionally being divided into zones, with the first being from 0–9 m (30 ft) from the structure, newer recommendations are beginning to isolate and focus heavily on the first zone being from 0–1.5 m (5 ft) [37], which may be the most critical zone to account for.

Most structures are lost in wildfires that are burning under severe weather and wind conditions [2], such that burning embers are capable of crossing large, multi-lane freeways and have been reported to blow as far as 1–2 km ahead of a fire front [2,25]. Therefore, one of the primary reasons for the importance of vegetation modification directly adjacent to homes as opposed to longer distances, is that homes are generally not ignited by the fire front but more often by wind-driven embers landing on combustible fuels in or on the house [17,29,38]. Material closest to the house is thus the most likely to cause a proximate spark that can penetrate the structure. To this point, irrigating vegetation and removing dead plant material to reduce ignitability may be as or more important than fuel volume, which is a finding borne out by recent research [24]. While defensible space distances <30 m may be sufficient for increasing structure survival probability, another important reason for requiring 30 m (100 ft) is firefighter safety and providing a zone of protection [39]. Finally, while the inspectors recorded defensible space distances, part of the definition of defensible space in California revolves around the horizontal and vertical spacing of fuels; thus, if these factors matter as much or more than distance, they could not be accounted for here.

The nature of building loss via ember flow factors such as exterior siding or roof material were much less important than exposed eaves, vents, or windows. This again is likely due to the extreme weather condition characteristics of destructive wildfires. That is, the fire-resistance of materials such as roofs or siding, i.e., preventing them from catching fire, was less important than building characteristics that provided gaps in the structure that could allow penetration of wind-borne burning debris. These results suggest that one of the potentially most effective methods of protecting homes from wildfire destruction would be to perform simple building retrofits, such as placing fine mesh screens over vents and coverings other openings in the structures, such as gaps in roofs, and enclosing structure eaves. Specific recommendations for these types of retrofits are easily found online, e.g., [40], and suggest that improving the fire safety of structures does not necessarily require expensive replacement of construction materials but rather careful attention to structure details.

The previous post-fire study of the role of construction materials in structure survival also found that windows, particularly framing material and panes, were more important than roof or siding material, although the methods and overall suite of variables differed in that study [23]. In the case of windows, they can, like other parts of the structure, provide an easy entry point for firebrands [26]. Additionally, however, they are also vulnerable to radiant heat, and multi-pane windows can withstand much higher levels of thermal exposure than single-pane windows [41]. Although not recorded here, the type of glass used in the window is also important for resistance to cracking [26].

Although individual structural characteristics were highly influential in this study, structure age did not explain a lot by itself, which may mean that, at a broad scale, it does not necessarily serve well as a proxy for the building characteristics most likely to protect homes. On the other hand, Syphard et al. [23] found that structure age did correlate with both building characteristics and structure survival, but that study was only conducted in San Diego County, where building codes had already been updated several times in response to wildfires in the regions. Although the state of California has also recently adopted strict building codes for wildfires [42], those codes only apply to new housing, so the effects may not have been seen yet. Further analysis might be warranted to compare structural characteristics and outcomes as a function of date of code enforcement.

Another consideration is that, despite the importance of structure age in the San Diego study, that study also determined that building location and arrangement were more important in predicting structure loss than structure age, building materials, or defensible space. The effect of structure age was primarily important in higher-density neighborhoods where structure loss was overall less likely. Thus, the role of housing arrangement and location, found to be the most important predictors of structure loss in several California studies [13–15] and nationwide [43] should ultimately be factored into discussions of reducing future fire risk; and this looks to be a challenge given trends of rapid ongoing development in the wildland–urban interface [44].

One of the reasons that housing arrangement and location are such strong predictors of structure loss may be structure accessibility by firefighters, who must divide manpower and resources to reach communities located in dispersed or remote locations [45,46]. The role of defensive actions in determining the extent and location of structure survival has been historically difficult to quantify, mostly because data are sparse, but also because defining suppression effectiveness is an inherently difficult task [47]. In the North-Interior region, defensive action explained more than any other factor in structure survival, although it was less important than building characteristics in Southern California. Even given the high importance of defensive action in the North-Interior, the total number of structures with unknown defensive action was substantial, and the proportion of unknown actions was even larger in Southern California. Thus, while these results suggest that defensive actions may be one of the most important and overlooked factors in structure survival, it remains difficult to make definitive conclusions. Given that building inspectors have just started collecting this information, it is important to recognize this is an on-going process of increasing our knowledge base as more data are collected.

5. Dataset and Limitations

Given the enormous number of structures lost in California in recent years, the dataset compiled for this study may represent the largest existing source of information on homeowner mitigation practices associated with structure loss. Other large databases and studies of house loss have been developed in other countries, however, where wildfires result in substantial losses in structures and human life; much of this work has been conducted in Australia, a country with a long history of destructive wildfires with substantial structure losses [48], and human fatalities [49]. This ongoing data collection process, especially if more exposed but unburned homes are included, will be important for continued understanding of structure loss and identifying the most effective strategies for prevention.

Despite the unprecedented opportunity the DINS data have provided for this broad-scale analysis of structure loss, there are nevertheless uncertainties and limitations within the data, and Cal Fire is working to improve the collection process on an ongoing basis [30].

The primary limitation is, as we discussed previously, that defensible space was presented uni-dimensionally as a function of distance categories and thus excluded other relevant factors such as vegetation spacing, height, type, age, moisture content, or composition. Nevertheless, given the broad scale of the data and similar conclusions for all study areas, these additional vegetation characteristics do not appear to be biased in one direction or the other; thus, our conclusions about distance classes are likely robust.

Another limitation of the dataset is the potential uncertainty inherent in recording building characteristics after a wildfire for homes that have been badly burned with materials largely consumed in the fire. This likely explains the missing data seen throughout the records. Cal Fire is aware of this and is beginning to combine their reports with pre-fire information from county assessors' offices [30]; however, the extent to which pre-fire data may have been incorporated in the reports used for this study is unclear.

Finally, as mentioned previously, this study only focused on the relative importance of the local-scale factors reported by the building inspectors, and full understanding of structure loss will need to include additional factors. Ongoing research will account for a fuller range of landscape-scale factors as well as information on fire behavior and spatial patterns.

6. Conclusions

We have explored the factors correlated with structure loss and survival during a recent five-year period in California. In most regions home structural characteristics are far more important in determining home survival than defensible space. Statewide, the most critical factor was eave construction. Windowpanes were also widely important in the state. Exterior siding was an important structural characteristic in the Bay Area, but vent screens were much more important in southern California. The likely explanation for why structure characteristics play a greater role than defensible space is that most homes burn by embers, which often come from long distances; and the impact of the ember cast is not likely affected by distance of defensible space. Whether or not the embers ignite is largely a function of structure.

Given that the primary role of building inspectors is to assess building damage, most structures in the data were destroyed. As such, one of the striking outcomes of this study is the finding that many of these destroyed structures could be characterized as "fire-safe," such as having >30 m defensible space or fire-resistant building materials. While the number of structures lost in these fire events was unprecedented in California history, structure loss during severe fire-weather and wind conditions similar to some of the fires represented here has occurred for decades in the state [2]. Therefore, it may be safe to assume that these data are broadly representative.

Supplementary Materials: The following are available online at http://www.mdpi.com/2571-6255/2/3/49/s1, Figure S1: Proportion of defensible space distance classes for survived and destroyed structures (a) and proportion of survived and destroyed structures within defensible space distance classes (b) for three California regions, Figure S2: Figure S2: Proportion of defensible action type for survived and destroyed structures (a) and proportion of survived and destroyed structures within defensive action types (b) for two California regions, Figure S3: Proportion of deck material type for survived and destroyed structures (a) and proportion of survived and destroyed structures within deck material type classes (b) for three California regions, Figure S4: Proportion of roof material type for survived and destroyed structures (a) and proportion of survived and destroyed structures within roof material type classes (b) for two California regions, Figure S5: Proportion of eave type for survived and destroyed structures (a) and proportion of survived and destroyed structures within eave type classes (b) for three California regions, Figure S6: Proportion of Exterior siding classes for survived and destroyed structures (a) and proportion of survived and destroyed structures within exterior siding classes (b) for three California regions, Figure S7: Proportion of vent screen classes for survived and destroyed structures (a) and proportion of survived and destroyed structures within vent screen classes (b) for three California regions, Figure S8: Proportion of windowpane type for survived and destroyed structures (a) and proportion of survived and destroyed structures within windowpane type (b) for three California regions. Table S1: Number or average value of destroyed and survived structures within building inspection classes for three California regions.

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