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Housing arrangement and vegetation factors associated with single-family home survival in the 2018 Camp Fire, California

Eric E. Knapp[1*], Yana S. Valachovic[2], Stephen L. Quarles[3] and Nels G. Johnson[4]

Abstract

Background: The 2018 Camp Fire, which destroyed 18,804 structures in northern California, including most of the town of Paradise, provided an opportunity to investigate housing arrangement and vegetation-related factors associated with home loss and determine whether California's 2008 adoption of exterior building codes for homes located in the wildland-urban-interface (WUI) improved survival. We randomly sampled single-family homes constructed: before 1997, 1997 to 2007, and 2008 to 2018, the latter two time periods being before and after changes to the building code. We then quantified the nearby pre-fire overstory canopy cover and the distance to the nearest destroyed home and structure from aerial imagery. Using post-fire photographs, we also assessed fire damage and assigned a cause for damaged but not destroyed homes.

Results: Homes built prior to 1997 fared poorly, with only 11.5% surviving, compared with 38.5% survival for homes built in 1997 and after. The difference in survival percentage for homes built immediately before and after the adoption of Chapter 7A in the California Building Code (37% and 44%, respectively) was not statistically significant. Distance to nearest destroyed structure, number of structures destroyed within 100 m, and pre-fire overstory canopy cover within 100 m of the home were the strongest predictors of survival, but significant interactions with the construction time period suggested that factors contributing to survival differed for homes of different ages. Homes >18 m from a destroyed structure and in areas with pre-fire overstory canopy cover within 30–100 m of the home of <53% survived at a substantially higher rate than homes in closer proximity to a destroyed structure or in areas with higher pre-fire overstory canopy cover. Most fire damage to surviving homes appeared to result from radiant heat from nearby burning structures or flame impingement from the ignition of near-home combustible materials.

Conclusions: Strong associations between both distance to nearest destroyed structure and vegetation within 100 m and home survival in the Camp Fire indicate building and vegetation modifications are possible that would substantially improve outcomes. Among those include improvements to windows and siding in closest proximity to neighboring structures, treatment of wildland fuels, and eliminating near-home combustibles, especially in areas closest to the home (0–1.5 m).

Keywords: Building codes, Defensible space, Flame impingement, Fuels, Radiant heat, Structure loss, Wildfire, Wildland-urban interface

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* Correspondence: eric.e.knapp@usda.gov
[1]U.S. Forest Service, Pacific Southwest Research Station, 3644 Avtech Parkway, Redding, California 96002, USA
Full list of author information is available at the end of the article

Resumen

Antecedentes: El incendio de Camp Fire, el cual destruyó 18.804 estructuras en el norte de California, incluido la mayor parte del pueblo de Paradise, proveyó una oportunidad de investigar la ubicación de las casas y factores vegetales asociados con la pérdida de hogares, y determinar si la adopción de los códigos de construcción de California de 2008 para el exterior de las viviendas ubicadas en las áreas de interfaz urbano rural, mejoraban su supervivencia. Muestreamos al azar casas individuales construidas antes de 1997, de 1997 a 2007, y de 2008 a 2018, las últimas por dos períodos, anterior y posterior a los cambios en los códigos de construcción. Luego cuantificamos los doseles de la vegetación aledaña y la distancia a la vivienda y estructura más cercana destruidas por el fuego usando imágenes satelitales. Usando fotografías post-fuego, también determinamos el daño por fuego y asignamos una causa de daño, pero no casas destruidas.

Resultados: Las casas construidas antes de 1997 se desempeñaron pobremente, con solo un 11,5% de supervivencia, comparado con un 38,5% de supervivencia de aquellas construidas en 1997 y a posteriori. La diferencia en el porcentaje de supervivencia para las casas construidas antes y después de la adopción del Capítulo 7A del código de Construcción de California (37% y 44%, respectivamente), no fue estadísticamente significativa. La distancia a la estructura más cercana destruida por el fuego, el número de estructuras destruidas dentro de los 100 m, y la cobertura del dosel vegetal previo al fuego fueron los predictores de supervivencia más importantes, aunque las interacciones más significativas con el período de construcción sugieren que los factores que contribuyeron a la supervivencia difirieron para casas de diferentes edades. Las casas distantes > 18 m de una estructura destruida y en áreas con cobertura de vegetación previa dentro de los 20-100 m de esa casa < 53% sobrevivió a tasas superiores que aquellas en proximidad de una estructura destruida o en áreas con mayor cobertura vegetal pre-fuego. La mayoría de los daños a las casas supervivientes parece resultar del calor radiante de las estructuras quemadas próximas o por el impacto de las llamas de igniciones de materiales combustibles cercanos a las casas.

Conclusiones: Las fuertes asociaciones entre la distancia de la estructura destruida más cercana y la vegetación dentro de los 100 m y la supervivencia de las casas en el incendio de Camp Fire indican que es posible que las modificaciones en las construcciones y en la estructura de la vegetación mejoren los resultados en relación a su supervivencia. Entre ellos se incluye el mejoramiento de las ventanas y paredes en la proximidad de estructuras vecinas, el tratamiento de los combustibles vegetales, y la eliminación de combustibles cercanos, especialmente en áreas muy cercanas a las casas (entre 0 y 1,5 m).

Background

California, like many other regions having a Mediterranean climate, is set up to burn. Cool, wet winters, which promote vegetation growth, are followed by long, hot, nearly rain-free summers during which these wildland fuels are primed for combustion (Sugihara et al. 2018). In forested areas such as the northern Sierra Nevada, where the town of Paradise is located, wildfires ignited by indigenous peoples and lightning were historically frequent (mean fire return interval of mostly <15 years) (Van de Water and Safford 2011) and integral to shaping vegetation composition and structure (Leiberg 1902; Sugihara et al. 2018). The historical fire return interval in shrub-dominated chaparral vegetation was somewhat longer—15 to 90 years (Van de Water and Safford 2011). While overall acres burned in wildfires today is still substantially less than what burned historically (Stephens et al. 2007), both acres burned and associated losses to infrastructure have been increasing in recent times with 15 of the 20 most destructive events in modern California history, based on the number of structures destroyed, occurring since 2014 *(see California Fire Statistics: https://www.fire.ca.gov/media/t1rdhizr/top20_destruction.pdf).*

The increase in destructive wildfire events has been linked to changes in fire frequency, development patterns, and climate. Loss of indigenous burning and active fire suppression over the past 150 or more years following Euro-American expansion into California reduced the incidence of fire in many forested areas. Where fire historically burned most frequently, surface and vegetative fuels have increased, often leading to more severe fire when it does burn (Steel et al. 2015). Such fires are also frequently more intense because fire suppression has effectively eliminated much of the lower intensity burning under more benign weather conditions. When landscapes now experience fire, most often it is when wildfire escapes initial attack under worst-case scenario weather conditions (Calkin et al. 2014). In addition, over the last several decades, warmer temperatures and longer fire seasons (Westerling et al. 2006) have increased fuel volatility and the probability of ignitions coinciding with extreme weather conditions. In other areas such as chaparral ecosystems in southern California, fire suppression has had less influence on the fire regime—fire frequency has increased in some areas on account of numerous human ignitions, but stand-replacing fire was and still is the norm (Conard and Weise 1998). Further complicating the wildfire challenges, human populations have increased nearly ten-fold over the last 150 years, with a substantial proportion of houses built within or among wildland vegetation (Radeloff et al. 2018). Partly due to the effectiveness of fire suppression, most of these homes were not built or maintained with the goal of being able to withstand wildfire in the absence of fire suppression resources. In addition, home design or construction codes and standards to enhance a building's exterior resistance to wildfire are relatively recent (International Code Council 2003), with substantial development having occurred prior.

Post-wildfire analyses provide an opportunity to investigate why some houses survive and learn how to better co-exist with wildfire in fire-prone environments. During wildfire, buildings can be subjected to three different wildfire exposures—wind-blown embers, radiant heat, and direct flame contact (Caton et al. 2017). Embers are produced when vegetation ignites and burns (Koo et al. 2010). In large, fast-moving wildfires burning under extreme conditions, embers can be transported several kilometers or more (Koo et al. 2010) and ignite buildings directly or indirectly (Caton et al. 2017). A direct ember ignition includes embers igniting decking or siding by accumulating on or next to the material or penetrating vents or open windows and entering the building (Quarles et al. 2010; Hakes et al. 2017). In contrast, indirect ignitions occur when embers ignite combustible materials such as vegetation, bark mulch, leaf litter, neighboring buildings, or near-home objects such as stored materials, decks, or wood fences (Quarles et al. 2010; Hakes et al. 2017). Indirect ignition scenarios ultimately result in radiant heat and/or flame contact to the home or building. Direct flame contact and extended radiant heat exposures can ignite siding and other exterior-use construction materials or break glass in windows. Radiant heat exposure often occurs when a neighboring structure ignites. The dominant mechanism of home loss in numerous particularly destructive wildfires has been described as initial direct or indirect ember ignitions, with burning homes then leading to house-to-house fire spread (Murphy et al. 2007; Cohen and Stratton 2008). However, the potential influence of housing density on structure losses in wildfires has varied, with some studies finding a greater probability of loss at higher housing densities (Price and Bradstock 2013; Penman et al. 2019), while other studies have reported a greater risk at lower housing densities (Syphard et al. 2012, 2014, 2017). Amount of near-home combustible vegetation has also been linked to the probability of home loss in wildfires (Price and Bradstock 2013; Syphard et al. 2014; Penman et al. 2019).

California leads the USA in having a building code with the objective of limiting the impact of wildfires on the built environment. In the 1960s, the state began requiring homeowners to implement defensible space fuel modifications, initially within the first 9 m (30 ft) of a building, but since expanded to 30 m (100 ft) (https://leginfo.legislature.ca.gov/faces/codes_displaySection.xhtml?sectionNum=4291.&lawCode=PRC). Work on standardized test methods to evaluate exterior-use construction materials for fire performance began in the late 1990s and later incorporated into Chapter 7A, an addition to the California Building Code which was adopted in 2008. Chapter 7A provides prescriptive and performance-based options for exterior construction materials used for roof coverings, vents, exterior walls, and decks (https://codes.iccsafe.org/content/CBC2019P4/chapter-7a-sfm-materials-and-construction-methods-for-exterior-wildfire-exposure) and applies to new construction of residential and commercial buildings in designated fire hazard severity zones. In some jurisdictions, provisions of Chapter 7A also apply to "significant remodels" of existing buildings. The 2018 Camp Fire, which destroyed much of Paradise, California, provided an opportunity to evaluate the performance of buildings constructed after the adoption of Chapter 7A and explore factors associated with home survival.

The Camp Fire started on the morning of November 8, 2018, with the failure of an electrical transmission line and spread rapidly through wildland fuels comprised of mixed conifer forest, brush, grass, and dead and down surface fuels (Maranghides et al. 2021). Surface fuels were unusually dry due to persistently low relative humidity throughout the summer and fall and the late onset of fall rains (Brewer and Clements 2019). Driven by strong NE winds, the fast-moving fire quickly reached the towns of Concow, Paradise, and Magalia and became the most destructive wildfire in California history. At least 85 people were killed and 18,804 structures were destroyed. A high proportion of the home and business losses occurred in Paradise—the largest town within the fire footprint. The fire passed from one side of Paradise to the other during one burn period over less than 12 h (Maranghides et al. 2021). With the focus on saving people's lives, very few homes were subject to firefighting efforts, and survival was therefore largely a function of characteristics of the home and surrounding environment. Previous similar analyses have typically combined data across multiple fires and years, with an unknown extent of defensive intervention.

While conditions as the Camp Fire burned through Paradise were still highly variable, the massive home loss in a single burn period presents an opportunity to investigate factors with potentially lesser confounding by differences in geography, weather, and defensive action by firefighters or civilians.

The objective of this research was to answer three questions as follows: (1) did proximity to nearby burning structures factor into the probability of home survival, (2) did fuels associated with nearby vegetation factor into the probability of home survival, and (3) was the full adoption in 2008 of Chapter 7A into the California Building Code associated with improved odds of home survival?

Methods

The Butte County Assessor's database, dated June 1, 2018, was used to extract 11,515 parcels within the Paradise city limits (Fig. 1). Parcels were sorted by use code and 7949 single-family dwellings were selected, after discarding 89 without a listed build year. Mobile homes, businesses, and other non-single-family structures were excluded. We then linked Damage Inspection (DINS) data, obtained from CAL FIRE, to parcel number to ascertain damage sustained in the Camp Fire and whether the building was destroyed, partially damaged, or had no impact from the Camp Fire. We lumped homes classified as "damaged" into the "survived" category, because in most instances, the damage, based on photos included with the DINS data, was minor—e.g., cracked windows, bubbled exterior paint, or melted vinyl gutters and window frames, with the structure itself intact.

Sample population

For our analyses, we randomly selected 400 single-family dwellings in Paradise, stratified by three time periods (Fig. 1): time 1 = homes built before 1997, while time 2 (homes built from 1997 to 2007) and time 3 (homes built from 2008 to 2018) represented the two 11-year periods on either side of the 2008 adoption of Chapter 7A in the California Building Code. If the changes to the building code improved home survival, survival percentage in time 3 should be significantly higher than survival in time 2, especially after adjusting for any potentially confounding variables. The stratification was done to ensure a large enough sample size in time period 3. Two hundred homes (out of 7288) were randomly selected in time 1, one hundred homes (out of 519) were selected in time 2, and 100 homes (out of 142) were selected in time 3 (Fig. 1). More homes were selected during time 1 because such a low percentage (13%) of older (pre-1997) homes survived. Of the population of homes that were randomly selected by the construction period, 24 of the surviving homes were noted as damaged in the DINS report, the rest undamaged. Damage was listed as "affected (1–9%)" for 23 of the damaged homes and "minor (10–25%)" for one.

Variables

For each randomly selected home, we used Google Earth to measure the distance from the edge of the home (as defined by edge of the roof, using pre-fire images when destroyed) to the closest edge of the nearest home and nearest structure, as well as the nearest home and nearest structure that burned. "Nearest structure" was in most cases another single-family home, but also

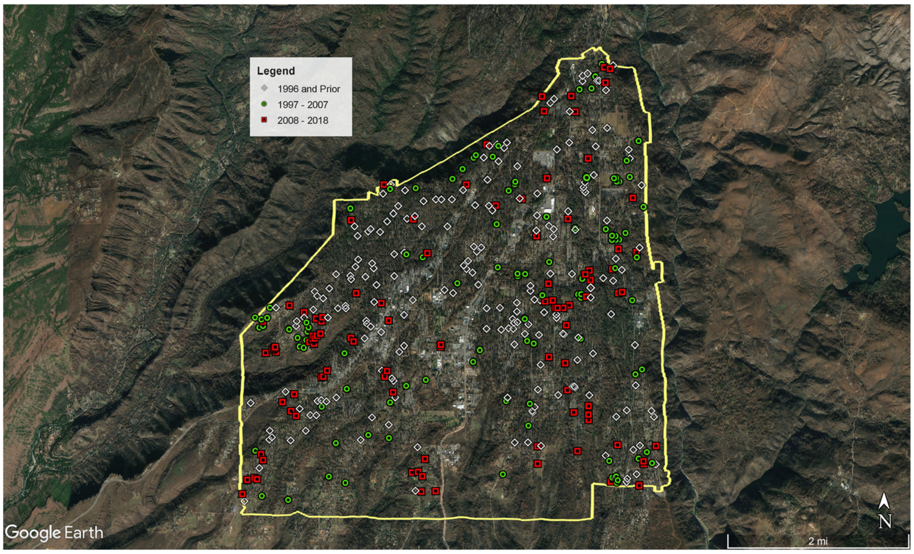

Fig. 1 Map showing the perimeter of Paradise, California, with the location of 400 randomly selected homes built during three time periods (pre-1997, 1997–2007, and 2008–2018)

included mobile homes, businesses, detached garages, or outbuildings such as larger sheds. Small sheds—those <120 ft^2, where a building permit is not required—were excluded. Such smaller sheds may have posed a threat to the home as well but were more challenging to consistently quantify, especially if under a tree canopy. We determined the density of structures in the surrounding area by counting the number of single-family homes, partially-built homes, mobile homes, and businesses (excluding small sheds) with midpoints (based on a visual estimate) included within a 100-m radius centered on the target home. We then counted how many of those structures were destroyed. We visually estimated the percentage cover of overstory vegetation from Google Earth images taken prior to the fire in 2018 and/or 2017 within a 30-m radius circle centered on the selected home and between 30 m and 100 m from the selected home. Cover of the understory of grass and/or shrubs or landscape plantings was not estimated, as pre-fire overstory canopy cover was relatively high, and this often obscured the understory. Some larger mid-story shrubs might have been included with the tree overstory due to the difficulty in distinguishing them from trees. The lot size was provided in the Butte County Assessor's data. Whether the house was located in the Wildland Urban Interface (defined as developed areas that have sparse or no wildland vegetation but are near a large patch of wildland) or the Wildland Urban Intermix (defined as areas where houses and wildlands intermingle) was determined by overlaying a University of Wisconsin data layer on the city of Paradise (Radeloff et al. 2005). We used Radeloff et al. (2005) to define the interface as census blocks with at least 6.17 housing units km^{-2} that contained <50% wildland vegetation but were within 2.4 km of a heavily vegetated area (>75% wildland vegetation) larger than 5 km^2. Intermix was defined as an area with more than 6.17 housing units km^{-2} but dominated by wildland vegetation. Percent slope was calculated as the rise between the lowest and highest point along a 100-m radius circle centered on the home.

Analysis approach

Possible explanatory variables (S1 Table) were first analyzed individually using a generalized linear model in SAS PROC GENMOD and assuming a normal distribution to evaluate whether they differed by time period or by outcome (survived, destroyed). To account for the sampling scheme, in this and all subsequent analyses, each observation was weighted by the inverse of its probability of selection—i.e., homes from time period 1 had a weight of 7288/200, homes from time period 2 had a weight of 519/100, and homes from time period 3 had a weight of 142/100. Comparisons among main effects (outcome, time period) and interactions (outcome × time period) were determined using Tukey's HSD test for multiple comparisons, when significant.

To determine the relative strength of factors associated with home survival, we used a generalized linear model fit for binary response data, with a logit link function and weighting to account for the sampling scheme. Variables in the initial model were as follows:

1. Y-variable: Outcome (Survived/Destroyed); X-variables: construction time period, year built, Wildland Urban Interface/Intermix category, distance to nearest destroyed structure, total structures destroyed within 100 m, overstory canopy cover within 30 m, overstory canopy cover between 30 m and 100 m, slope, and the interaction of each with the construction time period.

When independent variables were highly correlated ($R > 0.6$), only the one most clearly mechanistically linked to outcome was included. For example, "distance to nearest structure" was highly correlated with "distance to the nearest destroyed structure," and "total structures–100 m" was highly correlated to "total structures destroyed—100 m" (Table 1), so only the latter were included. Lot size was not included as there was no clear mechanistic link with home survival, and we hypothesized that elements contributing to fire behavior would be captured by correlated variables. The Wildland Urban Interface/Intermix category was included to quantify differences in vegetation and housing arrangement at scales larger than 100 m. Non-significant interactions and non-significant main effects for variables that did not have a significant interaction with time were sequentially removed to produce the final model. To determine whether homes constructed after the Chapter 7A building code update survived at a significantly higher rate after factoring in all other possible confounding variables, the same analysis was conducted except without interactions with the construction time period.

We then designed models to first test the effect of variables that may have directly influenced home survival during the fire and second, to test the effect of just the variables available prior to the fire. The latter variables were ones that might be mitigated preemptively through planning, retrofitting, or vegetation management. For each of these models, we determined the effect size and performed a regression tree analysis. Variables included for each approach (accounting for the fire, pre-fire only):

1. Y-variable, accounting for the fire: Outcome (Survived/Destroyed); X-variables: year built, distance to nearest destroyed structure, total structures destroyed within 100 m, canopy cover within 30 m,

Table 1 Significance of individual factors by time period, outcome (destroyed, survived), and outcome × time period for a subset of single-family homes in Paradise, CA. Means for time period, outcome, and outcome × time period (when interaction was significant) are provided below (standard error in parentheses). Levels within variables followed by different letters were significantly different ($P<0.05$)

		N	Lot size (ha)	Dist. nearest struct. (m)	Dist. nearest destr. struct. (m)	Total structures 100 m	Total structures destr. 100 m	% Canopy cover 0–30 m	% Canopy cover 30–100 m	Slope (%)
			P							
Outcome			*0.946*	*0.971*	*<0.001*	*0.004*	*<0.001*	*0.154*	*0.001*	*0.532*
Time period			*0.153*	*0.010*	*<0.001*	*0.002*	*<0.001*	*<0.001*	*0.664*	*0.290*
Outcome × time period			-	-	*0.026*	-	-	-	-	-
			Average (standard error)							
Destroyed		296	0.42 (0.07)	15.4 (1.6)	-	10.3^{a} (0.8)	8.9^{a} (0.7)	40.5 (3.1)	49.1^{a} (2.8)	6.9 (0.6)
Survived		104	0.42 (0.08)	15.5 (1.9)	-	8.1^{b} (0.9)	5.5^{b} (0.9)	36.0 (3.7)	40.0^{b} (3.3)	7.2 (0.6)
Before 1997		200	0.30 (0.04)	10.9^{b} (0.8)	-	11.4^{a} (0.4)	9.4^{a} (0.4)	49.5^{a} (1.6)	46.7 (1.4)	6.4 (0.3)
1997-2007		100	0.45 (0.09)	16.1^{a} (2.1)	-	8.0^{b} (1.0)	5.9^{b} (1.0)	35.7^{b} (4.1)	43.7 (3.7)	7.5 (0.7)
2008-2018		100	0.51 (0.17)	19.3^{ab} (4.0)	-	8.1^{ab} (1.9)	6.3^{ab} (1.8)	29.5^{b} (7.9)	43.2 (7.0)	7.2 (1.4)
<1997	Dest.	177	-	-	12.3^{c} (0.8)	-	-	-	-	-
<1997	Surv.	23	-	-	22.3^{b} (2.1)	-	-	-	-	-
1997–2007	Dest.	63	-	-	20.0^{bc} (3.4)	-	-	-	-	-
1997–2007	Surv.	37	-	-	34.6^{ab} (4.4)	-	-	-	-	-
2008–2018	Dest.	56	-	-	16.1^{bc} (6.8)	-	-	-	-	-
2008–2018	Surv.	44	-	-	54.0^{a} (7.7)	-	-	-	-	-

canopy cover between 30 m and 100 m, wildland urban interface/intermix category, slope.

2. Y-variable, pre-fire only: Outcome (Survived/Destroyed); X-variables: year built, distance to nearest structure, total structures within 100 m, canopy cover within 30 m, canopy cover between 30 m and 100 m, wildland urban interface/intermix category, slope.

To quantify the relative strength of continuous variables for explaining home survival, each of the dependent (x) variables were centered and scaled to have a mean of zero and standard deviation of one. Logistic regression (McCullagh and Nelder 1989) was then used to calculate coefficients and compare effect sizes. The logistic regression models were fit using the *svyglm* function from the *survey* package in R (Lumly 2020). A decision tree for predicting home survival was produced using the *rpart* function in the *rpart* package (Therneau and Atkinson 2019) in R, fit for binary response data with a logit link function (Breiman 1998). This approach is similar to logistic regression, where the linear predictor is a decision tree model. To determine the number of splits in the decision trees, we performed cross-validation 10,000 times to compute the optimal pruning parameters. We then used the average of the 10,000 optimal pruning parameters as the pruning parameter in the final decision tree. The latter group of statistical analyses was completed using R version 4.0.0 (R Core Team 2020). Figures were made in R using the *ggplot2* package (Wickham 2016).

Visual evaluation of damaged homes

To learn more about vulnerabilities of the Paradise home sample and gain insight into potential points of fire entry, we reviewed the CAL FIRE damage inspection (DINS) spreadsheet (obtained from CAL FIRE 12/18/2018) and obtained photographs of all damaged homes (*N*=310 homes with pictures).

Photographs typically keyed in on the damage, and we reviewed each, along with notes about damage in the DINS summary. Observed home damage was assigned to radiant heat, direct ember ignition, or flame impingement categories (S2 Table), based on the nature of the damage, location on the home, and visual as well as photographic (aerial imagery) evidence of other burned fuels, including homes, in the immediate vicinity. Homes where flame impingement was recorded were further split into three categories: (1) caused by fuel continuity with the broader landscape (which allowed fire to reach the home), (2) indirect ember ignition (e.g., gutter contents, near-home fuels) with flames then impacting the home, or (3) unknown/undetermined. [The DINS assessment gathered similar information, but the full suite of data was not collected for over a quarter of homes and ember ignition was not separated into direct and indirect categories.] Where DINS data were collected, our evaluation was often in agreement, but there were a few instances where we differed. For example, if the DINS assessment noted “direct flame impingement” but the photo showed no charring or near home fuels consumed, we listed the damage caused as “radiant heat.” Gutter fires were variously categorized but we assigned them all to the “indirect ember ignition” category. The DINS assessment also only lists a single cause of fire damage when a considerable number of homes displayed multiple causes.

Results

Overall, most (86%) of the single-family homes in Paradise were built before 1990, and homes of this age fared poorly, with only 11.6% surviving the Camp Fire (Fig. 2). Survival increased to 20.6% for homes built between 1990 and 1996, 34.3% for homes built between 1997 and 2007, and 43.0% for homes built between 2008 and 2018. The 400 randomly selected homes in our sample had similar survival rates to the full population of single-family homes—11.5% vs. 13.3%, respectively, for the <1997 time period (time = 1), 37.0% vs. 34.3%, respectively, for the 1997–2007 time period (time = 2), and 44.0% vs. 43.0%, respectively, for the 2008 to 2018 time period (time = 3). Many of the potential explanatory variables differed over the three time periods as well and were therefore confounded with potential construction or building code differences (Table 1). Older homes (<1997) were on average in areas with higher housing density and had more homes burn within 100 m than homes built from 1997 to 2007 (Table 1). Homes built prior to 1997 had a higher average pre-fire overstory canopy cover in the first 0–30 m from the home than homes

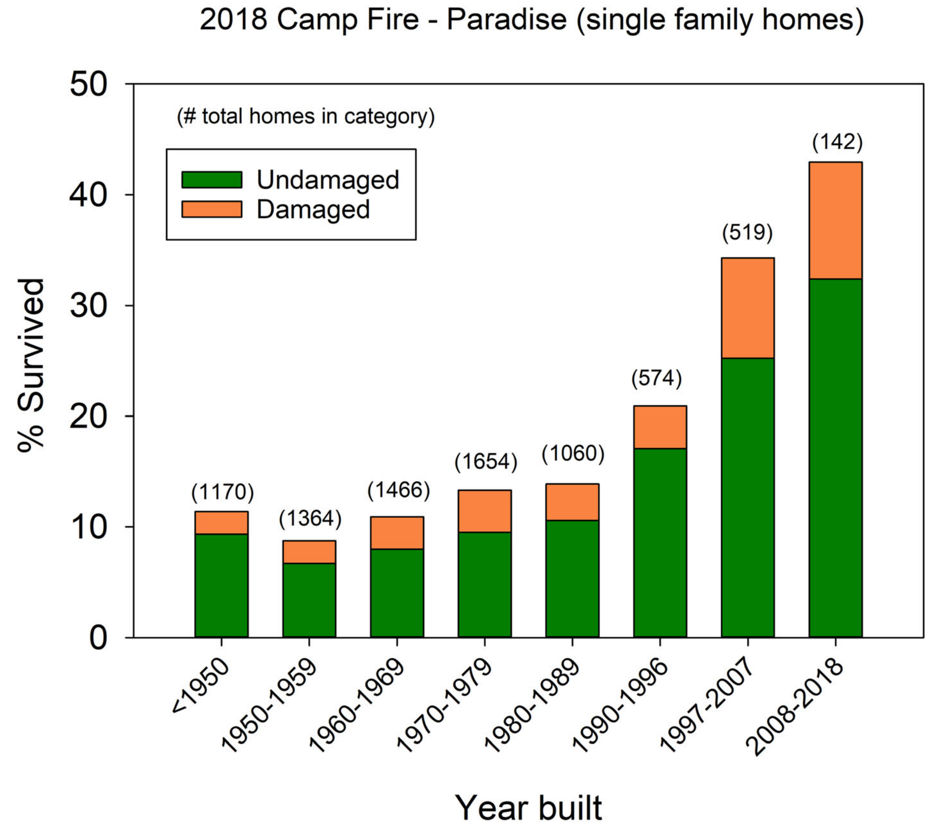

Fig. 2 Percentage of surviving single-family homes in Paradise by decade of construction

built afterwards (Table 1). The "distance to nearest destroyed structure" × time interaction was significant, with surviving homes a greater distance from the nearest destroyed structure in time periods one and three. This difference was especially pronounced for the newest homes (Table 1). While average lot size trended larger over time, the differences were not significant (Table 1). Pre-fire overstory canopy cover 30–100 m from the home was significantly lower for surviving homes (37.0%) than destroyed homes (50.4%) but did not differ between time periods (Table 1). With most houses situated on top of a plateau, the average percent slope was relatively low and did not differ significantly among outcomes or time periods (Table 1). None of the variables differed between time periods 2 and 3—immediately pre- and post-Chapter 7A adoption.

Many of the continuous variables we analyzed were significantly correlated with each other, with distance to nearest structure and distance to nearest destroyed structure (r = 0.625) and total structures within 100m and total structures destroyed within 100m (r = 0.926) being the most strongly correlated (Table 2).

Factors influencing home survival

Eliminating the two most highly correlated variables (distance to nearest structure and total structures per 100m) and analyzing the remaining variables together in the same model showed that both nearby destroyed structures and overstory canopy cover within 100 m were significantly associated with home survival. The "distance to nearest destroyed structure" × construction time period interaction was significant (Table 3), with a much higher survival probability when homes were a larger distance from a destroyed structure, especially for homes built 1997–2007 and 2008–2018 (Fig. 3a). Total structures destroyed within 100 m also was strongly linked to home survival (Table 3), with a much higher survival probability when fewer surrounding homes burned (Fig. 3b). For the vegetation variables, the "CanopyCover 0–30m" × construction time period interaction was significant (Table 3). Higher survival was noted with lower canopy cover for homes built since in 1997 and after but was not related to survival in older (<1997) homes (Fig. 3c). CanopyCover 30–100m also was highly significant, with a higher survival probability at lower canopy cover percentages across times (Table 3, Fig. 3d). Wildland urban interface/intermix category was significant, with a higher survival rate for homes in the wildland urban intermix (29.3%) than homes in the wildland urban interface (16.0%). Year built [within construction time period] and slope were not significant and did not make it into the final model (Table 3).

When the same analysis was conducted without interactions to test the effect of construction time period after correcting for covariates, homes built between 1997–2007 and 2008–2018 both survived at a significantly higher rate than homes built prior to 1997 ($P < 0.001$). Even though the survival rate was numerically higher for homes built after the 2008 building code update (44%) than homes built in an equivalent time period

Table 2 Correlation matrix of variables considered in the analyses of factors potentially contributing to home survival. The correlation coefficient (R) is above the diagonal, with statistical significance below. Distance to nearest destroyed home includes only single-family homes. Distance to nearest destroyed structure includes single-family homes, mobile homes, businesses, outbuildings, detached garages, and other large buildings

	Lot size	**Year built**	**Dist. nearest structure**	**Dist. nearest dest. structure**	**Total struct. 100 m**	**Structures destroyed 100 m**	**Canopy Cover (%) 0–30 m**	**Canopy cover (%) 30–100 m**	**Slope (%)**
Lot size		0.166	0.544	0.462	−0.499	−0.435	−0.111	−0.001	0.368
Year built	*<0.001*		0.262	0.283	−0.406	−0.424	−0.419	−0.146	0.156
Dist. nearest structure	*<0.001*	*<0.001*		0.625	−0.497	−0.432	−0.069	0.009	0.260
Dist. nearest dest. structure	*<0.001*	*<0.001*	*<0.001*		−0.471	−0.537	−0.263	−0.226	0.216
Total struct_ 100m	*<0.001*	*<0.001*	*<0.001*	*<0.001*		0.926	0.215	−0.007	−0.299
Struct. destroyed_ 100m	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*		0.300	0.134	−0.233
Canopy Cover 0-30m	*0.026*	*<0.001*	*0.171*	*<0.001*	*<0.001*	*<0.001*		0.571	−0.001
Canopy Cover 30-100m	*0.983*	*0.003*	*0.853*	*<0.001*	*0.890*	*0.007*	*<0.001*		0.135
Slope (%)	*<0.001*	*0.002*	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*0.984*	*0.007*	

Table 3 Fixed effects in a generalized linear mixed model (PROC GENMOD) analysis of variance of the influence of nearby destroyed structures and pre-fire overstory canopy cover on Paradise single-family home loss in the Camp Fire, taking into account other potentially confounding variables. All variables plus their interactions with time period were put in the preliminary model with non-significant interactions and main effects sequentially dropped for the final model

Variable	DF	Chi-square	*P*
Construction time period	2	68.84	*<0.001*
Dist. nearest destroyed structure	1	57.10	*<0.001*
Tot. structures destroyed 100 m	1	179.77	*<0.001*
Canopy cover_0–30 m	1	1.61	*0.205*
Canopy cover_30–100 m	1	162.48	*<0.001*
Wildland urban intermix/interface category	1	4.54	*0.033*
Dist. nearest destroyed structure × time	2	16.45	*<0.001*
Canopy cover_0–30 m × time	2	25.35	*<0.001*

immediately before (37%), the difference was not statistically significant (adjusted *P* = 0.309).

For the next set of analyses, separate models (this time without specifying construction time period) were run on normalized data for (1) variables in play during the Camp Fire (including fire-related variables) and (2) variables present prior to the Camp Fire (i.e., variables that might factor into pre-fire planning). For the first model, distance to the nearest destroyed structure had the largest effect size, suggesting that the greater the distance to a burning structure, the higher the probability of survival (Fig. 4a). Also significant were canopy cover within 30–100 m and the number of destroyed structures within 100 m. Both the latter two variables had a negative relationship with survival, with higher survival where canopy cover within a 30–100 distance was lower, and number of destroyed structures within 100 m was fewer (Fig. 4a). Year built, slope, and canopy cover within 0–30 m all had confidence intervals that overlapped with zero. When only pre-fire variables were included, housing density had the largest effect size, with greater survival when the number of structures within 100 m was low (Fig. 4b). Canopy cover within 30–100 m had the second largest effect size, with greater survival at lower canopy cover levels (Fig. 4b). Distance to nearest structure, year built, slope, and canopy cover within 0–30 m all had confidence intervals that overlapped with zero (Fig. 4b).

Decision tree analysis using variables present during the fire indicated a threshold of 18 m from nearest destroyed structure best predicted whether a home survived or not. Survival probability for homes <18 m to the nearest destroyed structure was very low (0.058), compared with a 0.354 survival probability for homes $\geq$18 m from the nearest destroyed structure (Fig. 5a). Based on our sample, a majority (73.6%) of the homes in Paradise were <18 m from a destroyed structure. For the 26.3% of homes $\geq$18 m from a destroyed structure, if the pre-fire overstory canopy cover was also < 53% within 30–100 m, the survival probability improved to 0.481 (Fig. 5a). If the home was also built during or after 1973, the survival probability improved to 0.606 (Fig. 5a). The final split, involving just 10.2% of the homes in Paradise, suggested that for homes meeting these criteria (i.e., $\geq$18 m from the nearest destroyed structure, <53% canopy cover within 30–100 m, and built $\geq$1973), the survival probability improved to 0.733 if slope was less than 8.2%. For the decision tree including just pre-fire variables, year built was the first split, with a probability of survival of only 0.111 for homes built before 1996 (90.8% of homes in Paradise), compared with 0.396 for homes built during or after 1996 (9.2% of homes) (Fig. 5b). For homes in this latter category, survival probability improved to 0.766 if the pre-fire overstory canopy cover within 30–100 m was <33%. If pre-fire canopy cover within 30–100 was $\geq$33%, the survival probability fell to 0.239.

Damaged homes—nature of damage and cause

In our review of photographs of the 310 fire-damaged homes in Paradise, 63% had radiant heat damage (Fig. 6a), mostly to windows and exterior walls (Fig. 6b). Window damage consisted of cracked or broken glass and damaged window framing, but frequently included both. Blistered paint or melted/sagging vinyl siding were the most common wall (siding) damages. In most cases, the source of the radiant heat was difficult to assess, as the photos focused on the damage. However, a closer investigation of 20% of randomly sampled of homes where radiant heat damage was identified demonstrated that all had at least one neighboring structure that was destroyed during the fire, with an average distance to the destroyed structure of 12.1 m. Flame impingement was the next most common cause of damage (44% of damaged homes) (Fig. 6a). In most flame impingement cases (28% of the total damaged homes), the damage was interpreted to be the result of indirect ember ignition. For only 10% of damaged homes was the continuity of fuels from the broader surroundings (often needle or leaf litter) identified as the likely reason for flame impingement. For another 10% of damaged homes, whether needle or leaf litter was continuous with the surroundings or just localized next to the home could not be determined from the photograph. [Note—these three flame impingement categories do not add to 44% because some houses showed evidence of multiple flame impingement causes.] For the cases of flame impingement via indirect ember ignition, embers ignited near home flammable objects (e.g., fences, patio furniture, stored lumber), near home leaf litter, near home vegetation (or litter under that vegetation), leaf litter in gutters, or wood bark mulch, in order of frequency from most to least (S2 Table). Direct

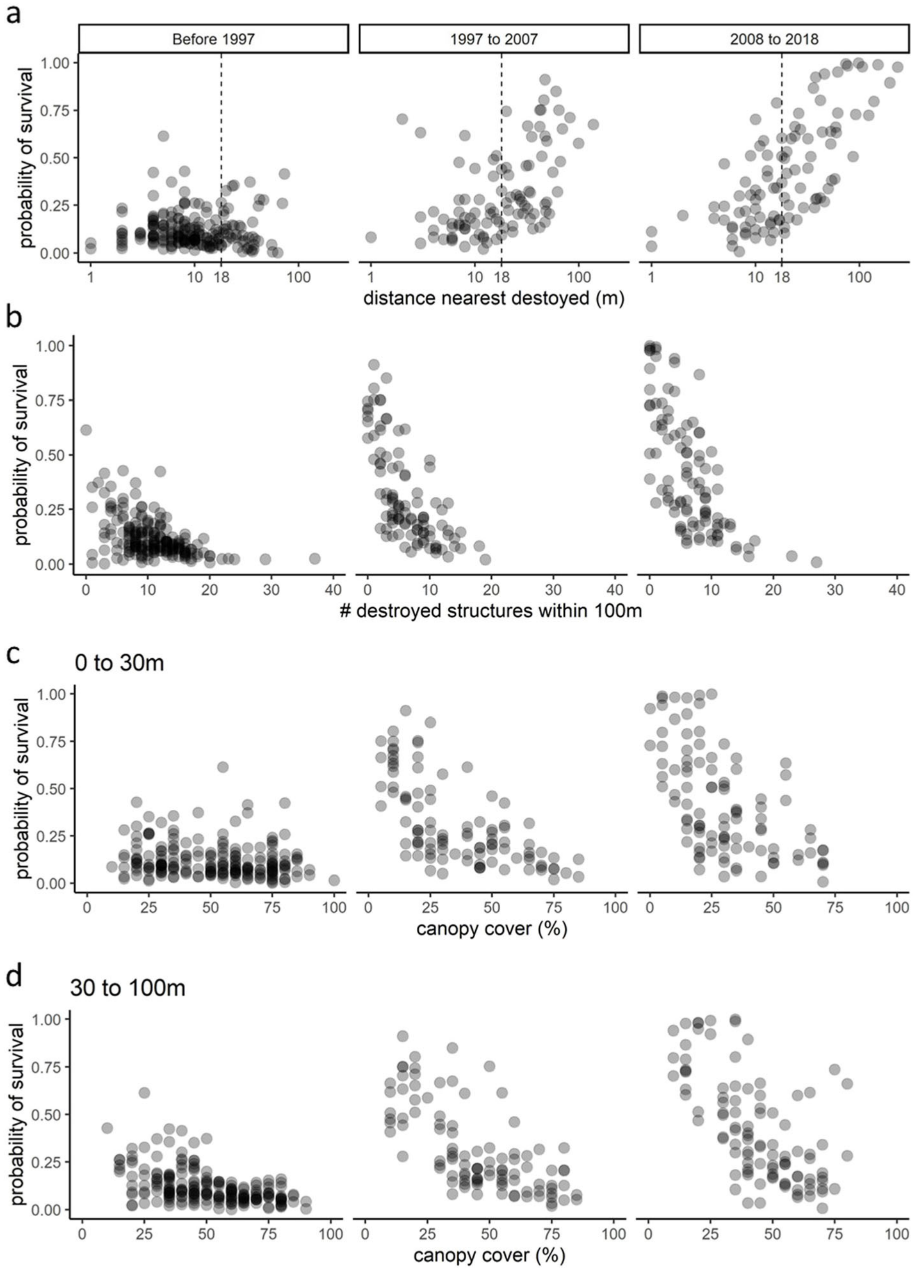

Fig. 3 Probability of home survival with **a** distance (m) to nearest destroyed structure, **b** the number of destroyed structures within a 100-m radius, **c** pre-fire overstory canopy cover within 0–30 m, and **d** pre-fire overstory canopy cover within 30–100 m, for homes built during three time periods (before 1997, 1997–2007, and 2008–2018). A vertical dotted line in **a** shows the 18-m threshold between survival and destruction identified by the regression tree analysis (Fig. 5a)

ember ignition was identified as the likely cause of damage for fewer than 6% of homes (Fig. 6a). The most common locations for embers to ignite were attached wood stairs, decking, and window trim. Counting either direct ember ignition or flame impingement due to indirect ember ignition, embers were implicated as a cause in 33% of damaged homes.

Discussion

Burning structures and wildland fuels both influence home survival

Our analysis of post-fire outcomes in the town of Paradise suggested that both the proximity to other burning structures and nearby wildland fuels factored in the probability of home survival, with several measures of

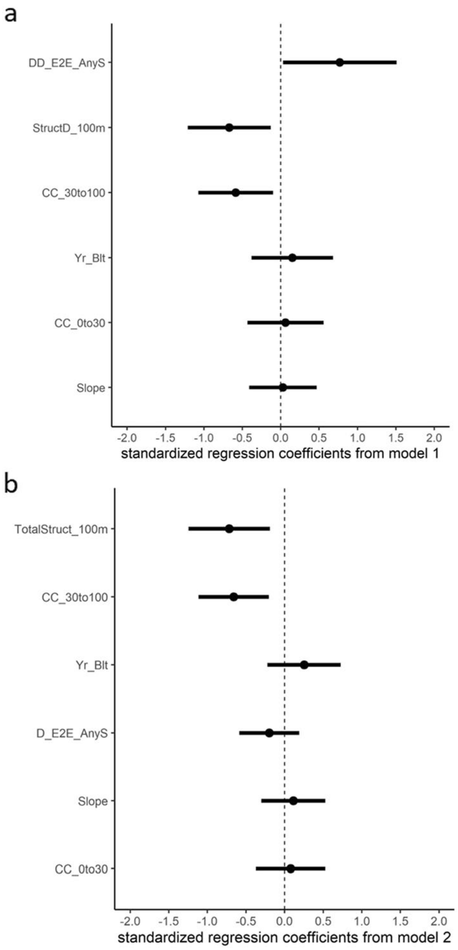

Fig. 4 Effect sizes for two logistic regression models of home survival in the town of Paradise during the 2018 Camp Fire, including continuous variables **a** present during the fire and **b** only variables present pre-fire. Regressions were based on a random sample of 400 homes

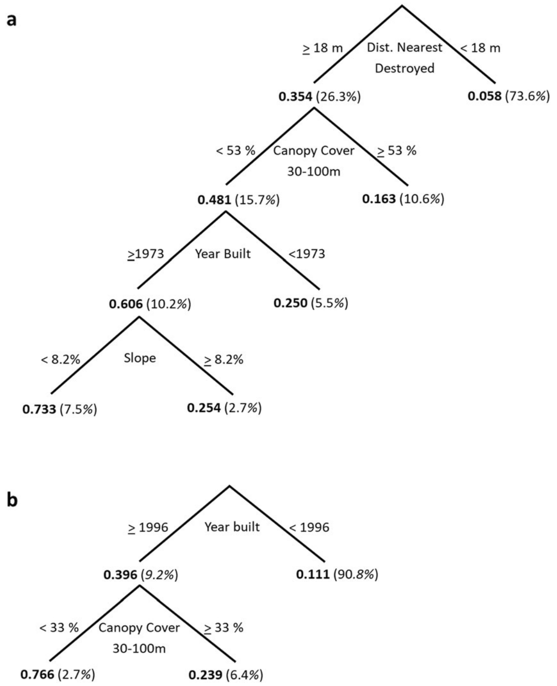

Fig. 5 Regression trees for predicting home survival in the town of Paradise in the 2018 Camp Fire, with models including continuous variables **a** present during the fire and **b** only variables present pre-fire, both based on a random sample of 400 homes. Survival proportion is listed in bold under each branch, along with the percentage of homes in Paradise that each branch applied to (in parenthesis)

distance and density of destroyed structures and nearby pre-fire overstory canopy cover emerging as significant explanatory variables. The relative importance of nearby burning home variables versus surrounding vegetation in explaining outcomes has varied among studies, with Gibbons et al. (2012) reporting canopy cover within 40m of the home to be the strongest predictor. Number of buildings within 40m was also a significant variable in their analysis. Even though nearby burning structure and vegetation variables were both included in the models in our study, interpretations about relative strength of these two sets of factors are tempered by limitations of the vegetation data, with overstory canopy cover an imperfect measure of wildland fuel hazard.

One possible clue to the relative importance of adjacent structures burning comes from the different outcomes for wildland urban intermix and interface homes. Houses built amongst wildland vegetation (intermix) survived at a higher rate (29%) than houses built in more of a subdivision arrangement with wildland fuels nearby (interface) (16%). Average pre-fire overstory canopy cover within 0–30 m was similar for intermix and interface homes (42% and 43%, respectively), but pre-fire overstory canopy cover within 30–100 m was higher for intermix than interface homes (49% vs. 42%, respectively). If proximity to wildland fuels had been the dominant driver, greater percentage losses in the wildland urban intermix would have been expected. The higher survival of intermix homes may therefore have been more a function of greater average distance to the nearest destroyed structure (24 m vs. 11 m in the intermix and interface, respectively) and lower average density (7.7 vs. 11.1 structures within 100 m in the intermix and interface, respectively). (Kramer et al. 2019) in an analysis of three-decade's worth of wildfires in California, also reported higher survival of homes in the wildland-urban intermix compared to the wildland-urban interface, and together with our results provide some additional evidence of the importance of nearby burning structures to home loss, relative to variables associated with wildland fuels. However, in our study, other factors

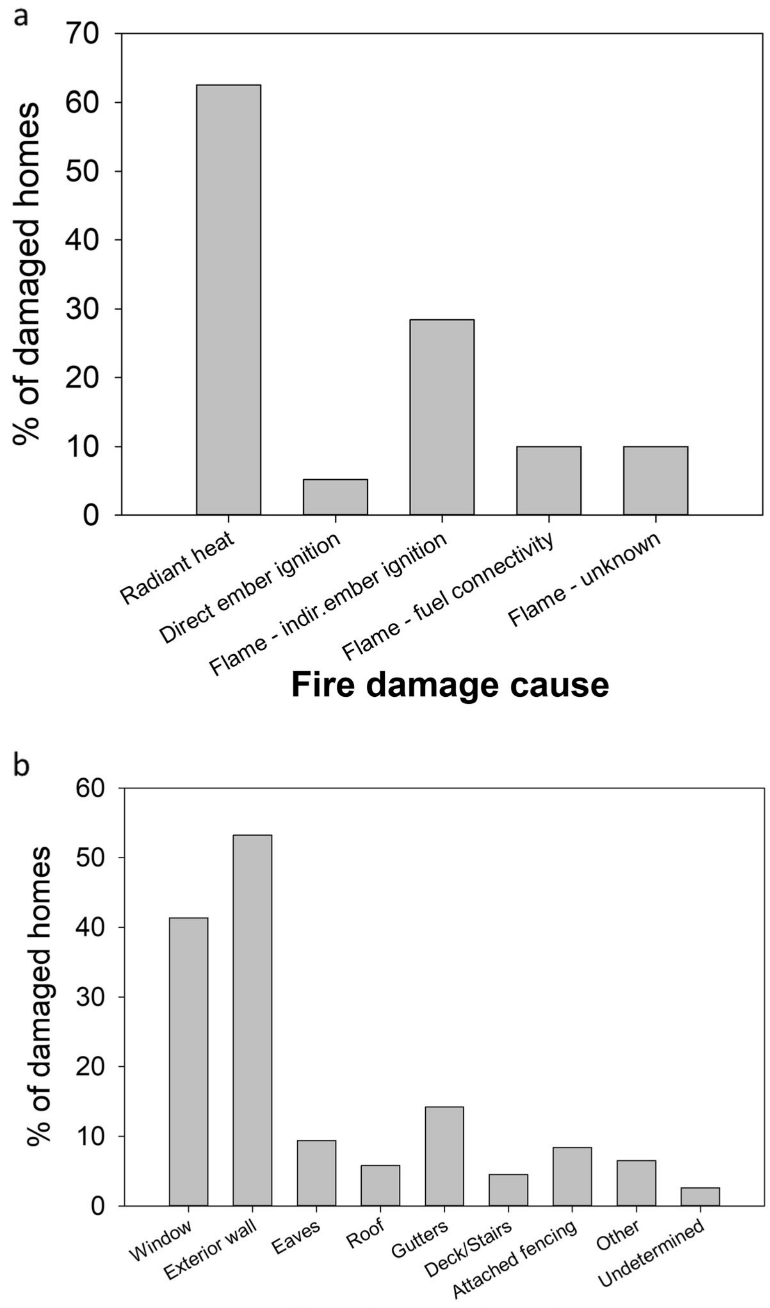

Fig. 6 Percentage of damaged but not destroyed homes in Paradise by **a** fire damage cause category and **b** fire damage location. Fire damage cause was either radiant heat, direct ember ignition, or flame impingement. Flame impingement was further subdivided into flame impingement due to indirect ember ignition, fuel continuity with the broader landscape, or unknown. Numbers were based on visual assessment of photos taken by the CAL FIRE inspectors and information in the CAL FIRE DINS (damage inspection) data. Totals exceed 100% because some homes had multiple sources of fire damage

were likely in play as well, with intermix homes being somewhat newer. In Paradise, an increasing percentage of homes were located in the intermix vs. the interface over time: 66% in time period 1, 80% in time period 2, and 88% in time period 3.

Homes as fuel

Distance to nearest destroyed structure and the total number of destroyed structures within 100 m were consistently the strongest predictors in our analyses. This makes intuitive sense because burning structures produce a substantial amount of radiant heat, which can ignite adjacent homes or break glass in windows, allowing embers to enter the home. Nearby burning structures are also a source of embers, which can result in direct or indirect ember ignitions of nearby structures. Our visual analysis of 310 damaged homes corroborated the results of the statistical analyses, with more homes showing evidence of damage from radiant heat exposure (often from adjacent structures burning) than from flame impingement. Our findings are consistent with other analyses of destructive wildfires showing housing density to be strongly associated with home loss (Price and Bradstock 2013; Penman et al. 2019), but in contrast to Syphard et al. (2012, 2014, 2017) and Syphard and Keeley (2020), who have reported reduced probability of home loss at higher housing densities. The difference between studies likely has to do with variation in density ranges evaluated, as well as variation in vegetation type and housing arrangement. Syphard et al. (2012) sampled large fire-prone regions with shrub-dominated vegetation in southern California, ranging from outlying WUI areas to denser cities that did not burn to answer the question of housing arrangements most prone to loss in a wildfire. Since the entire scope of our analysis was within the Camp Fire perimeter, our research question differs: when burned, what factors influenced survival? In any case, the interpretation of Syphard et al. (2012, 2014, 2017) of lower loss probability with higher density development may not apply to different development patterns, including those present in Paradise. Such intermediate to low density wildland urban intermix and interface development interspersed with native (and non-native) vegetation is prevalent in foothills and lower mountainous regions of central and northern California (Hammer et al. 2007). In chaparral dominated ecosystems of southern California, high-density housing might result in more of the proximate shrub vegetation being removed, but in Paradise, overstory canopy cover within 0–30 m of the home was actually positively correlated with housing density.

At what distance an adjacent burning structure presents a vulnerability is not well studied. Our analyses identified a threshold of 18 m from the nearest destroyed structure that best differentiated surviving and destroyed homes (Fig. 5a). Price and Bradstock (2013) found the presence of houses within 50 m to be predictive of loss. Radiant heat flux, which is inversely related to distance from the flaming source, can be a factor up to 40 m from a burning structure (Cohen 2000). Cohen (2004) reported that models predicted ignition of wood walls when less than 28 m from a crown fire in forested vegetation, with actual experimental crown fires finding ignition at a 10-m distance, but not 20 m or 30 m. The radiant heat flux adjacent to burning structures is different and likely more sustained than a similar heat flux adjacent to crowning wildland vegetation.

Between home spacing has been evaluated in post-fire assessments conducted after the Witch Fire in San Diego County, California (Insurance Institute for Business and Home Safety 2008), the Waldo Canyon Fire in Colorado Springs, Colorado (Quarles et al. 2013), and the Black Bear Cub Fire in Sevier County, Tennessee (Quarles and Konz 2016). During each of these fires, home-to-home spread was observed with spacing less than 10 m. The IBHS Witch Fire report (Insurance Institute for Business and Home Safety 2008) referred to home-to-home spread as “cluster burning,” which was not observed when homes were located more than 14 m apart. Our finding of an 18-m threshold is similar to the IBHS Witch Fire results. Regardless of the actual ideal home separation level, many homes in fire-prone areas of the western USA are on lot sizes that do not permit more than 18 m of separation between buildings.

Wildland fuels and defensible space actions

Pre-fire overstory canopy cover was a significant predictor of home survival in the statistical models, with the canopy cover 30–100 m away having a larger effect size than canopy cover in the immediate vicinity of the home (0–30 m) (Fig. 4a, b). This result (and other evidence, below) suggests that overstory canopy cover may only be correlated to factors that contributed to fire spread and increased the threat to homes, rather than a direct contributor. The often indirect influence of tree canopies on home survival, mediated by the litter fuels produced rather than canopy combustion, has been noted by others (Keeley et al. 2013). Wildland fire spread is dependent on surface fuels—litter, duff, and dead and down woody material, which would be expected to be most abundant and continuous under or adjacent to overstory tree canopy. The link between overstory canopy cover and surface fuel abundance may have been weaker from 0 to 30 m than distances farther removed from the home because of the greater likelihood that such surface fuels were better managed near homes, perhaps as a result of defensible space activities. In addition, the continuity of vegetative fuels is more likely to be broken up by lawns, driveways, or irrigated landscaping near the home. While vegetation abundance within 30 m has been reported to be associated home loss in southern California fires burning in shrubland vegetation types (Syphard et al. 2014, 2017), Alexandre et al. (2016) found vegetation near a building not to be a strong factor in models of loss for fires in southern California and Colorado. They theorized that the connectivity of vegetation to the home was more critical than vegetative cover.

While burning trees and associated vegetation may generate substantial flame lengths and embers which can then threaten homes, the overstory tree canopies themselves did not appear to drive fire intensity in most cases. With the Camp Fire, many overstory trees located away from burning homes survived (Keeley and Syphard 2019; Cohen and Strohmaier 2020) (Fig. 7). Rather than tree torching directly impacting nearby structures, the torching of trees and other vegetation appeared from photographs and personal observation to frequently be caused by heat from nearby burning structures. Additionally, a substantial proportion of the canopy of native tree vegetation in Paradise at the time of the fire was comprised of California black oak (*Quercus kelloggii* Newb.), a native deciduous species that would have shed at least a portion of its leaves by the time of year when the Camp Fire burned through Paradise. Even when fully leafed out, the crowns of black oak trees are relatively open with low canopy bulk density. Deciduous oak litter breaks down faster than conifer litter, and the light fuel loads in pure black oak stands tend to promote low-intensity surface fire rather than crown fire (Skinner et al. 2006). Ponderosa pine (*Pinus ponderosa* Lawson & C. Lawson) was the other major native tree species. Leaf and needle litter can carry flames to the home or provide receptive fuels for ember ignitions and would likely have been positively correlated to pre-fire overstory tree canopy cover, especially in the fall. Embers can also ignite litter that has accumulated in gutters and roofs. High pre-fire overstory canopy cover may also indicate areas where associated vegetation and surface fuels had developed to the greatest extent in the absence of fire and active management, especially at a distance from homes. With the lands in the Paradise area having no record of fire in modern recorded history (Maranghides et al. 2021), considerable vegetative ingrowth and accumulation of dead and down surface fuels was likely, especially relative to historical amounts. Ingrowth could have included brush and smaller conifers that acted as ladder fuels, leading to torching and ember generation.

Even though our data showed a stronger association between pre-fire overstory tree cover and home survival for distances beyond which defensible space is typically mandated (100 ft or 30 m), this does not mean that vegetation modification within 30 m is any less important. For reasons described earlier, the fuel hazards contributing to outcome were likely not well captured by the overstory canopy cover variable, especially in this near-home zone. In addition, once structures become involved, defensible space vegetation modification to 30 m (100 ft) may be insufficient to mitigate ember and radiant heat exposures contributing to home loss. In an analysis of CAL FIRE DINS data over multiple fires, including the Camp Fire, Syphard and Keeley (2019) reported that defensible space was a poor predictor of outcome, with structural variables (e.g., eave construction details, numbers of windowpanes (double vs. single), vent screen size) more highly correlated with home survival. The low predictive power of defensible space may be partially due to the coarseness with which defensible space is classified in the DINS data, with broad distance categories not fully capturing spacing, composition, or flammability of the vegetation. In addition, in many destructive wildfires, a large portion of homes are lost through direct or indirect ember ignition and not flame impingement associated with the continuity with

Fig. 7 Aerial image showing a portion of Magalia just NW of Paradise, illustrating a gradient of fire damage to overstory vegetation with distance from destroyed homes. At least in some areas, burning homes may have influenced the effects to overstory vegetation more so than burning overstory vegetation influenced the outcome to homes. Photo: Owen Bettis, Deer Creek Resources

wildland fuels (Murphy et al. 2007; Cohen and Stratton 2008). With embers capable of igniting fuels over 1–2 km away, the protective effect of vegetation modification within 30 m of the house does not guarantee survival when fire-fighting resources are not present. Vegetation modifications in this zone, however, do provide access and a safer means of protecting a home when firefighting resources are available.

Our analysis relied upon aerial photo interpretation, and we could not assess surface fuels under dense tree canopies. As a result, and because of the likely indirect effect of leaf litter coming from the canopy, we caution against using cover percentages in the decision trees as forest thinning targets. Furthermore, surface and near-ground live fuels are considered the priority for altering fire behavior and influencing fire hazard (Agee and Skinner 2005). Higher canopy cover may be correlated to the rate of surface litter and woody fuel accumulation but does not necessarily directly translate to high fire hazard if these surface fuels are managed and maintained at low levels. In other words, higher overstory canopy cover can provide important amenities (e.g., shade, habitat—Gibbons et al. 2018) without undue fire hazard as long as the resulting litter and surface fuels are maintained and gutters are cleaned. Gibbons et al. 2018 also noted that patchiness and arrangement relative to prevailing winds can also reduce threat posed by near-home vegetation.

Did the adoption of Chapter 7A into the California Building Code influence survival?

While the survival rate for homes built in the 11 years after the adoption of Chapter 7A to the California Building Code in 2008 was numerically slightly higher than the survival rate of homes built in the 11 years immediately before, the difference was not statistically significant. It is possible that significance might have been found with a larger sample size, but even so, any influence of the building code update was likely overwhelmed by other factors. This was not a surprise because of the many interacting variables that affect building performance, in addition to building products rated to resist exterior fire exposures. The 2008 Chapter 7A building code update institutionalized several important and worthwhile changes to construction in high fire hazard zones, including the use of ember and flame-resistant vents. These changes may improve the probability of survival for some types of wildfire (e.g., vegetation and wind-driven fires); however, the changes were apparently not sufficient to fully protect buildings from radiant heat exposures from nearby burning structures. One of the primary mechanisms for radiant heat impact is the breaking of window glass, which can allow embers to enter the building (Penman et al. 2019). A common method for complying with Chapter 7A is through the use of tempered glass in one pane of a double-paned window. However, the magnitude of radiant heat exposure was likely still too much in many cases, or other vulnerabilities remained.

Variation in factors contributing to home loss across construction time periods

In models for predicting survival, the significant interaction of several of the potential explanatory variables with construction time period suggested that factors most strongly influencing home vulnerability differed for homes of different ages. Homes built in the most recent two 11-year periods (1997–2007 and 2008–2018) survived at a significantly higher rate than homes built prior to 1997. Factors potentially contributing to this increase include trends towards a longer average distance to the nearest structure and nearest destroyed structure, and a larger average lot size. Newer homes had lower pre-fire overstory canopy cover in the immediate vicinity (0–30m), whereas the older homes tended to be concentrated near the center of Paradise, where pre-fire overstory tree cover was higher. The two most recent construction time periods also saw changes in building construction including roofing materials having longer periods of robust performance (i.e., 30–50 years of service life), double-pane windows (as a result of changes to the energy code), and increased use of noncombustible fiber-cement siding. Many of these improvements, which potentially make newer homes less vulnerable to wildfire exposures, occurred well before the 2008 Chapter 7A update to the building code. Older homes may also have developed vulnerabilities resulting from overdue home maintenance. We speculate that with a higher proportion of newer homes surviving the ember onslaught, outcome then depended to a greater extent on degree of radiant heat exposure from nearby burned structures. This hypothesis is supported by the much stronger influence of distance to nearest burned structure and the number of structures burned within 100 m for newer (1997 and after) than older <1997) homes. A substantially lower proportion of older homes survived regardless of the distance to or density of nearby burned structures, suggesting other vulnerabilities (such as maintenance issues). Another factor that may have increased the survival probability of newer homes was simply less time for occupants to accumulate combustible items on their properties (e.g., sheds, stored objects, wood piles, play structures). The difference between distance to nearest home and distance to nearest structure was much greater for older than newer homes (data not shown), indicative of structures such as sheds, detached garages, or other outbuildings being added to properties over time. Our summary of damage location and cause for damaged homes as well as first-hand accounts (Maranghides et al. (2021); N. Wallingford, personal communication) indicated such non-vegetative items were frequently ignited by embers and the reason for a flame impingement exposure.

Difficulties in post-wildfire interpretation

A primary challenge in determining the potential causes for building survival after wildfire can be the variation in fire behavior experienced. The Camp Fire was no exception, with considerable observed differences in fire spread rates driven by ember-ignited spot fires, along with complex topography and local variation in wind speed (Maranghides et al. 2021). However, the Camp Fire burning through Paradise in 1 day may still have provided a more homogenous burn environment than present in many other post-fire evaluations of home survival, most of which combined data across multiple fires in different geographic locations and years (e.g., Syphard et al. 2012, 2017; Alexandre et al. 2016; Penman et al. 2019; Syphard and Keeley 2019)). Another factor that can often complicate interpretation is variation in the extent of firefighter intervention (McNamara et al. 2019). In the case of the Camp Fire, with the focus of first responders initially on evacuation, relatively few homes experienced defensive action by firefighters or civilians (according to the DINS assessment, defensive action was noted for only seven of the 400 randomly selected homes (1.7%), six of which survived). More broadly, while similar factors as those analyzed in this study may be pertinent in other wildfires, it is important to recognize that the variables identified here were specific to the housing, vegetation, and topographic conditions found in Paradise and may not apply elsewhere.

Determining pre-fire structural characteristics post-fire is difficult and availability of such data is generally limited (Syphard and Keeley 2019). Details about near-home vegetation, especially within the first 1.5 m of the structure, which has been shown to be an especially vulnerable location for ember ignition, were not available. We were also not able to quantify the presence and distance to small sheds and other storage structures, the age and condition of the roofing, or individual residents' maintenance practices. The DINS data (e.g., extent of vegetation clearing for defensible space, siding type, type of window glass (single or multi-pane), deck construction, and presence of attached fencing) have value, but missing data and lack of information for structures not damaged or destroyed limit the utility for some analyses. We instead focused on variables that could be consistently evaluated on every home, such as pre-fire overstory canopy cover and distance to the nearest destroyed structure. Our vegetation variables were, however, coarse, and likely missed factors that contributed to home survival.

Lastly, for the damaged home cause and area of damage summary, it is important to acknowledge that the vulnerabilities may differ for damaged and destroyed homes. With evidence for what contributed to loss no longer available for destroyed homes, damaged homes provide a picture of the different vulnerabilities, but the relative contribution of factors involved may not be the same.

Conclusions

The results of this study support the idea that both proximities to neighboring burning structures and surrounding vegetation influence home survival with wildfire. Denser developments, built to the highest standards, may protect subdivisions against direct flame impingement of a vegetation fire, but density becomes a detriment once buildings ignite and burn. Recent examples of losses in areas of higher density housing include the wind-driven 2017 Tubbs Fire in northern California, where house-to-house spread resulted in the loss of over 1400 homes in the Coffey Park neighborhood (Keeley and Syphard 2019), and the wind-driven 2020 Almeda Fire in southern Oregon, which destroyed nearly 2800 structures, many in denser areas in the towns of Talent and Phoenix (Cohen and Strohmaier 2020). Once fire becomes an urban conflagration, proximity to nearby burned structures becomes especially important because occupied structures contain significant quantities of fuel, produce substantial heat when burned, and are a source of additional embers. For density to be protective, home and other structure ignitions would need to be rare. Fifty-six percent of homes in Paradise built during or after 2008 did not survive, illustrating that much improvement is needed in both current building codes and how we live in wildfire prone WUI areas before proximity to nearby structures becomes a benefit rather than a vulnerability. The threat posed by nearby burning structures as well as our finding of an apparent strong influence of vegetation 30–100 m from the home—a distance that in most cases encompasses multiple adjacent properties—demonstrates that neighbors need to work together to improve the overall ability of homes and communities to resist wildfire exposures.

To maximize survivability, homes need to be designed and maintained to minimize the chance of a direct flame contact, resist ember ignition, and survive extended radiant heat exposure. Our analyses demonstrating the strong influence of nearby burning structures on home survival suggests improvements to resist radiant heat exposures may be warranted in the California Building Code—i.e., increasing the standards for buildings within a certain minimum distance of other structures. Some possible improvements might include noncombustible siding with rating minimums tied to proximity to other structures, both panes in windows consisting of tempered glass, or installation of deployable non-combustible shutter systems. Additionally, certain options for complying with Chapter 7A are better for resisting radiant heat and flame contact exposures and could minimize fire spread to other components. Whereas the International Code Council's Wildland Urban Interface Building Code (International Code Council 2017) provides three ignition-resistant construction classes to allow for material restrictions as a function of exposure level, Chapter 7A consists of one level, so is binary in nature in that a building either needs to comply, or it does not. The Australian building code for construction in bushfire prone areas, AS 3959 (Standards Australia 2018), incorporates six different construction classes based on anticipated radiant heat, flame, and ember exposure levels. Interaction between components, for example, siding, window, and the under-eave area on an exterior wall, is not considered.

Our summary of damaged but not destroyed homes in Paradise was in line with other reports showing a high proportion of home ignitions indirectly resulting from embers (Mell et al. 2010). Embers frequently ignited near home combustibles such as woody mulch, fences, and receptive vegetative fuels with flames and/or associated radiant heat then impacting the home itself, supporting awareness of the importance of combustibles within the first 1.5 m (5 ft) of the building on home survival. A re-interpretation of defensible space fuel modifications is needed to increase the building's resistance and exposure to embers and direct flame contact, especially in the area immediately around a building and under any attached deck or steps. This does not diminish the value of defensible space fuel modifications 9 to 30 m (30 to 100 ft) away from the home, which not only reduces fuel continuity and the probability of direct flame contact to the home, but also provides firefighters a chance to intervene.

While our data show a relationship between home loss and vegetative fuels (high pre-fire overstory canopy cover likely associated with a greater litter and woody fuel abundance, as well as other wildland understory vegetation) that can contribute to fire intensity and ember generation, the WUI fire loss issue has been described as home ignition problem more so than a wildland fire problem (Cohen 2000; Calkin et al. 2014). The damaged home data were in line with this view, with few homes showing evidence of continuity with wildland fuels that would contribute to flame impingement, but numerous homes with near home fuels, both from manmade and natural sources, that led to direct or indirect ember ignitions.

California's Mediterranean climate will continue to challenge its residents with regular wildfire exposure throughout the state. Whether through modifying the nearby surface and vegetative wildland fuels or the home itself, adapting to wildfire will take time. The good news is that the trend in survival is improving with newer construction practices. However, with 56% of houses built after 2008 still succumbing to the Camp Fire, much room for improvement remains. Our data suggest it is possible to build (and maintain) buildings that have a high probability of surviving a worst-case scenario type of wildfire, even in fire-prone landscapes such as the Paradise area. Newer homes built after 1972, where the nearest burning structure was >18 m away, and fuels associated with vegetation 30–100 m from the home kept at moderate and lower levels (<53% canopy cover) had a 61% survival rate—an approximately 5-fold improvement over the Paradise housing population as a whole. Survival percentages substantially higher still are potentially possible if all components of risk, including ember generation in nearby wildland fuels, continuity of wildland and other fuels on the property, and home ignitability are sufficiently mitigated.

Abbreviations

DINS: Damage inspection; WUI: Wildland urban interface

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s42408-021-00117-0.

Additional file 1: S1 Table. Raw data for the random sample of 400 single-family homes in Paradise.

Additional file 2: S2 Table. Summary of fire damage cause and damage location for damaged by not destroyed single-family homes in Paradise.

Additional file 3: S3 Text. Metadata for the two data tables used in the analyses for this paper.

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Authors' contributions

EK, YV, and SQ developed the research questions and designed the study, with statistical guidance provided by NJ. Statistical analyses were performed by NJ and EK. All authors contributed to writing the manuscript. The authors read and approved the final manuscript.

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Availability of data and materials

All data generated or analyzed during the study are included in the published article and its supplementary information files.

Declarations

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Not applicable.

Consent for publication
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Competing interests
The authors declare that they have no competing interests.

Author details
[1]U.S. Forest Service, Pacific Southwest Research Station, 3644 Avtech Parkway, Redding, California 96002, USA. [2]University of California Cooperative Extension, 5630 South Broadway, Eureka, California 95503, USA. [3]University of California Cooperative Extension (Emeritus), Mill Valley, California, USA. [4]U.S. Forest Service, Pacific Southwest Research Station, 800 Buchanan Street, Albany, California 94710, USA.

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