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The importance of building construction materials relative to other factors affecting structure survival during wildfire

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ABSTRACT

Structure loss to wildfire is a serious problem in wildland-urban interface areas across the world. Laboratory experiments suggest that fire-resistant building construction and design could be important for reducing structure destruction, but these need to be evaluated under real wildfire conditions, especially relative to other factors. Using empirical data from destroyed and surviving structures from large wildfires in southern California, we evaluated the relative importance of building construction and structure age compared to other local and landscape-scale variables associated with structure survival. The local-scale analysis showed that window preparation was especially important but, in general, creating defensible space adjacent to the home was as important as building construction. At the landscape scale, structure density and structure age were the two most important factors affecting structure survival, but there was a significant interaction between them. That is, young structure age was most important in higher-density areas where structure survival overall was more likely. On the other hand, newer-construction structures were less likely to survive wildfires at lower density. Here, appropriate defensible space near the structure and accessibility to major roads were important factors. In conclusion, community safety is a multivariate problem that will require a comprehensive solution involving land use planning, fire-safe construction, and property maintenance.

1. Introduction

With recent increases in wildfire frequency and extent [37], structure loss to wildfires has become a growing problem in fire-prone ecosystems worldwide (e.g., [3,51,47]). In addition to structure loss, increasing wildfire activityconnotes a much wider range of economic, social, and ecological issues, such as loss of human lives, exorbitant firefighting expenses, and impacts to biodiversity. Unfortunately, future projections suggest that these losses are likely to continue, or even worsen, due to the potential for increased fire activity resulting from climate change [26], coupled with ongoing housing development within and adjacent to wildland areas i.e., the Wildland Urban Interface (WUI) [42].

Given the serious nature of this ongoing problem, a growing body of research has focused on understanding the factors that influence community vulnerability to fire, and in turn, identifying those land management practices that may provide the best protection against structure loss [17]. Historically, fuels-based hazard assessments and the use of fuels management for protecting communities have been the central focus of study [16,44], but recent research has contributed to a growing recognition that community safety is a function of a large suite of variables, which when considered together, may lead to the most effective management [18,35,9]. For example, studies now show how land use decision-making [47,48,7], defensible space and homeowner preparation [11,49,8], and ignition prevention strategies [10,39,46], can complement traditional management actions of fire suppression and fuels management.

Another factor that is broadly recognized as critical for preventing structure loss to fire is the design and materials used in the building's construction. That is, the physical attributes of a structure confer ignitability either through flames and heat [12] or via embers produced during wind events, which can blow 1–2 km ahead of a fire front [41]. In fact, it is these embers that are most responsible for homes igniting during wildfires [25,29,41,43].

In many regions, building construction standards are now being incorporated into policies regulating new housing development (e.g., http://www.fire.ca.gov/fire_prevention/downloads/2007CaliforniaBuildingCode.pdf, http://www.nash.asn.au/nash/publications/nash-standards accessed 11/4/16,). Many of these standards are based on test results from laboratory experiments in

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which different wall, window, roofing, or deck materials are exposed to heat fluxes from flaming fronts [4,33]. Tests are also being developed to evaluate the potential for firebrand ignitions of different materials, design, and construction choices under simulated wind conditions (e.g., [27,28]).

While the data resulting from these lab tests are critical for understanding fire resilience of different materials, there nevertheless has been little empirical research examining the role of structural attributes in home survival during actual wildland fires, where a wide range of other conditions are present. Thus, systematic study using empirical pre- and post-fire data has been identified as critical research needed for better understanding structure loss at the WUI, particularly in terms of the relative effectiveness of building design materials, relative to other factors such as defensible space and housing density [33]. Different components of building structure and design may also vary in their importance for structure survival.

In previous work, we developed an extensive geographical database of homes destroyed and unburned during wildfires and analyzed the data relative to a range of local and landscape factors explaining structure loss to wildfire (e.g., [47,48,1]). Despite the comprehensive nature of the dataset, it lacked information on the physical attributes or age of structures. Thus, for this study, we acquired site-specific data on building construction materials for a subset of homes in this dataset that were either destroyed or survived exposure to wildfires. We also attained year of construction, an indirect measure accounting for all building construction material and design, for a larger proportion of the dataset of burned and unburned homes [49]. This information allowed us to evaluate the role of building construction in structure survival during wildfires, particularly relative to other important local and landscape factors.

Using two different datasets, one a subset of the other, we conducted analyses at both local and landscape scales. Using the dataset for which we obtained specific construction material information, we evaluated the role of local-scale factors associated with homeowners' properties to answer:

1) Which feature in building construction is most important for structure survival?
2) How does the importance of building materials compare to defensible space variables?

In addition, we used a larger, more geographically expansive database with structure age information, to answer the question:

1) How important is structural design (as determined by age) when compared to a full suite of local and landscape factors known to affect structure loss?

2. Methods

2.1. Study area

The study area encompassed a portion of San Diego County, CA, USA extending from the coast through the foothills and mountains (Fig. 1). During the last decade, thousands of structures were destroyed in a number of large fire events, and this region is where some of the highest housing losses to fires occurs in the world [22,23]. The area has a Mediterranean climate, with cool wet winters and hot dry summers, and at the end of a long summer drought, fuel moisture is very low in the fire-prone native shrublands. Periodic large, high-intensity crown fires are part of the natural fire regime, and these large fires are typically driven by an offshore flow of hot, dry Santa Ana winds that occur annually at the end of the summer drought. These are the fire events associated with the most loss in housing and lives [21].

Community vulnerability is due not only to the severe fire-weather conditions, but also to the extent and pattern of housing development, as there has been a trend of enormous expansion of low to medium-density housing into wildland areas [20]. These exurban housing developments are also located within complex terrain and may be more difficult to access by fire suppression crews; thus, low housing density has shown to be a major factor contributing to structure destruction in the region [47]. Given the vast extent of WUI in the region, many fire-safe councils and local organizations are strongly encouraging homeowners to appropriately prepare their homes and properties for better resilience to fire when it occurs (http://www.firesafesdcounty.org/home.aspx#, accessed 2/28/16).

The County of San Diego has been enforcing fire codes for building construction in the WUI since 1997, when it adopted a requirement for class "A" residential roof covering on new construction; which means that the roofing material must pass a relatively stringent series of fire tests (http://www.buildings.com/article-details/articleid/15175/title/the-abcs-of-roof-fire-ratings/viewall/true.aspx, accessed 2/27/16). Adopted in 2001 and made a requirement in 2002, the first comprehensive WUI code in the county required, in addition to the above, dual glazed/tempered windows, residential fire sprinklers, rated exterior construction, fire resistant decks and patios, no eave vents, no paper-backed insulation in attics, and 30 m (100 ft) vegetation modification around structures (Clay Westling, personal communication, 3/3/15). The WUI fire code has undergone minor revisions in 2004 and 2008 in response to the large fire events of 2003 and 2007. These regulations for fire-safe building construction are enforced through the issuance of building construction permits and approval of new subdivisions, and thus they do not apply to older homes.

2.2. Data assembly

The building construction data were collected during several damage assessments conducted by the County of San Diego Department of Planning and Land Use (DPLU) after the large fire events that occurred in October of 2003 and 2007. Although we did not have the information to account for the exact fire behavior at the time of structure exposure, the fire weather and environmental conditions were remarkably similar in both years. Both fire events occurred after extraordinarily long antecedent drought during severe Santa Ana wind conditions [22,23]. To perform these assessments, DPLU staff with a range of expertise in fire science, architecture, and engineering conducted site inspections and interviews to evaluate the degree of structure damage or destruction and to record characteristics of the properties.

Although documentation of destroyed structures in the 2003 Cedar Fire accounted for the majority of the data collection, DPLU teams also collected some information on structures that were unburned or had only experienced minor damage. The number of homes inspected equaled approximately one-third of the homes destroyed in that fire. After the fires of 2007, a more concentrated effort was focused on collecting information on homes that survived fires in addition to those that were destroyed. For these assessments, the DPLU evaluated a random sample of homes that survived within areas where many other homes had been destroyed, allowing for comparison among properties with similar exposure and fire behavior, but different outcomes. Although we included all of these data in our analysis, we simplified the classification of outcome so we could conduct a comparative analysis with a binary outcome of survived or destroyed. Thus, we specified structures with minimal damage to belong with the unburned homes, and labeled them "survived." We grouped those with moderate damage with the "destroyed" structures. Although minimal and moderate damage to homes was not quantitatively determined, the number of structures in these two categories only comprised eight percent of the dataset.

From the DPLU data available in the 2003 and 2007 assessments, we focused on four structural characteristics that are considered

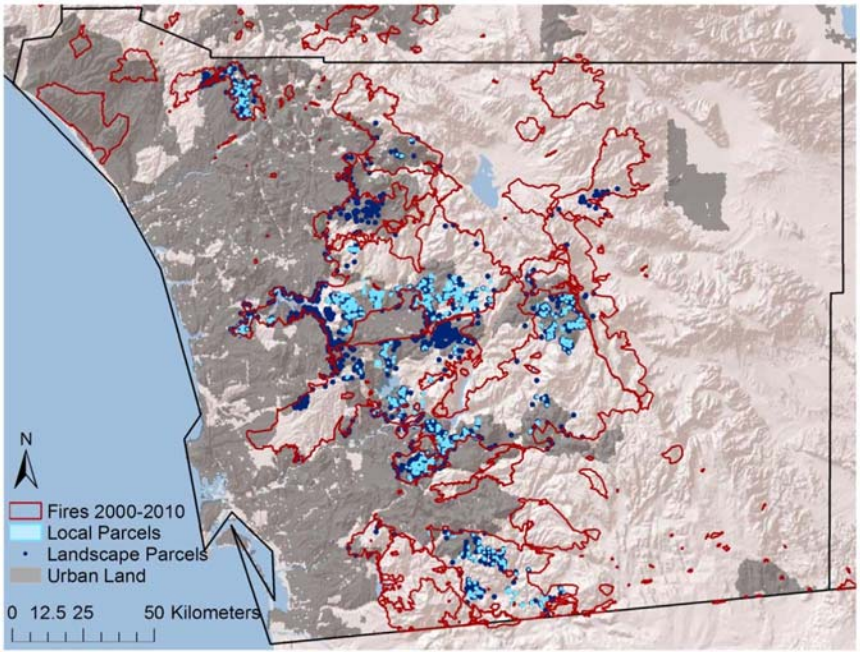

Fig. 1. Study area showing fire perimeters between 2000–2010 and the location of parcels analyzed at the local and landscape scales.

important factors in home safety, which include including exterior construction material; roofing material; window pane type; and window frame material [41]. For each variable, we created a categorical classification that we felt best represented the range of variation in the data, while minimizing the number of categories. Therefore, we identified the most common material types for each variable, and either combined other, similar material types with those or put them into an "other" class (< 1% of the data). For exterior construction material, most structures were classified as having either "wood," "stucco," "metal," or masonry." If the material was described as "aluminum" or "steel," we labeled it "metal," and "brick," we combined with "masonry." If the structure was described as a combination of materials, we consistently labeled it with the first-named material (e.g., "wood/rock" was labeled "wood."). The most common roofing materials were "composite," "shingle," and "tile," but approximately five percent of the structures had either "metal" or "wood shake" roofs, and we kept those classes separate for the analysis. Window frame material was either "metal," "wood," or "vinyl," and window pane was either "single" or "dual."

All structure data from the DPLU assessment were assigned a corresponding unique parcel number, which we then were able to link with the spatial data and attributes of other explanatory variables we collected for prior research [47–49]. Because of the limited sample size and spatial extent of the building construction material data relative to our entire building dataset (1099 records with 163 having survived the fire), we focused exclusively on local-scale variables for our first analysis; that is, we compared the relative importance of different building material types to other factors like defensible space within the immediate vicinity of the home. Some of the structure data with building construction material had not been within our database of defensible space data [49]. Therefore, we employed the same methods as before to calculate defensible space for these additional properties. This involved analysis of pre-fire aerial photography to measure and map a suite of variables quantifying: the mean distance of defensible space from structure, percentage woody cover across property boundary, and distribution of defensible space around homes (i.e., number of sides on which woody vegetation touched the structure and whether or not vegetation was overhanging the roof) before they were exposed to fire. More specific details are presented in Syphard et al. [49].

To expand the dataset, we acquired information on the "effective year" of construction for a much larger sample of structures across the county. We obtained these data from the San Diego County Office of the Assessor/Recorder/Clerk. Although we will refer to this variable as structure age, "effective year" could sometimes signify the last year in which significant construction occurred on the property. Therefore, "effective year" was occasionally more recent than the original year the building was constructed. For these data, we again linked them with the larger defensible space dataset that encompassed a wider range of landscape-scale conditions [49]. The defensible space variables were the same as in the local dataset. We calculated the landscape-scale variables using the same spatial data as described in Syphard et al. [47,48,49], including interpolated housing density within a 1 km radius of each structure, percentage slope at the location of the structure derived from a 30 m digital elevation model, Euclidean distance to major and minor roads, and fuel type (landscaping, grass, shrubland, and forest & woodland). Previous studies showed that structures in the study area were most likely to be destroyed at low to intermediate housing density, on steep slopes, and at longer distances to roads. Fuel type was not shown to be highly influential. In total, we analyzed 1564 parcels for the landscape analysis, 929 of which survived.

2.3. *Analyses*

To help visualize which construction materials resulted in the most positive outcomes for structure survival, we calculated and plotted simple summary statistics describing the proportion of structures that survived within each class of the four building construction variables in the analysis. We also calculated the mean age of structures within these classes as a way of summarizing the primary characteristics of older versus newer homes in our dataset.

To estimate the relative importance of different factors influencing structure survival at both the local and landscape scales, we developed generalized linear multiple regression models, as in Syphard et al. [49], using a logit link and the binary response variable of a structure either surviving fire or being destroyed. For the local-scale dataset, our explanatory variables included the four characteristics of building construction in addition to percentage slope at the structure location and four important metrics of defensible space as described above. For our landscape-scale analysis, we substituted the four construction material variables with structure age, included the slope and defensible space variables used in the local-scale analysis, and added the landscape-scale variables described above.

We hypothesized there could be an interaction between structure density and age based on the lower-density spatial pattern of recent construction; although newer construction is expected to be more fire resistant, low-density housing in this region is also associated with higher likelihood of structure destruction in a fire [1,47,49]. Thus, we considered an interaction term between these variables in our analysis.

Because our primary objective for both datasets was to assess the relative importance of variables, and not to create a prediction, we did not employ any bias-correction techniques to account for the relatively lower prevalence of survived to destroyed structures. We used the package MuMln in R (version 1.15.6, [2]) to facilitate a comparison and ranking of all possible combinations of the explanatory variables in both analyses. Variable importance was determined on a scale of 0–1, which is derived from the sum of Akaike weights for all models containing each explanatory variable and represents the weight of evidence that the models containing each variable were in fact the best models [6]. We also reported the proportion of models (with delta < 4) that contained each of the explanatory variables.

In addition to the multiple-regression models to assess relative variable importance, we also developed a classification tree [5] to facilitate interpretation of the interrelationships among the landscape-scale explanatory variables, particularly because we expected a potential interaction between structure age and housing density. Classification trees are nonparametric tools that operate through a binary recursive partitioning process that iteratively evaluates a dataset relative to a dependent variable through a series of rules for dividing the data via different combinations of explanatory variables. The resulting classification tree is formed through the set of partitioning rules that best separate the data into homogenous classes [5]. These statistical models are particularly well-suited for analyzing and interpreting data that may include interactions or categorical variables, and the set of rules for partitioning data are useful for identifying thresholds [15]. They can also be represented graphically to visualize the structure of the data.

Using the rpart package in R (version 4.1–10, [45]), we built a full classification tree using structure survival as the binary dependent variable and the same set of landscape-scale explanatory variables that we used in the multiple-regression analysis. After building the full tree, we pruned it to reduce overfitting using an algorithm that automatically selects the complexity parameter associated with the smallest cross-validated error [52]. We used the R package rpart.plot (version 1.5.3, [34]) to plot the tree.

3. Results

Overall, some construction materials were more common than others, and there was variation in the amount of data available for the different construction variables analyzed (Table 1). Nevertheless, the plots of building construction variables revealed that there was one class for each variable that was clearly and substantially more favorable for structure survival than the others. Specifically, the largest proportion of structures survived with: vinyl window framing rather than metal or wood; stucco exterior construction rather than masonry, metal, or wood; dual pane windows rather than single; and tile roofs rather than composite, metal, shake or shingle (Fig. 2a). In all four cases, the building material classes with the largest proportion of surviving structures were also the ones with the youngest mean age of the structure, although the distinction wasn't as sharp for exterior construction material (Fig. 2b).

The all-subsets multiple-regression analysis of local-scale factors showed that, among the building construction materials, the two window variables were most important in explaining structure survival, followed by roofing and exterior construction material (Table 2). In fact, exterior construction was the least important of all the local-scale variables with roofing near the middle. At the local scale, vegetation modification on the property was nearly equally important as building construction. Properties with a positive distance of defensible space and a lack of vegetation overhanging the roof were within the same range of importance as the window variables. The total percentage explained deviance for the top-ranking model was low at 14%.

Table 1
Number of structures that survived or were destroyed within different classes of building construction materials.

Construction variable	Survived	Destroyed
Window framing material		
Metal	70	527
Vinyl	47	55
Wood	29	211
Window panes		
Single	56	463
Dual	85	220
Exterior construction material		
Masonry	6	58
Metal	1	17
Stucco	100	435
Wood	46	387
Roofing material		
Composite	60	526
Metal	2	22
Shake	1	9
Shingle	12	123
Tile	79	212

At the landscape scale, the multiple-regression analysis showed that the most important variables for explaining structure survival included a combination of local-scale and landscape-scale factors (Table 3). Younger structure age and higher structure density, and the interaction between these two variables, were among the top five most important explanatory variables. The other top two variables included a positive percentage clearance on the property and lower percentage slope. Vegetation overhanging the roof was almost as important as the top variables, followed by a negative distance to major and minor roads, fewer sides of the structure touching vegetation, and a positive distance of defensible space. The surrounding fuel type was the least influential variable. The top model had a percentage deviance explained of 21%.

The classification tree analysis showed that the variable that best differentiated surviving and destroyed homes was structure density (Fig. 3). Specifically, structure survival was most likely if the density was higher than 54 structures per km^2. For structures located within this density or higher, the next most important split of the data was structure age. Specifically, all homes with a structure density of at least 54 structures per km^2 and that were constructed within the last 30 years survived the fire. Survival of structures aged between 30 and 83 years old was further differentiated by slope and road variables. Structures older than 83 years old were destroyed.

On the other side of the classification tree, where structures were most likely to be destroyed with structure density less than 54 structures per km^2, percentage clearance of woody vegetation was the first most important factor to further subdivide the data. That is, structures with low housing density and less than 30% of the vegetation cleared were destroyed. Otherwise, if structures were at a low density, more than 30% of the vegetation was cleared, and less than half a side of the house had vegetation touching it, it survived. But if more than a half side of the house was touching any vegetation, structure survival further depended on a different density threshold and distance to a major road.

4. Discussion

The results of this study confirm the expectation that building construction and design play important roles in structure survival

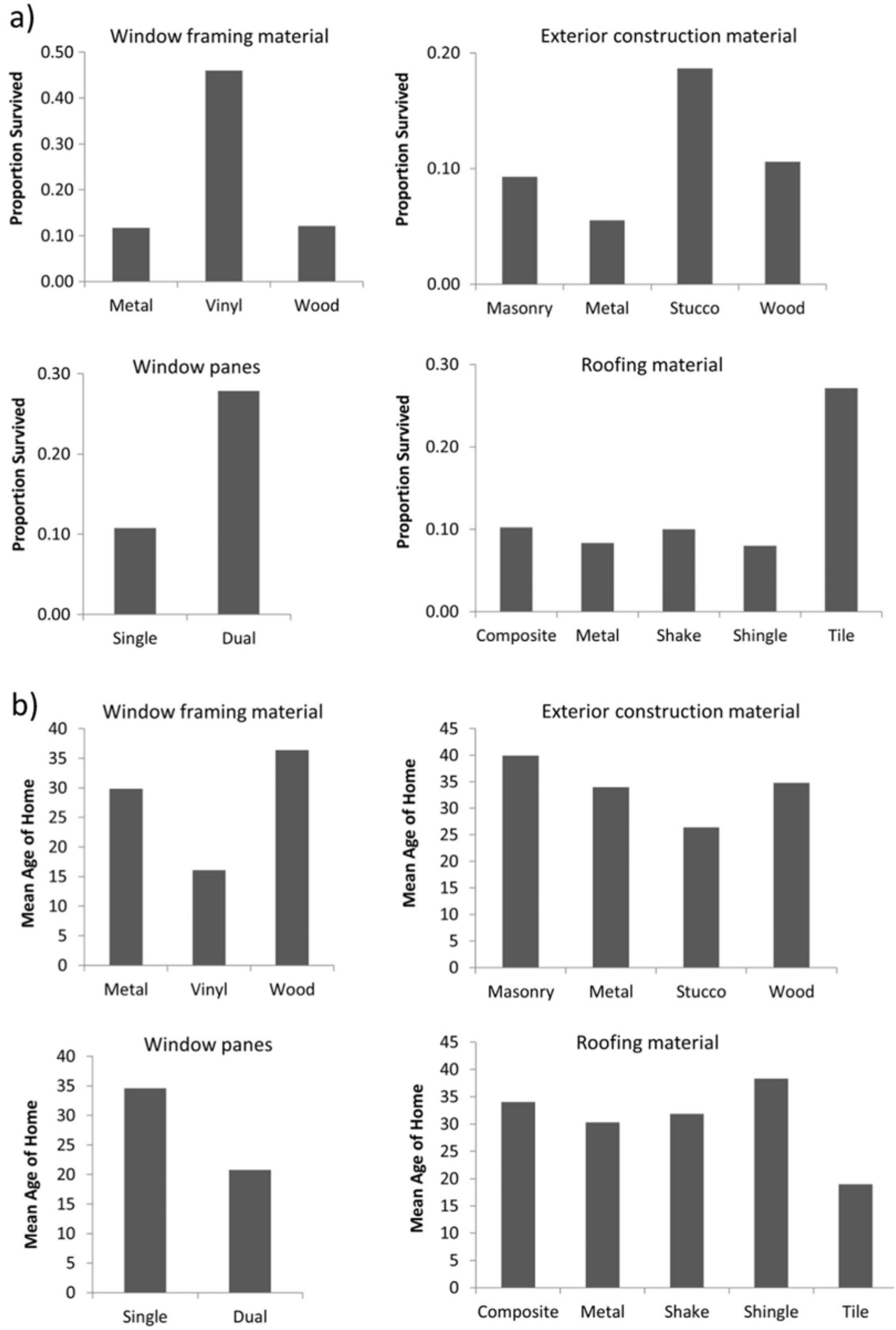

Fig. 2. Charts illustrating a) the proportion of structures that survived a fire relative to building construction factors, and b) the mean age of structures relative to building construction factors.

during large wind-driven fire events in San Diego County, CA. At both local and landscape scales of analysis, building construction or structure age were among the top variables explaining a structure's fate. Analyses at both scales also showed, however, that other factors such as vegetation modification on the property at the local scale, and the location and arrangement of structures at the landscape scale are equally if not more important than building construction. In addition, despite the wide range of factors considered here, the models nevertheless showed large percentages of unexplained variation, suggesting that even more factors are responsible for explaining structure loss. This underscores the complexity of the problem and illustrates the multivariate nature of community vulnerability to wildfire [17,18,33,35], and accordingly, points toward the need for a comprehensive planning approach to prevent structure loss at the WUI.

Table 2
Local-scale multiple-regression models explaining structure loss to wildfires. Model-averaged coefficients are not applicable (NA) for categorical variables.

Variable in order of importance	Relative variable importance*	Model-averaged coefficient	Proportion models containing variable
Window framing	1	NA	1
Distance defensible space	0.99	0.006	0.95
Window panes	0.91	NA	0.75
Vegetation overhanging roof	0.8	NA	0.66
Roofing material	0.6	NA	0.56
Percent clearance	0.45	0.002	0.49
Sides vegetation touching structure	0.31	−0.008	0.42
Slope	0.27	−0.001	0.41
Exterior construction material	0.04	NA	0.15
D2 of best model: roofing material +vegetation overhanging roof +window framing +window panes +distance defensible space			0.14

Table 3
Landscape-scale multiple-regression models explaining structure loss to wildfires. Model-averaged coefficients are not applicable (NA) for categorical variables.

Variable in order of importance	Relative variable importance*	Model-averaged coefficient	Proportion models containing variable
Structure density	1.00	0.0048	1.00
Structure age	1.00	−0.0204	1.00
Percent clearance	1.00	−0.01	1.00
Slope	1.00	0.0348	1.00
Structure density*Structure age	1.00	0.0003	1.00
Vegetation overhanging roof	0.90	NA	0.67
Distance to major road	0.62	−0.0001	0.67
Sides vegetation touching structure	0.47	−0.0008	0.50
Distance to minor road	0.32	−0.0012	0.42
Distance defensible space	0.30	0.0218	0.42
Fuel type	0.01	NA	0.04
D2 of best model: structure density +structure age +structure density*structure age +percent clearance +slope+vegetation overhanging roof +distance to major road			0.21

Within the data we examined at the local scale, structure survival was explained substantially better with homeowner preparation of windows than with roofing or exterior construction, but roofing was ranked as more important than exterior construction. Although the material used in exterior construction varied in terms of fire resistance (in this case, stucco was superior) and could reduce home ignition or house-to-house spread, other construction factors are generally considered more important than a home's siding [41]. On the other hand, roofing is considered to be very important in fire-safe construction

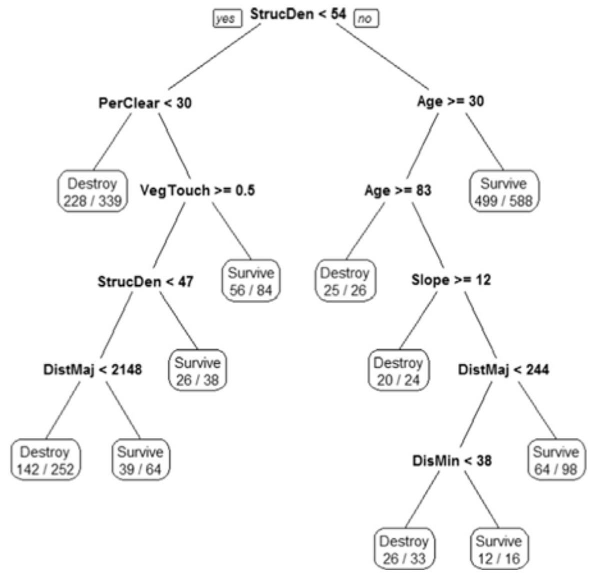

Fig. 3. Classification tree depicting the structure of landscape-scale factors associated with homes surviving wildfires in San Diego, CA. The number of correct classifications and the number of observations are displayed in each terminal node.

[41]; thus, one caveat to our study is that we only looked at the primary material used for the roof covering. There are other components to roof design that may also be important, such as the edge, the roof complexity, or whether the roof was treated with a fire retardant [41].Especially important is the susceptibility of the roof or gutters to accumulate combustible leaf litter or debris [24,41]. Also, despite the fact that structures with tile roofs were most likely to survive fire in this study, those roofs could be problematic if not sealed, as they could allow ember entry into the roof cavity.

For residents living in existing, older developments, who need to prioritize which actions they can take to retrofit their homes, our analysis suggests that treating the windows should be among the first updates to consider. One reason for this is that windows provide an easy point of entry for firebrands or embers [4]. Dual pane rather than single pane windows provided significant protection to the structures in this study, and the importance of multi-paned windows, particularly in protecting against thermal exposure, has been recognized in other research [14,31,4]. Bowditch et al. [4] showed that the performance of window systems depended mainly on the type of glass, the frame, and the seal. Plain glass (annealed) would crack at 12 kW/m2 while toughened glass can resist up to 40 kW/m2. Double glazing can be made from one or the other, or a combination of glass, and their resistance will depend on the resistance of the most resistant glass type.

The data in our study also show a clear advantage to having vinyl rather than metal or wood framing material. Although vinyl has a lower melting point and ignition temperature than aluminum, it did not perform well in lab tests [36]. This may be due to the fact that the testing involved radiant heat exposure rather than direct flame contact with an ember or firebrand. As such, it could be beneficial to do additional study on the role of window framing relative to exposure to firebrand or ember attack. Other studies show that the issue with vinyl may have instead been due to separators in the middle of the window [40,41]. Thus, its importance here could also be related to its association with newer construction in general, in which there are fewer gaps and entry points to the inside of the home.

The variables considered here are only a subset of the components of building construction and design deemed important for structure survival, and other construction factors could play a major role in house survival rates [41]. In addition, given the low overall explained deviance in the local-scale model using individual construction materials, the relative importance of different materials in this analysis should be interpreted with some caution. Nevertheless, the results also highlight how there is a relative difference in effect among different factors deemed important for protecting the home. At the local level, homeowners are typically guided to perform a series of actions to reduce their fire risk without knowing which action will be most effective relative to the cost and ease of adequately performing that task [32,38]. This is in part due to the lack of empirical data available to quantify those differences in the presence of a real wildfire situation difference [33]. Thus, knowing these relative differences can be helpful in prioritization.

The data in our study show that newer buildings are more likely to be constructed using the materials and design that our data show to be empirically associated with structure survival. This is an encouraging sign for newer construction in the region, and it helps to explain why structure age was one of the most important variables in the landscape-scale analysis. Clearly, building ordinances adopted by the county are effectively changing the design of new housing to become more fire resilient. Nevertheless, while the San Diego County adoption of fire-safe building codes started in 1997, the classification tree analysis suggested that structures fewer than 30 years old had the highest likelihood of survival in high-density areas. Thus, it is possible that newer homes are becoming more fire-resilient despite the adoption of building codes. On the other hand, the protective effect of newer homes, may not be totally due to their construction material, as older housing developments also tend to have older, more flammable landscaping with higher plant biomass located close to the homes [24]. Other changes in regulations, such as for energy efficiency or safety, could also indirectly affect the design and fire safety of a structure.

Despite the clear improvement in fire-resistance of construction in the county, the landscape scale analysis also demonstrated how the location and arrangement of the home can override the protective benefits of fire-safe structure design, and accounting for these factors may explain why the landscape model produced a better fit. This was evident through the top ranking of structure density and the interaction term with age in the multiple-regression models, and was clearly illuminated via the graphical depiction of the classification tree results. In classification tree analysis, the variables most important for explaining the response are those which are located closest to the top; that is, the first split of the data provides the best prediction of the response outcome [15]. In our landscape scale analysis, therefore, the classification tree shows that the single most important determinant of a structure's survival is the surrounding density of homes.

This result, that structure density is so strongly correlated with structure survival, is consistent with other studies in this region [1,47,49] or other regions [1]. What is different in this study, however, is the finding that housing location and pattern may be even more important than fire-safe construction and homeowner preparation. Clearly, local-scale factors are critically important, but the significant implication is that homeowners could do everything correctly to prepare their house for fire safety, but if the structure is located in a hazardous setting, none of these actions may be enough.

There may be multiple reasons for this strong correlation between structure density and fire risk. At low-to-medium housing density, homes are interspersed within larger, more connected areas of wildland vegetation and are thus more exposed to a wildfire if it occurs [1].; fire frequency does tend to be highest in these lower-density locations. Another probable explanation is the ease of fire suppression and defensive actions. Lower-density, rural developments may be more difficult and expensive to access, and they may not be prioritized over larger, high-density developments with larger numbers of home at stake [19]. This is likely why distance to major road was one of the important criteria for low-density structure survival in the classification tree analysis. Another consideration is that, at least in our study area, lower-density development is likely to be located in areas with more complex terrain, which may also increase fire hazard [23].

Although structure destruction is most likely in low to medium density development across the landscape, there may be a threshold in some communities at which very high- density development can also become a hazard. For example, Alexandre et al. [1] found that, within one of the communities in our study area, small housing clusters with large numbers of buildings had a high probability of structure destruction. The likely reason is that houses very close to one another may be susceptible to home-to-home fire spread [13,41]. The potential for this happening may not only depend upon the flammability of the structures but could also be a function of the landscaping that connects the homes together.

The importance of defensible space for structure survival was evident at both scales of analysis, although the relative importance of the variables was slightly different at local and landscape scales. For example, although the distance of defensible space was important at the local scale, this variable was barely important across the landscape, where percent clearance and vegetation overhanging the roof were more important. This difference could reflect the smaller sample size of the local analysis or simply reveal how these variables compare when combined with a different set of predictors. In all cases, however, the most important variables support the findings in Syphard et al. [49] that the most important component of defensible space preparation is to focus on the vegetation immediately adjacent, touching, or overhanging the structure. Even for the low-density structures, the threshold of percent clearance in the classification tree was 30%, meaning a homeowner could leave up to 70% of the woody vegetation on the property and still maintain adequate protection. The key is to do the clearance close to the structure.

In addition to the variables considered here, there are a number of other factors that may explain structure loss to wildfire that we did not explore. For example, case studies have shown that fire and ember exposure can vary greatly within communities at relatively small scales [29,30]. That is, fine-scale variation in aspect, slope, and location of the house relative to prevailing wind conditions, outbuildings, and the defensible space of neighboring homes can all factor into the outcome. The relationship to exposure may be why slope was such an important variable in the landscape-scale analysis but not the local-scale analysis, where the investigation teams tried to control for exposure in their sampling design. Furthermore, defensive actions taken by firefighters were not accounted for in this study but may have played a significant role in saving structures, although effectiveness of defensive actions has also been shown to vary based on the exposure of the structure [30]. Another factor that may be important is irrigation of ornamental vegetation due to its effect on fuel moisture and flammability [30].

In conclusion, as we move into a future that will likely bring more hazardous wildfire conditions due to some mixture of climate change and development patterns, this study demonstrates the importance of considering community vulnerability in a multivariate framework. That is, structure survival is not just a function of one or two variables; it is a product of multiple factors coming together at any point in time [30]. While all factors merit consideration, comparing the relative importance of many variables at multiple scales suggests that attention to some factors may be more effective than others. Thus, careful consideration will be needed in determining which management actions should be prioritized given limited time and resources. Land use planning [48,7,50] and ignition prevention [46] likely represent the most effective long-term solutions, and continuation of the traditional management actions of fire suppression and carefully planned strategic fuel breaks will also play a role. Although land use planning may be an effective way to reduce hazardous construction patterns or locations in the future, homeowners in existing developments will need to consider the best way to increase their resilience to wildfire should it occur. To protect existing homes, it may be important to first consider the location, in low or high density, and then to identify an appropriate combination of construction retrofitting and defensible space.

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