1   **Title: An Analysis of Factors Influencing Structure Loss Resulting from the 2018 Camp Fire**

2   **Running Head: Camp Fire Structure Loss**

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Abstract:

Despite the intensity of the 2018 Camp Fire, many structures survived in heavily burned areas. Logistic

regressions were run to determine which structural and parcel characteristics predicted structure survival

using two data sets. The first, CAL FIRE's Damage Inspections (DINS) dataset, included 14,518

destroyed and 622 partially damaged structures. The second, combining information from the DINS and

Defensible Space (DINS+DSPACE) databases, had many more attributes and was better balanced

between destroyed (n=728) and surviving (n=676) structures but was much smaller. Several approaches

were compared for filtering out records with null values. Results were largely consistent with previously

literature, finding that structural hardness factors (e.g., double-paned windows, enclosed eaves, ignition-

resistant roofs and siding, no vents, etc.) are important in determining structure survival. Newer

structures, built after California's recent (2005 and 2007) fire safe building code updates, were more

likely to survive, as were homes with higher improvement values. Mobile homes were far more likely to

be destroyed. The role of fuel mitigation around structures was less conclusive; defensible space

clearance had only a weak association with structure survival although DINS+DSPACE results suggested

a slight reduction in risk due to removing leaves and needles from gutters/roofs and keeping surrounding

dead grass mowed.

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Background and Literature Review:

The Wildland Urban Interface (WUI), where houses and flammable wildland vegetation occur in

relatively close proximity, is the landscape with the fastest rate of residential growth in the country,

resulting in the exposure of far more properties to wildfire hazard than ever before (Radeloff et al., 2018).

Given this uneasy coexistence, it is critical to understand how risk to structures and inhabitants can best

be assessed and mitigated.

39 When major wildfires occur, property damage can be quite heterogeneous, . in a pattern that might

40 initially seem random. But, in fact, structure ignition is often directly attributable to the characteristics of

41 the structures themselves and their immediate surroundings, which modeling has identified as within 40

42 meters of a structure (Cohen, 2000).

43 In most WUI fires, homes are typically lost more frequently due to ember casting than to the fire front

44 itself. For instance, in the Grass Valley Fire in 2007, of 199 structures destroyed, only 6 were destroyed

45 by the fire front directly, while the other 193 were destroyed by direct intrusion of firebrands/embers or

46 by spread from immediately adjacent surface fuels ignited by embers (Cohen & Stratton, 2008).

47 Given this, it is not surprising that much of the literature has found that predictors of structure survival

48 frequently relate to "structural hardness," or features that prevent penetration of embers or flame. Syphard

49 and Keeley (2019) found that enclosing of eaves, the presence of vent screens, and use of multi-paned

50 windows are the strongest predictors of structural survival because they prevent wind-borne ember

51 penetration into structures which, they contend, is the most common mechanism by which fire destroys

52 homes in their California study regions. By comparison, structural features that do not address ember

53 penetration, like fire-resistant siding and combustibility of roof material, were found to have less impact

54 on structural survival, although they were still statistically significant. Syphard et al. (2017) found that

55 material type for many of these features was also predictive; vinyl framed windows performed better than

56 wood framed windows, tile roofs performed better than metal, shake, shingle or composite, and stucco

57 siding performed better than masonry, metal or wood. The better-performing materials tended to be more

58 prevalent in newer structures, making age correlated with probability of survival.

59 Fuel treatments are widely considered to mitigate the spread and intensity of wildfire when they are

60 appropriately placed and designed (Agee et al., 2000; Finney et al., 2007). However, the extent to which

61 individual defensible space clearance and fuel reduction on properties can protect structures is less well

62 understood. Fire behavior simulation models have predicted that defensible space clearance in the home

63 ignition zone can reduce fire intensity and flame length (Braziunas et al., 2021). A simulation model

64   found that defensible space can significantly reduce the chance of structure loss, but only given certain

65   conditions, including presence of a non-flammable roofs and of landscape treatments that are able to

66   keep flames and firebrands at least 40 meters from the structure, as well as the absence of long-distance

67   ember casts (Cohen, 2000), all of which limits the study's generalizability.

68   Empirical studies are mixed in terms of the relationship between defensible space and structure loss.

69   While removal of immediately overhanging or abutting woody vegetation was found to measurably

70   increase structure survival in several studies (Syphard et al., 2014, 2017), the effect on home survival of

71   vegetative clearance in the larger defensible space zone is less clear. One study found a significant effect

72   for defensible space treatments between 5 and 20 meters from the structure, but not at distances greater

73   than 30m (Syphard et al., 2014) while another found the effect of defensible space to be negligible across

74   numerous California case studies regions, except one (Bay Area), where only a slight effect was found

75   (Syphard & Keeley, 2019). Yet another study found that landscape-level vegetation was a better

76   predictor of structure loss than vegetation at the granular scale of defensible space (Syphard et al., 2021).

77   Similarly, Knapp et al (2021) found that while vegetation in the 0-30 meter defensible space zone did not

78   significantly predict home survival, there was a strong correlation between vegetation cover and home

79   survival in the 30-100 meter zone. Contrasting those findings, a study by Schmidt (2020) of four

80   California wildfires found that structure loss rates increased in association with vegetation cover for a 25

81   meter zone immediately surrounding the structure in three of the four fires studied, including the Camp

82   Fire. Similarly, a study from Australia found that vegetation within 20 meter of a structure was more

83   predictive of structure loss than tree cover within 100 meters (Penman et al., 2019).

84   Vegetative composition around homes has been found to be predictive too. In Australia, Gibbons et al.

85   (2012) concluded that the likelihood of structural survival was positively associated with the proportion

86   of vegetation surrounding the structure that was planted, as opposed to naturally occurring or remnant

87   vegetation, which were associated with greater structure loss. They also found that increased tree cover

88   percentage within 40 meter of the structure decreased structure survival likelihood.

89   Topography has also been found to be a key site factor in structural survival (Alexandre et al., 2016;

90   Syphard et al., 2014), given that ignition probability is higher on drier south-facing slopes (Haire &

91   McGarigal, 2009) and that steep slopes can increase the speed of fire spread (Finney et al., 2010) as well

92   as the difficulty of defensive action (Alexandre et al., 2016).

93   Recognizing the importance of site and structural factors in determining survivability, California, the state

94   with the most severe record of property damage due to wildfire in recent decades, has passed laws over

95   the last two decades augmenting its building code to promote fire safety. The first notable code change

96   occurred in 1995, when a new state law required Class B ignition-resistant roofs in new or reroofed

97   residences in the State Responsibility Area (SRA) and in certain Local Responsibility Areas (LRAs). Far

98   more aggressive action was taken in 2005, with the adoption of California Building Code Chapter 7a

99   (https://codes.iccsafe.org/content/CBC2019P4/chapter-7a-sfm-materials-and-construction-methods-for-

100   exterior-wildfire-exposure), whose standards are designed to apply to WUI homes in both the SRA and

101   LRA. The law addresses factors related to structural hardness and ember-proofing, including roof, attic

102   ventilation, exterior wall, and underfloor standards. It also establishes standards for ancillary buildings,

103   structures, and decks. An update to this code was passed by the Legislature in 2007 and implemented in

104   2008 (California Residential Code section R327). This update provided more specificity about materials

105   and construction methods.

106   Knapp et al (2021) found that construction date was of key importance in the survival of structures during

107   the Camp Fire, but it did not coincide with the 2007 law. While there was no statistically significant

108   difference between pre- and post-2007 structure age survival, they found that homes built after 1997 had a

109   38% survival rate while those built before had only an 11.5% survival rate. By contrast, a recent

110   unpublished working paper found that the aforementioned California building codes have had a

111   significant impact on structural survival during wildfires (Baylis & Boomhower, 2021). It finds that a

112   home built in 2010 or after (three years after the second code implementation) is 15 percentage points less

113   likely to be destroyed than a 1985 home experiencing a similar wildfire. Further, a home next to one of

114   these newer built homes is 3 percentage points less likely to be destroyed by house-to-house fire, with that

115   number going even higher when multiple neighbors fall in the newer category.

116   The purpose of this research was to determine what structural and property-level site factors contributed

117   to the survival of buildings during the 2018 Camp Fire in Paradise, CA. We explored the relative

118   importance of structural hardness factors that are expected to inhibit ember entry as well as parcel-level

119   characteristics related to defensible space, vegetative litter, topography, and accessory structures. Related

120   to this we also tested the extent to which the probability of home survival relates to housing age and,

121   specifically, construction after both the 2005 and 2007 California building code changes.

122

123   **Study Area and Data**

124   Occurring in November 2018, the Camp Fire was the deadliest and most destructive fire in California

125   history in terms of lives and property lost. Over 60,000 hectares burned, with approximately 18,800

126   structures destroyed, over $16.5 billion in property damage, and at least 85 civilian fatalities. The fire was

127   centered in and around the town of Paradise, CA, and included impacts in both the LRA and SRA (Figure

128   1). While much of the SRA had undergone extensive forest management, with 80 ongoing and completed

129   fuel reduction projects in the County, thousands of acres of treated Forest Service land, and active

130   thinning in nearby private forests, it has been observed that fire's speed and rate of ember casting

131   rendered most treatments ineffective (Brown, 2020).

132   [Figure 1 around here]

133   Two data sets were obtained for properties in the Camp Fire burn zone (Figure 2). The first was Damage

134   Inspection (DINS) data from the California Department of Forestry and Fire Protection (CAL FIRE),

135   which aggregates information primarily about structures greater than $10,000 in value that were destroyed

136   or damaged by wildfire. Most DINS data are collected only after an incident, using forensic methods to

137   reconstruct the characteristics of structures and parcels before the fire, which introduces a significant

138   possibility of collection error. The other problem with this data set was a lack of records representing

139   totally undamaged structures, complicating statistical analysis of determinants of structure loss. While

140   DINS data does exist for undamaged properties in this area, records for these structures are lacking in

141   most of the structural and lot attributes needed to conduct this analysis. In fact, the only attributes that

142   exist for non-damaged properties in the DINS data set are year of construction and assessed improvement

143   value. Therefore, we were unable to use the subset of DINS data for totally undamaged structures in our

144   analysis, and instead used records for partially damaged structures to populate our category of non-

145   destroyed structures.

146   The initial DINS data set consisted of 19,558 properties in both the SRA and LRA in and around

147   Paradise. However, an analysis of the data reveled many duplicate records for the same address. It was

148   determined that this was due to the fact that records existed for non-primary structures (e.g., outbuildings)

149   on parcels that also had a record for the primary structure. Once these were filtered out, a total of 15,140

150   records remained. Of these, 14,518 were destroyed and 622 were partially damaged or only slightly

151   damaged. This was not an ideal ratio for use in a statistical analysis of binary outcomes, but the large

152   sample size still yields sufficient statistical power. Our GIS assessment of the DINS data overlaid on

153   high-resolution drone data captured just after the fire confirmed that the properties not included in this

154   data set are almost entirely non-damaged (Figure 3).

155   [Figures 2 and 3 around here]

156   The second data set used was the combined DINS and defensible space inspection (DSPACE) data

157   collected under CAL FIRE supervision, referred to here as DINS+DSPACE. This data set was much

158   smaller, with only1,404 records, after filtering out duplicates (from repeat inspections) and several

159   hundred unusable records with extensive null values. The data set only includes properties in the SRA

160   (outside of the Paradise municipal boundary), but it has advantages over DINS in some respects: its ratio

161   of destroyed to non-destroyed structures is almost even (728 destroyed to 676 not destroyed); data

162   collection for it occurred before the fire (as opposed to forensic reconstruction used for DINS); it includes

163   some totally undamaged structures (which were lumped with the "affected" structures in forming the

164   "non-destroyed" category); and it contains attributes about yard fuels and their maintenance, based on a

165   14-point inspection for violations (although violations are only shown for less than 12% of total records).

166   As with the DINS data, the DINS+DSPACE dataset only accounted for a small proportion (<5%) of the

167   total number of undestroyed structures.

168   In summary, then, each data set has strengths and limitations: DINS' far larger sample size gives it more

169   statistical power and its inclusion of the built-up LRA core of Paradise is critical in terms of geographic

170   representation; while DINS+DSPACE has better balance between destroyed and not destroyed, contains

171   some undamaged structures, was collected before the fire, and has more attributes about vegetation and

172   other fuels on the property.

173

174   **Methods**

175   Logistic regression was used to analyze both datasets (DINS and DINS+DSPACE), with a response value

176   of "1" representing a total structure loss and a value of "0" representing a non-destroyed structure. In the

177   DINS data set, all records with a zero value have partial damage. In the DINS+DSPACE data set, records

178   with a zero value include both structures that were partially damaged and totally undamaged. Most

179   predictor variables were originally included in the dataset as categorical variables that had to be recoded

180   as binary "dummy" variables. One predictor variable was generated from original GIS analysis: structure

181   shape angularity, meant to quantify where a structure fell on the spectrum from a simple box to a footprint

182   with many corners and angles. This was coded by dividing the square of the structure's perimeter by its

183   area. Many variables were tested for inclusion in our models using sequential multi-model selection, and

184   all consistently non-significant variables were dropped. A list of variables tested and dropped for both

185   data sets is provided in Table 1 and descriptive statistics for included variables are given in Table 2.

186   [Tables 1 and 2 around here]
187

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190   After running regressions, coefficients were exponentiated and odds ratios were calculated, describing the

191   probabilistic relationship between exposure and outcome. Models from the larger DINS database are

192   denoted with "D" and a model number (Table 1), while the one model presented from the combined

193   DINS+DSPACE dataset is referred to as DD1.

194   A key methodological challenge to be addressed was the presence of many null values. Several hundred

195   records had to be deleted from the DINS+DSPACE database because all structural values were null,

196   rendering them unusable. However, for the DINS data, there were several thousand records where just

197   one or a few attribute values were null. Among the fields in the DINS dataset with high numbers of null

198   values were vegetation clearance (1,900 null records), slope (2,952), and year built (569). All other

199   variables had fewer than 30 null records. Rather than discard all these records, we chose instead to

200   compare a model where all null-containing records were filtered out against two other models with

201   differing allowable thresholds of null-containing records. The first model had no nulls filtered (D1). For

202   the records with null values, we assumed that a blank meant a value of "zero," which we felt was in the

203   realm of possibility. The second had all records containing nulls filtered (D2). The third had all records

204   with null values for vegetation clearance filtered (D3). There was a total of 3,654 records with some null

205   value across all variables.

206   One variable where nulls were treated differently was 'Defensive Action,' which Syphard and Keeley

207   (2019) had found to be highly significant in predicting structure loss. In our DINS+SPACE dataset this

208   column had a very high number of null (9,583) and "unknown" (9,673) values, while all non-null or non-

209   unknown records had a value of "yes," yielding only 1.5% of records with an affirmative response (i.e.,

210   defensive action occurred). When we ran regressions showing all 98.5% of the nulls/unknowns as zeros,

211   this variable was still highly significant in the expected direction. We chose therefore to assume that

212   null/unknown records received no defensive action and so did not filter any data based on this record.

213

214 **Results**

215 <u>DINS models</u>

216 Models D1-3 (Tables 3, 4 and 5) indicated that structural hardness factors were especially important in

217 the survival of structures. One key proxy indicator of structural hardness is whether the structure was built

218 after the state's fire safe building code updates were passed. As mentioned earlier, there were two such

219 laws passed in 2005 and 2007, with the latter not implemented until 2008. Seeking to avoid over-

220 specification, we tested which of the dates was more predictive. Our results indicated that the dummy

221 variable for construction after 2007 was the more predictive of the two, with a higher coefficient and

222 Wald statistic, so, in the interests of parsimony, it was included instead of the 2005 dummy variable, and

223 the 2005 results are not included, as they shed little additional light. We additionally tested several other

224 date range dummy variables and found that including one for construction between 1996 and 2007 was

225 warranted in the model as well. Its coefficient was just slightly lower than that for 2007 in all D models

226 (i.e., -1.001 for 2007 vs -0.917 for 1996-2007 under model D1, yielding 60% and 63% respective

227 reductions in odds of destruction). This indicated that the marginal effect on loss probability was slightly

228 less for this date range, as expected. Furthermore, the Wald statistic for the 2007 variable was more than

229 three times that of the 1996-2007 dummy variable (i.e. 55.5 vs 14.7), indicating that the former is a more

230 reliable predictor.

231 Assessed improvement value served as a proxy variable for structural hardness, given that more

232 expensive structures tend to be higher quality in construction methods and materials. This variable was

233 significant and negative in models D1 and D3, indicating a drop of between 0.4 and 0.5% in the odds of

234 destruction for each $100,000 increment in value.

235

236 [Table 3 around here]

237

238   [Tables 4 and 5 around here]

239

240   Other structural features that were associated with lower probability of loss in the D models include, in

241   order of their marginal effects, 1) absence of attic/crawlspace vents, 2) enclosed eaves, 3) resistant siding,

242   and 4) presence of double-paned windows. The signs of all these coefficients were as expected. The

243   marginal effect for the highest of these, absence of attic/crawlspace vents, ranged from a 77% reduction in

244   odds of destruction in models D2 and D3, to 74% in D1. The lowest of these marginal effects, for multi-

245   pane windows, ranged from 23% in model D1 to 35% in Model D2. The odds changes for the other

246   variables can be seen in Tables 3, 4 and 5. In addition to having the highest coefficient, the variable for

247   absence of attic/crawlspace vents also has by far the highest Wald statistics (96.36 in Model D1,

248   compared 65.2 for enclosed eaves, the next highest Wald statistic among structural variables).

249   Two structural variables were associated with an increased probability of destruction. The first, asphalt

250   roofs, was associated with a 75% increase in odds of destruction in Model D1, and insignificant in

251   Models D2 and D3. The second such variable indicated if the structure was a mobile home. This was the

252   highest scoring structural variable in any of the DINS models, with an increase in odds of destruction

253   ranging from 379% in Model D2 to 524% in Model D1 and Wald statistic values ranging from 57.5 in

254   Model D2 to 105.7 in Model D1. Like age of construction, this is considered a composite metric because

255   mobile home status represents a wide array of construction features and materials. The mobile home

256   variable is therefore somewhat colinear with many other structural variables since this type of home tends

257   to have lower quality construction.

258   Parcel factors were important too. As expected, the variable for sloped property (the minimum angle to be

259   considered sloped is not given in the metadata but was based more on subjective measures) was

260   consistently significant across models and indicated an increase in probability of destruction between

261   54% and 77%. The variable for attached fence (of any material) was significant and negative in all D

262   models. The fact that it is negative is somewhat surprising given that many fences are made of wood. This

263   may be an artifact of data quality or it may be that fencing provides an effective barrier against embers or

264   even the fire line in some cases. Regardless, its effect ranged from a 24% to a 35% drop in odds. When

265   we ran the model with the variable for combustible attached fence (rather than any fence), it was not

266   significant. The variable for attached wood deck at grade was, as expected, positive, but was only

267   significant in Model D1, showing a 31% increase in the probability of destruction.

268   A key parcel-level predictor addressed in this study and throughout the fire safety literature is defensible

269   space clearance. Three mutually exclusive dummy variables for vegetative clearance were recorded for

270   each property representing clearance at the following intervals: 1) from 0-30 feet (0-9 m) from the

271   structure; 2) from 30-100 feet (9-30.5 m); and 3) greater than 100 feet (30.5m +). The latter two variables,

272   representing more aggressive defensible space clearance, are not significant in any model. The first,

273   representing the lowest possible level of defensible space, is significant, with a positive coefficient

274   indicating a 62% increase in odds of loss. In other words, our results only indicate a significant effect

275   from the first (least clearance) interval, and its effect is to increase risk of destruction, which is as

276   expected. We do not know from the data how many of the structures in this lowest interval have no

277   clearance at all (i.e., vegetation up to the structure), but enough probably do to make this variable

278   essentially a proxy for the existence of no or minimal defensible space. But it is only significant in Model

279   D1, suggesting that this result is not stable. Further, the fact that the variables for clearance at the 30-100

280   and 100+ intervals are not significant on their own when the variable for 0-30 is not included (results not

281   shown here) also suggests an inconclusive relationship between defensible space and structure loss in this

282   particular data set.

283   Finally, for the D models, defensive action is highly predictive of structure survival, yielding the highest

284   Wald statistic and coefficient of any variable in the models (D1: B=-4.29; W=434.26; D2: B=-4.24,

285   W=358.26; D3: B=-4.34, W=435.37), and resulting in a drop in odds of destruction of between 85% and

286 99%. This strong statistical signal indicated to us that this is an important variable and that it was

287 warranted to keep it in despite the issue with null values.

288 DINS+DSPACE

289 Model DD1 (Table 6) resulted in fewer significant variables, likely because of the small sample size.

290 Only two structure variables were significant: multi-pane windows, resulting in a decrease in odds of loss

291 of 49%, and presence of a wood roof, resulting in a massive 539% increase in odds. As with the D

292 models, structures that were mobile homes were more likely to be destroyed, although at a much smaller

293 magnitude, with an increase to odds of loss of 41%. Several lot characteristics increased the chance of

294 loss, including: 1) presence of elevated and at-grade wood decks (odds increased by 78% and 141%

295 respectively), 2) presence of a combustible fence (odds increased by 64%), and 4) presence of water

296 storage on the property (odds decreased by 32%). The risk-increase associated with combustible fences

297 contrasts with the risk-reduction associated with the fence of any material variable for the D models,

298 suggesting that the effects of fences may be too complex to model with simple dummy variables, or that

299 there is an issue around post-fire data collection regarding fences. Year of structure construction was not

300 included in these models because only 12% of records had values for this variable.

301 Only two of the vegetation management violation variables were found to be significant in this data set

302 (see Table 1 for dropped variables): violation due to a failure to remove "leaves, needles or other

303 vegetation on roofs, gutters, decks, porches and stairways, etc." and to "mow dead or dying grass to a

304 maximum of 4 inches in height" (California Department of Forestry and Fire Protection Notice of Fire

305 Hazard Inspection Form, PRC §4291(a)(6) and PRC §4291(a)(1)) . Results indicated that these violations

306 were associated with an increase in odds of loss of 277% and 247% respectively.

307 The vegetative clearance distance variables from the D models were not available for this data set.

308

309 [Table 6 around here]

Discussion

<u>Structural Characteristics</u>

Our results are consistent with those of Syphard and Keeley (2019) in finding that structural hardness characteristics are important in predicting building survival, at least in this type of extreme "mega fire" event. Characteristics that limit ember penetration, such as multi-pane windows, ignition resistant siding, enclosed eaves, and lack of vents, appear to be of particular importance, which is consistent with the literature. The lack of crawlspace and attic vents is important because they can provide an access point for embers into attics, which are generally hot and dry (due to lack of climate control) and filled with combustible materials (Quarles et al., 2010). Many fire-safe building codes require at least mesh covers on vents, following the advice of the National Fire Protection Association. Interestingly, our results found that the presence of mesh-covered vents was not statistically significant in reducing risk of loss. Enclosed eaves, also known as "boxed in eaves," are somewhat more controversial in terms of their effectiveness. While some guidance suggests this type of eave construction is preferable to an open eave design (FEMA, 2008; Slack, 1999), Quarles et al. (2010) highlighted that evidence to date of this superiority is largely anecdotal. This study adds to the empirical evidence that the enclosed eave design may be superior to open eaves.

The importance of multi-pane windows is also well-established, although it has been pointed out that the better performance of these windows may have more to do with the fact that they are more likely than single-paned windows to have tempered glass (California code requires that at least one pane be tempered), which is about four times stronger than regular glass (Quarles et al., 2010).

We do not know the exact siding type of structures in our data set that are classified as ignition-resistant, but we do know that under California code such a classification requires a high level of resistance to flames in a test, and often includes materials such as multi-coat stucco, or metal and fiber cement, in addition to chemically treated wood products. Resistant siding plays a role by preventing easy ignition of

334   siding followed by flame spreading up the wall to the more vulnerable soffits, eaves and vents. In other

335   words, good siding keeps flame at bay from those areas most likely to allow penetration to the interior.

336   The role of roof material in mitigating or increasing fire risk has been the subject of great concern in

337   building codes. Our DINS dataset included six types of roofs: asphalt, wood, tile concrete, metal and

338   other. However, the D models only found the asphalt roof dummy variable to be significant, maybe

339   because the vast majority (83%) of our records had asphalt roofs. Asphalt roofs were found to

340   significantly increase the odds of structure loss. This was expected because, although asphalt roofs are a

341   Class A fire-safe material, they are less safe than the other two major Class A types found in the database:

342   metal and ceramic tile. This is because asphalt tiles will combust if exposed to fire for several hours given

343   that they generally contain at least some wood products, unlike most other Class A roofing materials

344   (FEMA, 2008). As mentioned, this variable lost significance when run on the data sets filtered for nulls.

345   Interestingly, the variable for asphalt roofing was not significant in the DD model, while the wood roof

346   variable was, resulting an increase in odds of destruction of over 500%. Attempts were made to code a

347   single dummy variable for all combined "safe" roof types in both data sets, but none was significant.

348   Overall, then, while roofing material appears to be important in our analysis, the particulars remain

349   relatively inconclusive compared to other structural factors.

350   Three variables likely serve as proxies for a wide range of structural characteristics: year of construction

351   (built after 2007 or between 1996-2006), assessed improvement value, and mobile home. The first serves

352   as a proxy because the later the construction, the more elements of fire-safe building codes the structure is

353   likely to incorporate. The second does so because more expensive homes typically have higher quality

354   building materials which have a higher likelihood of preventing ember penetration or otherwise igniting.

355   The third variable, mobile homes, is of clear importance given its outsized Wald statistics and odds

356   impacts indicated by our D models. We have no way of knowing which characteristics of mobile homes

357   make them more vulnerable from this data but some limited research in the past has proposed several

358   possible causes for mobile home vulnerability to wildfire, including the ability for wildfire to run under

359   the floor when not fitted with proper skirting, their unprotected sliding glass doors and picture windows,

360   prevalence of attached carports and porch canopies or sundecks, and the close spacing in mobile home

361   parks allowing quick structure-to-structure spread (Moore, 1981). According to Moore's study, not only

362   are mobile homes more likely than other homes to be destroyed by wildfire, but they also yield a

363   mortality rate that is several times that of stationary homes due to the flashy nature of interior spread in

364   mobile units, the highly toxic and thick smoke their materials often produce when combusted, and the

365   general lack of safe escape routes.

366

367   <u>Lot characteristics</u>

368   Parcel-level variables appear mostly consistent with guidance in the literature: buildings on sloped

369   properties are more prone to destruction (significant in the D models, but not DD) and wood decks

370   increase the odds of loss (significant for at-grade decks in both, but only for elevated in the DD model).

371   Interpreting the results with respect to fences is difficult. In the D models, combustible fencing was not

372   significant, but fencing of any kind was associated with reduced structure loss. This may be a statistical

373   artifact due to data collection issues, or it may reflect the fact that fences, on average, may slow the

374   progress of fires and wind-borne embers. The variable for combustible fences in the DD model was

375   significant and associated with higher risk of structure loss, a finding consistent with the literature, which

376   tends to classify fences as fuel (FEMA, 2008).

377   Defensive action by firefighters was also found to be extremely important—in fact more so than any other

378   factor in the D models. This is despite the considerable uncertainty about how to handle the large number

379   of blank values for this field. While we do not know how accurate our interpretation of the response

380   variable was, our findings are consistent with Syphard and Keeley (2019) in finding that this is an

381   extremely predictive variable. We believe it should be studied further.

382   Of key policy and management importance is the question of defensible space and fuel management

383   surrounding structures. This study fails to find a consistent and significant reduction in the risk of

384   structure loss due to implementing defensible space actions on a parcel. Our D models found no

385   indication that higher levels of defensive space, as indicated by the dummy variables for clearance at the

386   30-100' and 100'+ intervals, are associated with better outcomes. We did find that the 0-30' clearance

387   interval, representing the lowest possible category for defensible space, was associated with an increased

388   chance of loss, but only in the first, unfiltered model (D1). So, not only is there a lack of agreement

389   among models on defensible space, but the one model with a significant result merely indicates that

390   membership in the lowest defensible space category is associated with more loss, not that more extensive

391   defensible space clearance reduced the probability of loss. Interpretation of this already vague result is

392   further confounded by the fact that it is impossible to say how many of the records in the 0-30' clearance

393   interval have no clearance at all (i.e., a distance of 0, or vegetation up to the structure) versus defensible

394   space extending to the upper boundary of 30 feet. Regardless, our results suggest that the 0-30' dummy

395   variable is acting as a proxy for the existence of no or minimal defensible space.

396   While defensible space results were inconclusive, results from the DD model suggests that other elements

397   of yard maintenance matter. Failure to remove needles/leaves from surfaces immediately adjoining the

398   structure (e.g. gutters, porches, roofs) increased the odds of destruction by 277% while failure to mow

399   dead grass within 30-100 feet of the structure increased those odds by 247%. These are important

400   findings, but the fact that only 3% of records were positive for these violations does somewhat limit the

401   reliability of the result. Further, the lack of significance for the remaining 13 violation code variables adds

402   even further uncertainty. To truly address the risks associated with the violations, a far bigger data set

403   would be needed with many more recorded violations. In fact, only 12% of all records in this data had at

404   least one violation, suggesting either that conditions that would lead to violation were minimal among

405   these homes or that data on these characteristics was not fully collected for most homes. In either case this

406   limits the utility of this data set for statistical analysis.

407 All of this suggests that evidence for defensible space's effect on structure survival is limited in these data

408 sets, even though logic and fire science suggest that a reduction of fuels through defensible space should

409 make a nearby structure safer under a range of fire weather and fuel conditions. There are many possible

410 reasons for this lack of a result. One is that because this was a "mega-fire" environment, where fire

411 resources were spread thin or focused on evacuations or maintaining crew safety, there was less direct

412 structure protection activity occurring that could have utilized defensible space. Another is that structures

413 of all types may have been exposed to extensive ember showers regardless of defensible space clearance.

414 The nature of the two datasets, which included many inaccurate or incomplete records, may have been a

415 factor too. The relative lack of records for undamaged properties with full data attribution may have

416 resulted in a selection bias characterized by relative lack of observations with large amounts of defensible

417 space in the data set. Also, the forensic estimation of pre-fire lot conditions for destroyed properties may

418 have suffered from measurement errors, particularly for smaller trees, shrubs and grasses that were likely

419 incinerated beyond recognition. This also may apply for structural attributes; due to the forensic nature of

420 much of the data collection, it is very possible that many of the collected variables were not particularly

421 accurate. Clearly, this calls out the need for pre-fire inspections of property, of which the DD dataset was

422 an example.

423 The lack of results on defensible space, however, may also relate to the specific nature of the Camp Fire.

424 Perhaps, the Camp Fire's behavior was so intense that ember casting and house-to-house transmission

425 overwhelmed the effect of the reductions in proximate fuel loads (and associated convective heating)

426 provided by defensible space. If ember showers were the primary means of transmission, then it would

427 make sense that defensible space would have relatively little impact on structure survival since the

428 defensible zone is typically not the main source of embers. Further, the extreme nature of this event may

429 have negated the role that defensible space typically plays in providing conditions needed for fire crews to

430 protect homes. These types of question can only be answered by looking comparatively at the outcomes

431 of different fire events.

432   Moving forward, ramping up the quantity and quality of data will be valuable in answering questions

433   about the effects of both structure characteristics and defensible space. Ultimately, more and better data

434   means a greater ability to predict how structures will fare in the next wildfire event. Such information will

435   be critical to writing the next generation of fire-safe building codes and lot standards.

436   **Conclusion**

437   The Camp Fire was one of the most intense and destructive fires in U.S. history, yet many structures

438   survived. This study statistically analyzed data on loss and property characteristics to try to better

439   understand the determinants of structural survival. While our findings are not entirely consistent between

440   the two data sets we analyzed, overall, we found that that structural hardness factors, such as the presence

441   of fire-resistant siding and roofing and double paned windows, and the absence of entry points like

442   uncovered vents, are very important determinants. Year of construction was also an important predictor,

443   with structure built after California's 2007 fire-safe building code updates experiencing lower rates of

444   destruction. Defensive action by fire fighters was also found to be extremely important—in fact more so

445   than any other factor. Various lot-level factors were important too, but the role of defensible space in

446   preventing structure loss was inconclusive from these data sets.

447   **Acknowledgments**

451   **Data Availability Statement**

452   Camp fire damage inspection data can be viewed at: https://CAL FIRE-

453   forestry.maps.arcgis.com/apps/webappviewer/index.html?id=5306cc8cf38c4252830a38d467d33728

454   **Conflicts of Interest**

455   The authors declare no conflicts of interest.

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459   **References**

460   Agee, J. K., Bahro, B., Finney, M. A., Omi, P. N., Sapsis, D. B., Skinner, C. N., van Wagtendonk, J. W.,

461   & Phillip Weatherspoon, C. (2000). The use of shaded fuelbreaks in landscape fire management.

462   *Forest Ecology and Management*, *127*(1), 55–66. https://doi.org/10.1016/S0378-1127(99)00116-

463   4

464   Alexandre, P. M., Stewart, S. I., Mockrin, M. H., Keuler, N. S., Syphard, A. D., Bar-Massada, A.,

465   Clayton, M. K., & Radeloff, V. C. (2016). The relative impacts of vegetation, topography and

466   spatial arrangement on building loss to wildfires in case studies of California and Colorado.

467   *Landscape Ecology*, *31*(2), 415–430. https://doi.org/10.1007/s10980-015-0257-6

468   Baylis, P., & Boomhower, J. (2021). Building codes and community resilience to natural disasters.

469   *Working Paper, University of British Columbia*.

470   Braziunas, K. H., Seidl, R., Rammer, W., & Turner, M. G. (2021). Can we manage a future with more

471   fire? Effectiveness of defensible space treatment depends on housing amount and configuration.

472   *Landscape Ecology*, *36*(2), 309–330. https://doi.org/10.1007/s10980-020-01162-x

473   Brown, H. (2020). The Camp Fire Tragedy of 2018 in California. *Fire Management Today*, *78*(2), 11-

474   13,15-21.

475   Cohen, J. D. (2000). Preventing disaster: Home ignitability in the wildland-urban interface. *Journal of*

476   *Forestry*, *98*(3), 15–21.

477   Cohen, J. D., & Stratton, R. D. (2008). Home destruction examination: Grass Valley Fire, Lake

478   Arrowhead, California. *Tech. Paper R5-TP-026b. Vallejo, CA: U.S. Department of Agriculture,*

479   *Forest Service, Pacific Southwest Region (Region 5). 26 p.*

480   https://www.fs.usda.gov/treesearch/pubs/31544

481   FEMA. (2008). *Home builder's guide to construction wildfire zones. Technical Fact Sheet Series,* (P-

482   737).

483 Finney, M. A., Cohen, J. D., Grenfell, I. C., & Yedinak, K. M. (2010). An examination of fire spread

484   thresholds in discontinuous fuel bedsA. *International Journal of Wildland Fire*, *19*(2), 163–170.

485   https://doi.org/10.1071/WF07177

486 Finney, M. A., Seli, R. C., McHugh, C. W., Ager, A. A., Bahro, B., Agee, J. K., Finney, M. A., Seli, R.

487   C., McHugh, C. W., Ager, A. A., Bahro, B., & Agee, J. K. (2007). Simulation of long-term

488   landscape-level fuel treatment effects on large wildfires. *International Journal of Wildland Fire*,

489   *16*(6), 712–727. https://doi.org/10.1071/WF06064

490 Gibbons, P., Bommel, L. van, Gill, A. M., Cary, G. J., Driscoll, D. A., Bradstock, R. A., Knight, E.,

491   Moritz, M. A., Stephens, S. L., & Lindenmayer, D. B. (2012). Land Management Practices

492   Associated with House Loss in Wildfires. *PLOS ONE*, *7*(1), e29212.

493   https://doi.org/10.1371/journal.pone.0029212

494 Haire, S. L., & McGarigal, K. (2009). Changes in Fire Severity across Gradients of Climate, Fire Size,

495   and Topography: A Landscape Ecological Perspective. *Fire Ecology*, *5*(2), 86–103.

496   https://doi.org/10.4996/fireecology.0502086

497 Knapp, E. E., Valachovic, Y. S., Quarles, S. L., & Johnson, N. G. (2021). Housing arrangement and

498   vegetation factors associated with single-family home survival in the 2018 Camp Fire, California.

499   *Fire Ecology*, *17*(1), 25. https://doi.org/10.1186/s42408-021-00117-0

500 Moore, H. E. (1981). *Protecting Residences from Wildfires: A Guide for Homeowners, Lawmakers, and*

501   *Planners*. U.S. Department of Agriculture, Forest Service, Pacific Southwest Forest and Range

502   Experiment Station.

503 Penman, S. H., Price, O. F., Penman, T. D., & Bradstock, R. A. (2019). The role of defensible space on

504   the likelihood of house impact from wildfires in forested landscapes of south eastern Australia.

505   *International Journal of Wildland Fire*, *28*(1), 4–14. https://doi.org/10.1071/WF18046

506 Quarles, S. L., Valachovic, Y., Nakamura, G. M., Nader, G. A., & De Lasaux, M. J. (2010). *Home*

507   *survival in wildfire-prone areas: Building materials and design considerations*.

508 Radeloff, V. C., Helmers, D. P., Kramer, H. A., Mockrin, M. H., Alexandre, P. M., Bar-Massada, A.,

509   Butsic, V., Hawbaker, T. J., Martinuzzi, S., & Syphard, A. D. (2018). Rapid growth of the US

510   wildland-urban interface raises wildfire risk. *Proceedings of the National Academy of Sciences*,

511   *115*(13), 3314–3319.

512 Schmidt, J. (2020). Vegetation Cover and Structure Loss in Four Northern California Wildfires: Butte,

513   Tubbs, Carr, and Camp. *Munich Personal RePEc Archive Paper No. 104232*.

514 Slack, P. (1999). Firewise construction: Design and materials. *Publications-Colorado State Forest

515   Service*.

516 Syphard, A. D., Brennan, T. J., & Keeley, J. E. (2014). The role of defensible space for residential

517   structure protection during wildfires. *International Journal of Wildland Fire*, *23*(8), 1165–1175.

518   https://doi.org/10.1071/WF13158

519 Syphard, A. D., Brennan, T. J., & Keeley, J. E. (2017). The importance of building construction materials

520   relative to other factors affecting structure survival during wildfire. *International Journal of

521   Disaster Risk Reduction*, *21*, 140–147. https://doi.org/10.1016/j.ijdrr.2016.11.011

522 Syphard, A. D., & Keeley, J. E. (2019). Factors Associated with Structure Loss in the 2013–2018

523   California Wildfires. *Fire*, *2*(3), 49. https://doi.org/10.3390/fire2030049

524 Syphard, A. D., Rustigian-Romsos, H., & Keeley, J. E. (2021). Multiple-Scale Relationships between

525   Vegetation, the Wildland–Urban Interface, and Structure Loss to Wildfire in California. *Fire*,

526   *4*(1), 12.

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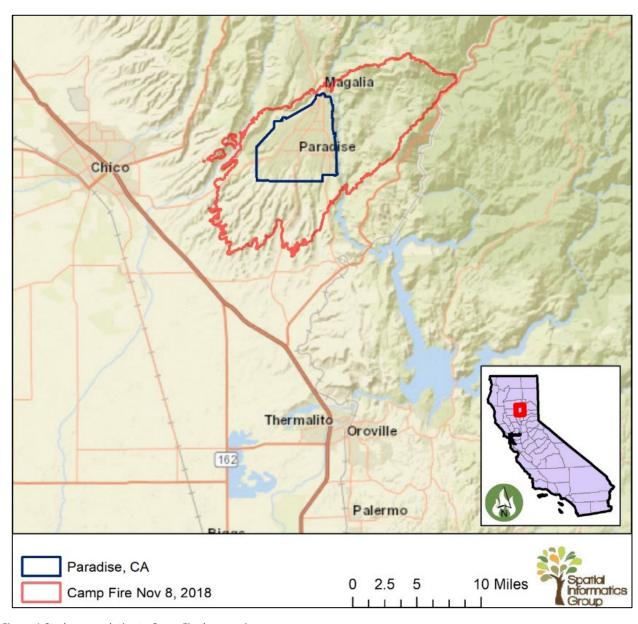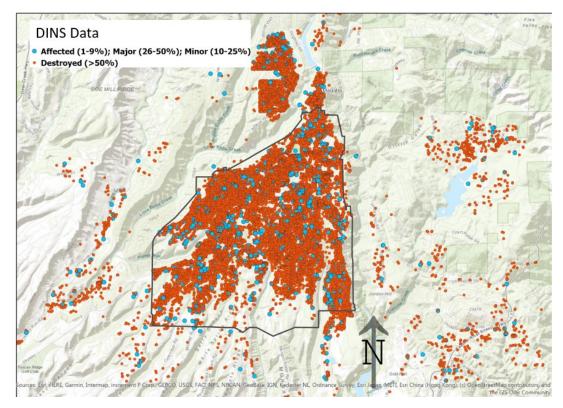
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532   **Figure and Tables**

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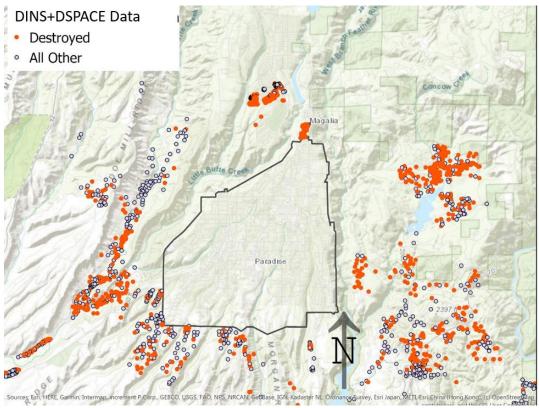*Figure 1.Study area relative to Camp Fire burn perimeter*

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DINS Data
● Affected (1-9%); Major (26-50%); Minor (10-25%)
● Destroyed (>50%)

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DINS+DSPACE Data
● Destroyed
○ All Other

539   *Figure 2. DINS data set (top) and DINS+DSPACE data set (bottom)*

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Likely classed as "undamaged"

Figure 3. Post-fire imagery overlaid with DINS data; circles represent structures coded as destroyed, squares as

structures partially damaged, and ovals are structures, apparently undamaged, that were not listed in the DINS

dataset.

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552 *Table 1: Variables dropped from analysis.*

DINS variables not significant	DINS+DSPACE variables not significant
- Vegetation clearance at 30-100 ft - Vegetation clearance at 100 ft + - South Aspect - No Eaves - Wood or metal roof - Mesh screen on vents - Non-habitable - Low Value - Combustible patio cover - Single family residence - Building Shape complexity (perimeter^2/ area)	- Violations for failure to: - Remove all branches within 10' of any chimney or stovepipe outlet. - Remove all dead and dying trees, branches, shrubs, and plants adjacent to buildings or overhanging roofs.Remove all dead grass, plants, shrubs, trees, branches, leaves, weeds and needles within 30' of structures. - Remove or separate live combustible ground cover and shrubs within 30' of structures - Remove combustible vegetation and materials, on, adjacent to, or below combustible decks, balconies, stairs. - Relocate exposed firewood or lumber outside of zone 1 unless covered in a fire resistive material. - Provide separation between shrubs and trees, with increased separation on slopes - Cut and remove all pyrophytic combustible vegetation within 30' of structures. - Remove all piles of accumulated dead vegetation on the property. - Logs or stumps embedded in soil must be removed or isolated from vegetation within 100' of structures. - Equip all chimney or stovepipe openings with a metal screen having openings between 3/8" and 1/2". - Remove tree limbs and growth less than 3" diameter to 10' above ground (or 1/3 the tree's height). - Recommended vegetative clearance (10/15 ft) - Metal grate on chimney - No vents - Enclosed eaves - Vent screen - Combustible siding - Combustible carport - Sloped terrain - Number of dead trees - Asphalt roof - Fire resistant roof material - Covered patio

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562   *Table 2: Descriptive statistics of included variables.*

Variable Name	Description	Mean/ Frequency	Std. Dev.
DINS Models (D1, D2, D3)			
Destroyed	1 = home destroyed	0.96	0.198
Mobile	1 = home is mobile	0.25	0.431
DefAction	1 = defensive action taken	0.01	0.100
VegClr030	1 = vegetative clearance ranges from nothing to less than 30 ft from structure (worst of three categories)	0.77	0.418
RoofAs	1 = Roof is made of asphalt composite	0.83	0.378
Blt2007	1 = house built after 2007 (year of second building code)	0.01	0.118
Blt972007	1 = house built between 1998 and 2007	0.06	0.235
MultiPaneWin	1 = multipaned windows in structure	0.57	0.495
EnclEaves	1 = enclosed eaves	0.15	0.352
NoVents	1 = no attic/crawlspace vents in exterior	0.09	0.282
ResistSiding	1 = ignition-resistant siding	0.39	0.488
Fence	1 = fence of any material on property	0.40	0.489
Slope	1 = sloped property	0.34	0.473
WoodDeckGrade	1 = wood deck at grade	0.19	0.391
Imp100000	Structure improvement value (in $100,000 increments)	1.85	14.58
DINS+DSPACE models (DD1) after filtering for null records			
Destroyed		0.519	.50
VRemLeavesNeedles	1=violation for "failure to remove leaves, needles or other vegetation on roofs, gutters, decks, porches and stairways etc." (PRC §4291(a)(6))	0.033	0.180
VCutGrsFrb4Inch	1= violation for "mow dead or dying grass to a maximum of 4 inches in height" in 30-100 foot zone around structures (PRC §4291(a)(1))	0.036	0.185
WATSTOR	1 = water storage on property	0.140	0.347
MobileHome	1 = mobile home	0.223	0.416
ROOFWOOD	1=roof made of wood	0.022	0.147
MultiPane	1 = multi-pane windows	0.837	0.370
WoodDeckElev	1 = elevated wood deck near structure	0.222	0.415
WoodDeckGrade	1 = at-grade wood deck near structure	0.505	0.500
CombFence	1 = combustible fence	0.173	0.378

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566   *Table 3. Model D1: Results with no filtering of null records (assumed value of 0)*

Variable	B	Wald	Sig. (p)	Exp(B)	Δ Odds of destruction
Increased likelihood of destruction					
Mobile	1.831	105.754	0.000	6.242	524% ↑ in odds
Slope	0.571	28.054	0.000	1.770	77% ↑ in odds
RoofAs	0.557	19.095	0.000	1.745	75% ↑ in odds
Vegclr030	0.421	18.539	0.000	1.523	62% ↑ in odds
WoodDeckgrade	0.268	3.643	0.056	1.307	31% ↑ in odds
Decreased likelihood of destruction					
DefAction	-4.290	434.258	0.000	0.014	85% ↓ in odds
NoVents	-1.347	96.362	0.000	0.260	74%↓ in odds
Blt972007	-1.001	55.557	0.000	0.367	63% ↓ in odds
Blt2007	-0.917	14.768	0.000	0.400	60% ↓ in odds
EnclEaves	-0.847	65.211	0.000	0.429	57% ↓ in odds
ResistSiding	-0.297	10.352	0.001	0.743	26% ↓ in odds
AnyFence	-0.276	8.949	0.003	0.759	24% ↓ in odds
MultiPaneWin	-0.267	6.999	0.008	0.766	23% ↓ in odds
Imp100k	-0.0043	9.843	0.002	0.996	0.4% ↓ in odds/$100k
Constant	3.011	339.947	0.000	20.303	
N = 15,140; 14,518 = 1; 622 = 0					
-2 Log Likelihood	4133.2	Nagelkerke R Square			0.232

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570 *Table 4. Model D2: Results where all records with any null values filtered other than for DefAction*

Variable	B	Wald	Sig. (p)	Exp(B)	Δ Odds of destruction
Increase likelihood of destruction					
Mobile	1.569	57.574	0.000	4.799	379% ↑ in odds
Slope	0.431	13.468	0.000	1.539	54% ↑ in odds
Decrease likelihood of destruction					
DefAction	-4.242	358.285	0.000	0.014	98.6% ↓ in odds
NoVents	-1.479	80.964	0.000	0.228	77% ↓ in odds
Blt972007	-1.080	46.303	0.000	0.340	66% ↓ in odds
Blt2007	-1.010	12.742	0.000	0.364	64% ↓ in odds
EnclEaves	-0.747	33.640	0.000	0.474	53% ↓ in odds
ResistSiding	-0.487	18.430	0.000	0.614	39%↓in odds
AnyFence	-0.433	14.749	0.000	0.649	35%↓in odds
MultiPaneWin	-0.431	11.873	0.001	0.650	35%↓in odds
Constant	4.367	949.427	0.000	78.777	
N= 12,348; 11,932=1; 416=0					
-2Log Likelihood	2861.1	Nagelkerke R Square			0.239

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572 *Table 5. Model D3: Results where all records with null vegetation values filtered*

Variable	B	Wald	Sig. (p)	Exp(B)	Δ Odds of destruction
Increase likelihood of destruction					
Mobile	1.601	75.301	0.000	4.959	379% ↑ in odds
Slope	0.563	25.364	0.000	1.757	54% ↑ in odds
Decrease likelihood of destruction					
DEfAction	-4.343	435.372	0.000	0.013	98.7% ↓ in odds
NoVents	-1.473	98.133	0.000	0.229	77% ↓ in odds
Blt972007	-1.108	58.270	0.000	0.330	67% ↓ in odds
Blt2007	-1.058	16.505	0.000	0.347	65% ↓ in odds
EnclEaves	-0.879	55.757	0.000	0.415	58% ↓ in odds
MultiPaneWin	-0.432	14.432	0.000	0.649	35% ↓ in odds
AnyFence	-0.376	13.324	0.000	0.686	31% ↓ in odds
ResistSiding	-0.374	13.222	0.000	0.688	31% ↓ in odds
Imp100k2	-0.005	12.089	0.001	0.995	0.5% ↓ in odds/$100k
Constant	4.191	1083.057	0.000	66.107	
N= 13,682; 13,175 = 1; 507 = 0					
-2Log Likelihood	3375.4	Nagelkerke R Square			.25

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576 *Table 6. Model DD1: Results with null-containing records filtered*

Variable	B	Wald	Sig. (p)	Exp(B)	Δ Odds of destruction
Increase likelihood of destruction					
ROOFWOOD	1.855	8.637	0.003	6.395	539% ↑ in odds
VRemLeavesNeedles	1.327	8.077	0.004	3.769	277% ↑ in odds
VCutGrsFrb4Inch	1.244	8.826	0.003	3.470	247% ↑ in odds
WoodDeckGrade	0.879	33.955	0.000	2.409	141% ↑ in odds
WoodDeckElev	0.577	22.271	0.000	1.780	78% ↑ in odds
CombFence	0.495	10.039	0.002	1.641	64% ↑ in odds
MobileHome	0.342	4.867	0.027	1.407	41% ↑ in odds
Decrease likelihood of destruction					
MultiPane	-0.670	15.642	0.000	0.512	49% ↓ in odds
WATSTOR	-0.394	5.482	0.019	0.675	32% ↓ in odds
Constant	-0.027	0.023	0.878	0.973	
N= 1,404; 728= 1; 676 = 0					
-2Log Likelihood	1,733.8	Nagelkerke R Square			0.186

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