The Butte Fire: A Case Study in Using LIDAR Measures of Pre-Fire Vegetation to Estimate Structure Loss Rates

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Abstract: The Butte Fire occurred in the northern Sierra Nevada foothills of California in September, 2015, resulting in the loss of two lives and an estimated 1,565 structures in 70,000 acres (28,000 ha.) burned. This study evaluates the utility of vegetation measures derived from pre-fire LIDAR data in predicting structure loss for the Butte Fire. Additional explanatory variables such as elevation, topography, structure density, and structure access are also examined to determine their impact on structure loss rates. Loss estimates based on LIDAR-derived vegetation measures are compared to estimates derived from infrared aerial imagery to evaluate the relative effectiveness of using LIDAR for this purpose.

LIDAR-derived vegetation density in the 50-foot (15 m.) zone around each structure was found to be the most significant variable associated with structure loss. Elevation was the second most statistically significant predictor of structure loss. On average, a 10% increase in vegetation density in the 50-foot (15 m.) zone around each structure led to an estimated 10.2% increase in structure loss. A 1000 foot (300 m.) rise in elevation was associated with a 15% increase in structure loss. Topographic variables such as slope, aspect, and topographic position did not appear to have an important effect on structure losses. Measures of structure density and structure access also were not statistically significant predictors of structure loss rates.

Vegetation cover derived from infrared aerial imagery proved nearly as accurate as LIDAR-derived vegetation density in estimating the probability of structure loss.

Keywords: wildfire, forest fire, structure loss, vegetation, LIDAR, California, MODIS, wildland urban intermix, Sierra Nevada

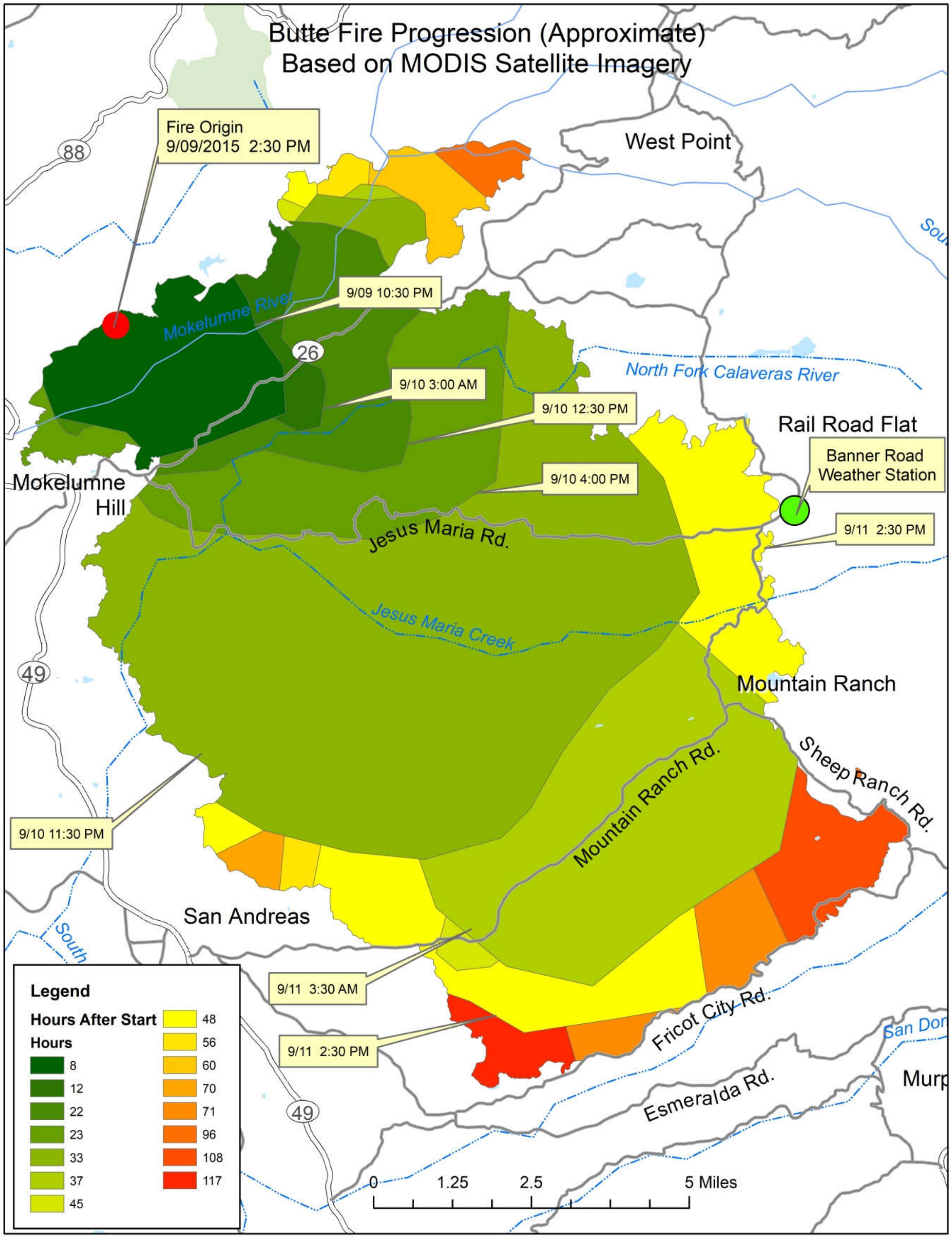
Introduction: The Butte fire began in the Sierra Nevada foothills in Amador County on the afternoon of September 9, 2015, when a tree branch came into contact with a power line. Vegetation was extremely dry following four years of drought and a summer with no rain. The fire spread south and southeast, crossing over the Mokelumne River drainage into Calaveras County soon after starting.

"*The fire made significant runs to the south at a dangerous rate of spread on September 10th and 11th, consuming approximately 25,000 acres and 29,000 acres respectively… In all, the Butte fire burned 70,868 acres…The vegetative communities within the fire area range from grasslands, to young and mature brush/chaparral, to mature timber... The majority of the burn area ranges in elevation from about 2600 feet to about 1000 feet…*" (*Butte Fire Emergency Response Team Report, Oct. 12, 2015*).

From the Butte Fire's *Incident Action Plan* on the afternoon of Sept. 10 : "*The fuels in the area are a mix of oak woodland with grass and brush understory and fields of brush with light grass understory. The fuels are highly stressed and the fuel moisture in the brush is at critical levels below 60 percent. Single and groups of trees are torching creating spot fires ¼ to ½ mile ahead of the head of the fire. The head of the fire is progressing at a rapid rate of spread…The southern portion of the fire south of Highway 26 will continue to spread south at a rapid rate of spread with the north wind. Flame lengths in these areas will be 30 to 100 feet depending on the vegetation…"*

Weather conditions during the Butte fire were characterized by moderately strong winds from the north, high temperatures, low humidity and low fuel moisture. On the afternoon of Sept. 9, the Banner Road weather station (ESPC1), located at 2800 feet (850 ha.) in elevation to the east of the fire, recorded a temperature of 102 degrees F. (39 C.). Winds were from the northwest averaging 12 mph (19 kph) with a maximum of 24 mph (39 kph). Humidity was around 10%. Fuel moisture levels were at 3-4%. Winds subsided in the evening of Sept.9, but rose again in the morning of Sept. 10 with maximum winds of 20 - 22 mph (32 – 35 kph) - between 10:00 AM and 1:00PM. Maximum winds again rose to 15 - 20 mph (24 – 32 kph) between 10:00 AM and 4:00 PM on Sept. 11.

By September 11, there were 805 personnel assigned to the fire including 20 hand crews, 82 engines and 16 helicopters (*National Interagency Coordination Center (NIFC) Incident Management Situation Report*, Sept. 11, 2015).


Butte Fire Progression (Approximate)
Based on MODIS Satellite Imagery
Fire Origin
9/09/2015 2:30 PM
West Point
88
9/09 10:30 PM
Mokelumne River
26
9/10 3:00 AM
North Fork Calaveras River
9/10 12:30 PM
Rail Road Flat
Banner Road
Weather Station
Mokelumne
Hill
9/10 4:00 PM
9/11 2:30 PM
Jesus Maria Rd.
Jesus Maria Creek
49
Mountain Ranch
Sheep Ranch Rd.
Mountain Ranch Rd.
9/10 11:30 PM
San Andreas
9/11 3:30 AM
9/11 2:30 PM
Fricot City Rd.
Esmeralda Rd.
49
Legend
Hours After Start
Hours
8
12
22
23
33
37
45
48
56
60
70
71
96
108
117
0 1.25 2.5 5 Miles

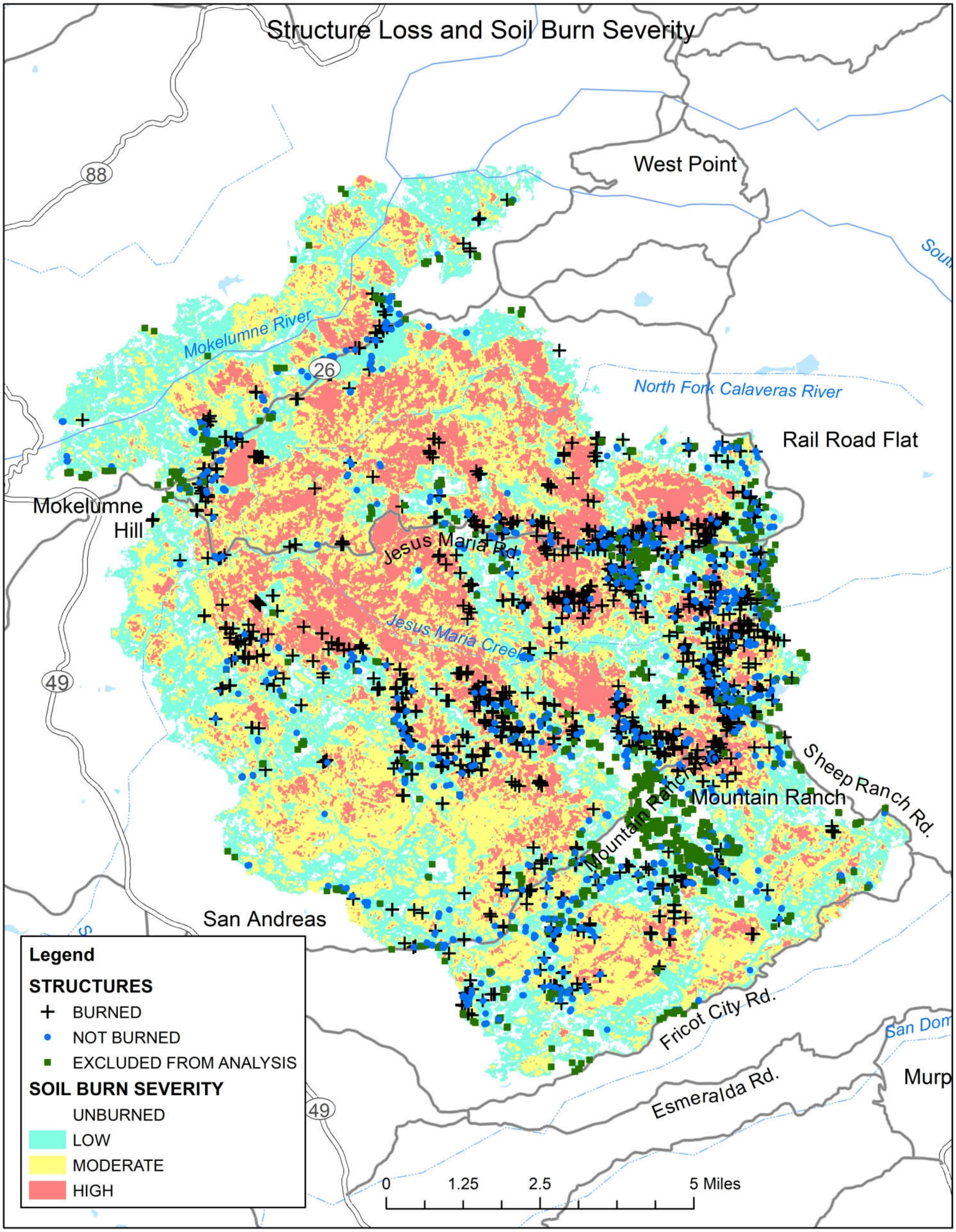
Methods: Structures existing within the Butte fire perimeter before and after the fire were mapped using a combination of LIDAR from a 2011 flight and aerial imagery from the National Agricultural Imagery Program (NAIP). For purposes of this study, it was assumed that all structures that were removed or replaced between the 2014 NAIP imagery and the 2016 NAIP imagery were losses due to the Butte fire. 3,596 structures were mapped before the fire and 2,031 structures after the fire, for a net loss of 1,565 structures (43%). Counting only structures larger than 500 square feet (46 sqm.) in size, there were 2,219 structures before the fire and 1,301 after the fire for a net loss of 918 (41%). This compares to a total of 818 structures recorded as burned by CALFIRE, the state fire agency that managed the fire response. *(Note: A small portion of the fire on the north side of the Mokelumne River was not covered by the 2011 FEMA LIDAR flight. Structures within that area were not included in this analysis).*

Most of the structures within the fire perimeter fell into the Wildland Urban Intermix category, as mapped by the SILVIS lab at the University of Wisconsin (http://silvis.forest.wisc.edu/data/wui-change/). There were 1,344 land parcels with structures in the Butte Fire area, averaging 21 acres (8.5 ha.) in size. Only 46 of those parcels were less than one acre (0.4 ha.) in size. About 12,000 acres (4,800 ha.) within the fire perimeter were managed by the federal government's Bureau of Land Management and had no structures.

Structure exposure to fire was estimated using the post-fire Soil Burn Severity (SBS) map produced by the Butte Fire Emergency Response Team. The SBS map was based on pre and post-fire 30-meter resolution LANDSAT imagery and modified by ground surveys. The resulting map classified burn intensity into four classes: unburned, low, moderate, and high severity. For this analysis, only those structures that were within 50 feet (15 m.) of a mapped burned area (low, moderate, or high intensity) were considered. The objective was to limit the analysis to structures that had significant exposure to fire in order to assess the importance of vegetation characteristics near structures.

Of the 3,596 structures mapped within the fire perimeter, 2,896 structures were within 50 feet (15 m.) of a mapped burned area. 1,559 of those structures were destroyed in the fire (53.8%). Of the 700 structures with low fire exposure (greater than 50 feet (15 m.) from mapped burned areas), only 6 structures were recorded as destroyed (less than 1%). About half of the structures with low fire exposure were in the area of the Mountain Ranch townsite.

(*Note: The SBS map produced by the Emergency Response Team was used in this analysis rather than the burn severity mapped by the Monitoring Burn Severity Program (MTBS)* https://www.mtbs.gov). *The SBS mapped by the Emergency Response team immediately after the fire captured low intensity burns in light fuels, such as grass, that recover quickly. Some of those areas were shown as unburned in the MTBS version because the MTBS focuses on changes in vegetation that are still evident one year after a fire.)*


Structure Loss and Soil Burn Severity
West Point
88
Mokelumne River
26
North Fork Calaveras River
Rail Road Flat
Mokelumne Hill
Jesus Maria Rd.
Jesus Maria Creek
49
Sheep Ranch Rd.
Mountain Ranch Rd.
Mountain Ranch
San Andreas
Fricot City Rd.
Esmeralda Rd.
Legend
STRUCTURES
BURNED
NOT BURNED
EXCLUDED FROM ANALYSIS
SOIL BURN SEVERITY
UNBURNED
LOW
MODERATE
HIGH
0
1.25
2.5
5 Miles

Vegetation characteristics existing before the Butte fire were mapped using LIDAR data from a 2011 flight sponsored by the Federal Emergency Management Agency (FEMA). That flight took place in November and December of 2011, after leaf fall, using a nominal spacing of one pulse per 0.7 meters. LIDAR pulses with a high angle (22 degrees or greater) were excluded from this analysis to reduce artifacts in the vegetation density mapping.

The LIDAR point cloud within the Butte Fire was classified into a structure class and into vegetation classes by height: 0-1 meters, 1-4 meters, 4-8 meters, and 8-120 meters in height.

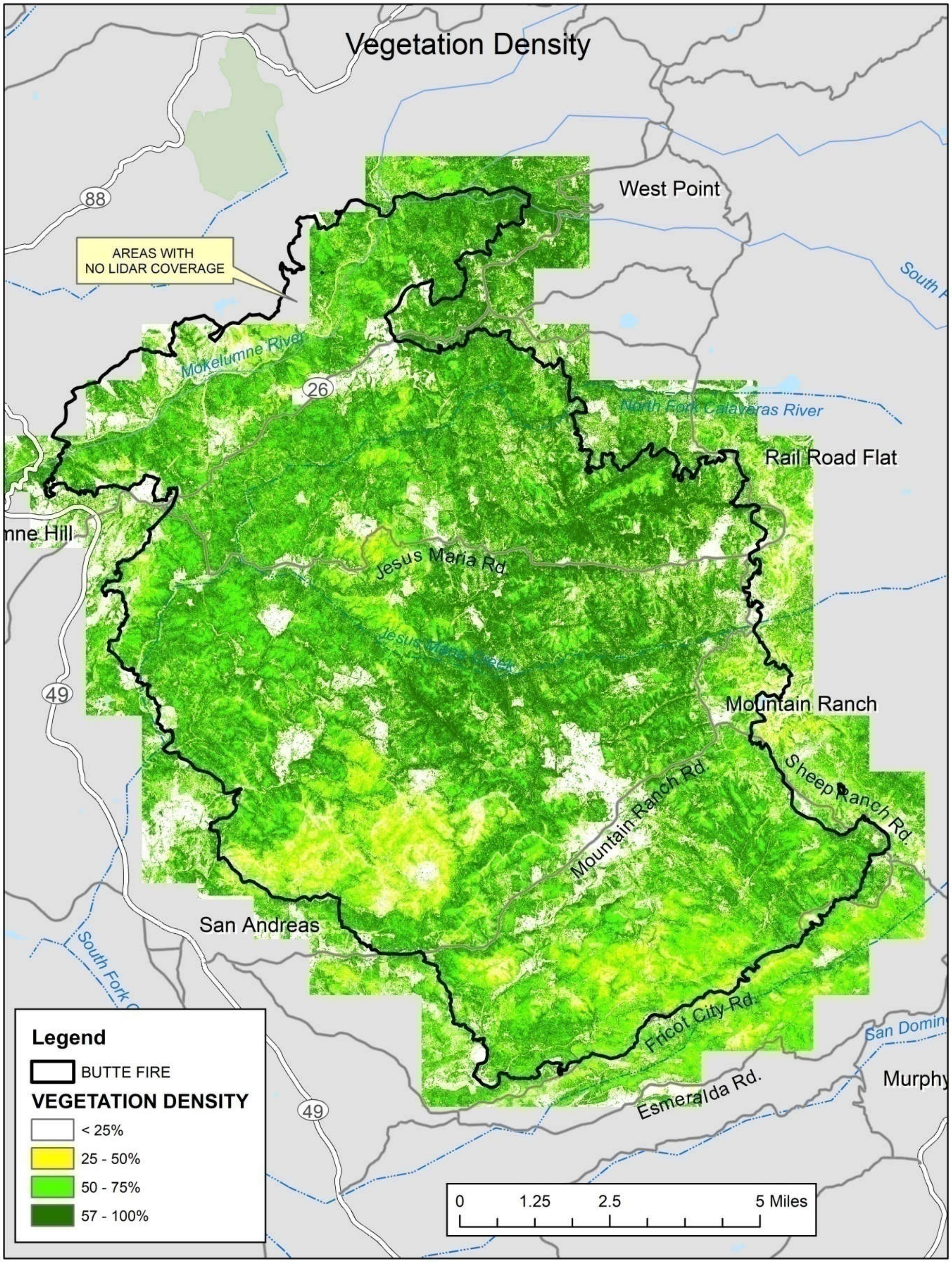
Initial measures of vegetation from the LIDAR data included the following:

- Average density of all vegetation greater than 1 meter in height
- Average density of vegetation in the 1 to 4 meter height class ("ladder fuel")
- Average density of vegetation in the 1 to 8 meter height class
- Ratio of 1 to 4 meter density ("ladder fuel") to total vegetation density greater than 1 meter in height
- Ratio of 1 to 8 meter density to total vegetation density greater than 1 meter in height
- Vegetation cover: Proportion of the area covered by non-structure returns greater than 1 meter in height
- Vegetation volume : Average canopy height (all returns greater than 1 meter in height not classified as a structure) multiplied by area of vegetation cover
- Average vegetation density overhanging structure
- Proportion of structure covered by vegetation
- Minimum distance of vegetation from structure

Vegetation density was calculated using methods described in *Kramer, et al., 2014* : To determine overall vegetation density, vegetation LIDAR returns greater than 1 meter in height were divided by all vegetation returns plus structure returns and ground returns. For ladder fuel density, all LIDAR returns between 1 and 4 meters in height (excluding structures) were divided by the total of ground returns plus returns from 0 - 1 meters and 1 - 4 meters in height. All measures of vegetation density were calculated on a five meter grid. Vegetation variables were averaged over several different distance zones around each structure as discussed below.

(*Note on limitations of LIDAR data: Despite efforts to correct classification errors, some non-vegetation returns from small unmapped structures, vehicles, fences, power lines, etc. were included in the vegetation totals. Further, in areas of tall, dense tree canopy, LIDAR pulses did not always reach lower levels of the canopy. This may have led to an underestimate of ladder fuels as compared to taller vegetation*).

The following map shows the overall distribution of the estimated vegetation density:



In addition to vegetation variables, the following variables were tested to see if they had a significant impact on the loss rate of structures:

- Distance to the nearest neighboring structure
- Distance to the nearest burned structure
- Structure density per square kilometer (structures over 500 sqft. (46 sqm.) in size)
- Size of the structure
- The size of the parcel where the structure was located
- Travel time to the nearest fire station
- Driving distance to the nearest fire station
- Driving distance to the nearest high standard road
- Straight-line distance to the nearest paved road
- Average slope of the area around the structure
- Elevation of the structure
- Aspect of the structure
- Topographic position of the structure
- Average wind speed, temperature, and humidity during the estimated period of fire arrival (based on the MODIS-derived progression map)

See Appendix for additional details on how independent variables were calculated.

Initially, the vegetation variables were calculated for a 100-foot (30 m.) zone around each of the 2,086 selected structures. Distance was measured from the exterior of the structure. The zone included the area covered by the structure in order to account for overhanging vegetation. Multiple linear regression analysis was used to determine which vegetation and non-vegetation variables seemed to have the most impact on structure loss. Stuctures were assigned a value of 1 if burned and 0 if not burned. The analysis indicated that the strongest predictor of structure loss was the average vegetation density in the 100-foot (30 m.) zone. The second most important variable was the proportion of the vegetation classified as "ladder fuel" – vegetation in the 1-4 meter height class. The only non-vegetation variables that appeared to be related to structure loss were elevation and structure density. Topographic variables such as slope, aspect or topographic position did not prove to be significant, nor did the estimated weather parameters or measures of access such as distance to paved roads or fire stations.

The size of the distance zone around each structure was then varied along with the analysis cell size to determine which zone and cell size had the best predictive value for structure loss. Zones of 25, 50, 100, 200 and 500 feet (8, 15, 30, 60, and 150 meters) were compared using only the average vegetation density as the independent variable. Analysis cell sizes of 1 and 5 meters were also compared. The results of that analysis, shown in the following table, indicated that vegetation density in the 50-foot zone (15m.) zone was the best predictor of structure loss. A cell size of 1 meter made a slight improvement in proportion of explained variance, as measured by the R-squared values, compared to a 5 meter cell size, but at the cost of much longer processing times. The 5-meter cell size was used in subsequent analysis.

Vegetation Density vs. Structure Loss Effects of Distance Zone and Cell Size		
Zone	R-Squared 5 METER CELL SIZE	R-Squared 1 METER CELL SIZE
25 feet (8 meters)	0.103	0.114
50 feet (15 meters)	0.121	0.123
100 feet (30 meters)	0.114	0.117
200 feet (60 meters)	0.107	0.111
500 feet (150 meters)	0.088	0.082

To reduce the effects of spatial autocorrelation, to improve the accuracy of vegetation mapping, and to focus on the most valuable structures, a subset 500 structures was selected for more detailed analysis. The largest structure on each parcel was identified. Structures with a mapped area of less than 500 square feet (45 sqm.) were excluded from consideration. Application of these criteria resulted in a set of 937 possible structures for detailed analysis. From that set of 937 structures, 500 were randomly selected. Within the selected set, 282 of the structures had burned (56%). Additional edits were made to the LIDAR point cloud data for each of the 500 selected structures and the surrounding area to correct mis-classification errors. The most frequent correction was the reclassification of vegetation returns to structure returns. 280 previously unmapped small structures were located in this process. Structure shapes from previous mapping efforts were refined. LIDAR returns from vehicles parked near structures and returns from nearby power lines were reclassified to exclude them from the analysis.

Linear regression analysis was performed to identify the most effective distance zone to predict structure loss for the 500 selected structures, using vegetation density as the only independent variable. Vegetation density in the 50-foot (15 m.) zone around each structure again proved to be the best predictor of structure loss with an R-squared of .136. This compared to an R-squared value of .134 for the 25-foot (8 m.) zone and 0.124 for the 100-foot (30 m.) zone.

Variables for the proportion of ladder fuels, elevation, and structure density were then added to the linear regression model. Elevation remained a significant predictor or structure loss. The density of structures and the proportion of ladder fuels, however, no longer appeared to have a significant impact on structure loss for the 500 selected structures. The final estimated regression equation was as follows:

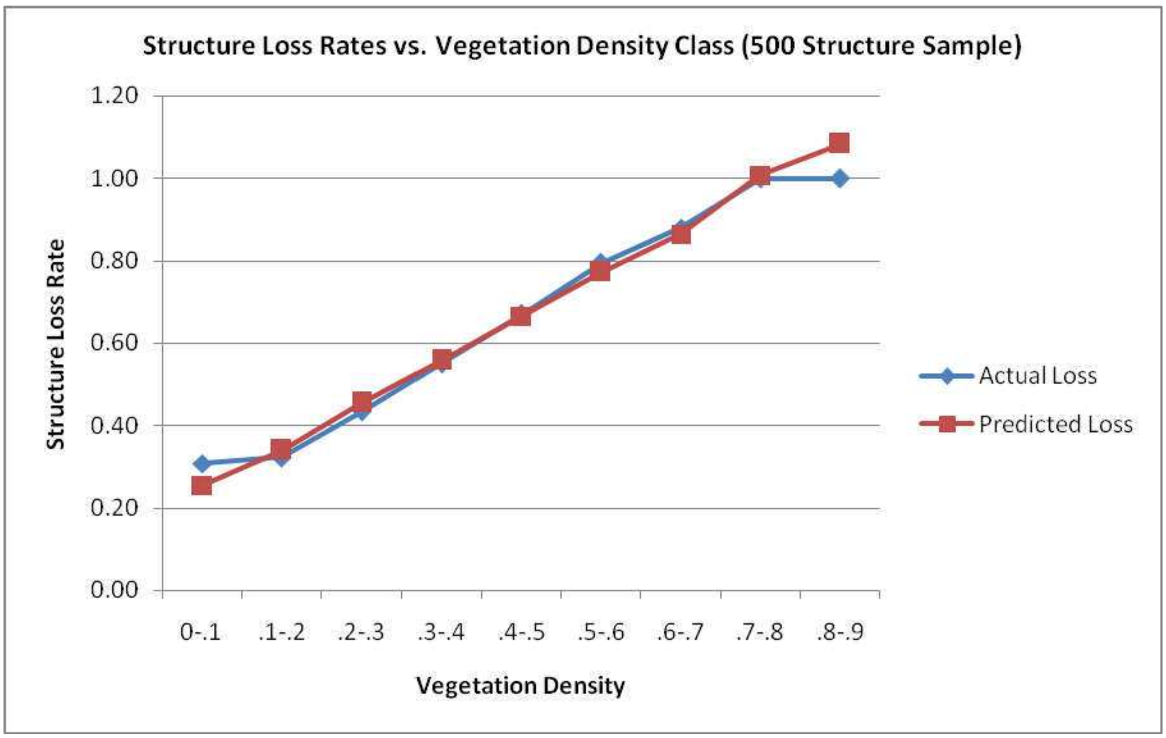
Probability of Loss = -0.138 + (1.0207 * Vegetation Density) + (0.0005 * Elevation in meters) with an R-squared value of **0.148**

Using a Repeated K-fold Cross Validation, the averaged R-squared value was 0.159.

(*Note: In addition to the linear regression analysis, a logistic regression was also performed, using the same data and variables as in the linear regression. While the logistic regression showed that the same variables were significant, the R-squared value was slightly less than the linear regression (.110 vs. .148).*

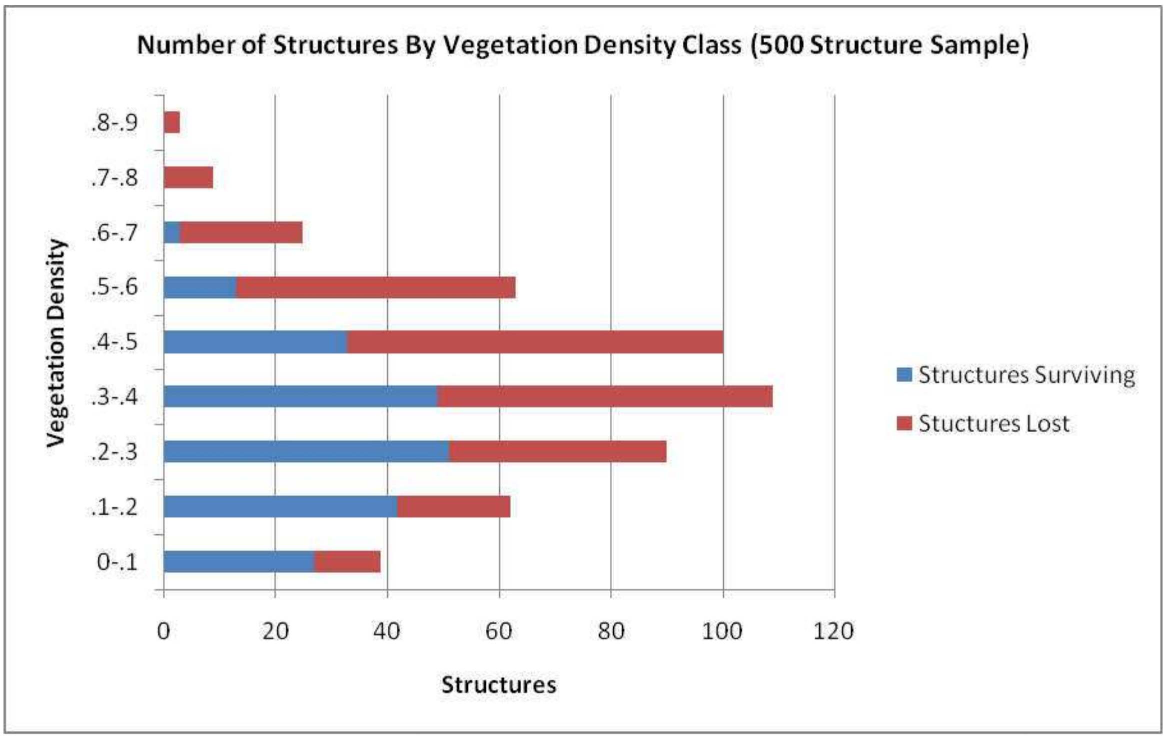
Complete regression statistics can be found in the Appendix.

Grouping the vegetation density in the 50-foot (15m.) zone into 10% classes, the following graph shows the relationship between vegetation density, the predicted structure loss, and the actual structure loss:



As the chart shows, the predictive equation is less accurate at the extremes of the vegetation density data. It underestimates structure loss when vegetation density is very low (less than 0.2) and overestimates the loss when vegetation density exceeds 0.8. It appears that loss rates reach a lower plateau at about 30% loss even as vegetation density drops below 0.2. This may reflect the effects of long distance ember transport or the fact that vegetation not detected by LIDAR, such as grasses or small vegetation immediately adjacent to the structure, still contribute to structure loss when tree cover is absent. The overestimate of structure loss when vegetation densities exceed 0.8 (resulting in probabilities greater than 1.0) demonstrates one of the limitations of linear regression for this type of analysis. Predicted values may be less than zero or greater than one, even though those values cannot occur in reality. In actual practice, only 3 of the 500 structures exceeded 0.8 vegetation density, as seen in the next chart.

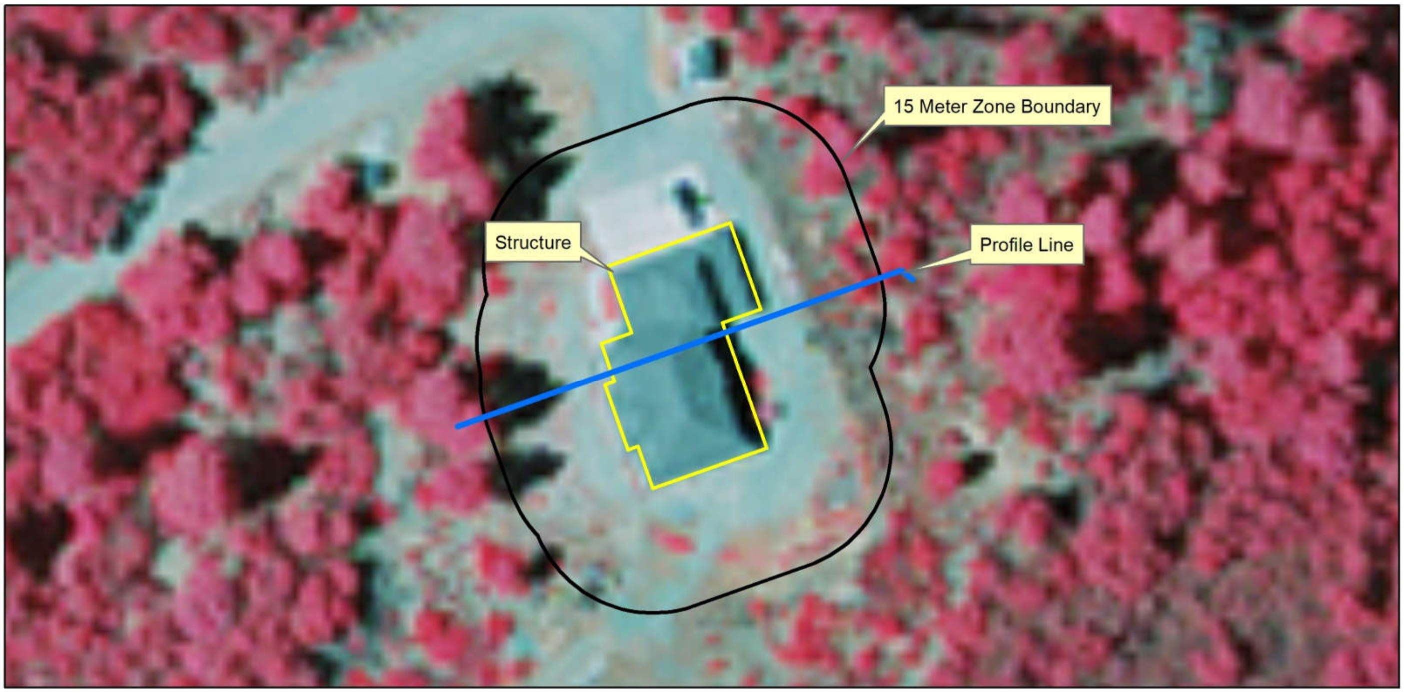
The following chart displays the total number of structures and the proportion lost in each vegetation density class:



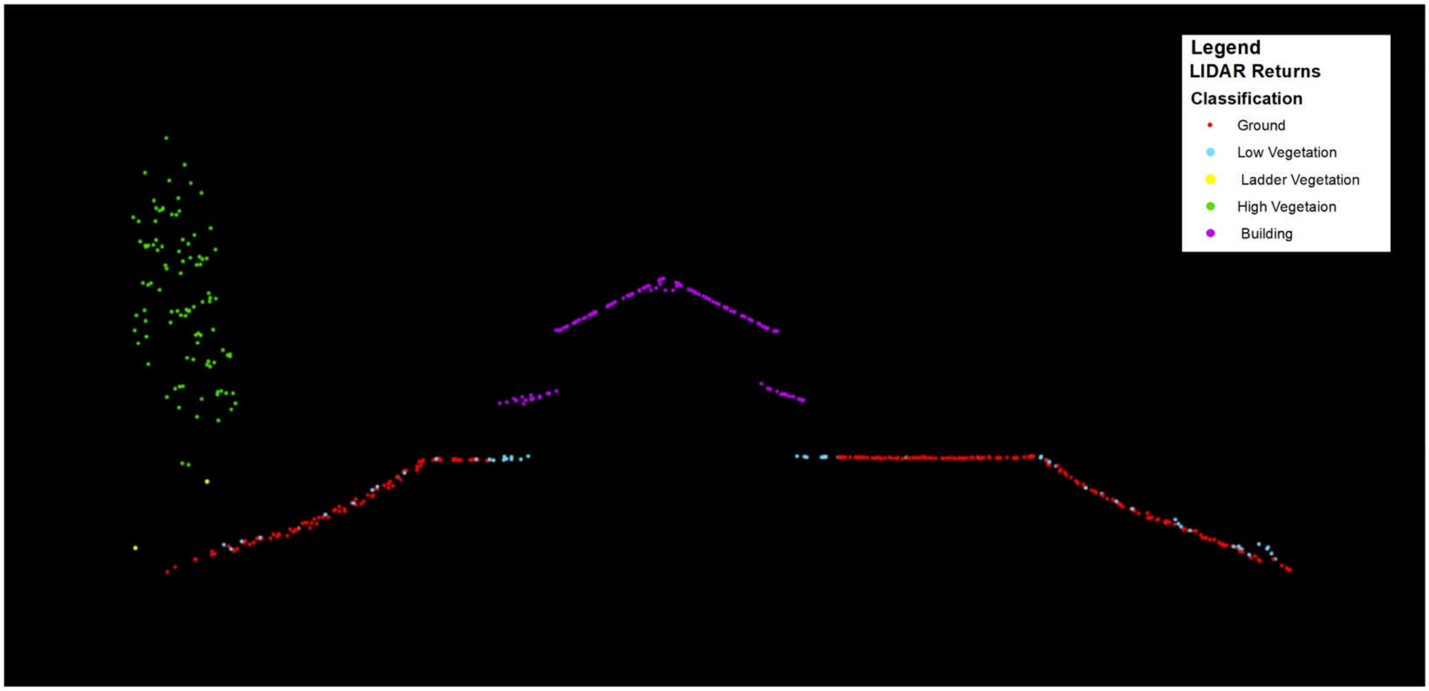
Both the Vegetation Density and Elevation variables have positive coefficients in the regression equation, indicating that structure loss increases as those variables increase. The positive relationship between vegetation and structure loss is as expected – as vegetation around the structures increases, there is more fuel for the fire to consume, leading to greater radiant and convective heat, and more ember transport. The linear regression equation estimates that, in the case of the Butte Fire, a ten percent increase in vegetation density within the 15 meter zone resulted in, on average, a 10.2% increase in structure loss.

A 300 meter (1000 ft) rise in elevation is associated with a 15% increase in structure loss. This may reflect the changing character of vegetation as elevation increases. Tree cover tends to increase with elevation and conifers increase relative to oaks and brush.

Examples using the LIDAR-based structure loss equation:

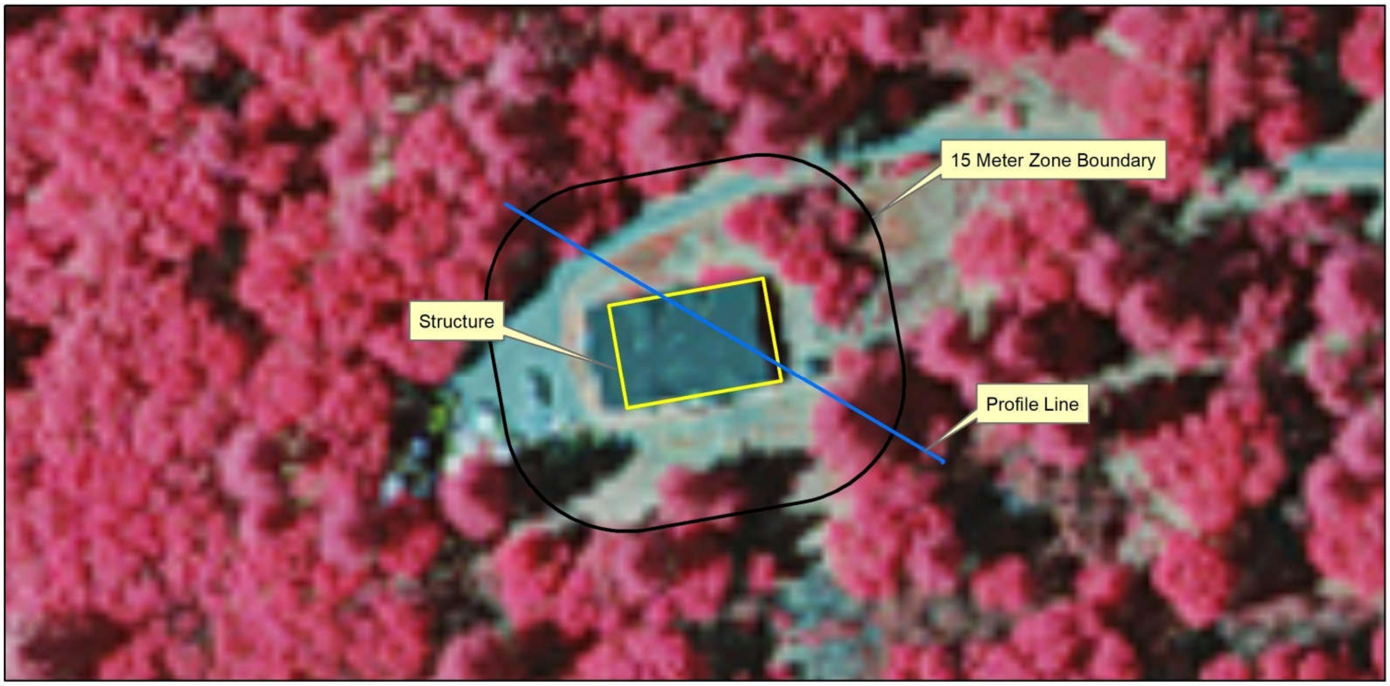


Example 1: 0.18 Predicted Probability of Structure Loss Based on Vegetation Density of 0.02 and an Elevation of 622 meters (2041 feet). NAIP Color Infrared Image from 2014.

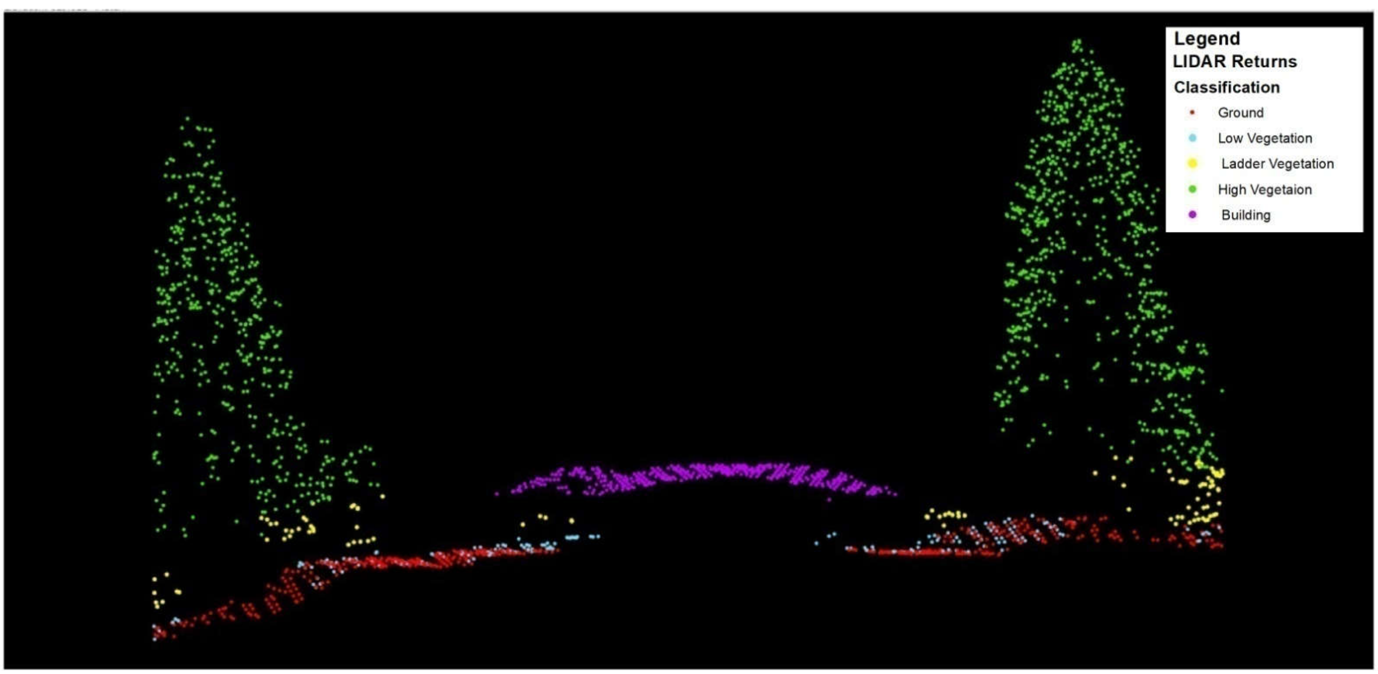


Example 1 LIDAR Returns - Profile View

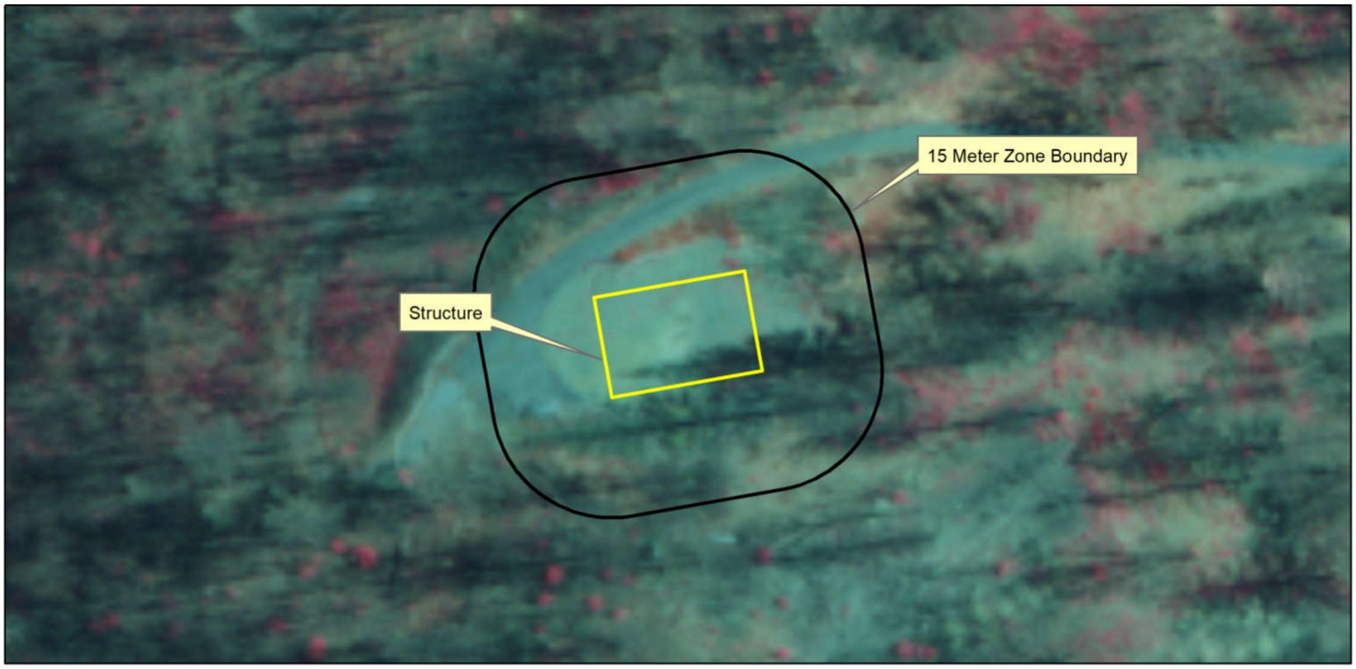
Example 1: Post Fire NAIP Color Infrared Image from 2016.



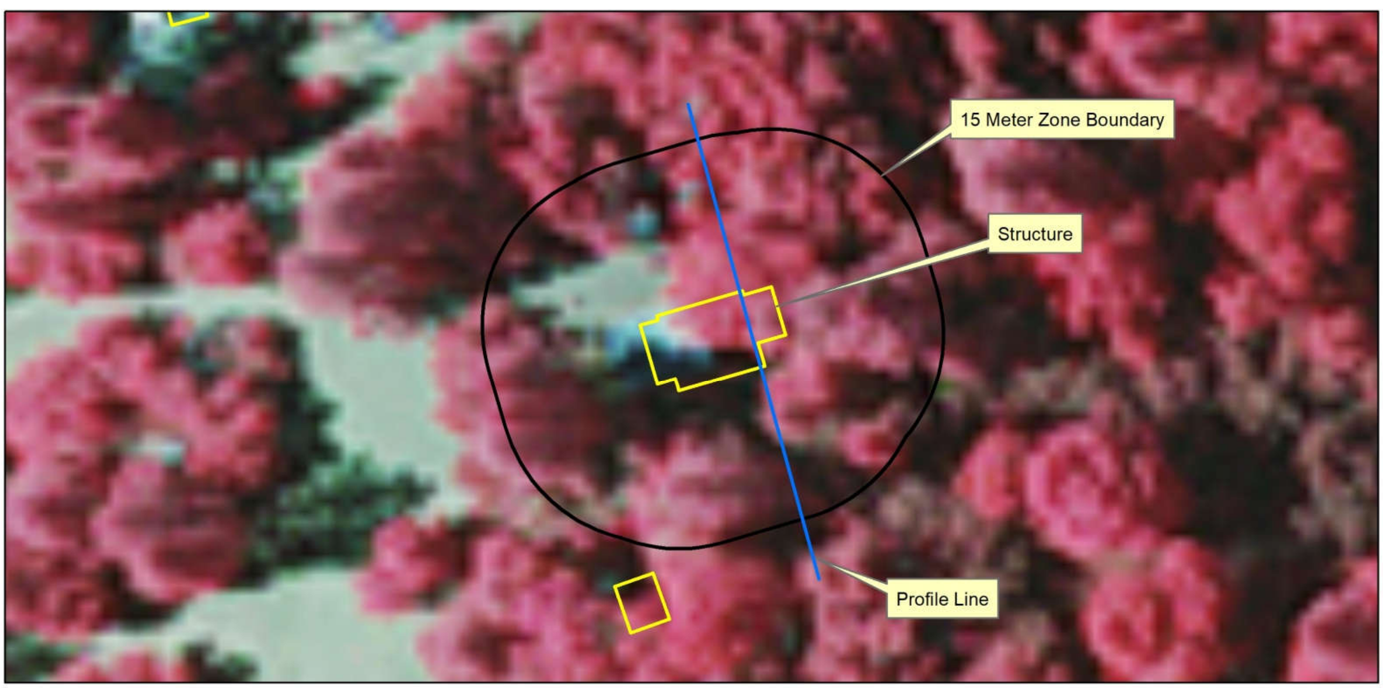
Example 2: 0.50 Predicted Probability of Structure Loss Based on Vegetation Density of 0.24 and an Elevation of 808 meters (2651 feet). NAIP Color Infrared Image from 2014.



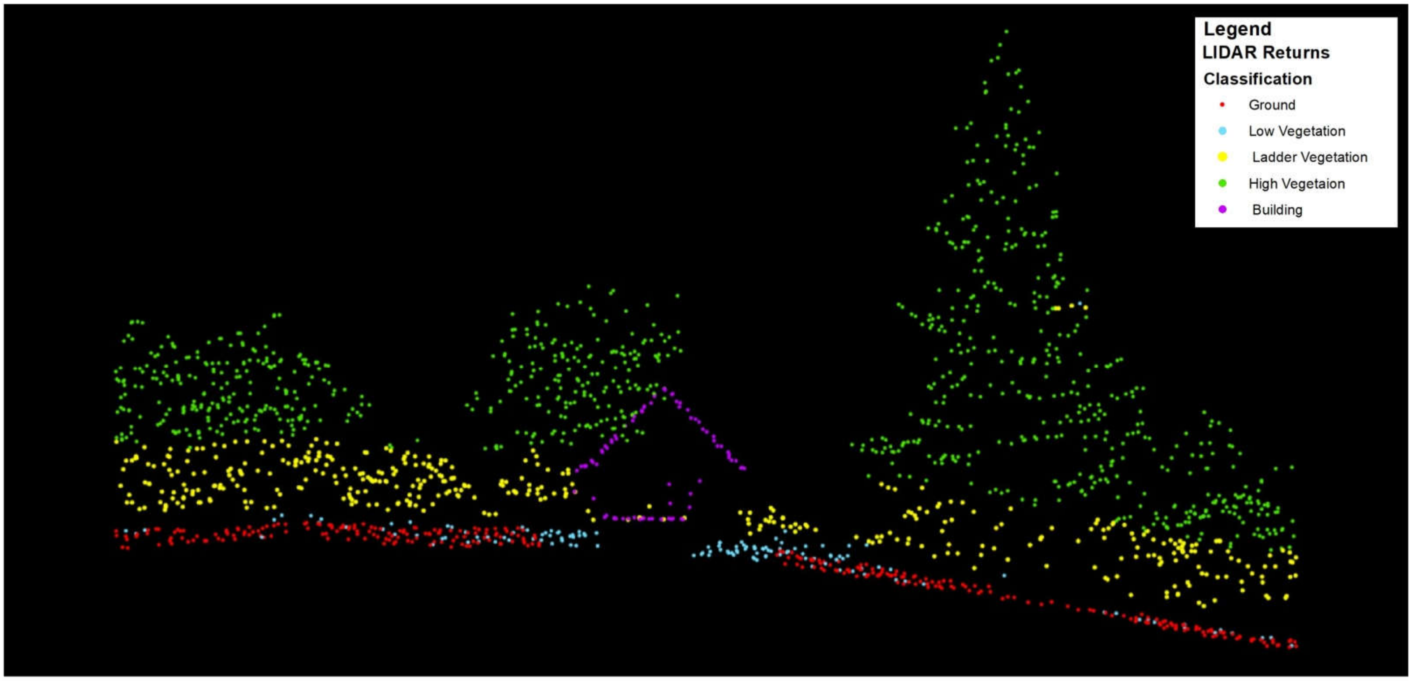
Example 2 LIDAR Returns - Profile View



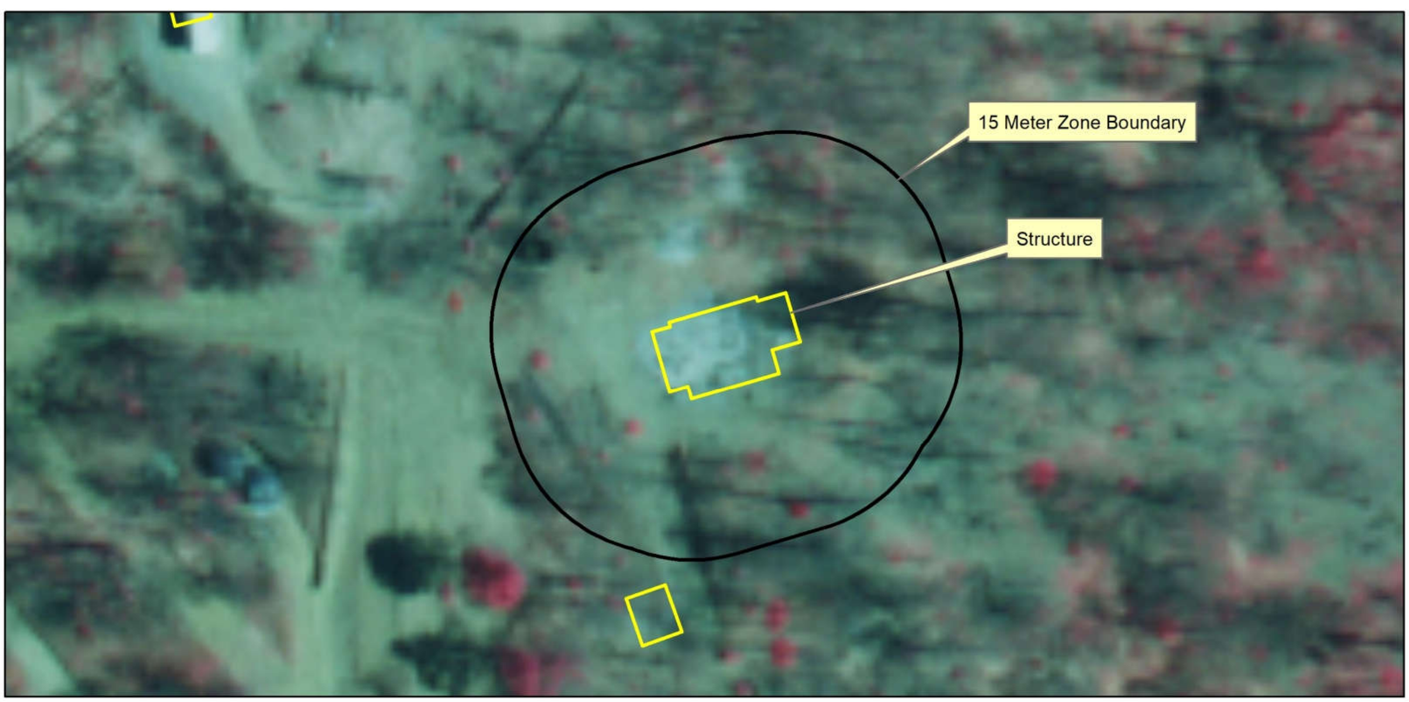
Example 2: Post Fire NAIP Color Infrared Image from 2016.



Example 3: 0.91 Predicted Probability of Structure Loss Based on Vegetation Density of 0.67 and an Elevation of 739 meters (2425 feet). NAIP Color Infrared Image from 2014.



Example 3: LIDAR Returns - Profile View



Example 3: Post Fire NAIP Color Infrared Image from 2016.

To assess the effectiveness of LIDAR-based vegetation measures compared to aerial imagery, two variables derived from the 2014 NAIP 1-meter resolution infrared imagery were calculated for the 50-foot (15 m.) zone: the average Normalized Difference Vegetation Index (NDVI) for the entire zone and the proportion of vegetation cover within the zone. To calculate vegetation cover, only pixels having an NDVI greater than 0.25 were counted as vegetation.

The best result in terms or R-squared value was the following equation:

Probability of Structure Loss = -0.122 + (0.883 * Vegetation Cover) + (0.0004 * Elevation in meters)

with an R-squared value of **0.147.** This result is nearly identical to the R-squared value **(0.148)** for the predictive equation discussed earlier which used LIDAR-derived vegetation density as the independent variable. It implies that a 10% reduction in vegetative cover in the 50-foot (15 m.) zone, reduced structure loss probability by 8.8 %.

Discussion: A number of previous studies have attempted to use empirical data to estimate the likelihood of structure loss to wildfire in California. *Syphard et al*. (2014) used aerial imagery to map vegetation near 2000 structures threatened by wildfires in southern California. That study found that most important variables in explaining structure loss, in order of importance, were: low housing density, distance to major roads, vegetative clearance, slope, and vegetation overhanging the roof. The study found that the most effective treatment distance varied between 5 and 20 meters from the structure; that treatment beyond 30 meters was not effective; and that reducing the vegetative cover to less than 40% did not reduce structure loss. The regression models in the *Syphard et al.* (2014) study resulted in R-squared values in the 0.12 – 0.13 range.

Unlike the *Syphard et al.* (2014) study, the Butte Fire analysis found that vegetation density was the most important determinant of structure loss. Housing density, distance to roads, slope, and overhanging vegetation were not significant factors in the structure loss rates. The Butte Fire analysis did find that the most important zone for vegetation clearance was within 15 meters of the structure, which is consistent with the *Syphard et al.* (2014) findings. In addition, there appeared to be a lower limit in the effectiveness of reducing vegetation density. Reduction of vegetation density to less than 20% did not appear to reduce structure loss rates in the case of the Butte Fire. This compares to a lower effective limit of 40% vegetation cover in the *Syphard et al*. (2014) study.

The greater importance of vegetation cover in the Butte Fire case may be explained, in part, by the higher fuel loads and lower wind speeds in the Butte fire as compared to fires in southern California. Differences in structure density between the two areas may also be important. The Butte Fire area had a relatively low density of structures and was classified as wildland urban intermix. As noted in *Kramer et al*. (2019), defensible space may be more effective in reducing losses in the lower housing density intermix areas than in higher density interface areas. One explanation could be that structure density tends to affect where fire fighting resources are concentrated. That was demonstrated in the Mountain Ranch area of the Butte Fire. Though still classed as urban intermix, the Mountain Ranch townsite was an area of relatively higher housing density within the Butte Fire with many parcels around 2 acres (0.4 ha) in size. Fire fighters were able to preserve an unburned island around the townsite and save most of the 120+ homes in the area.

R-Squared values for Butte Fire regression models (0.147 – 0.148) were comparable to those of the *Syphard et al.* (2014) study. These relatively low R-squared values indicate that the models in both cases result in substantial unexplained variation. Model results might be improved by accounting for factors such as: structure materials and design, the availability of fire-fighting resources, the presence of leaves on roofs or gutters, the existence of shrubbery immediately adjacent to the structure, or the weather at the time at the time the fire arrives at a structure.

Syphard et al. (2017) augments the data in the 2014 study by adding structure age as a proxy for structure characteristics. Adding structure age to the model increased the percent of deviation explained to 21%. Looking at a subset of the structures for which detailed structure information was available, and considering only on-site data (structure and vegetation characteristics, and slope), the *Syphard et al.* (2017) study finds that "window preparation was especially important but, in general, creating defensible space adjacent to the home was as important as building construction". Structure characteristics, in order of importance, were window framing material, number of window panes, roofing material, and siding material. The percentage of deviation explained by the on-site model was 14%.

Syphard et al. (2019) used a California state-wide dataset compiled by the CALFIRE Damage Inspection (DINS) Program consisting of 40,000 post-fire structure inventories for 2013 through 2018. Structure and vegetation characteristics and fire-defense actions at destroyed structures were compared to those same parameters for structures that received minor damage. That study concluded that, for the state as a whole, structural characteristics such as enclosed eaves, vent screens, and multi-pane windows appeared to be more important than vegetation (as measured by defensible space distance) in explaining structure survival. In the North-Interior part of the state, the study found that active firefighting was the most important factor in structure survival, though data on active firefighting only began to be collected in 2018. The overall deviance explained by the data was "relatively low, suggesting that other factors need to be accounted for to understand the full loss of structure loss contributors."

CALFIRE DINS data was obtained for the current study of the Butte Fire. The dataset contained information on 967 structures: 936 destroyed and 31 with minor damage. Unfortunately, information on structure characteristics was complete for only 130 structures and no information on defensible space or fire fighting actions was recorded. As a result, that data was not used in this analysis.

The *Gibbons et al*. (2012) study examined a sample of 499 houses after the 2009 Black Saturday fires in south-eastern Australia. The top two variables affecting structure survival were found to be: percent vegetation cover within 40 meters of the structure and a Forest Fire Danger Index (FFDI) for each structure. Terrain variables such as slope were not significant. The regression model predicted that for every 10% reduction in remnant native vegetation around houses, the likelihood of loss was reduced by about 5%. The FFDI was calculated based on temperature, wind, relative humidity and a drought factor. An FFDI value was assigned to each house by estimating the time when the fire reached each house given its location on fire progression maps. Weather data for the estimated time was extracted from nearby weather station data. The R-squared value of the regression model was not reported.

As in the *Gibbons et al*. (2012) study, an attempt was made in the Butte Fire analysis to link structure locations to weather data at the time of fire arrival. It was theorized that higher wind speeds, higher temperatures, and lower humidity would lead to greater fire intensity, greater ember transport, and greater probability of structure loss. Because the Butte Fire spread so rapidly and because fire progression maps were only produced once a day, it was difficult to estimate the time of fire arrival at each structure with any precision.   In an attempt to develop a more detailed fire progression map, MODIS satellite heat detections were mapped. Those heat detections are available at a 1 kilometer spatial resolution approximately every 6 hours. (See map on page 3). For each time interval on the MODIS-derived fire progression map, average and maximum wind speeds, average temperature, and average humidity were calculated using data from the near-by Banner Road weather station. The resulting weather variables did not prove to be significant predictors of structure loss rates. Weather values averaged over the 6-hour time intervals and over thousands of acres may still not be sufficiently detailed to get an accurate measure of fire weather conditions at the time of fire arrival at a given structure.

To summarize, the Butte fire analysis demonstrates that, in the Sierra Nevada foothills, where structure density is low and fuel levels high, reducing vegetation around the structures can have a large effect on structure survival. In the case of the Butte Fire, reducing vegetation density as measured by LIDAR in the 15 meter zone around a structure by 10% lowered the probability of structure loss by about 10.5%. Reducing the vegetation cover in the 15 meter zone as measured by aerial imagery by 10% resulted in a reduction of loss probability by about 8.8%. The estimated models have considerable unexplained deviation.   Addition of information on structure characteristics might reduce that unexplained deviation, but has not made a large improvement in other studies to date. Weather variables were successfully linked to structure loss in one study in Australia, *Gibbons et al*. (2012), but attempts to do so in the Butte Fire analysis were not successful.

The LIDAR measures of vegetation examined in this study did not offer a substantial advantage over aerial imagery in assessing the probability of structure loss. Vegetation cover estimated using 1-meter infrared aerial imagery was nearly as effective in predicting structure loss as the LIDAR vegetation measures. This may be due, in part, to the fact that the FEMA LIDAR flight was designed to map floodplains, not vegetation. It was flown in a leaf-off period, and the pulse density was relatively low (0.7 per square meter). A higher pulse density during a leaf-on period might have resulted in a more accurate estimate of vegetation density and the amount of ladder fuels, and a better estimate of structure loss probablility.

The application of this analysis to other situations should be done with caution. The Butte Fire occurred in extremely dry conditions after several years of drought in an area with a relatively high vegetation density. Different weather conditions, vegetation conditions, fire protection resources, structure characteristics, etc. could give substantially different results.

Appendix I: Independent Variables

Key Vegetation Variables From LIDAR:

1. Vegetation Density: Distance zones were created around every structure analyzed, measured from the edge of the structure. The zones included the structure area of the primary structure and any other structures within the distance zone. LIDAR returns were classified into ground returns, vegetation height classes, structures, and other returns (powerlines, vehicles, and fences). Vegetation density was calculated on a 5 meter grid by dividing all vegetation returns with a height of 1 meter or greater by all vegetation returns, plus ground returns, plus structure returns. LIDAR returns from powerlines, vehicles, and fences were excluded, if mapped. The zone density was calculated as the average vegetation density of all 5 meter cells centers that fell within the zone.

2. Vegetation cover: LIDAR vegetation cover was defined as the area of all 5 meter cells having a positive vegetation density within a distance zone divided by the total area of the zone.

3. Ladder Fuel Proportion: Ladder fuel (vegetation 1-4 meters in height) density was calculated by dividing the returns from the 1-4 meter height class by the returns from ground, plus vegetation returns from 0-4 meters, plus returns from structures, on a 5 meter grid. Ladder fuel proportion was calculated by dividing the ladder fuel density by the total vegetation density for the zone (see 1. above). (Note: A similar calculation was made to estimate the proportion of vegetation in the 1 – 8 meter height class).

4. Overhanging vegetation density: Vegetation density as described in 1. above was averaged for the 5 meter grid cells falling within each structure polygon.

Vegetation Variables from Aerial Imagery:

1. Average NDVI - The average Normalized Difference Vegetation Index (NDVI) for the 50-foot (15 m.) zone around and including each structure was calculated on a 1 meter grid, using the red and infrared bands from the 2014 National Agricultural Imagery Program (NAIP) digital imagery.

2. Vegetation cover – The area of all 1 meter cells having an NDVI value of greater than 0.25 within the 50-foot (15 m.) zone around each structure was divided by the total area of the zone, including the structure. The 0.25 cutoff value was based on a visual comparison of NDVI values with the presence or absence of vegetation in the aerial image (the 2014 NAIP aerial image). The 2014 NAIP image appears to be a late-summer image. As a consequence, seasonal grasses would have largely cured and would not have been counted as vegetation cover, due to low NDVI values.

KEY Non-Vegetation Variables:

1. Structure Density : Density per square kilometer was calculated for a 800 meter distance zone around each structure. Structures outside the fire perimeter were included in the density count. Only structures over 500 square meters in size were counted.

2. Structure Access: The road network from the Calaveras County GIS department was used as the base. Road\driveways were added using LIDAR and aerial imagery to connect all structures to the road network. Time and distance variables were calculated from this augmented network using a 10 meter cost-distance grid: driving time and driving distance to: the nearest fire station, to the nearest high-standard road, and to the nearest paved road. Straight-line distance to the nearest paved road was also calculated.

3. Topographic variables: Using a 10-meter dem created from the LIDAR data and the centroid of each structure, the following topographic variables were calculated: elevation (meters), aspect, Beer's aspect and topographic position (using *Topography Tools 10.3* by Thomas Dilts, University of Nevada, Reno). Slope for each structure was calculated by averaging slope within the 15 meter zone around each structure.

Appendix II: Regression Statistics

Linear Regression with LIDAR Vegetation Density as Primary Independent Variable:

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.389
R Square	0.151
Adjusted R Square	0.148
Standard Error	0.458
Observations	500

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	18.622	9.311	44.356	1.88E-18
Residual	497	104.330	0.210		
Total	499	122.952			

	Coefficients	*Standard Error*	*t Stat*	*P-value*
Intercept	-0.1380	0.1222	-1.1293	0.2593
Vegetation Density	1.0207	0.1204	8.4811	2.57E-16
Elevation (meters)	0.0005	0.0002	2.8622	0.0044

Results of K-fold Cross-Validation

Linear Regression ; 500 samples; 2 predictor; No pre-processing

Resampling: Cross-Validated (10 fold, repeated 3 times)

Summary of sample sizes: 450, 450, 450, 450, 450, 450, ...

Resampling results:

RMSE	**Rsquared**	**MAE**
0.4589978	0.1589699	0.4211309

Linear Regression with Vegetation Cover From Aerial Imagery as Primary Independent Variable:

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.388
R Square	0.151
Adjusted R Square	0.147
Standard Error	0.458
Observations	500

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	18.552	9.276	44.160	2.225E-18
Residual	497	104.400	0.210		
Total	499	122.952			

	Coefficients	*andard Err*	*t Stat*	*P-value*
Intercept	-0.1223	0.1218	-1.0035	0.3161
Vegetation Cover	0.8831	0.1044	8.4587	3.04E-16
Elevation (meters)	0.0004	0.0002	2.5152	0.0122

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