The Effects of Vegetation, Structure Density, and Wind on Structure Loss Rates in Recent Northern California Wildfires

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Abstract

Objectives: This study is focused on the following questions: What is the effect of reducing vegetation on structure loss rates in wildfires, whether that vegetation is near homes (i.e. in the "defensible space") or at some distance from homes? How does structure density influence loss rates and the effectiveness of vegetation treatments? What is the impact of wind and other weather conditions on loss rates? How effective are vegetation reductions in wildfires driven by high winds?

Analysis: Loss rates are analyzed for 26,915 single family homes threatened by wildfires in nine Northern California fires during the 2015-2021 time period. Of those homes, 21,504 were destroyed (79.8%). Five of the nine fires in this study (Butte, Camp, Claremont-Bear, Dixie and Caldor) occurred in the northern foothills of the Sierra Nevada Mountains. Three (Tubbs, LNU East, and LNU West) were located in the Coastal Mountains of the Bay Area. The Carr Fire occurred in the Klamath Mountains in northwestern California.

To match weather conditions with structures losses, data is limited to a single day for each fire – the day with the highest number of destroyed structures. Structure locations and degree of damage are derived from post-fire inventories conducted by the California Department of Forestry and Fire Protection (CalFire), augmented by other data sources. Only structure points within 25 meters of a burned area are considered. Vegetation cover is estimated for the area within 25 meters and within 500 meters of each structure point by reclassifying a pre-fire high resolution Normalized Difference Vegetation Index (NDVI) image. Weather parameters for the maximum loss day on each fire are taken from the nearest Remote Automatic Weather Station (RAWS). Logistic regression is used to estimate the probability of structure loss, considering weather variables, vegetation cover, and structure patterns.

Results: Structure density, vegetation cover within 25 meters and within 500 meters of a structure point, maximum wind levels and maximum temperature levels are all statistically significant and positively related to structure loss. Structure density has a large impact on loss rates directly and also on the relative impact of vegetation cover. Homes in high structure density areas (i.e., more than 400 structures per km2 within a 200-meter distance) have a predicted loss rate 20% higher than homes in low structure density areas (SDA's), most likely due to increases in structure-to-structure spread. 33% of the losses in high SDA's can be attributed to structure density compared to 13% of losses in the low SDA's.

Changes in vegetation cover have much less impact on structure loss rates in high SDA's than in low SDA's. A 10% reduction in vegetation cover in the 25-meter zone is estimated to reduce loss rates by 1.8% in the high SDA's compared to 3.9% in the low SDA's. For the 500-meter vegetation zone, those figures are similar: 1.4% and 3.0%. Because of the size of the areas involved and the relative effectiveness, approximately 28 acres in the 500-meter zone would need to be treated for every acre treated in the 25-meter zone in order to achieve the equivalent reduction in structure loss rates.

An increase in the maximum daily wind speeds from 20 mph (8.9 mps) to 60 mph (26.8 mps) is estimated to boost loss rates by 14%. With 60 mph winds, reductions in vegetation cover are 45% less effective in reducing losses compared to those same reductions in 20 mph winds.

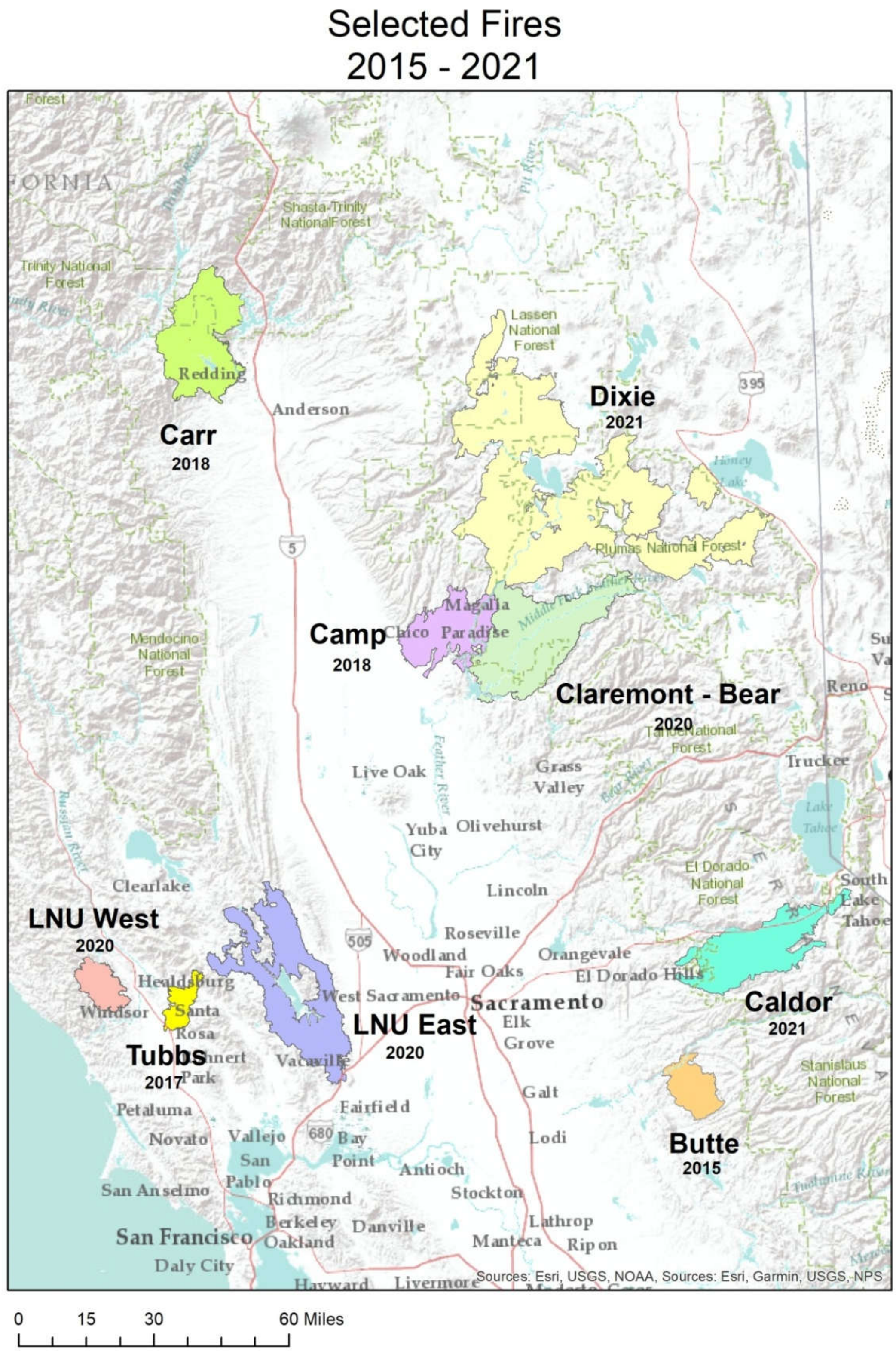
Conclusions: Lower vegetation cover in both the 25-meter and 500-meter zones does result in lower structure loss rates. Reducing vegetation cover in the 25-meter zone in low SDA's gives the best result for the least amount of area requiring treatment. Reducing vegetation cover in high SDA's is less effective, given the large proportion of homes lost to structure-to-structure spread. Even substantial vegetative reduction, however, will not reduce losses to low levels during high wind events. With a reduction of 50% in the average vegetation cover levels in both the 25-meter and 500-meter zones, predicted loss rates for these fires would still be over 50% for low SDA's and close to 80% for high SDA's.

Keywords: Defensible space, structure loss, wildfire, WUI, fuel reduction, radiant heat, structure density, embers, flames, fire prevention, NDVI, Sierra Nevada, Bay Area, wind, Northern California, Camp Fire, Tubbs Fire, Butte Fire, Dixie Fire, Caldor Fire, LNU Complex Fire, Claremont-Bear Fire, Carr Fire

Note: The term "10% change" refers to a 0.10 change in the proportion of vegetation cover or to a 0.10 change in loss rate, unless otherwise stated.

The fires included in this study are displayed in the map in Figure 1.

Figure 1:


Selected Fires
2015 - 2021
Carr
2018
Dixie
2021
Camp
2018
Claremont - Bear
2020
LNU West
2020
Tubbs
2017
LNU East
2020
Caldor
2021
Butte
2015
Shasta-Trinity National Forest
Trinity National Forest
Lassen National Forest
Plumas National Forest
Mendocino National Forest
Tahoe National Forest
El Dorado National Forest
Stanislaus National Forest
Redding
Anderson
Chico
Magalia
Paradise
Live Oak
Grass Valley
Yuba City
Olivehurst
Lincoln
Roseville
Truckee
Reno
South Lake Tahoe
Lake Tahoe
Clearlake
Healdsburg
Windsor
Santa Rosa
Rohnert Park
Petaluma
Novato
Vallejo
San Pablo
San Anselmo
Richmond
Berkeley
Oakland
San Francisco
Daly City
Hayward
Livermore
Danville
Vacaville
Fairfield
Bay Point
Antioch
Stockton
Lathrop
Manteca
Ripon
Lodi
Galt
Elk Grove
Sacramento
West Sacramento
Woodland
Fair Oaks
Orangevale
El Dorado Hills
Honey Lake
Russian River
Feather River
Sources: Esri, USGS, NOAA, Sources: Esri, Garmin, USGS, NPS
0 15 30 60 Miles

Literature Review:

Gibbons *et al*. (2012) examined 499 houses after the 2009 Black Saturday fires in south-eastern Australia. Percent of native vegetation cover within 40 meters of the structure was identified as one of the top variables affecting structure survival, along with a Forest Fire Danger Index (FFDI), a combination of wind strength, temperature, relative humidity and a drought factor. Distance to a public forest and number of buildings within 40 meters of a house were also significant variables. The logistic regression model predicted that for every 10% reduction in remnant native vegetation around houses, the likelihood of loss was reduced by about 5%. The model predicted a 3% increase in destroyed houses for every additional building or shed located within 40m. Increasing the distance to a public forest from 200m to 2 km reduced loss rates by 12%.

Syphard *et al*. (2014) compared the impact of defensible space and other variables on a selection of 2000 homes in Southern California that had been threatened by past wildfires. That study found that reducing woody material within 20 meters of the structure was the most effective vegetative treatment but landscape factors such as low housing density and distance to major roads were more important in explaining structure loss. Loss rates were found to decrease as housing density increased.

Syphard *et al.* (2017) found that housing density was the most important factor in determining wildfire structure loss in Southern California and that higher housing density resulted in a lower rate of structure loss.

Kramer *et al*. (2019) assessed structure losses in wildfires in California during the 1985-2013 time period. The Interface WUI category was found to have higher a higher loss rate than the Intermix category, even though the amount of wildland vegetation was higher in the Intermix category.

Syphard and Keeley (2019) analyzed records for 40,000 structures included in the post-fire Damage Inspection Database (DINS) compiled by CalFire for the years 2013 through 2018. That study found that defensible space distance categories recorded in the DINS inspections were not a significant predictor of structure survival when compared to structure characteristics such as vent screens, enclosed eaves, and dual-pane windows.

Syphard *et al*. (2021) re-examined the 2013 – 2018 DINS data using a different method of measuring defensible space and adding unburned structures not inventoried by Cal Fire. Pre-fire vegetation near structures was estimated by calculating a normalized difference vegetation index (NDVI) from Landsat 30-meter resolution satellite imagery. Landscape level flammable vegetation (ie. within 2.5 kilometers of each structure) was estimated from the USGS National Land Database. That study found that for both the Bay Area and North Interior regions, neither vegetation measure explained a large percentage of the variability in structure survival. In the North Interior region, NDVI within 30 meters of structure points was higher for unburned structures than for burned structures. The Wildand Urban Interface (WUI) category was found to be a better predictor of structure survival than any of the vegetation measures in both the Bay Area and Northern Interior regions. For those regions, the Interface WUI category had a higher relative risk of loss than the Intermix WUI class.

Schmidt (2020) sampled 500 homes in the 2015 Butte fire and found the proportion of vegetation cover within 15 meters of the structure perimeter was the best predictor of structure loss along with elevation. Measurement of vegetation cover using pre-fire LIDAR and using high-resolution infrared aerial imagery produced similar results: A 10% reduction in vegetation cover reduced the likelihood of loss by about 10%.

Knapp *et al*. (2021) sampled 400 homes in the Camp fire and concluded that distance to destroyed structures, the density of destroyed structures within 100 meters, and pre-fire canopy cover within 30-100 meters of the home were the most significant factors in predicting loss rates in single family homes. The fact that a home was built after more stringent state building codes were adopted in 2008 did not prove to be statistically significant. Knapp also examined photographs recorded for 310 partially damaged structures and estimated that 63% had radiant heat damage, most likely from a neighboring structure that was destroyed; 28% had damage due to indirect ember ignition of materials near the structure; 6% had damage due to direct ember ignition; 10% had damage due to continuity of surrounding fuels (often needle and leaf litter) and 10% had damage from an undetermined cause.

Data and Analysis:

Structures - Structure loss in a wildfire is the result of a complex interaction between weather conditions, vegetation, topography, defensive actions, structure characteristics and the spatial arrangement of structures. In an effort to reduce the complexity, the structures included in this study were limited to single family homes that were exposed to wildfire (i.e., the mapped point representing each structure was within 25 meters of a burned area) on a single day in each fire. The day chosen for analysis on each fire was the day with the greatest structure loss. Burned areas were determined from post-fire Burned Area Reflectance Classification (BARC) imagery available from the USDA Burned Area Emergency Response website (https://burnseverity.cr.usgs.gov/baer/) or were developed from pre- and post-fire satellite imagery using similar classification procedures. (*Note: Since the burned area maps were derived from satellite imagery with a resolution of 10 – 30 meters on the ground, the distance from a structure point to a burned area can only be approximated*.)

The primary source for structure locations and status was the DINS data compiled by Cal Fire after each fire. The DINS database contains a single location point for each structure inspected, an assessment of the damage to the structure, selected structure characteristics and, beginning in 2018, a description of defensive actions taken. In this study only structures identified as single-family dwellings in the DINS data were included, except for dwellings classified as motor homes. Structures with more than 10% damage were counted as a loss. Homes with less than 10% damage and with a recorded defensive action (283 in total) were dropped from the analysis to minimize the influence of defensive actions on the results.

While the DINS data is relatively complete for structures that are damaged in wildfires, undamaged structures are not always recorded. In addition, recorded structure points may not always be aligned with structure locations in aerial imagery. Pre-fire aerial imagery from the National Agricultural Imagery Program (NAIP) (https://gdg.sc.egov.usda.gov/), LIDAR data from the USGS National Map (in the case of the Butte fire only), (https://www.usgs.gov/programs/national-geospatial-program/national-map), and ancillary structure data from the Microsoft building footprint dataset (https://www.microsoft.com/en-us/maps/building-footprints) were employed to add points for unburned homes not found in the DINS database and to adjust point locations to align with structure locations in the NAIP imagery. Building locations initially derived from the Microsoft dataset were only used if confirmed on aerial imagery. In total, 1,328 homes were added to the DINS data.

Maximum Loss Day- For the Camp fire, nearly all the structure losses occurred on the first day of the fire, November 8, 2018. Structure losses for the Tubbs fire occurred over a 24-hour period starting in the evening of October 8, 2017. For purposes of this analysis, the weather data for the Tubbs fire was taken from October 9, the day when the highest winds occurred. For the Carr, LNU East, LNU West and the Claremont-Bear fires, daily perimeter maps produced by fire personnel (https://ftp.wildfire.gov/) were used to determine the area burned on the maximum structure loss day. For the Butte fire and Caldor fires, MODIS and VIIRS satellite data were employed to delineate the maximum loss day burned area. (https://firms.modaps.eosdis.nasa.gov/usfs/active_fire/).

Table 1 displays the single-family homes threatened and destroyed on each fire and on the maximum loss day of each fire.

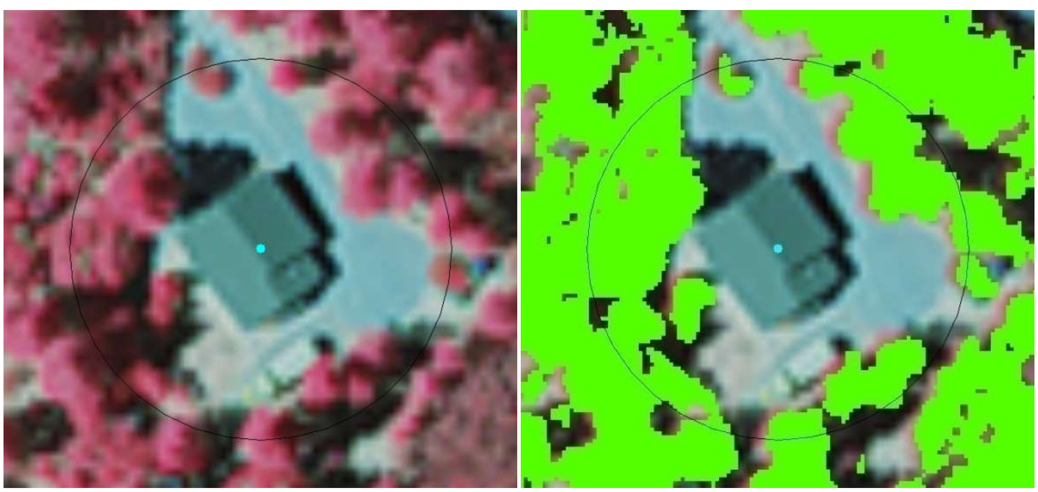
Table 1: Single Family Home Loss Rates by Fire

	Entire Fire			Maximum Loss Day		
Fire	**Homes**	**Destroyed**	**Loss Rate**	**Homes**	**Destroyed**	**Loss Rate**
Butte	1,186	657	0.55	537	354	0.66
Tubbs	5,079	4,337	0.85	5,079	4,337	0.85
Carr	2,233	1,091	0.49	1,608	974	0.61
Camp	15,977	13,283	0.84	15,874	13,283	0.84
LNU East	1,846	606	0.26	1,079	408	0.38
LNU West	341	150	0.44	152	94	0.62
Claremont - Bear	1,572	1,176	0.75	1,452	1,147	0.79
Dixie	1,606	654	0.41	582	452	0.78
Caldor	1,831	783	0.43	552	455	0.82
Total	**31,671**	**22,737**	**0.72**	**26,915**	**21,504**	**0.80**

Vegetation Cover - Pre-fire live vegetation cover around each home was estimated using NAIP infrared imagery. Image resolution varied from 0.6 to 1.0 meters per pixel. A Normalized Difference Vegetation Index (NDVI) was calculated for each pixel. Pixels with an NDVI value of 0.25 or greater were classified as vegetation cover. Based on the NDVI cutoff value of 0.25, live trees and brush would typically be classed as vegetation cover. Because the NAIP images are normally collected in late summer or early fall, seasonal grasses would usually be classified as non-vegetation but irrigated lawns may be counted as vegetation cover.

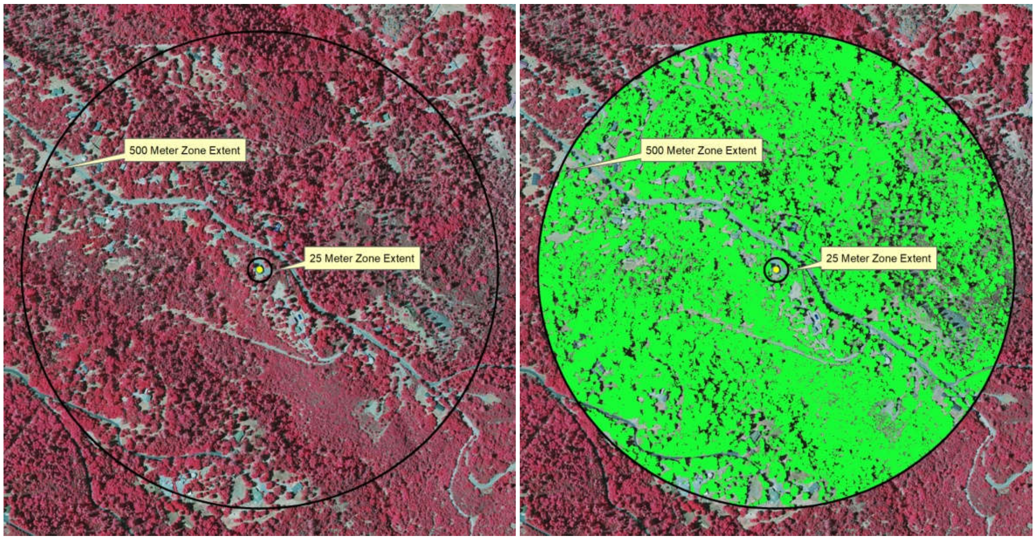
Vegetation cover was estimated for both a 25-meter circle and a 500-meter circle around each mapped structure point by calculating the proportion of pixels classified as vegetation in those zones. The area of the structure was included in the total area for which the vegetation cover proportion was calculated. The 25-meter circle is approximately 0.5 acres (0.2 ha) in size and is roughly equivalent to an average-sized house plus a 17-meter (55 foot) buffer area around it. The 500-meter circle is equivalent to an area of about 194 acres (79 ha). Figures 2 and 3 are examples of the NDVI vegetation classification for the 25-meter and 500-meter zones:

Figure 2



Infrared image on left shows a 25 meter circle around a structure central point. Image on the right shows the pixels classified as vegetation in green, based on an NDVI value greater than 0.25. This example has an estimated ***vegetation cover proportion of 0.37*** *in the 25-meter zone.*

Figure 3



Infrared image on left shows a 500 meter circle around a structure central point. Image on the right shows the pixels classified as vegetation in green, based on an NDVI value greater than 0.25. This example has an estimated ***vegetation cover proportion of 0.69*** *in the 500-meter zone.*

Additional variables estimated for each home – Variables for distance to the nearest home, structure density within 200 meters, and elevation were also estimated for each of the 26,915 homes. The structure density estimate counted all structures inventoried by Cal Fire in the DINS database plus any added unburned houses. Elevation was derived from a 30-meter DEM data from the USGS National Map.

Table 2 lists the variable names and units of measure for those variables estimated for each single-family home in the dataset.

Table 2: Variables Estimated for Each Home

Variable Name	**Description**	**Units**
VEG25	Vegetation Cover within 25 meters of Structure Point	Proportion
VEG500	Vegetation Cover within 500 meters of Structure Point	Proportion
NEAR_DIST	Distance to Nearest Home	Meters
STR_DENS	Density of All Structures within 200 meters	Structures per Sq. Km.
ELEV	Elevation	Meters

Weather Variables- Weather parameters on the maximum loss day for each fire are taken from the nearest RAWS weather station for each fire. (https://wrcc.dri.edu/wraws/ccaF.html) . Table 3 summarizes the weather variable names and data used for each fire in the analysis.

Table 3: Weather Variables Derived From Nearby Weather Stations On Maximum Loss Date

Fire	Max. Loss Date	Weather Station	Ave. Temp. (F.) (AVETEMP)	Max. Temp. (F.) (MAXTEMP)	Avg. Humidity (AVEHUMID)	Min. Humidity (MINHUMID)	Avg. Fuel Moisture (AVEFUELM)	Ave. Wind (mph) (AVEWIND)	Max. Wind (mph) (MAXWIND)	Days Since Last Rain (LASTRAIN)
Butte	Sept. 10, 2015	BANNER ROAD 2803 FT.	81.9	98	22	12	3.8	6	22	126
Tubbs	Oct. 9, 2017	SANTA ROSA 576 FT.	70.2	91	18	7	6.1	11	68	175
Carr	July 26, 2018	MULE MOUNTA 2044 FT.	94.5	111	20	7	3.5	4	21*	62
Camp	Nov. 8, 2018	JARBO GAP 2490 FT.	54.3	63	16	11	4.7	19	52	193
LNU East	Aug. 19, 2020	ATLAS PEAK 1934 FT.	86.7	96	16	10	4.5	12	32	93
LNU West	Aug. 20, 2020	HAWKEYE 2044 FT.	76.6	91	29	16	4.1	10	23	94
Claremont-Bear	Sept. 8, 2020	JARBO GAP 2450 FT.	77.9	86	12	6	4.4	32	66	86
Dixie	Aug. 4, 2021	CASHMAN 4520 FT.	78.6	98	19	9	3.0	6	37	101**
Caldor	Aug. 16, 2021	STEELY FORK 4006 FT.	67.9	74	44	27	5.7	12***	20***	113

*Notes: * The RAWS data for the Carr fire does not reflect the occurrence of a fire tornado at around 5:30 PM on July 26 as the fire approached west Redding. (CAL FIRE Carr Fire Greensheet, July 26. 2018). Wind levels from that event likely exceeded 100 mph (44.7 mps) over a two-hour period, with the tornado touching down at several locations over a three-mile area.*

*** From Chester Weather Station due to missing data.*

**** Winds are from forecast in the August 18 Caldor Incident Action Plan (https://ftp.wildfire.gov/) due to missing data at Steely Fork station.*

Logistic Model - Initially, all variables listed in Tables 2 and 3 for the 26,915 structures were analyzed in a stepwise linear regression. The dependent variable was set to 1 for a structure loss and 0 for a structure survival. Statistically significant variables were then re-analyzed with a logistic regression model. Variables in the logistic model that were not significant at the 95% confidence level or which had the wrong theoretical sign were dropped. The resulting model is shown in Table 4, with variables listed in order of their statistical significance:

Table 4: Logistic Regression - All Single Family Homes, Maximum Loss Day
26915 Observations

	coeff	*s.e.*	*Wald*	*p-value*	*exp(b)*	*lower*	*upper*
intercept	-2.94211	0.15264	371.5	0	0.053		
STR_DENS	0.00260	0.00007	1399.6	0	1.003	1.002	1.003
VEG25	1.77007	0.09131	375.8	0	5.871	4.909	7.022
VEG500	1.38512	0.10627	169.9	0	3.995	3.244	4.920
MAXWIND	0.02009	0.00118	288.6	0	1.020	1.018	1.023
MAXTEMP	0.00957	0.00114	70.5	0	1.010	1.007	1.012

R-Squared (McFadden)	0.139
AUROC	0.748

The Area Under the Receiver Operating Curve (AUROC) is estimated to be 0.748, indicating that the model is a moderately good predictor of structure loss.

Table 5 displays the effects of changes in selected model variables on predicted loss rates, when all other model variables are set to their average values for the entire dataset. For each 10% decrease in structure density (STR_DENS), loss rates are projected to fall 2.8%. A 10% reduction in vegetation cover in the 25-meter zone (VEG25) leads to a predicted 2.8% decrease in structure loss. In the 500-meter zone (VEG500), a 10% reduction in vegetation cover leads to a decline in structure loss rates of 2.2%. A 10 mph (4.5 mps) decrease in wind speed (MAXWIND) causes an estimated 3.2% fall in loss rates.

Table 5: Model Predictions, All Single Family Homes

Variable	Average	STR_DENS -10%	VEG25 -0.10	MAXWIND -10mph	VEG500 - 0.10
Intercept	1				
STR_DENS	426.0	**383.4**			
VEG25	0.51		**0.41**		
MAXWIND	51.4			**41.4**	
VEG500	0.49				**0.39**
MAXTEMP	75.6				
Predicted Loss Rate	**0.818**	**0.790**	**0.790**	**0.786**	**0.796**
Change		**-0.028**	**-0.028**	**-0.032**	**-0.022**

Results By Structure Density Categories - To examine the relative effectiveness of defensive space in urban-suburban neighborhoods compared to more rural areas, homes were divided into two structure density classes based on the total number of structures within 200 meters and calculated on a structures per km2 basis. Using the Coffee neighborhood from the Tubbs fire as template for high density housing, a density of 400 structures per km2 (i.e., 1,036 per square mile) was selected as the dividing line between high and low structure density areas (SDA's). That density is equivalent to about 50 structures within 200 meters of each house or an average of one structure per 0.6 acres.

Table 6 summarizes the housing data by the SDA for the maximum loss day on each fire:

Table 6: Structures and Loss Rates by Structure Density Area and Fire - Maximum Loss Day

Fire	Single Family Homes	High Density	Low Density	Structure Density High SDA (per km2)	Structure Density Low SDA (per km2)	Loss Rate High SDA	Loss Rate Low SDA	Difference in Loss Rates (High - Low)
Butte	537	0	537	NA	31.5	NA	0.66	NA
Tubbs	5,079	2,515	2,564	854.0	164.9	0.93	0.78	0.15
Carr	1,608	188	1,420	498.9	149.7	0.71	0.59	0.12
Camp	15,874	10,904	4,970	636.3	210.6	0.90	0.70	0.20
LNU East	1,079	92	987	473.1	97.6	0.41	0.37	0.04
LNU West	152	0	152	NA	43.3	NA	0.62	NA
Claremont - Bear	1,452	0	1,452	NA	81.0	NA	0.79	NA
Dixie	582	274	308	732.7	169.0	0.90	0.67	0.23
Caldor	552	0	552	NA	128.8	NA	0.82	NA
All Fires	**26,915**	**13,973**	**12,942**	**674.5**	**157.8**	**0.90**	**0.69**	**0.21**

As shown in Table 6, four of the nine fires have no structures in the high-density class. Nearly all of the high-density structures (96%) occur in two fires: the Tubbs fire and Camp fire. The Camp fire alone accounts for 79% of the houses in high density class.

Table 7 gives the breakdown of the high and low SDA's according to the Wildland Urban Interface (WUI) classes as mapped by the SILVIS lab at the University of Wisconsin for the year 2010 (http://silvis.forest.wisc.edu/data/wui-change/). Structures in the high SDA's fall mainly into the WUI Intermix category, but many also fall into the WUI Interface and the non-WUI high and medium density areas. Structures in the low SDA's are mostly located in areas mapped as WUI Intermix with a small amount in WUI Interface and Non-WUI Other areas. The WUI Interface category for these fires has a significantly higher structure density per km2 than the Intermix category (564 vs. 356), but the density difference is smaller than between the high and low SDA's (674 vs. 158) as defined in this study.

Table 7: Homes and Structure Density by WUI Category and Structure Density Areas

Structure Density Area	WUI Interface	WUI Intermix	Non-WUI High & Medium Density	Non-WUI Other	Total	Structures per km2
High	**5,346**	**7,250**	**1,373**	**4**	**13,973**	**674**
	(38.3%)	(51.9%)	(9.8%)	(0.03%)	(100.0%)	
Low	**1,766**	**9,157**	**61**	**1,958**	**12,942**	**158**
	(13.6%)	(70.8%)	(0.5%)	(15.1%)	(100.0%)	
Total	**7,112**	**16,407**	**1,434**	**1,962**	**26,915**	**426**
	(26.4%)	(61.0%)	(5.3%)	(7.29%)	(100.0%)	
Structures per km2	**564**	**356**	**1034**	**53**	**426**	

The maps in Figures 4-6 highlight the high SDA's for the three fires with the greatest number of homes in that category: the Tubbs, Camp and Dixie fires.

Figure 4

Tubbs Fire Structure Density

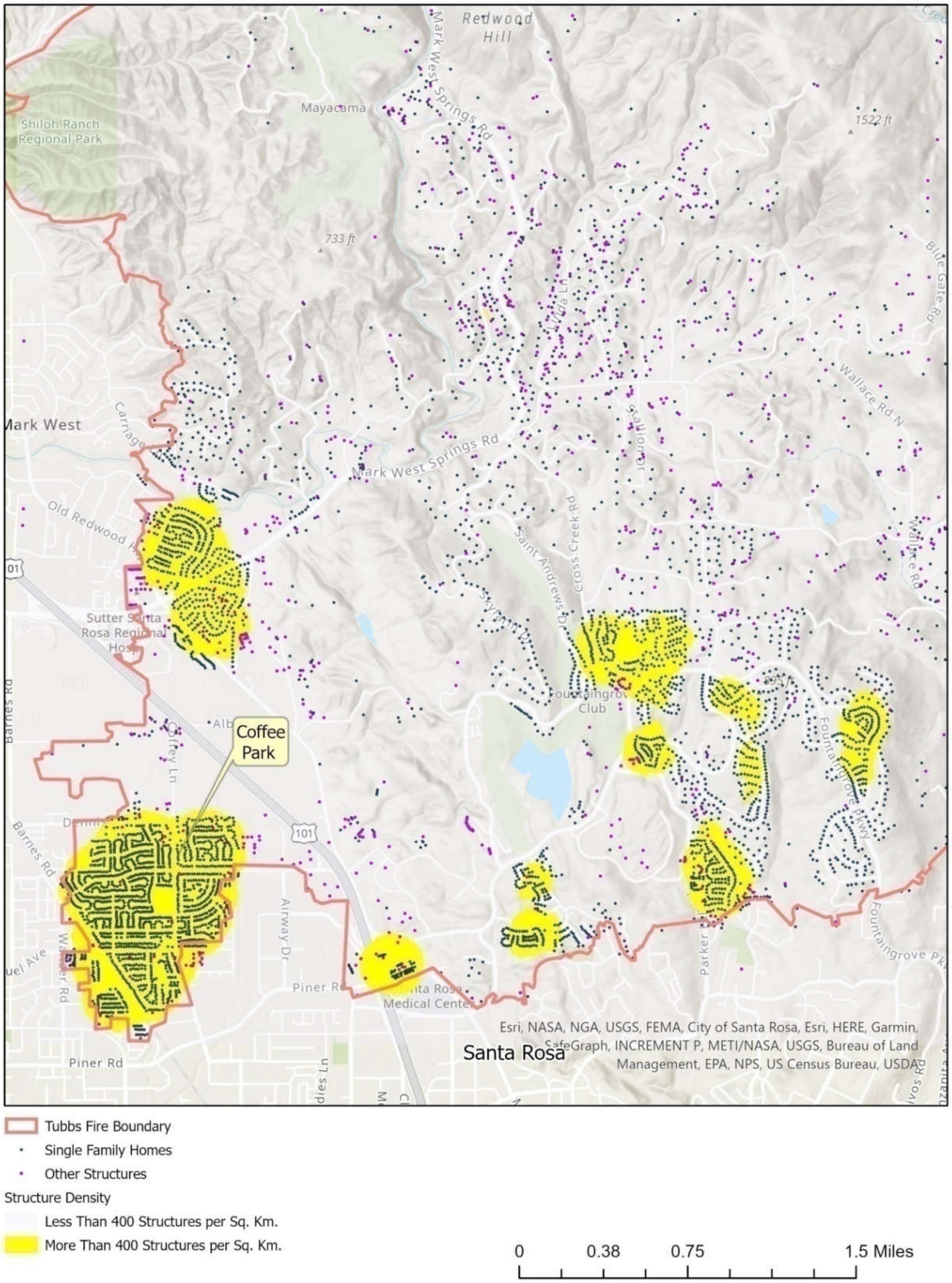
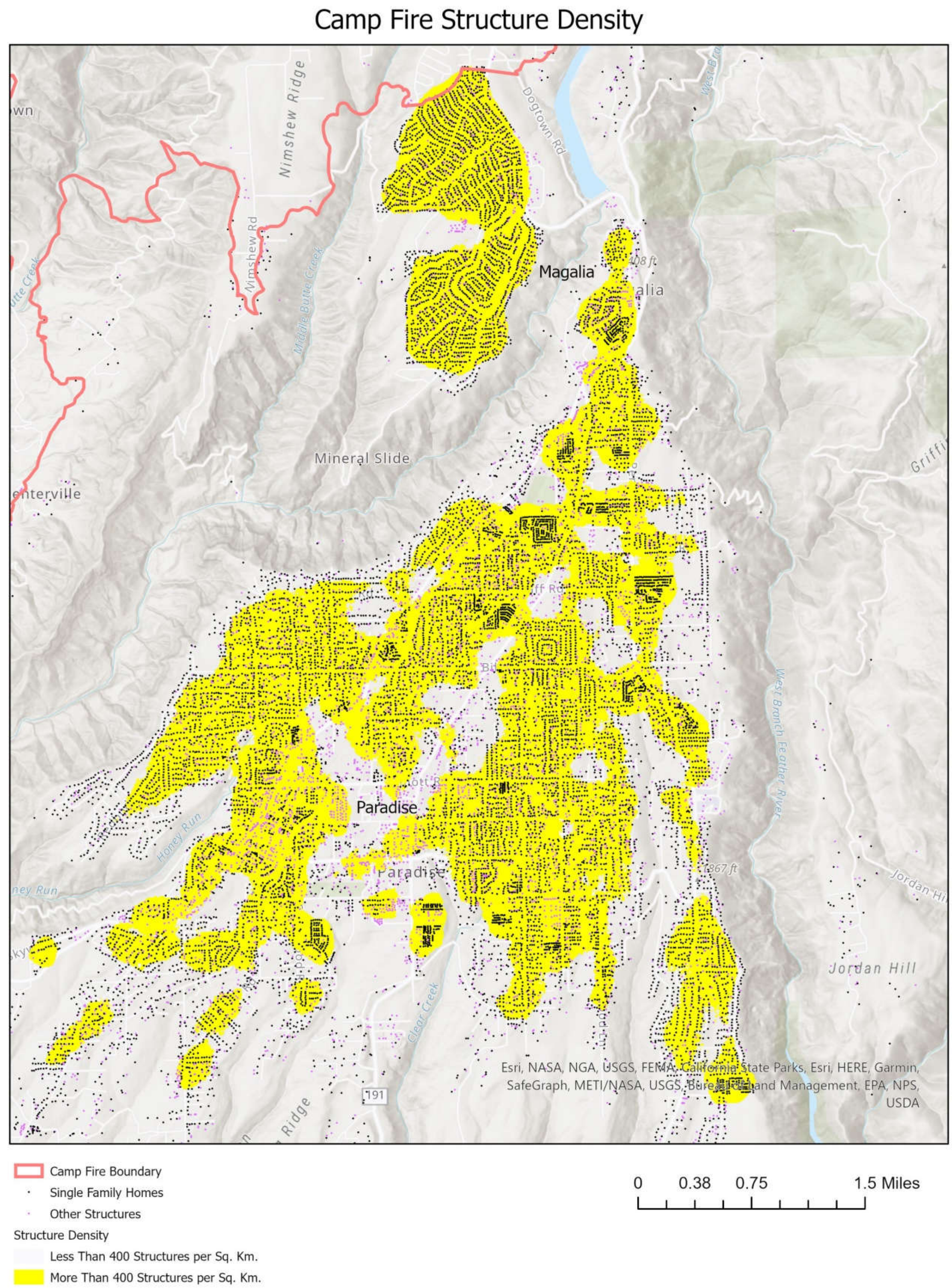


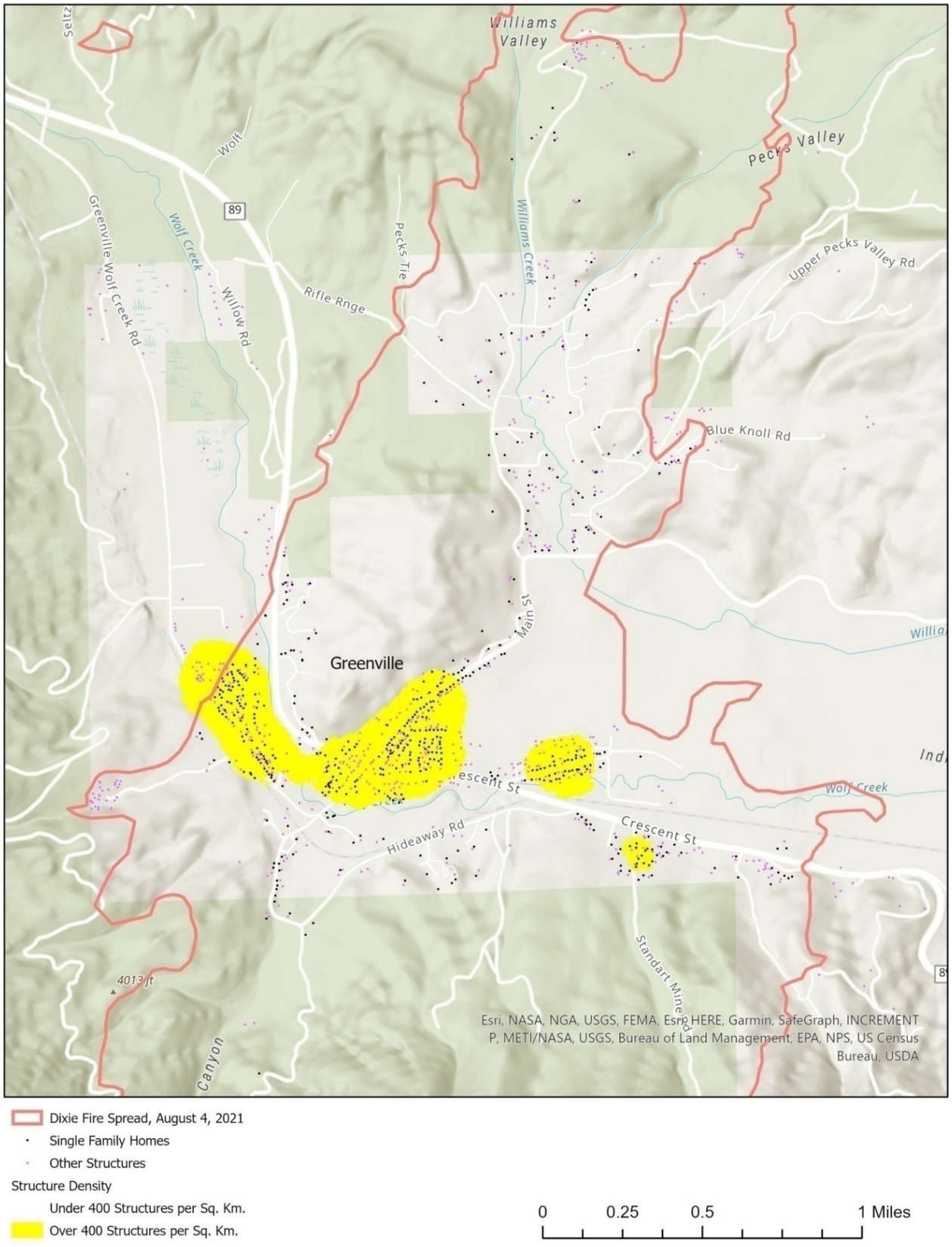
Figure 5



Camp Fire Structure Density
Nimshew Ridge
Nimshew Rd
Dogtown Rd
Magalia
Mineral Slide
Paradise
Jordan Hill
West Branch Feather River
Clear Creek
Honey Run
191
Esri, NASA, NGA, USGS, FEMA, California State Parks, Esri, HERE, Garmin, SafeGraph, METI/NASA, USGS, Bureau of Land Management, EPA, NPS, USDA
Camp Fire Boundary
Single Family Homes
Other Structures
Structure Density
Less Than 400 Structures per Sq. Km.
More Than 400 Structures per Sq. Km.
0
0.38
0.75
1.5 Miles

Figure 6

Dixie Fire Structure Density - Greenville Area



Figures 7-9 compare the relationship between vegetation cover in the 25-meter zone and structure loss rates for the high and low SDA's for the Tubbs, Camp, and Dixie fires. Structures are grouped into 20% vegetation classes (i.e., 0-20% cover, 20-40% cover, etc.) for purposes of illustration. Loss rate trendlines for the high SDA's are higher and flatter than those of the low SDA's for the same fire, suggesting that higher structure densities both increase loss rates and reduce sensitivity of loss rates to changes in vegetation cover.

Figure 7

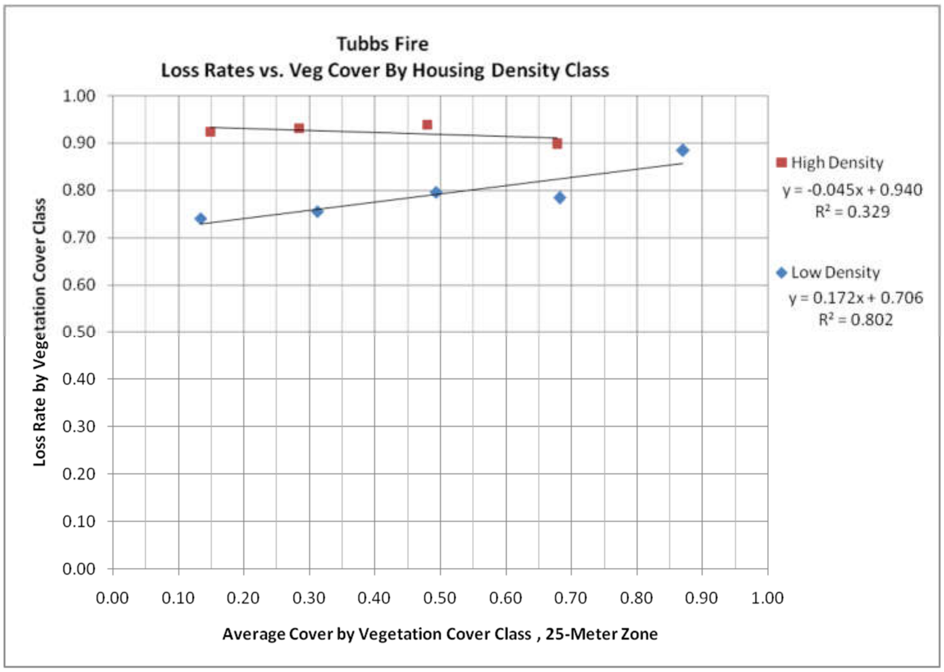


Figure 8

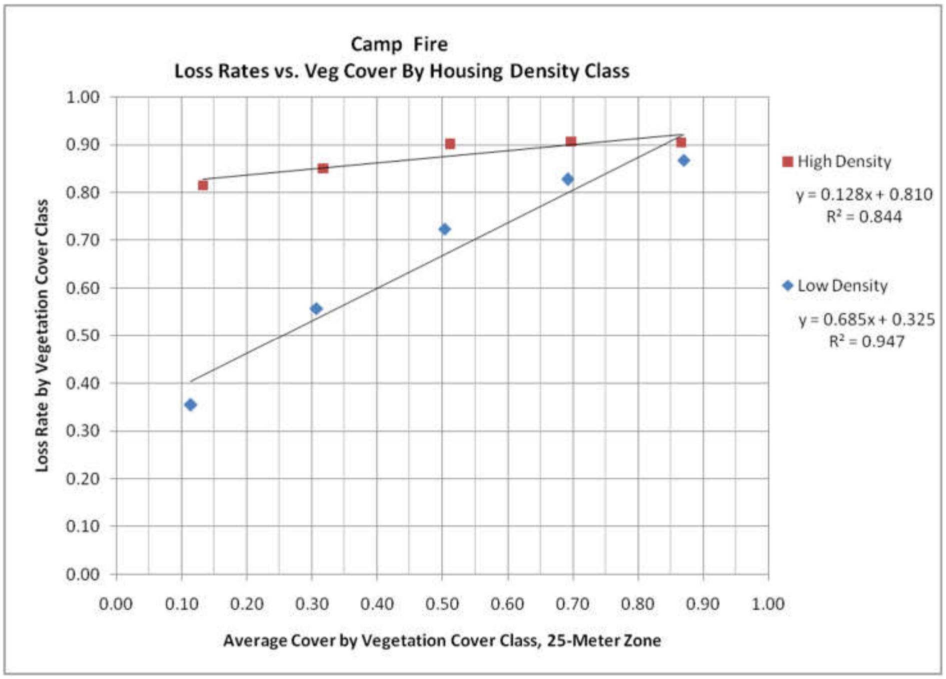
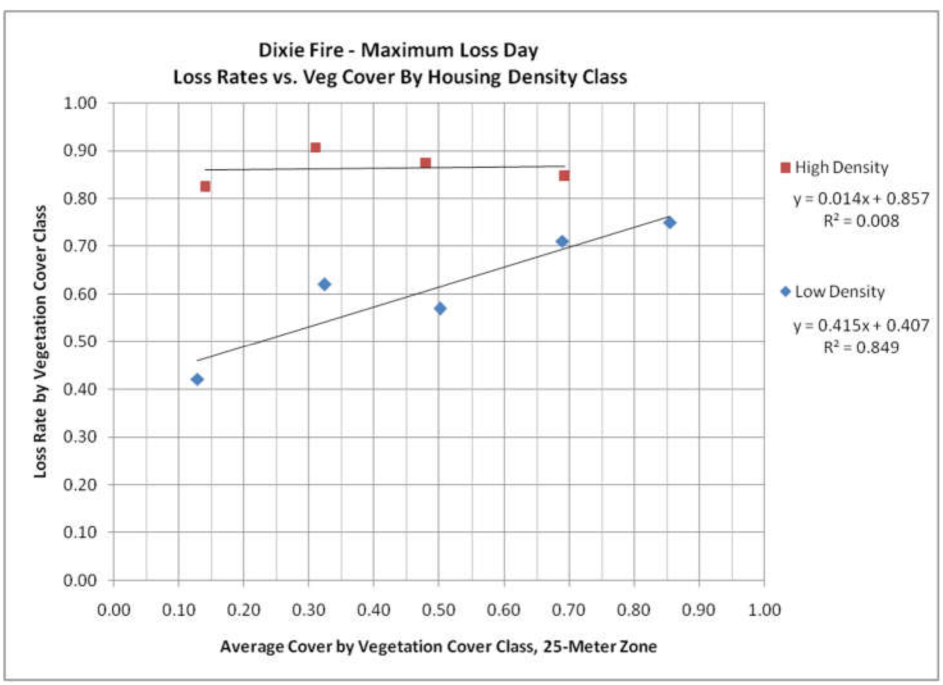


Figure 9



Note: Vegetation Classes 4 and 5 merged for Tubbs and Dixie High Density Class due to low number of occurrences.

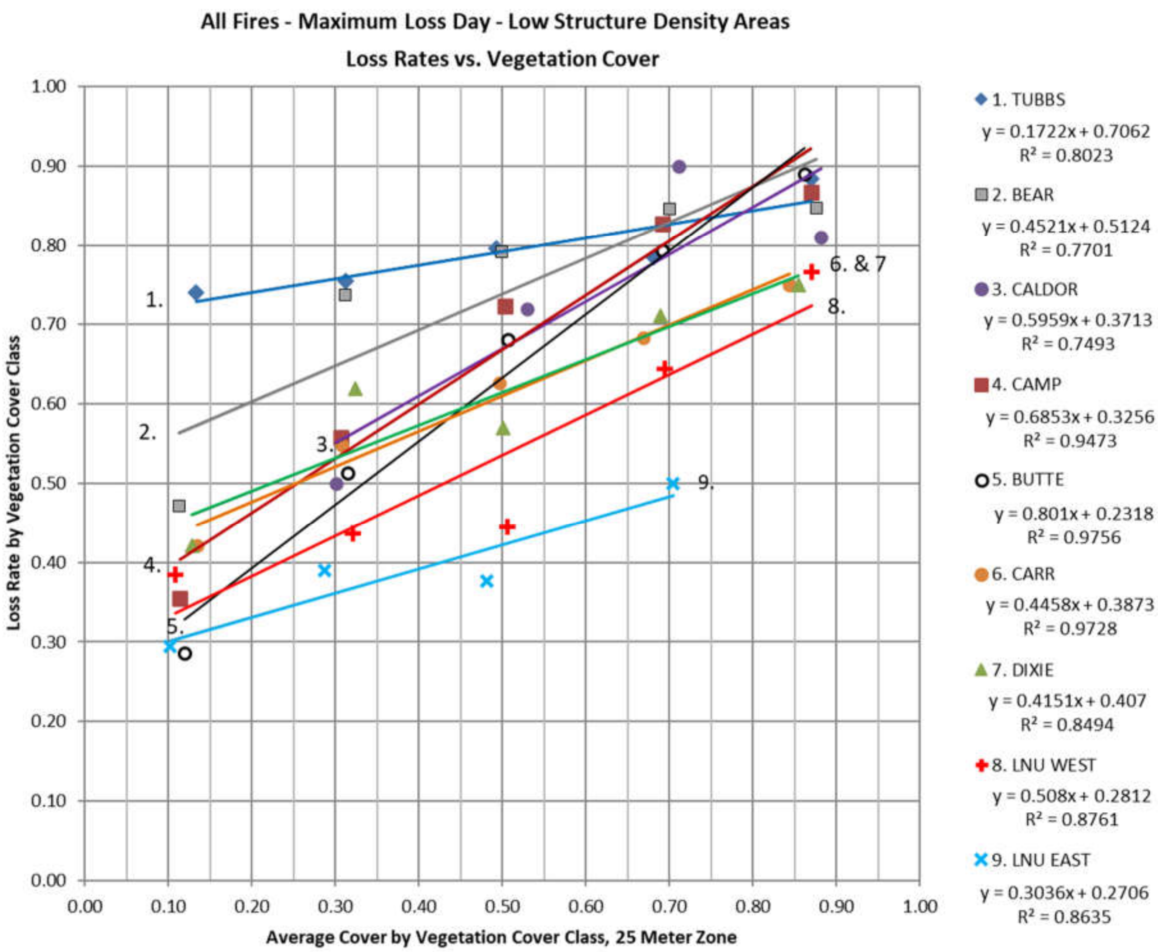
Table 8 displays the estimated impact of changes in selected model variables on predicted loss rates when structure density (STR_DENS) is set to its average value for the high SDA's (674.4) and all other model variables are at their average values for the entire dataset. A 10% reduction in vegetation cover in the 25-meter zone (VEG25) leads to a 1.8% reduction in structure loss compared to a 1.4% reduction when vegetation in the 500-meter zone (VEG500) is reduced by a similar amount. A 10 mph (4.5 mps) decrease in wind speed is estimated to reduce losses by 2.0%.

Table 9: Logistic Model Predictions - Low Structure Density Areas

Variable	**Average**	**STR_DENS 10%**	**VEG25 -0.10**	**MAXWIND - 10mph**	**VEG500 - 0.10**
Intercept	1				
STR_DENS	157.8	**142.0**			
VEG25	0.51		**0.41**		
MAXWIND	51.4			**41.4**	
VEG500	0.49				**0.39**
MAXTEMP	75.6				
Predicted Loss Rate	**0.691**	**0.682**	**0.652**	**0.647**	**0.661**
Change		**-0.009**	**-0.039**	**-0.044**	**-0.030**

Low Structure Density Areas: Figure 10 displays the average loss rates for homes in the low SDA's compared to vegetation cover in the 25-meter zone. Structures are grouped into 20% vegetation classes (i.e., 0-20% cover, 20-40% cover, etc.) for purposes of illustration:

Figure 10



The loss rate trendlines for all fires are positively sloped, consistent evidence that loss rates increase as vegetation cover near homes rises. Slope values range from a low of 0.172 for the Tubbs fire to a high of 0.801 for the Butte fire. The Butte fire has the lowest intercept value at 0.231 while the Tubbs has the highest at 0.706. These results are in line with structure densities and wind speeds. Among the low SDA's the Tubbs fire ranks near the top in structure density at 164.9 structures/km2 (Table 6) and wind speed at 68 mph (30.4 mps) (Table 3). Structure density and wind speeds for the Butte fire are among the lowest at 81.1/km2 and 22 mph (9.8 mps), respectively.

Table 9 displays the estimated impact of changes in selected model variables on predicted loss rates when structure density (STR_DENS) is set to its average value for the low SDA's (157.8) and all other model variables are at their average values for the entire dataset. A 10% reduction in the 25-meter zone vegetation cover results in a 3.9% reduction in predicted structure loss, compared to 1.8% in the high SDA'S (Table 8). A 10% reduction in vegetation cover in the 500-meter zone (VEG500) is estimated to reduce loss rates by 3% in low SDA's compared to 1.4% in high SDA's. A 10 mph (4.5 mps) decrease in wind speeds results in an estimated 4.4% decrease in loss rates in the low SDA's compared to 2.0% in the high SDA's.

Table 9: Logistic Model Predictions - Low Structure Density Areas

Variable	**Average**	**STR_DENS -10%**	**VEG25 -0.10**	**MAXWIND - 10mph**	**VEG500 - 0.10**
Intercept	1				
STR_DENS	157.8	**142.0**			
VEG25	0.51		**0.41**		
MAXWIND	51.4			**41.4**	
VEG500	0.49				**0.39**
MAXTEMP	75.6				
Predicted Loss Rate	**0.691**	**0.682**	**0.652**	**0.647**	**0.661**
Change		**-0.009**	**-0.039**	**-0.044**	**-0.030**

Discussion:

The structure density variable (STR_DENS) is a measure of the likelihood of ignition from embers or heat coming from other structures. Structure density is the most statistically significant predictor of structure loss among the variables examined and is positively related to structure loss rates. Gibbons *et al*. (2012) and Knapp *et al*. (2021) both found that loss rates increased with structure density. If WUI class is viewed, at least in part, as a proxy for structure density (Table 7), then the results of this analysis are also consistent with the findings of Kramer *et al*. (2019) for California as a whole and with Syphard *et al.* (2021) for the Bay Area and Northern Interior regions of California (although not for Southern California).

The proportion of losses due to structure-to-structure spread can be estimated by comparing predicted loss rates when structure density is at its lowest possible level (one structure within 200 meters or 7.95 structures per km2) to loss rates at higher structure density levels. Based on those comparisons (Table 10), the density-related loss rate represents about 26% of total losses. For the low SDA's, that percentage is estimated to be 12.8% while in the high SDA's it increases to 32.7% of total losses. Knapp *et al*. (2021) found that most (68%) fire damage to surviving homes in the Camp fire was caused by radiant heat from nearby burning structures, so the model-based estimates in Table 10 appear to be conservative. Options to reduce structure-to-structure spread caused by radiant heat or direct flames are somewhat limited for existing structures. Building modifications that will help protect against radiant heat, such as fire-resistant siding or multipane windows, are relatively expensive compared to modifications to protect against embers (Quarles and Pohl, 2018).

Table 10: Model Sensitivity to Changes in Structure Density

Variable	Average	Minimum Density	Low SDA	High SDA
Intercept	1			
STR_DENS	426.0	**7.95**	**157.8**	**674.4**
VEG25	0.51			
MAXWIND	51.4			
VEG500	0.49			
MAXTEMP	75.6			
Predicted Loss Rate	**0.818**	**0.602**	**0.691**	**0.895**
Increase Above Minimum	**0.215**		**0.089**	**0.293**
% of Predicted Loss	**26.3%**		**12.8%**	**32.7%**

The VEG25 variable represents the likelihood of loss from ignition by embers, radiant heat or direct flame exposure originating from vegetation within the zone approximately 55' around the structure. VEG25 is the second most statistically significant variable in the predictive model. On average, a 10% reduction in VEG25 results in a 2.8% decrease in loss rates (Table 5). This is about half of the 5% figure found in Gibbons *et al.* (2012) for vegetation within 40 meters of a structure in the 2009 Black Saturday fires in Australia.

In low SDA's, vegetation near homes has approximately double the impact on loss rates as it does in high SDA's. A 10% reduction in VEG25 in the low SDA's results in an estimated loss rate reduction of 3.9% compared to 1.8% in high SDA's (Tables 8 and 9). The 3.9% loss rate reduction for low SDA's is much less than the 10% response estimated for the Butte fire in Schmidt (2020). That may be due to the fact that, as seen in Figure 10, the Butte fire is an outlier, exhibiting the highest trendline slope coefficient (0.801) among the low SDA's.

The VEG500 variable is intended to capture the risk of loss from long distance ember transport to the structure itself or to flammable material within a few feet of the structure. Embers are known to travel several kilometers or more in high winds. The presumption here is that most of the embers reaching structures come from distances of 500 meters or less. The estimated impact of vegetation cover within 500 meters of the structure on loss rates is almost as large as that for vegetation near homes: on average, a 10% reduction in VEG500 leads to a predicted 2.2% reduction in loss rates compared to 2.8% for VEG25 (Table 5). A 10% reduction in VEG500 leads to a decrease in predicted loss rate of 1.4% for the high SDA's and 3.0% for the low SDA's (Tables 8 and 9). The relative importance of the VEG500 variable implies that embers from distant locations reach and ignite structures almost as often as do embers, radiant heat, and flames from nearby vegetation.

While the coefficients of the VEG25 and VEG500 variables are similar in magnitude, the area needing treatment to achieve the equivalent reduction in loss rates is quite different. On average, approximately 28 acres need to be treated in the 500-meter zone for every acre in the 25-meter zone to achieve the same effect on loss rates. Treatment costs on a per acre basis could be significantly lower in the 500-meter zone, however, particularly if large areas could be treated with prescribed fire.

The model estimates suggest that reducing vegetation cover has a relatively modest impact on loss rates. Reducing the average vegetation cover in the 25-meter zone by half would only cause average loss rates in the low SDA's to fall from 69% to 59%. In the high SDA's, the change would be even smaller: expected losses would fall from 90% to 85%. Combining a 50% reduction in the 25-meter zone with a 50% reduction in the 500-meter zone would still leave expected loss rates at 50% in the low SDA's and 79% in high SDA's.

The Ponderosa Fire, a 4,000 acre (1,619 ha) fire that burned in 2017 and re-burned in the Claremont-Bear fire in 2020, illustrates the magnitude of vegetation reduction that might be necessary in order to protect a high percentage of homes. Of the 18 homes located in the Ponderosa fire scar, 15 survived the Claremont-Bear fire. (See Figure 11). Those 15 homes had an average VEG25 value of 0.08, an average VEG500 value of 0.14, and a predicted loss probability of 0.40. The three homes that burned in the Claremont-Bear fire had a average VEG25 value of 0.21, an average VEG500 value of 0.34, and a predicted loss probability of 0.53. The actual loss rate for these 18 structures was 17% compared to the 79% loss rate for the Claremont-Bear fire as a whole.

Figure 11

Even if such dramatic vegetation reductions could be achieved over large areas, maintaining those vegetation levels would require frequent re-treatment. The Camp fire demonstrated how little time it takes for burned areas to recover sufficiently to support fire spread. In July, 2008 the BTU Complex Fire burned the entire area northeast of Paradise. In 2018, only ten years later, virtually the same area was re-burned as the Camp fire approached Paradise. With winds gusting at 55 mph (24..6 mps), it only took 45 minutes for the Camp fire to travel 7.6 miles (12.2 km) through the previously burned area (*National Weather Service Report: November 2018 Camp Fire*, 2020).

Given the modest benefits of vegetation reduction and the challenges in achieving and maintaining significant reductions, a strategy of concentrating first on the structure itself may be the most prudent approach. Building modifications to reduce susceptibility to ember ignition and the elimination of flammable materials within five feet of the structure are relatively inexpensive measures. (Cohen, 2002; Cohen and Stromaier, 2020; Syphard and Keeley, 2020). There are some indications, however, that building modifications will not make a large difference in loss rates. Knapp et al. (2021) found no significant reduction in loss rates in the Camp fire for structures built after 2008 when the California building code was revised to require a number measures designed to improve structure fire resistance.

Vegetation cover in the 25-meter zone is highly correlated with vegetation cover just beyond that zone. Similarly, vegetation in the 500-meter zone is highly correlated with vegetation cover in the 500-2500 meter zone. As a result, the effects of vegetation cover in any one zone cannot be cleanly separated from the effects of vegetation cover in adjacent areas. The significance levels and the coefficients estimated for the vegetation zones examined here are therefore likely overestimated to some degree. As a consequence, predictions of changes in loss rates in response to changes in vegetation cover should be treated as upper bound estimates.

The MAXWIND variable, the highest wind level recorded at the nearest weather station for each fire on the day of maximum loss, measures the influence that wind has on loss rates. As wind levels increase, so does ember quantity, size and distance travelled. Both flames and embers burn hotter when subjected to strong winds. The modelled average loss rate with a 20 mph (8.9 mps) wind is predicted to be 0.70 compared to 0.84 at 60 mph (26.8 mps), a difference of 14% (Table 11). Along with increasing loss rates, high wind speeds reduce the effectiveness of vegetation reduction. With 20 mph (8.9 mps) winds, a 10% reduction in vegetation cover is estimated to lower loss rates by 3.8% in the 25-meter zone and 3.0% in the 500-meter zone. With 60 mph (26.8 mps) winds, those loss rate reductions fall to 2.5% and 1.9%, about a 45% decline in effectiveness. (Table 11).

Table 11: Model Sensitivity to Changes in Maximum Winds

Variable	**Average**	**20 mph Winds**	**60 mph Winds**	**20 mph Winds, VEG25 - 0.10**	**60 mph Winds, VEG25 - 0.10**	**20 mph Winds, VEG500 - 0.10**	**60 mph Winds, VEG500 - 0.10**
Intercept	1						
STR_DENS	426.0						
VEG25	0.51			**0.41**	**0.41**		
MAXWIND	51.4	**20**	**60**	**20.0**	**60**	**20.0**	**60**
VEG500	0.49					**0.39**	**0.39**
MAXTEMP	75.6						
Predicted Loss Rate	**0.818**	**0.705**	**0.842**	**0.667**	**0.817**	**0.675**	**0.823**
Change from Average		**-0.113**	**0.024**				
Change due to 0.10 Veg Reduction				**-0.038**	**-0.025**	**-0.030**	**-0.019**

Although wind has a subtantial effect of loss rates, it's primary contribution to structure loss in wildfires may be on increasing the number of structures exposed to fire (Keeley and Syphard, 2019), particularly in high SDA's. The two fires with the most structures exposed to fire in this study, the Tubbs and Camp, were ranked number one and number three in wind speeds among the nine fires (Table 3) and also had most of the structures in the high SDA's.

Table 12 displays the model predictions when variables are set to their averages for each fire. Predictably, the model does reasonably well for the fires that are the source of most of the data, the Tubbs and Camp fires. The fires where the model is least accurate are the LNU East and Caldor fires, which are at opposite extremes in terms of vegetation cover. The Caldor fire also has the lowest estimated wind levels.

Table 12: Model Predictions by Fire

Fire	Homes	STR_DENS	VEG25	VEG500	MAXWIND	MAXTEMP	Predicted Loss	Actual Loss	Difference	Difference As Pct of Loss
Butte	537	31.5	0.51	0.73	22	98	0.608	0.659	-0.051	-7.7%
Tubbs	5,079	506.1	0.37	0.45	68	91	0.869	0.854	0.015	1.8%
Carr	1,608	190.6	0.40	0.53	21	111	0.617	0.606	0.011	1.9%
Camp	15,874	503.0	0.58	0.63	52	63	0.871	0.837	0.034	4.0%
LNU East	1,079	129.6	0.26	0.27	32	96	0.445	0.378	0.067	17.8%
LNU West	152	43.3	0.57	0.78	23	91	0.642	0.618	0.024	3.8%
Claremont-Bear	1,452	81.1	0.55	0.77	66	86	0.812	0.790	0.022	2.7%
Dixie	582	434.4	0.45	0.58	37	98	0.814	0.777	0.038	4.9%
Caldor	552	128.8	0.73	0.83	20	74	0.720	0.824	-0.105	-12.7%
Total\Average	**26,915**	**426**	**0.51**	**0.49**	**51**	**76**	**0.818**	**0.799**	**0.019**	**2.3%**

The predictive model used in this study is based on 26,916 observations of vegetation cover and structure density, but only 9 observations of wind levels, one for each fire. The statistical significance and coefficients of that variable should therefore be viewed as somewhat less reliable than those variables estimated for each structure. Winds can vary widely in speed and direction across the terrain and through time. Lack of detailed information on wind conditions when flames or embers arrive at a particular structure may be the most important limitation on the ability to identify why some structures survive and others do not.

Acknowledgement:

The data analysis for this paper was generated using the Real Statistics Resource Pack software (Release 7.6). Copyright (2013 – 2021) Charles Zaiontz. www.real-statistics.com

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Appendix:

					Correlation Coefficients								
	ELEV	*STR_DENS*	*VEG25*	*VEG500*	*AVEWIND*	*MAXWIND*	*AVETEMP*	*MAXTEMP*	*MINHUMID*	*AVEFUELMOIST*	*NEAR_DIST*	*LASTRAIN*	*BURNED*
ELEV	1.000												
STR_DENS	-0.003	1.000											
VEG25	0.449	0.019	1.000										
VEG500	0.639	-0.170	0.581	1.000									
AVEWIND	0.374	0.048	0.280	0.367	1.000								
MAXWIND	-0.292	0.271	-0.039	-0.069	0.429	1.000							
AVETEMP	-0.331	-0.373	-0.323	-0.258	-0.563	-0.385	1.000						
MAXTEMP	-0.446	-0.290	-0.366	-0.323	-0.671	-0.230	0.965	1.000					
MINHUMID	0.580	-0.016	0.291	0.299	0.078	-0.461	-0.387	-0.482	1.000				
AVEFUELMOIST	-0.461	0.206	-0.126	-0.226	-0.053	0.704	-0.186	-0.009	-0.081	1.000			
NEAR_DIST	0.008	-0.283	-0.079	0.010	-0.021	-0.095	0.166	0.136	-0.017	-0.084	1.000		
LASTRAIN	0.040	0.439	0.191	0.070	0.322	0.534	-0.919	-0.798	0.188	0.436	-0.181	1.000	
BURNED	0.100	0.273	0.205	0.143	0.102	0.178	-0.189	-0.151	0.020	0.123	-0.120	0.194	1.000