THE ROLE OF CANOPY COVER IN THE HOME IGNITION ZONE IN LOSS OF HOMES DURING TIMBERED WILDLAND-URBAN INTERFACE FIRES

A Thesis

Presented in Partial Fulfillment of the Requirements for the

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by

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Authorization to Submit Thesis

The thesis of Devin Michael Yeatman, submitted for the degree of Master of Science with a major in Natural Resources and titled, “THE ROLE OF CANOPY COVER IN THE HOME IGNITION ZONE IN LOSS OF HOMES DURING TIMBERED WILDLAND-URBAN INTERFACE FIRES,” has been reviewed in final form. Permission, as indicated by the signatures and dates given below, is now granted to submit final copies to the College of Graduate Studies for approval.

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Abstract

Increasing wildfire activity and an expanding wildland-urban interface (WUI) have produced a condition where wildfires are destroying thousands of homes annually and decimating land management budgets. To explore potential solutions for this issue, five wildfire events across the western U.S. were evaluated to examine the relationship between homes burning and pre-fire canopy cover in the 30-meter home ignition zone (HIZ). We found that only two of five fires showed strong relationships between canopy cover and home loss, with the other three exhibiting moderate to weak relationships. These results suggest that canopy cover is not a consistent driver of homes burning in timbered WUI environments, as well as point to the complex, interacting factors intrinsic to home ignitions. The findings indicate that reducing canopy cover in the HIZ may not be as important for preventing home loss as other measures that deter ignition from airborne embers or surface fires.

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Dedication

I would like to dedicate this work to my mother Debbie, who was a firm believer in pursuing higher education. Her presence is dearly missed.

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Thesis Introduction

Over the past several decades, the impact of wildfire on modern societies has been steadily increasing. Perhaps the most dramatic portrayal of fire's impact is exemplified by homes engulfed in flames. There has recently been an uptick of "disaster fires", in which thousands of homes are destroyed. These fires have increasingly occurred in regions that typically do not experience large-scale fires amidst settled areas, such as central Chile, northern Alberta in Canada, and the southeastern United States. Not surprisingly, this trend coincides with an increase in fire activity associated with anthropogenic climate change and migration patterns resulting in the increase of people living adjacent to flammable wildland vegetation, an area known as the wildland-urban interface (WUI). However, there is still relatively little research which exists on home loss due to wildfires in the forested areas common to the WUI in the western U.S. By better understanding this process, we can more effectively develop fire-adapted communities and prepare houses for the increased chance of wildfire exposure.

The wildland-urban interface in the western U.S. has expanded significantly since the latter half of the 20th century, and is projected to continue growing into the future. This is noteworthy because more than half of development in the western WUI occurs in vegetation types prone to high severity fires. This has resulted in the tripling of the number of structures lost to wildfire annually between 1990 and 2013. As one might expect, there has also been a corresponding rise in fire suppression costs, as the wildfire threat to private property and homes in the WUI has a strong positive correlation with suppression expenditures. The fire season of 2015 was the largest and costliest of the modern era, with two new milestones realized: more than 4 million hectares burned and over $2 billion USD spent on direct fire suppression. Similar fire seasons are expected to become more common as fire activity in the West is predicted to escalate further in the coming decades.

One commonly-touted solution for reducing wildfire risk in the WUI is through the targeted use of forest fuel-reduction treatments. Fuel treatment programs grew significantly in the early 2000s, and by 2014, federal land management agencies were treating an average of 1.5 million hectares per year. However, subsequent research has found that not only do fuel treatments have a low probability of encountering wildfire during their effective lifespan, but the most successful and cost-effective fire mitigation actions are those occurring directly around homes, thereby creating “defensible space”. Crown fire experiments testing home ignitability were first used to quantify defensible space, and found that at a distance of 30 meters, a wooden wall would not scorch when exposed to a flame front 20 meters tall. This area within 30 meters of a house is known as the home ignition zone (HIZ), and it forms the baseline recommendation for the area to focus vegetation management in the WUI. Previous research has examined the role of adjacent vegetation in homes burning during wildfires but it has been focused on the chaparral and shrub systems prevalent in Mediterranean climates (such as in southern California and southeastern Australia). To date, there is a lack of published research into how this process differs within the forested systems common to the WUI throughout the U.S. and globally.

The goal of this thesis/study was to investigate the relationship between canopy cover and home ignition during wildfires occurring in the ponderosa pine forest type, which is the most extensive across the WUI in the western United States. We looked at five fires across four states to quantify pre-fire canopy cover surrounding houses in ponderosa pine forests to address the following questions: (1) Is there a significant relationship between percentage canopy cover in the home ignition zone and whether houses are destroyed during wildfires? and (2) If so, what is the canopy cover threshold for increased probability of consumption?

The Role of Canopy Cover in the Home Ignition Zone in Loss of Homes During Timbered Wildland-Urban Interface Fires

Abstract

As wildfire activity has grown over recent decades, impacts to human values have increased dramatically. Migratory trends have significantly expanded the wildland-urban interface (WUI), producing a situation where wildfires destroy thousands of homes per year and further reduce depleted land management budgets. In response, support for creating communities that are adapted and resilient to evolving wildfire hazards, has gained considerable traction. A key question arising from the development of fire resilience strategies is, what role does forest cover surrounding houses play in facilitating home ignition? To assess this question, five wildfire events across the western U.S. were evaluated to examine the role of canopy cover in determining home loss. Using a combination of pixel-based image classification and manual techniques, this study quantified pre-fire tree canopy cover in the 30-meter home ignition zone (HIZ) to assess the relationship between proximal canopy cover to structures burned during wildfires. We found that only two of the five fires showed a strong relationship between proximal canopy cover and home loss, with the other three exhibiting moderate to weak relationships. These results suggest that proximal canopy cover is not a consistent driver of homes burning in timbered WUI environments, pointing to the complex, interacting factors intrinsic to home ignitions. The findings indicate that reducing canopy cover in the HIZ may not be as important for preventing home loss as other measures that deter ignition from airborne embers or surface fires. Additional research across a diversity of landscapes and canopy cover at greater distances from communities is needed to further understand this process.

1. Introduction

Recent decades have seen increased wildfire activity across the globe, posing a growing risk to human populations and the ecosystem goods and services they depend on (Flannigan *et al*. 2009; Smith *et al.* 2016). While the list of assets and resources imperiled by fire is extensive, this risk is highlighted through media images of homes engulfed in flames. Major wildfire events that destroy thousands of homes have become increasingly common globally, occurring in regions such as central Chile, northern Alberta in Canada, and the southeastern United States, which are areas that seldom experience the large-scale, extreme fire behavior typical of southeastern Australia and the western U.S. (Bowman *et al*. 2017). The increase in infrastructure losses to wildfire parallels both recent increases in fire activity associated with anthropogenic climate change and the expanding wildland-urban interface (WUI) (Dennison *et al*. 2014; Martinuzzi *et al*. 2015; Abatzoglou and Williams 2016). Despite these increases, limited research on home loss to forest fires exists to facilitate mitigation solutions for WUI homeowners and communities. Improving our understanding of factors contributing to structure loss in wildfires could enable more effective preparation of fire-resilient WUI communities in advance of future wildfires.

Many definitions of the WUI have been presented in the literature (Stewart *et al*. 2007). A common definition is simply, areas where human homes meet or interact with wildland fuels (USDA and USDI 2001; Lannom *et al.* 2014). Quantitative definitions have predominately focused around set numbers of houses or other structures per square kilometer (Radeloff *et al.* 2005). Recent estimates suggest that ~10% of the contiguous United States is considered WUI (Stewart *et al*. 2007). The WUI in the western 11 states (hereafter, the West) has grown significantly since the latter half of the 20th century, with some estimates suggesting an increase of more than 60 percent (Theobald and Romme 2007). Notably, studies have projected 12.3 million additional homes will be built in the West between 2000 and 2030, with half of these in WUI lands that are susceptible to high severity fires (Theobald and Romme 2007; Hammer *et al*. 2009). These trends have had consequences; since 1990, the average number of structures lost to wildfire annually in the United States has tripled (Quadrennial Fire Review 2015).

The economic impacts of fires extend beyond rebuilding and insurance costs to the cost of suppression. Fire suppression expenditures keep growing, with annual records broken with increasing frequency. The fire season of 2015 was no exception; it was the largest and costliest in the modern era. In 2015, two new milestones were realized: more than 4 million hectares burned and over $2 billion USD was spent on direct fire suppression. With more homes in the WUI at risk from wildfire, the cost of fire suppression, rebuilding, and insurance will continue to rise. In 2016, only half of the area burned but direct suppression expenditures were 93 percent of the 2015 total (National Interagency Fire Center 2016a). A significant contributor to this disparity is that 3,192 homes were destroyed by wildfire in the U.S. during 2016, more than twice the 15-year average of 1,449 (National Interagency Fire Center 2016b). Fire expenditures and adverse impacts to communities are predicted to escalate in coming decades as fire activity in the West is projected to increase further (Abatzoglou and Kolden 2011; Flannigan *et al*. 2013; Stavros *et al.* 2014; Barbero *et al.* 2015).

One strategy for reducing wildfire risk in the WUI is through targeted fuel reduction treatments, typically as prescribed fire and manual fuel removal (Schoennagel *et al*. 2009; Lafortezza *et al.* 2015). Fuel treatment programs were expanded significantly in the early

2000s, when the 2001 National Fire Plan and the 2003 Healthy Forests Initiative removed regulatory barriers and mobilized substantial financial resources towards addressing the national wildfire issue via fuels reduction (Stephens and Ruth 2005). Between 2010 and 2014, the federal land management agencies treated an average of 1.5 million hectares per year (Hoover and Bracmort 2015). Despite the extensive implementation of hazardous fuels reduction activities, recent research has shown that fuel treatments have a relatively low probability of encountering a wildfire during their effective lifespan (Rhodes and Baker 2008; Barnett *et al*. 2016). Furthermore, landscape-scale simulations and reconstructions of significant wildfires have illustrated that the most successful and cost-effective fire mitigation actions are those occurring in the direct vicinity of homes, thereby creating "defensible space" (Gibbons *et al*. 2012; Penman *et al*. 2014; Syphard *et al*. 2014; Scott *et al*. 2016).

Although defensible space is not widely defined, early work by Cohen (2000a) used crown fire experiments to illustrate that at a distance of 30 meters a wooden wall would not scorch when exposed to a spreading crown fire with flames approximately 20 meters high. This 30-meter space surrounding a structure was later dubbed the home ignition zone (HIZ) and currently is the recommended area for performing residential fuels reduction (Cohen 2008). Though the goal behind reducing flammable vegetation in the HIZ is to decrease a structure's exposure to radiant heat, flames, and firebrands, complete removal of vegetation has been demonstrated to be unnecessary (Cohen and Butler 1998). Clearly these distance recommendations rely on a radiative heat transfer mode assumption for wildland fires, an assumption that needs revisiting given recent research (Finney *et al.* 2015). Recommended spacing between tree crowns was a function of how far the trees were located from the house, with closer specimens requiring increased spacing between individuals. Decreasing tree canopy cover (density) in the HIZ resulted in diminished radiant heat exposure for the structure because less fuel was available to burn (Fig. 1). Similarly, a study by Syphard *et al*. (2014) found that reducing HIZ woody vegetation to ≤ 60 percent total cover was a sufficient mitigation strategy for homes in the shrublands of San Diego County, California. These recommendations are reflected in the vegetation guidelines of the FireWise Communities program, which advise variable spacing between plants and trees (depending on their size and how far from the house they are), as well as disrupting the fuel continuity of vegetation surrounding the house to reduce radiant heat exposure and direct flame impingement (FireWise Communities 2016).

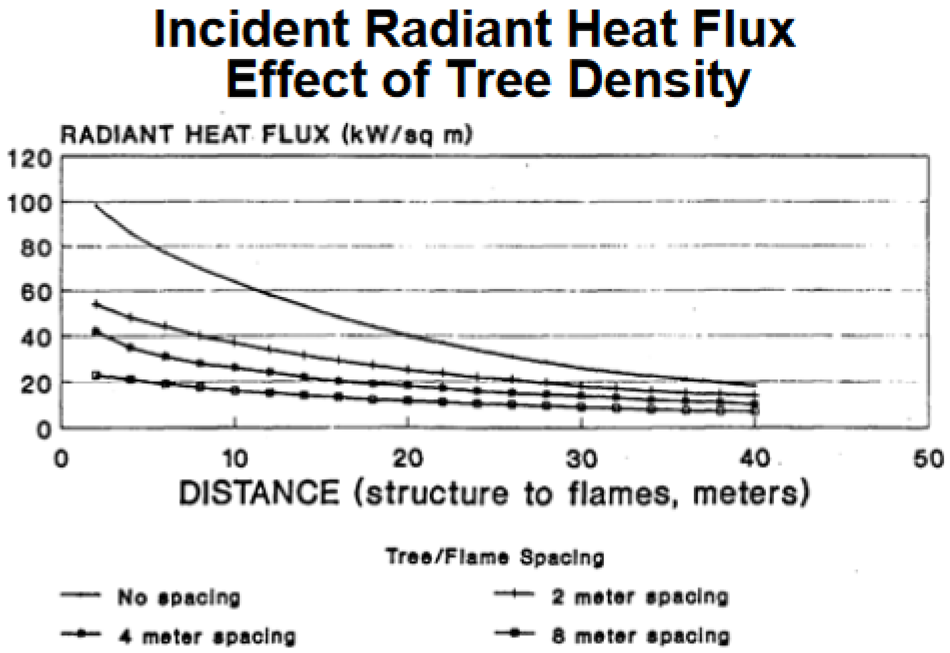

Fig. 1. Graph showing the effect of tree/flame spacing on radiant heat flux, from Cohen and Butler (1998). The benchmark heat flux the authors aimed to be under was 20 kW/m^2. At this threshold, a wooden wall would have an ignition time of approximately 5.5 minutes. This threshold is generous because the ignition time tested is much longer than the 1-2 minutes most structures are exposed to during passage of a wildfire flame front.

Interest in defensible space has grown in recent years as rates of home loss due to wildfire have risen, and several other studies have quantified defensible space and other vegetative factors influencing home ignition during major wildfire events (Table 1). However, excepting one national-level study focusing on general fuel type, all prior research on how adjacent vegetation influences home ignition during wildfires has been conducted on fires occurring in the chaparral and shrub systems prevalent in Mediterranean climates (Alexandre *et al*. 2016). To date, there is a lack of published research into how this process differs within the forested systems common to the WUI throughout the U.S. and globally.

Table 1: Studies reconstructing pre-fire vegetation conditions around homes to determine effective mitigation strategies for preventing future home loss

Primary vegetation type is as identified by studies' authors. "Vegetation variable analyzed" corresponds to whether general fuel type (at 30 m spatial resolution) or specific defensible space measurements (% cover, distance to house, etc.) were assessed for determining their effects on home ignition

Study	Fire event	Primary vegetation type	Vegetation variable analyzed
Alexandre *et al.* 2016	Fires across conterminous U.S. where structures were lost, 2000 to 2010	Diverse ecoregions across conterminous U.S.	Surrounding fuel type
Syphard *et al.* 2014	Southern California fires, 2001 – 2010	Shrublands	Reconstruction of defensible space around homes
Maranghides *et al.* 2013	Witch (CA), 2007	Diversity of vegetation, but scrub dominated	Reconstruction of defensible space around homes
Syphard *et al.* 2012	Southern California fires, 2001 – 2010	Shrublands	Surrounding fuel type
Gibbons *et al.* 2012	Black Saturday bushfires in SE Australia, 2009	Mix of fuel types	Reconstruction of defensible space around homes

The ponderosa pine (*Pinus ponderosa)* forest type is the most extensive across the WUI in the western United States (Theobald and Romme 2007). Currently, the degree to which canopy cover influences home ignition during wildfires in these forests is not well-understood. Prior studies focused on reducing HIZ vegetation and tree canopy density to diminish the exposure of structures to radiant and convective heat (Cohen and Butler 1998; Cohen 2000a). Still today, there is no published research directly analyzing the relationship between canopy cover and structural ignitions in forested environments. To fill this knowledge gap, we conducted an analysis of the role that HIZ tree canopy cover plays in determining whether a home is destroyed during a wildfire. We looked at five fires across four states to quantify pre-fire canopy cover surrounding houses in ponderosa pine forest types to address the following questions:

1. Is there a significant relationship between percentage canopy cover in the home ignition zone and whether houses are destroyed during wildfires?
2. If so, what is the canopy cover threshold for increased probability of consumption?

2. Methods

2.1 Study sites

Data was obtained for five wildfires in the West that occurred between the years 2012 and 2015 (Fig. 2). The fires ranged in size from 5,783 to 53,159 hectares, and the number of residences destroyed ranged from 38 to 509 (Table 2). Fuel types within the wildfires exhibited heterogeneity dependent on landscape factors, but the primary forest type where the majority of homes burned in each fire was ponderosa pine. This was determined by overlaying the raster dataset produced by Ruefenacht *et al*. (2008) onto the structure locations for each fire. The topography where the majority of homes burned in each fire ranged from relatively flat or gently sloping (Black Forest and Taylor Bridge) to large canyons (Elk and Canyon Creek) to dissected, mountainous terrain (High Park). These fires were chosen for analysis because they represented ponderosa pine forest types, had ≥ 30 homes burn, and had high resolution (1 m or better) aerial imagery available that was acquired less than a year prior to ignition.

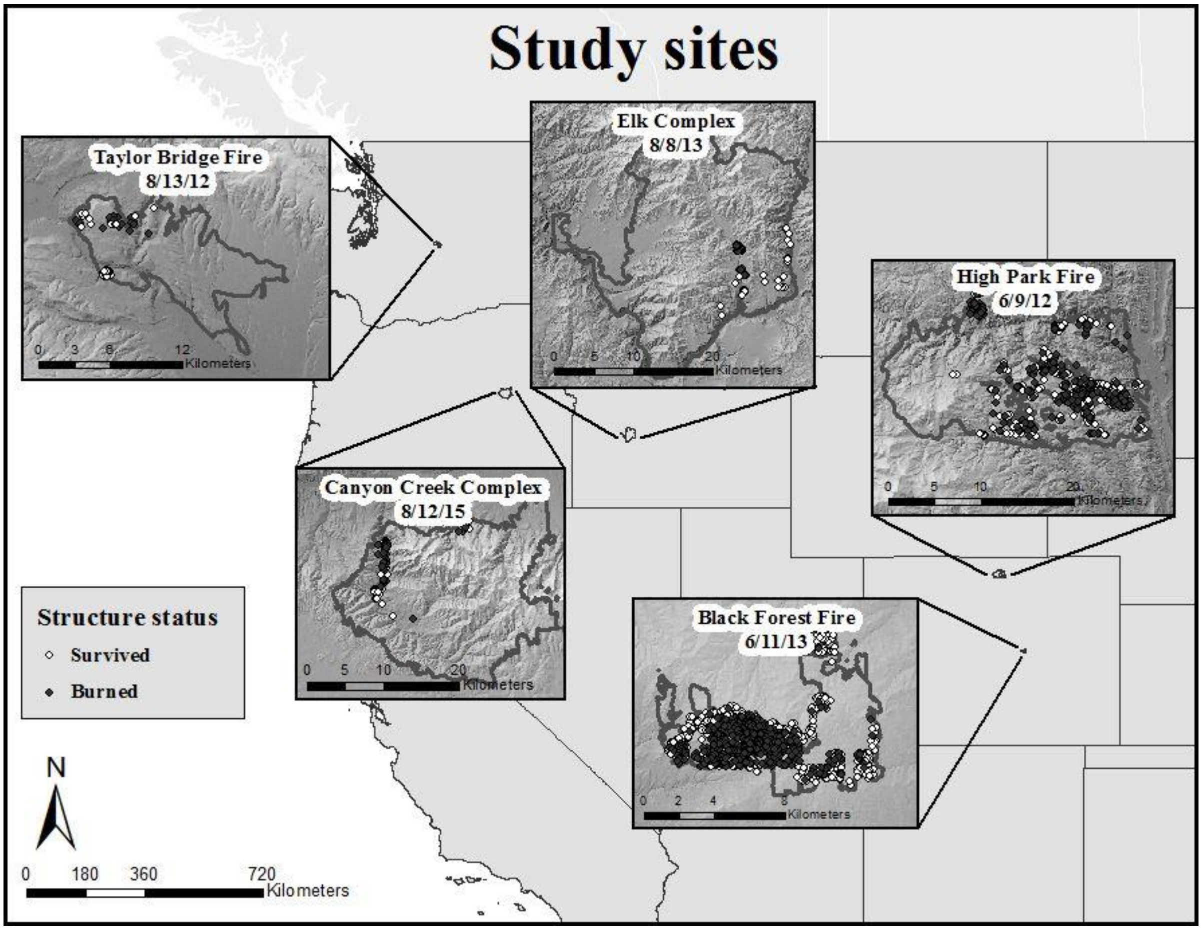

Fig. 2. Study site maps for the five wildfires evaluated in the western U.S. Individual fire perimeter maps show the location of the burned and unburned structures sampled for each analysis. Ignition date is also indicated.

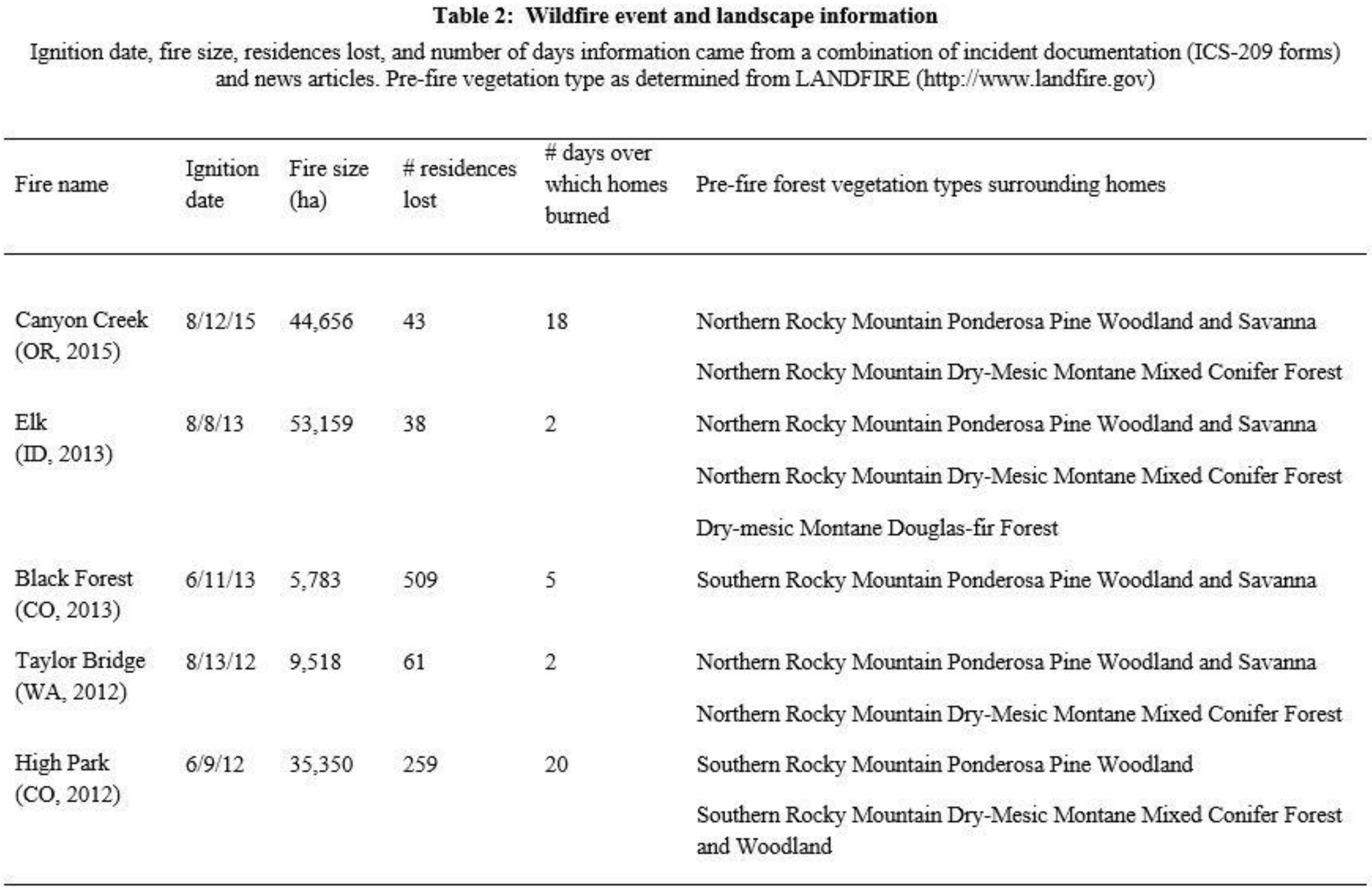

Table 2: Wildfire event and landscape information

Ignition date, fire size, residences lost, and number of days information came from a combination of incident documentation (ICS-209 forms) and news articles. Pre-fire vegetation type as determined from LANDFIRE (http://www.landfire.gov)

Fire name	Ignition date	Fire size (ha)	# residences lost	# days over which homes burned	Pre-fire forest vegetation types surrounding homes
Canyon Creek (OR, 2015)	8/12/15	44,656	43	18	Northern Rocky Mountain Ponderosa Pine Woodland and Savanna Northern Rocky Mountain Dry-Mesic Montane Mixed Conifer Forest
Elk (ID, 2013)	8/8/13	53,159	38	2	Northern Rocky Mountain Ponderosa Pine Woodland and Savanna Northern Rocky Mountain Dry-Mesic Montane Mixed Conifer Forest Dry-mesic Montane Douglas-fir Forest
Black Forest (CO, 2013)	6/11/13	5,783	509	5	Southern Rocky Mountain Ponderosa Pine Woodland and Savanna
Taylor Bridge (WA, 2012)	8/13/12	9,518	61	2	Northern Rocky Mountain Ponderosa Pine Woodland and Savanna Northern Rocky Mountain Dry-Mesic Montane Mixed Conifer Forest
High Park (CO, 2012)	6/9/12	35,350	259	20	Southern Rocky Mountain Ponderosa Pine Woodland Southern Rocky Mountain Dry-Mesic Montane Mixed Conifer Forest and Woodland

2.2 Relationship between HIZ canopy cover and home ignition

2.2.1 Property data

While the data received from the counties varied, we used a systematic process to convert the information into a standardized format (Fig. 3).

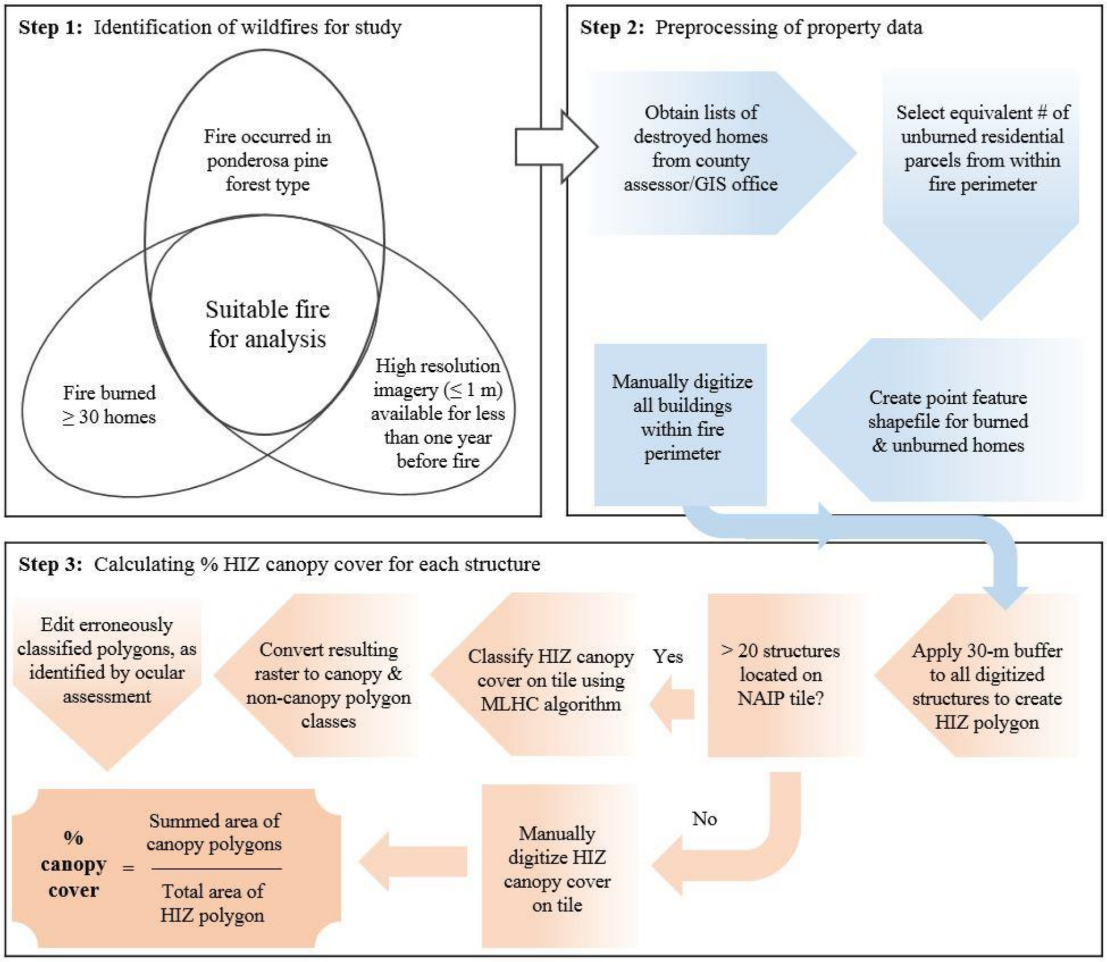

Fig. 3. The methodological workflow used to identify wildfires for this study, obtain and preprocess data, and calculate percentage canopy cover in the home ignition zone.

Data for all properties (parcels) within the fire perimeters and lists of homes damaged by fire (as addresses and/or parcel numbers) were obtained from the County Assessor's office for four fires, and from the county GIS department for El Paso County, Colorado (Table 3).

Table 3: Summary of study data

NAIP dates correspond to the different days that aerial images were acquired for the tiles analyzed in each fire. The # tiles column refers to how many tiles in each fire were classified using the automated MLHC method. Data sources illustrate the local government body that provided property data

Fire name	Pre-fire NAIP dates	NAIP spatial resolution	# tiles classified using MLHC	Data source for properties
Canyon Creek (OR, 2015)	7/10, 9/6/2014	1 m	2/6	Grant County assessor's office
Elk (ID, 2013)	8/6/2013	50 cm	1/5	Elmore County assessor's office
Black Forest (CO, 2013)	7/2, 7/8/2011	1 m	4/4	El Paso County GIS office
Taylor Bridge (WA, 2012)	8/27/2011	1 m	2/2	Kittitas County assessor's office
High Park (CO, 2012)	7/18, 7/30, 9/4/2011	1 m	2/11	Larimer County assessor's office

A number of unburned residential homes within each fire perimeter equivalent to the number of burned homes sampled were used to create the "unburned" data. To filter out unburned parcels that were not adjoining a ponderosa pine forest type, a greater number of unburned parcels was randomly selected, allowing the removal of parcels adjacent to unrelated land cover types. Point feature shapefiles were created for burned and unburned buildings within each fire by locating what appeared to be the primary residence using photo interpretation techniques in Google Earth. All buildings were then digitized using high resolution imagery from the National Agriculture Imagery Program (NAIP), which was acquired from USGS' EarthExplorer data center. This type of imagery was chosen for the study primarily because it is high resolution (0.5 – 1 m), freely available, acquisition is repeated regularly, and it covers the contiguous United States. The NAIP tiles are also 4-band (red, blue, green, and near infrared) multispectral images, making them useful for quantifying tree canopy cover (e.g., Mirik and Ansley 2012; Schwantes *et al*. 2016) as well as mapping urban features (e.g., Caggiano *et al*. 2016; Nagel and Yuan 2016). In total, 1,620 buildings were digitized for this study.

2.2.2 Calculating pre-fire canopy cover

To evaluate the relationship between adjacent tree cover and houses burning, percentage canopy cover in the HIZ was analyzed. A HIZ polygon was created by applying a 30-meter buffer around each digitized structure. Canopy cover for the HIZ was then calculated using a combination of automated and manual techniques to delineate tree cover from background, as a single, supervised classification for all NAIP tiles within a fire was not possible. Tonal differences from one tile to another resulting from different flight paths/times of day that images are acquired necessitated that each tile be classified individually (Table 3).

For each NAIP tile, a decision tree was utilized to determine if the tile should be classified using a Maximum Likelihood Classifier (MLHC) or using manual methods (Fig. 3). Generally, when there were less than 20 homes corresponding to a single tile, it was more accurate to hand-digitize HIZ canopy cover than it was to build a set of training samples then evaluate the classification output, in part because of the limited number of potential samples. For tiles that covered more than 20 homes, MLHC training samples were constructed for canopy and non-canopy classes by arbitrarily selecting then digitizing 15-20 polygons per class, similar to Mirik and Ansley's (2012) MLHC classification of mesquite canopy cover. After the automated classification was complete, isolated pixels were reclassified with a 3 x 3 window Majority filter. The resulting raster classification was then converted to canopy and non-canopy polygon features. All polygons received an ocular assessment to ensure accurate classification, with any erroneous polygons reassigned to the appropriate class or edited as needed. For all tiles, the summed area of the canopy polygons within each HIZ was divided by the total area corresponding to each structure's 30-meter HIZ polygon, achieving percentage canopy cover surrounding that residence (Fig. 4).

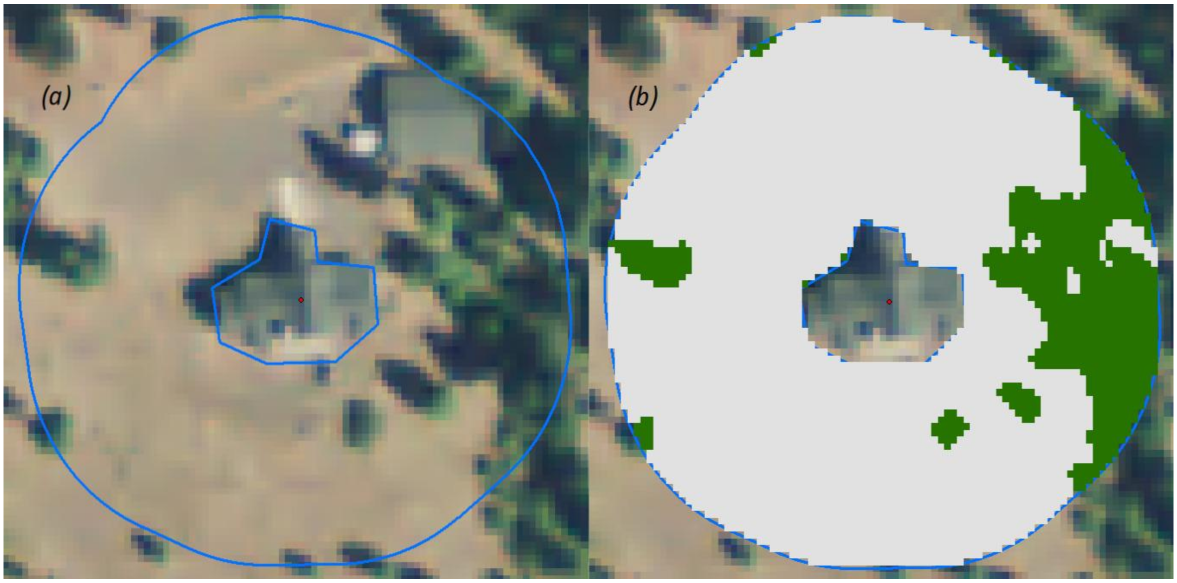

Fig. 4. Visual depiction of canopy quantification. (*a*) Raw pre-fire NAIP image illustrating a digitized structure and its corresponding 30-m buffer, representing the home ignition zone (HIZ). (*b*) Classified NAIP image showing how canopy and non-canopy classifications are used to calculate percentage canopy cover. Once the raster classification was converted to polygon features, erroneous polygons were reassigned to the appropriate class or edited as needed.

2.2.3 Accounting for spatial autocorrelation

A cursory visual inspection of the arrangement of burned structures demonstrated obvious clustering, so the models were evaluated for spatial autocorrelation. A test of the model residuals using Moran's I revealed that four of the five fires exhibited strong spatial autocorrelation: Black Forest (Moran's/P-value: 0.41/<0.001), Canyon Creek

(0.26/<0.001), Elk (0.72/<0.001), and High Park (0.18/<0.001). The Taylor Bridge dataset did not show significant clustering (0.01/0.24). To mitigate the spatial autocorrelation, we included an “autocovariate” as a separate term in each of the four models (Dormann *et al*. 2007). The autocovariate is calculated from the response variable in a matrix of neighbors surrounding each data point, with a neighbor’s weight being a function of the distance from the data point (inverse distance weighting). The neighborhood structure for each model was determined by examining Moran’s I correlograms to determine which most minimized the effects of autocorrelation. The “nearest neighbors” used in the models ranged between 1 and 10 (Table 4). Inclusion of the autocovariates in each model (hereafter, spatial model) reduced the autocorrelation to statistically insignificant levels (all P-values ≥ 0.34).

2.2.4 Statistical analysis

Due to the binary response variable in this study (house burned or did not burn), a logistic regression analysis was employed to assess the relationship between pre-fire canopy cover and homes burning during wildfire events. A separate regression model was constructed for each fire, with percentage canopy cover as the sole explanatory variable.

2.3 Canopy cover threshold for increased probability of consumption

Logistic regression curves were plotted for the fires that demonstrated at least a moderate relationship between canopy cover and home loss. The curves allowed us to ascertain the threshold of canopy cover at which the probability of a home burning was 50 percent or greater.

3. Results

Percentage canopy cover in the home ignition zone covered the full range from 0 to 100 percent, but the mean pre-fire canopy cover for all unburned homes was 31 percent, and 41 percent for all burned homes (Fig. 5). The difference in mean canopy cover between burned and unburned structures was the lowest for the High Park Fire (1%), and highest for the Taylor Bridge Fire (19%), with the Canyon Creek Complex (7%), Black Forest Fire (9%), and Elk Complex (15%) mean differences falling in between.

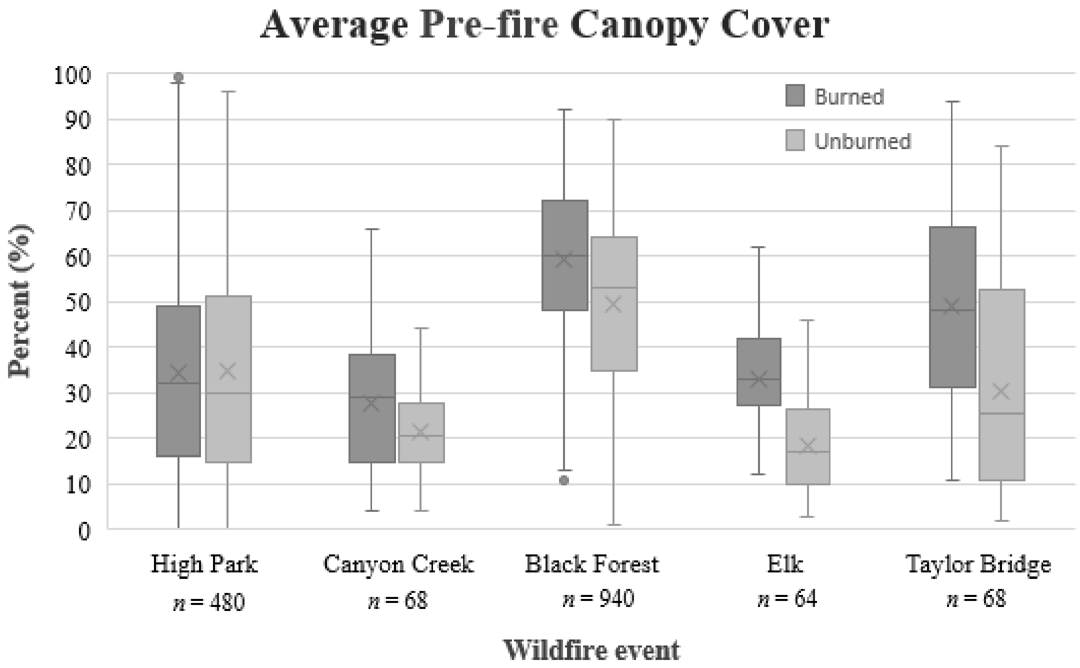

Fig. 5. Box and whisker plots of percentage canopy cover per fire. *n* represents total structures analyzed for the fire, with half being burned structures and the other half unburned. X's indicates the mean value. Bars on the boxes represent the interquartile range (IQR) values. Outer "whisker" values represent 1.5 x IQR. Values beyond the whiskers (represented as spheres) are outliers.

3.1 Relationship between HIZ canopy cover and home ignition

Canopy cover was found to be a strong factor in home ignitions for the Taylor Bridge Fire (P = 0.003) and the Black Forest Fire (P < 0.001), but not for the other three fires. The Canyon Creek Complex (P = 0.09) exhibited a moderate relationship between canopy cover and home loss. The original model created for the Elk Complex was very strong (P < 0.001), but after accounting for the spatial autocorrelation in the dataset, the influence of canopy cover dropped to more moderate levels (P = 0.17). The High Park Fire displayed a weak relationship between canopy cover and home loss (P = 0.62).

Table 4: Results of logistic regression for each fire

Half of structures sampled were burned and half unburned. The # of neighbors pertains to the number of nearest surrounding data points (the neighborhood structure) used to create the autocovariate term, which was determined by examining Moran's I correlograms. Coefficient columns illustrate the change in coefficient values between the original and new (spatial) models ± standard error.

Fire name	# structures sampled	# neighbors in spatial model	Coefficient in original model, ± s.e.m	Coefficient in spatial model, ± s.e.m	Pr(>|z|)
Canyon Creek (OR, 2015)	68	1	0.039 ± 0.02	0.037 ± 0.02	0.09
Elk (ID, 2013)	64	2	0.128 ± 0.033	0.074 ± 0.054	0.17
Black Forest (CO, 2013)	940	10	0.03 ± 0.003	0.023 ± 0.005	<0.001
Taylor Bridge (WA, 2012)	68	N/A	0.034 ± 0.011	N/A	0.003
High Park (CO, 2012)	480	7	-0.001 ± 0.004	-0.002 ± 0.004	0.62

Model coefficients maintained directionality (did not go from a positive to a negative relationship) after adding an autocovariate term to the original models, but the coefficients did change (Table 4). A 42 percent decline in coefficient value between the original and spatial models was observed for the Elk Complex (0.128 to 0.074), demonstrating high spatial autocorrelation among the burned homes. Additionally, the High Park Fire had a negative coefficient value, meaning that HIZ canopy cover was slightly negatively correlated with home loss at this location.

3.2 Canopy cover threshold for increased probability of consumption

For the three fires that demonstrated at least a moderate relationship between canopy cover and home ignitions, the level of canopy cover where the probability of homes burning was >0.5 was 70 percent cover for Black Forest, 39 percent cover for Taylor Bridge, and 26 percent cover for Canyon Creek (Fig. 6).

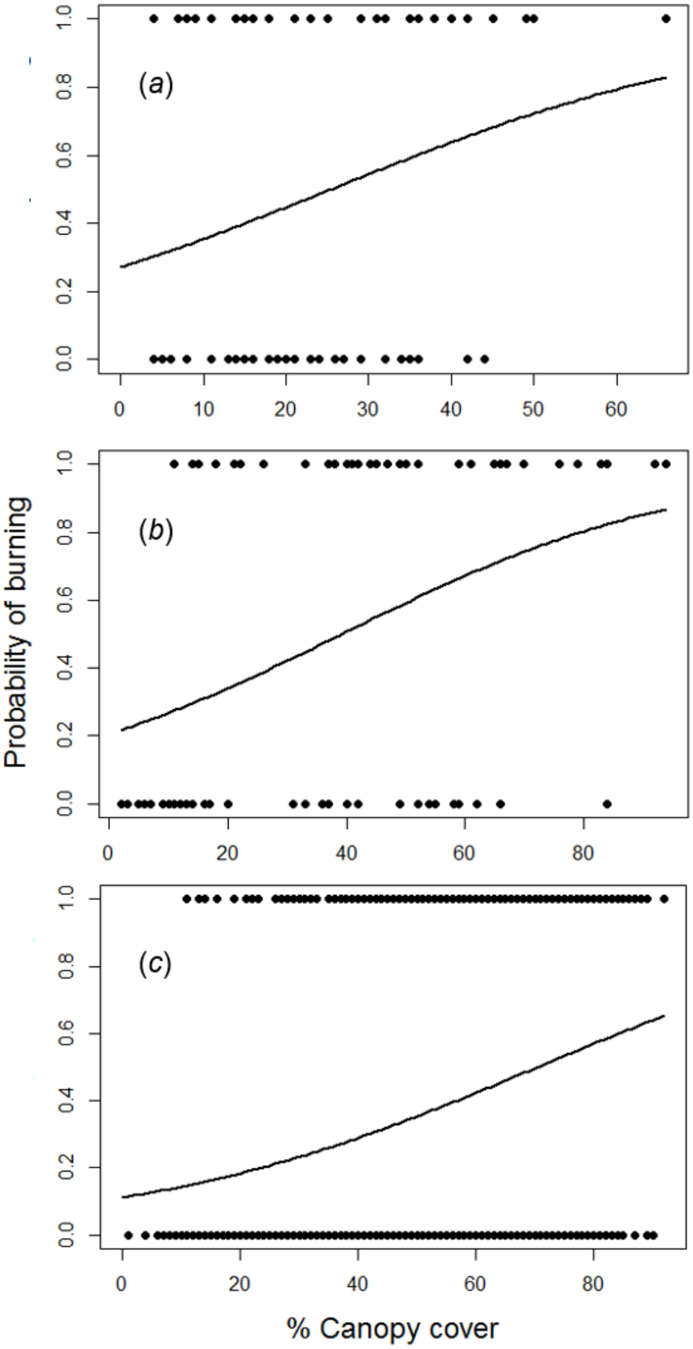

Fig. 6. Graphs plotting the probability of a home burning as a function of HIZ canopy cover in the (a) Canyon Creek (26%), (b) Taylor Bridge (39%), and (c) Black Forest (70%) fires. The black dots denote canopy cover values corresponding to burned (1.0 on y-axis) and unburned (0.0 on y-axis) homes.

4. Discussion

We found a strong relationship between forest canopy cover within the home ignition zone and probability of home loss for only two of five fires, Black Forest in Colorado and Taylor Bridge in Washington. This stands in contrast to previous studies occurring in Mediterranean landscapes, which found that percentage tree and shrub cover within 40 m of a home, and percentage woody vegetative cover within a home's property boundaries were significant drivers of home loss during wildfires (Gibbons *et al*. 2012; Syphard *et al*. 2014).

The other fires examined here demonstrated varying relationships between canopy cover and home loss. The Canyon Creek Complex displayed a moderate positive correlation between HIZ canopy cover and probability of home ignition ($P = 0.09$). In the Elk Complex, canopy cover had a strong positive relationship with home loss ($P < 0.001$) in the original model. However, the data had a very high level of spatial autocorrelation (Moran's $I = 0.72$), evident when looking at the arrangement of burned and unburned structures within the fire perimeter (Fig. 2). The considerable autocorrelation is due to the extreme fire behavior seen during one day where the plume-dominated fire made a run through the Fall Creek drainage. Consequently, none of the nearly 30 residences in the creek corridor survived. The subsequent correction for this clustering with the autocovariate term resulted in a large relative reduction in the coefficient value, diminishing the significance of the explanatory variable. Similarly, the fire with the second highest spatial autocorrelation, Black Forest, also experienced a notable change in its coefficient value (Table 4). While the P-value remained <0.001 in the spatial model, this coefficient change resulted in a canopy cover threshold for increased probability of burning (70%) that was substantially greater than its mean canopy cover value (54%).

The High Park Fire showed a weak negative correlation (P = 0.62) between canopy cover and home loss, resulting from a slightly higher average canopy cover around unburned structures than burned structures (Fig. 5). While there are many potential reasons for this equivalency, it is worth noting that Larimer County enacted regulations in 1998 requiring new construction to use fire-resistant building materials and maintain defensible space in compliance with current Colorado State Forest Service guidelines. Despite not being required of older homes, the county’s proactive efforts may have spurred other homeowners to maintain a more wildfire-ready property, manifesting as homogeneity in HIZ canopy cover. This behavior is consistent with previous research which indicates that peer influence and informal social interactions with neighbors play an important role in determining a homeowner’s perception of wildfire risk and likelihood of participating in mitigation activities (Brenkert-Smith *et al*. 2006; McCaffrey *et al*. 2011). But despite the presence of defensible space around many of the structures, canopy cover was not a predictor of home ignition, hinting at other processes at work. The wide-ranging degree to which tree canopy was correlated with home loss in each of the five fires speaks to the need for more comprehensive studies to better understand how houses ignite.

Logistic regression curves plotted to ascertain the canopy cover thresholds for increased probability of home ignition (≥ 50%) showed substantial variance in this metric among the three fires, despite occurring in relatively similar forest types (Fig. 6). These curves, along with the plots in the figure showing the distribution of percentage canopy cover values for burned/unburned homes, illustrate that HIZ canopy cover is a poor determinant of whether a house burns or not during a wildfire. The inconsistency of these results intimate the complex, interacting elements influencing home ignition in forested ecosystems and corroborate previous research detailing the many factors in mitigating structural ignitions (Smith *et al*. 2016).

Our quantitative findings support the conclusions made by previous case studies that inferred home ignition vectors after fires that burned in ponderosa pine systems. Forensic reconstructions of the 2000 Cerro Grande Fire (NM) and 2010 Fourmile Canyon Fire (CO) found that most of the houses burned were exposed to only low and moderate intensity fire rather than high intensity crown fire (Cohen 2000b; Graham *et al*. 2012). A similar report on the 2002 Hayman Fire (CO) showed that approximately half of the homes were lost to lower intensity fire, which commonly manifested as unconsumed tree canopy and variably burned understory vegetation adjacent to completely burned homes (Cohen and Stratton 2003). In contrast to ignitions from high intensity fire, where a fast-moving flame front ignites a home with high levels of radiant and convective heat flux, lower intensity fires typically ignite homes in less spectacular fashion. Duff and litter in the HIZ catches fire from nearby flames or lofted firebrands, and fire creeps through surface and ground fuels near the house. These lower intensity surface fires will often creep up to and ignite flammable objects next to the home, such as woodpiles, decks, and vegetative debris. Once these larger sources of fuel adjacent to the structure ignite, the structure will likely be lost without intervention. Additionally, lofted embers from a distant wildfire can ignite a home if they land in receptive fuels directly on the structure, causing the home to burn without any exposure to a flame source in the HIZ.

The time frames in which the homes were lost in each of the fires also varied considerably (Table 2). In the Taylor Bridge and Elk fire events, incident documentation (ICS 209 forms) noted residences as burning over two days, when the fires made significant, wind-driven runs. In contrast, the High Park and Canyon Creek fires saw homes burn under various weather conditions over the course of multiple weeks (20 and 18 days, respectively). The Black Forest Fire recorded houses as actively being lost over five days, but this cannot be accurately pinpointed due to the difficulty of triaging damages during the disarray inherent in hundreds of homes burning. There was no relationship between the number of days over which houses burned (as a proxy for uniformity of weather conditions) and whether the fire had a strong relationship with HIZ canopy cover. That the houses burned under various conditions while exhibiting differing relationships with canopy cover is further indicative that canopy cover in the HIZ is a relatively poor predictor of home loss.

It is often assumed that houses are mostly destroyed by high intensity, running crown fire, as evidenced by prior research seeking to quantify the vegetation removal necessary to sufficiently reduce structural exposure to radiant and convective heat to prevent ignition (e.g., Cohen and Butler 1998; Cohen 2000a). However, additional forensic case studies have also suggested that more homes burned due to lower intensity surface fires and firebrands lofted through the air (Leonard and Blanchi 2005; Maranghides and Mell 2011). The results of our study corroborate the conclusions of these case studies; if canopy cover was a universal factor in home ignitions during wildfires, we would see stronger relationships between canopy cover and home loss across all five fires.

Studies looking at the 2007 Angora Fire (CA) and the 2011 Wallow Fire (AZ) illustrated that reducing canopy cover and removing forest biomass with fuel reduction projects targeting the WUI moderated wildfire severity in forests surrounding communities (Safford *et al*. 2009; Kennedy and Johnson 2014; Waltz *et al*. 2014). Similarly, prior research has called for increasing collaboration between local, state, and federal organizations to complete similar WUI fuels projects across landownerships (Schoennagel *et al*. 2009). However, efficacy of treatments is predicated on many factors, including the timely burning of slash piles, an activity subject to weather constraints (Kalabokidis and Omi 1998). Several studies have illustrated that when slash piles are not removed, fire behavior mimics the higher severity of untreated stands (Murphy *et al*. 2007; Safford *et al*. 2009; Hudak *et al*. 2011). In some cases, incomplete fuel treatments have been shown to burn more intensely than adjacent untreated stands (Graham *et al*. 2012). Calkin *et al*. (2014) present a case study of the Fourmile Canyon Fire in which fuel treatments interspersed throughout a forested WUI area were unsuccessful in preventing significant structure loss. In addition to some of the treatments being incomplete (slash piles remained), their design and implementation were insufficient for the extreme weather conditions under which the largest fires typically burn. Carrying out these projects is further complicated by the fragmented nature of the WUI. As of 2000, 65 percent of the urban interface in the West was privately-owned, which limits the work able to be done by governmental organizations (Theobald and Romme 2007).

Furthermore, even if meaningful collaboration can occur amongst landowners and budgetary constraints can be overcome, implementing widespread WUI fuel treatments does not ensure success in reducing home loss during wildfires. Diminished fire behavior, the primary goal of forest fuels reduction in the WUI, does not necessarily correlate with decreased home loss during wildfires because it fails to address the ignitability of homes, which can be destroyed by even a low severity surface fire (Kennedy and Johnson 2014). Calkin *et al*. (2014) detail a risk management framework that is centered on fire-adapted communities, wildfire response, and resilient landscapes. They identify mitigation of the HIZ as the most cost-effective solution to preventing structure loss during wildfires. However, the results presented here suggest that at least one component of recommended HIZ modifications, reducing canopy cover, is not universally a good predictor of decreased home ignitions.

Previous research reconstructing pre-fire vegetation conditions around homes has focused primarily on Mediterranean landscapes, and this study helps to extend our understanding of home ignitions into the forested systems that comprise a large portion of the western WUI. The variable relationship demonstrated between HIZ canopy cover and structure ignitions does not support the assumption that high intensity crown fire is a chief driver of home loss in timbered environments. These results are consistent with previous findings that structure ignition is a complex mechanism involving many interacting human and biophysical components (e.g., Syphard et al. 2012; Alexandre et al. 2016). However, the weakness of canopy cover as a predictor of home loss in this study points to the value of other tenets in defensible space outside of vegetation management. These findings underscore the importance of the home-centric guidelines for defensible space, including the use of fire-resistant building materials, removing fuels directly adjacent to the residence (such as woodpiles), maintaining litter-free roofs/gutters, etc. Bolstering a structure's protections against wildfire exposures outside of radiant and convective heat flux is a critical component of proper wildfire preparation in forested areas (Smith *et al*. 2016).

5. Conclusions

This study demonstrates that tree canopy located within the 30-meter home ignition zone is not consistently a significant factor in structure loss during wildfires in western forests. There is mounting evidence that homes in these environments are not primarily burning due to direct flame impingement as is often assumed. Emphasizing all facets of defensible space and the importance of each one will help homeowners properly safeguard their residence against future wildfires. Moreover, the recognition that developing fire-resilient communities requires a multi-faceted approach is critical. The results from this analysis also support previous findings that structure ignition is a complex process involving many different factors. More studies looking at additional fires across diverse ecosystems and communities are needed to better understand this process. As defensible space regulations continue to gain traction and data availability improves, there will be growing opportunity to contribute to the science of home ignition.

6. Future work

This research builds upon previous work which used laboratory- and field-scale fires as well as forensic reconstructions to infer home ignition vectors during wildfires in timbered ecosystems. While knowing the exact cause of home ignition for structures that burn during wildfires will remain unlikely without reliable eyewitness accounts or video evidence, there are numerous other research trajectories which would complement this project and further clarify this process.

One potential path for future research is to more fully quantify the various tenets of defensible space and their influence on home loss during forest fires. By taking these factors into account, a more complete picture of why the house burned can be obtained. These include: mapping the vertical component of the forest structure with technologies like LiDAR; noting the presence of significant flammable fuels near the structure which were installed by the homeowner (woodpiles, decks, etc.); acquiring information about building materials currently installed on the home; evaluating the fuel continuity between the home and surrounding flammable vegetation, etc.

Another potential avenue would be a species-specific analysis of the vegetation present within the home ignition zone prior to homes being exposed to wildfire. Because certain species are more flammable than others, and certain species produce more embers than others, this would provide critical information detailing which types of vegetation are best to use or avoid in the home ignition zone. A spatially-explicit context would be especially useful, where the flammability/ember production potential of nearby vegetation and its distance from the home could be mapped. This could help further illuminate the role of firebrands and convective heat in home loss during forest fires.

The opportunities for research to improve our understanding of home ignition will grow as geospatial data quality and availability improves. The advancement of technologies like LiDAR and high-resolution remote sensing, as well as continued increases in the number of parties collecting geospatial information will ensure there will be ample opportunity to further elucidate the process of home ignition.

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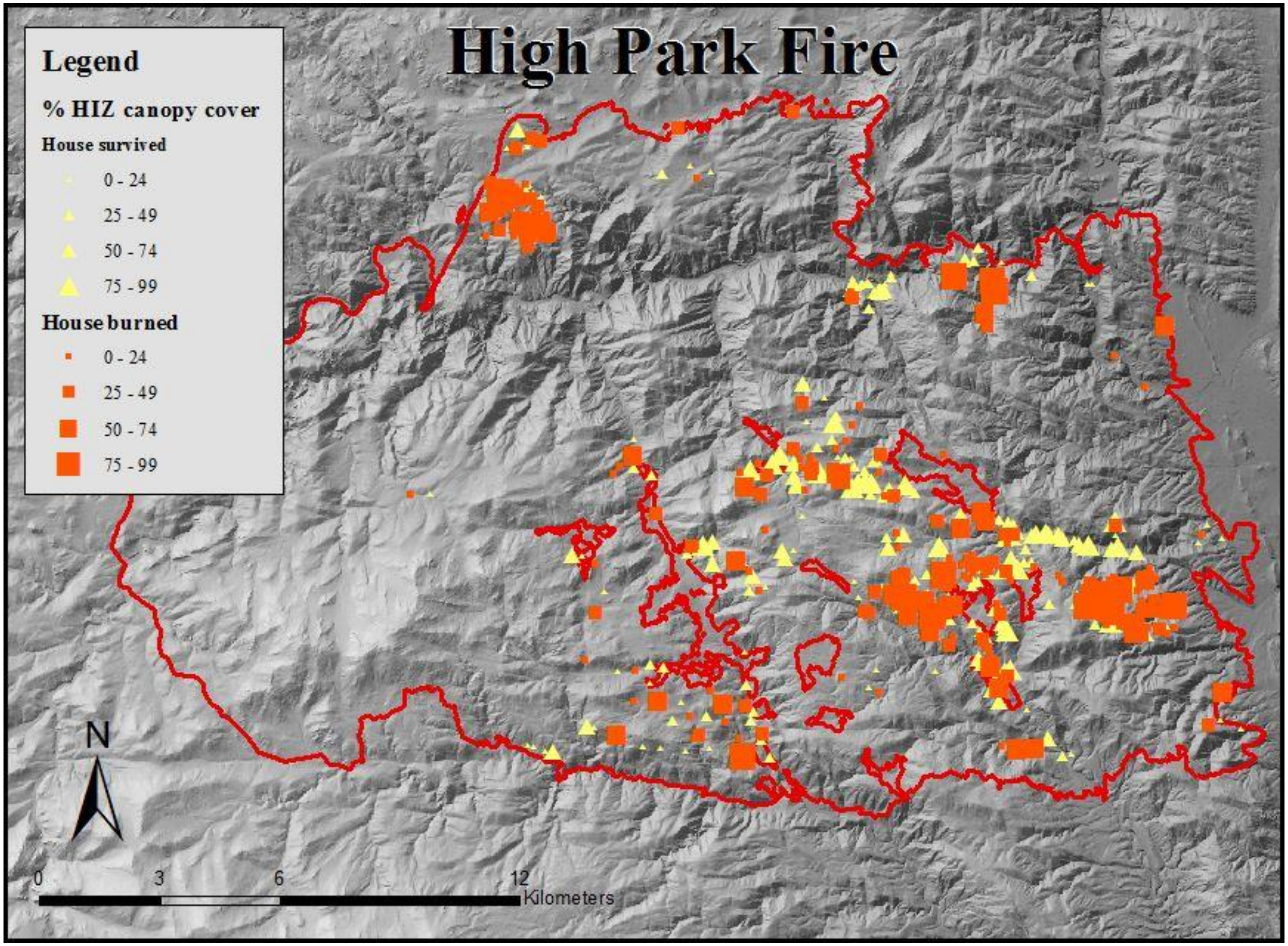
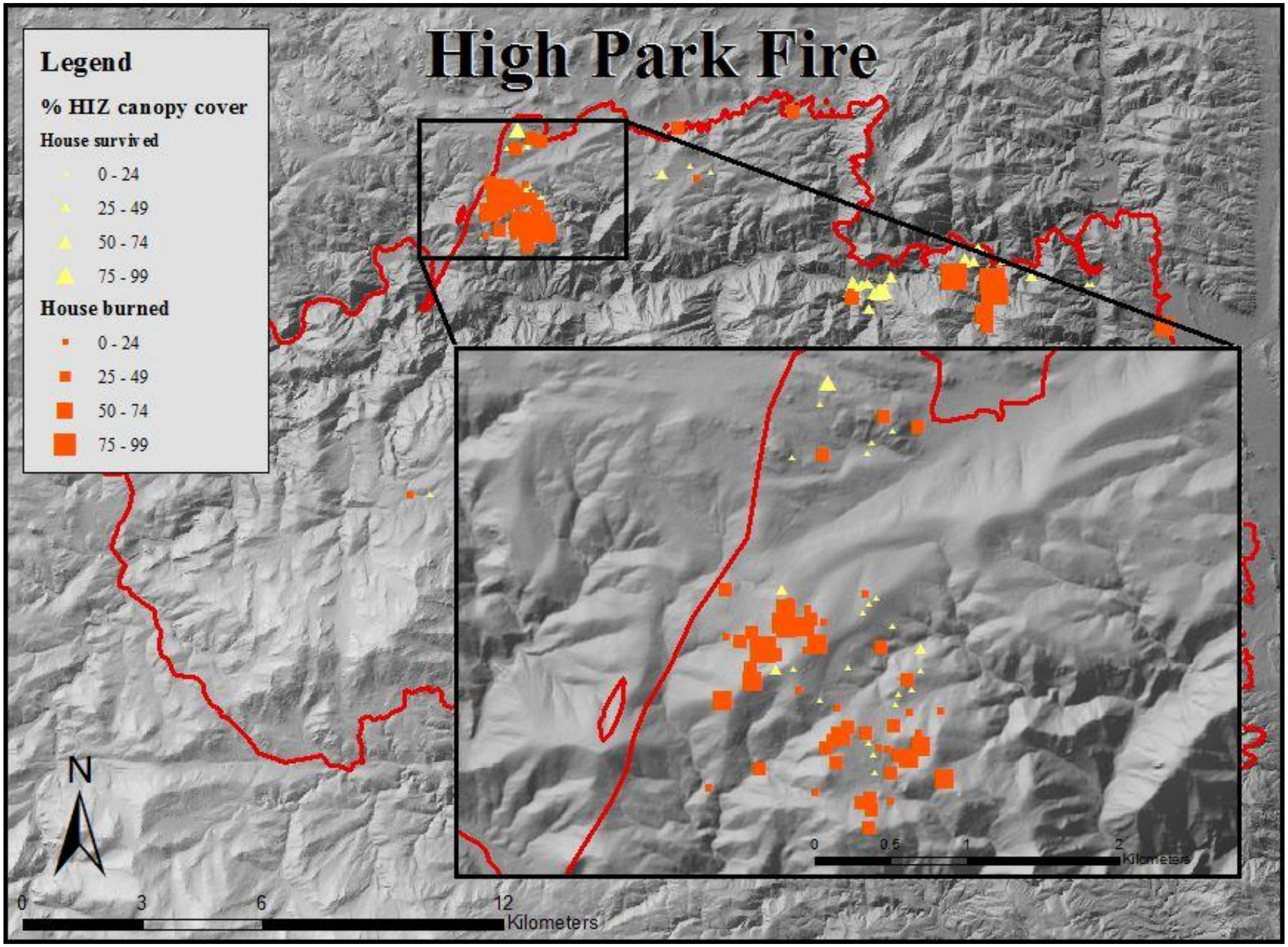
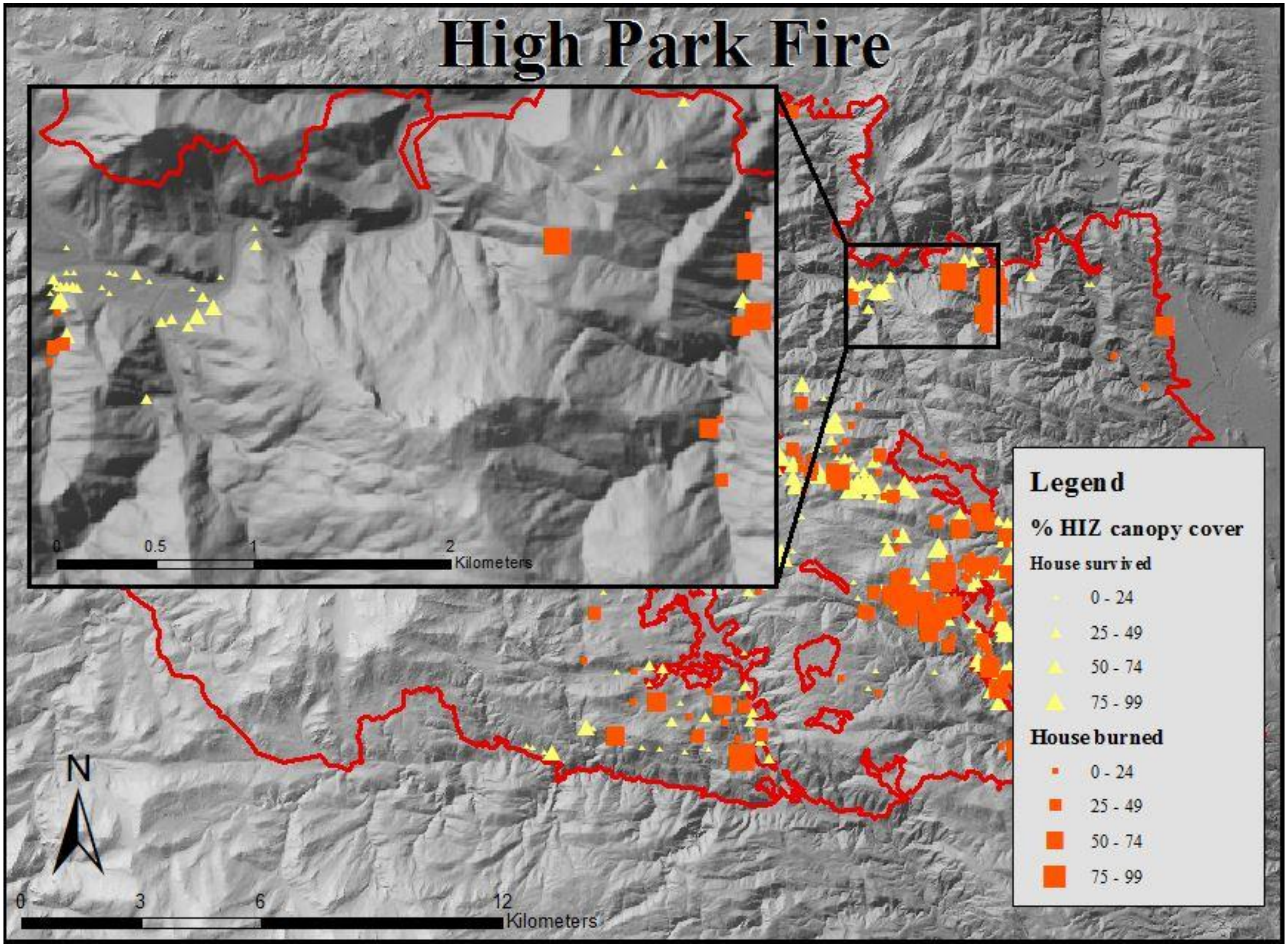
Appendix A: High Park Fire – % HIZ Canopy Cover Overview Map



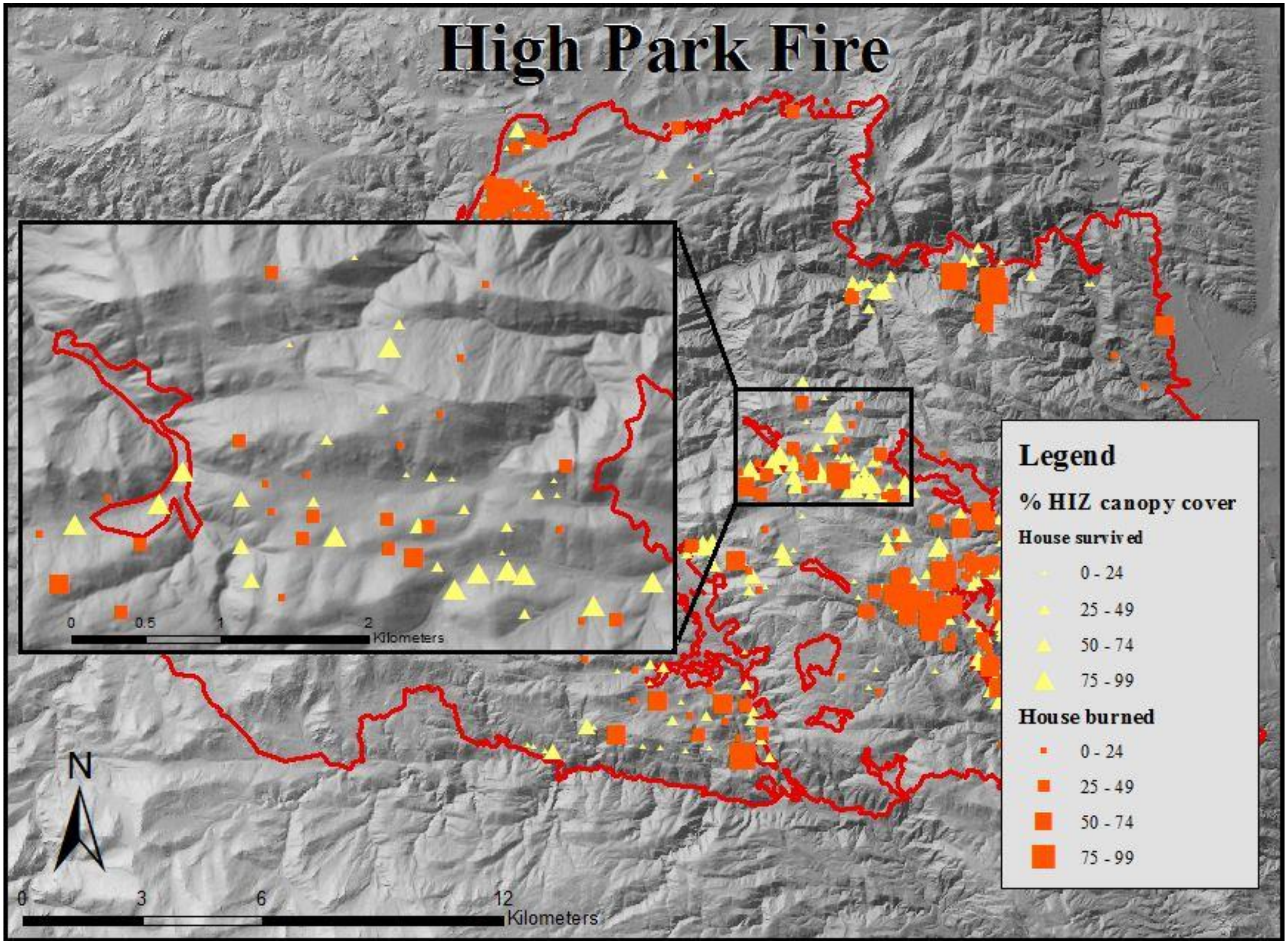
Appendix B: High Park Fire – % HIZ Canopy Cover Inset Map #1



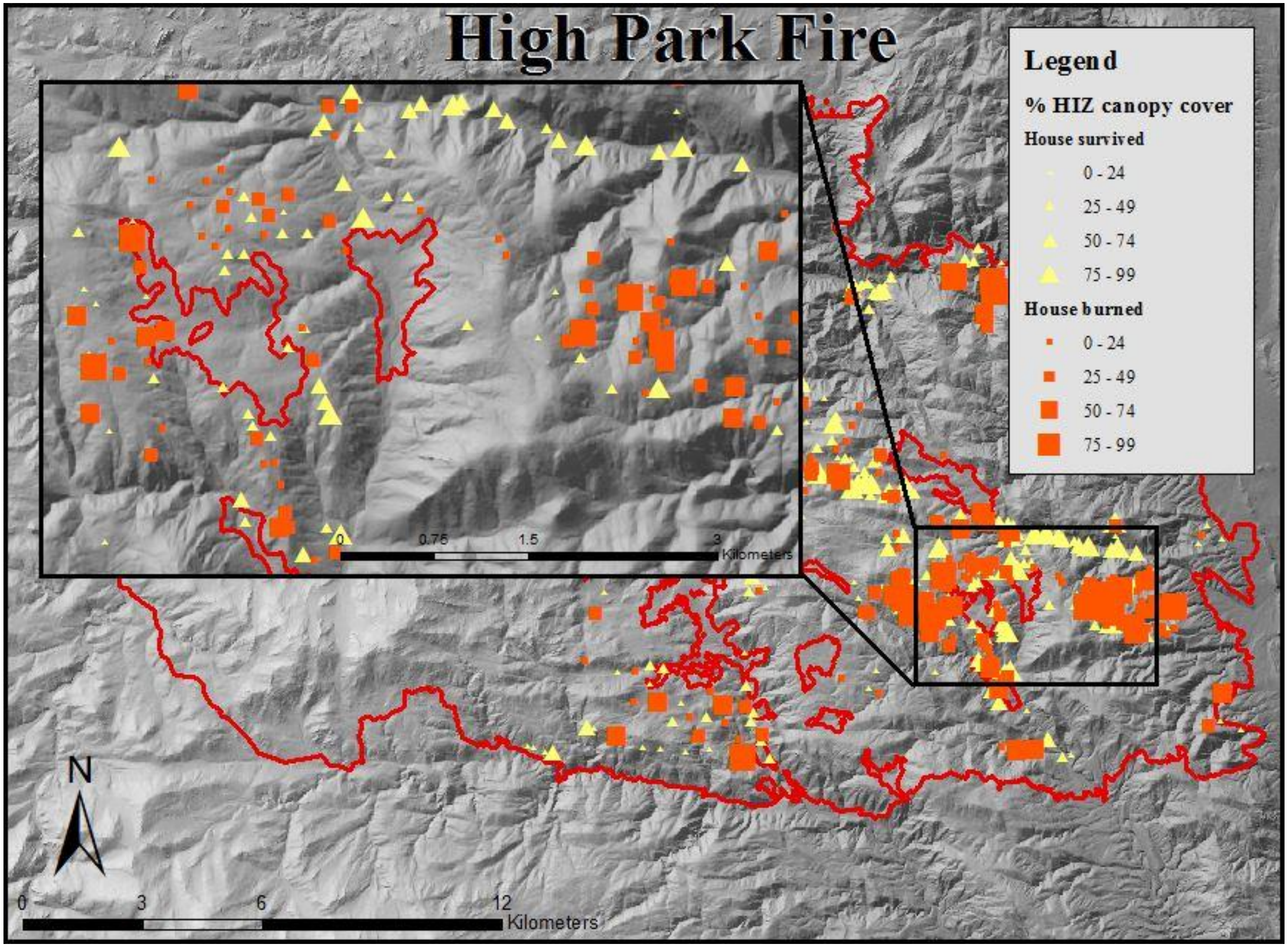
Appendix C: High Park Fire – % HIZ Canopy Cover Inset Map #2



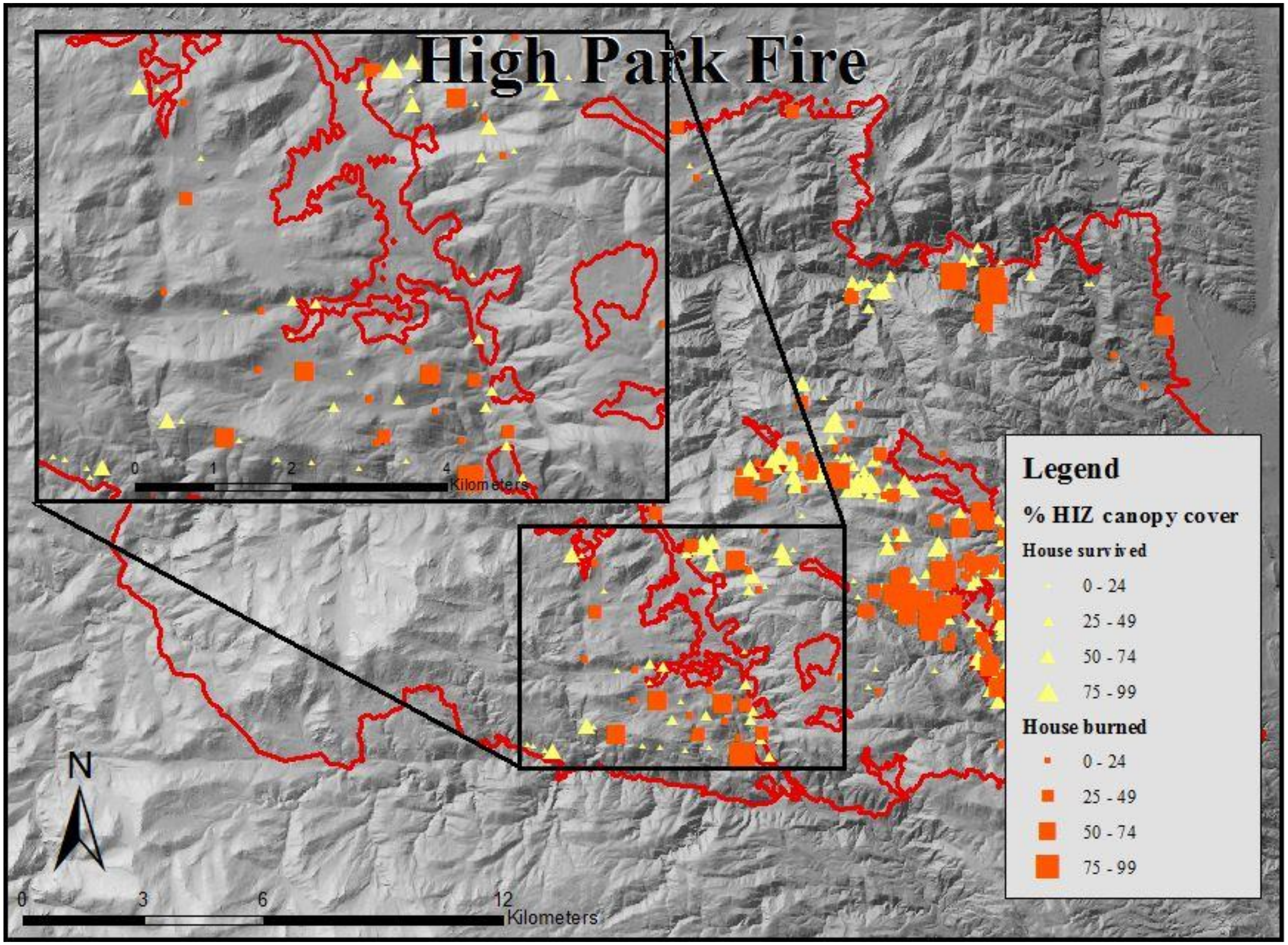
Appendix D: High Park Fire – % HIZ Canopy Cover Inset Map #3



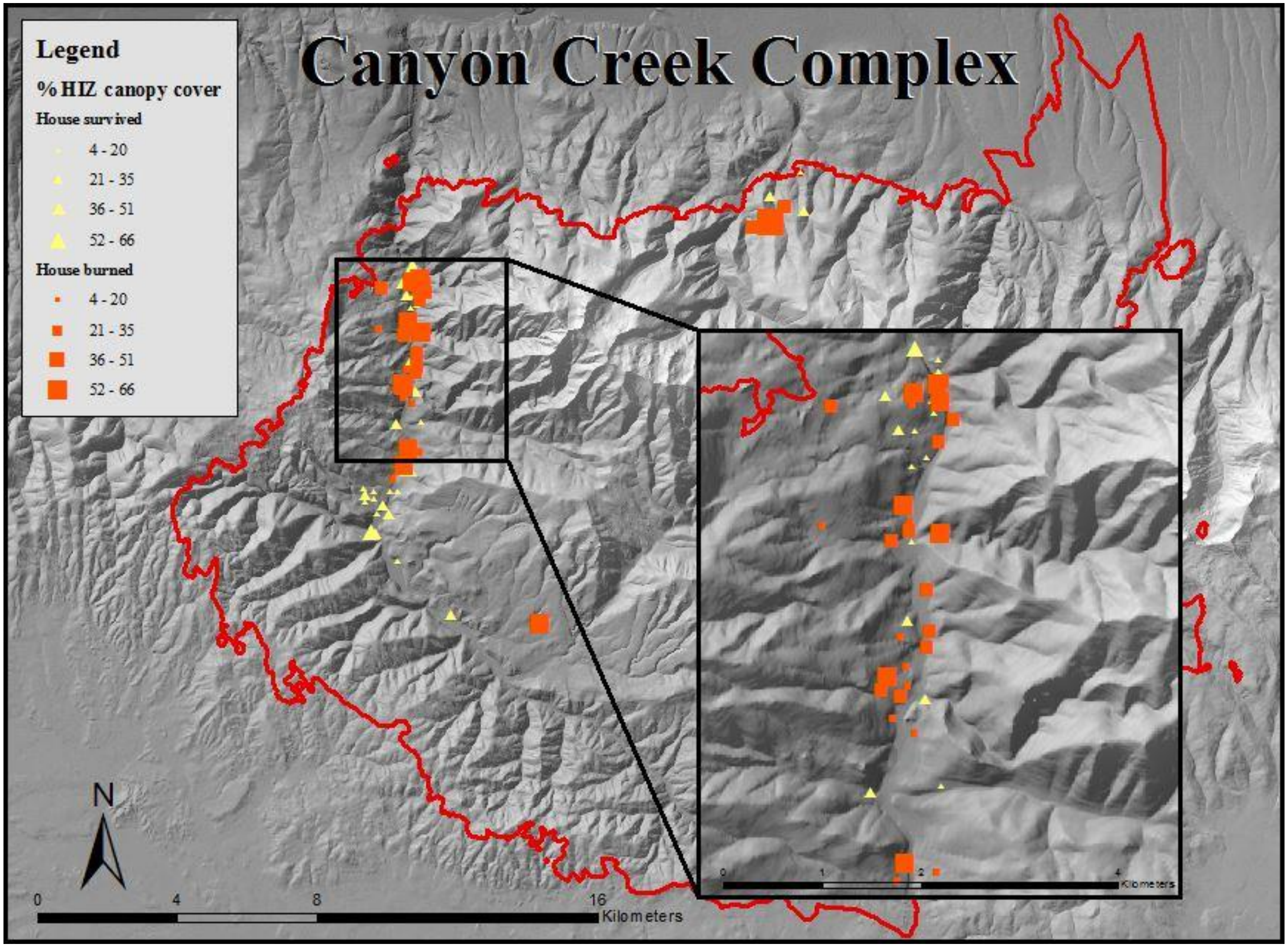
Appendix E: High Park Fire – % HIZ Canopy Cover Inset Map #4



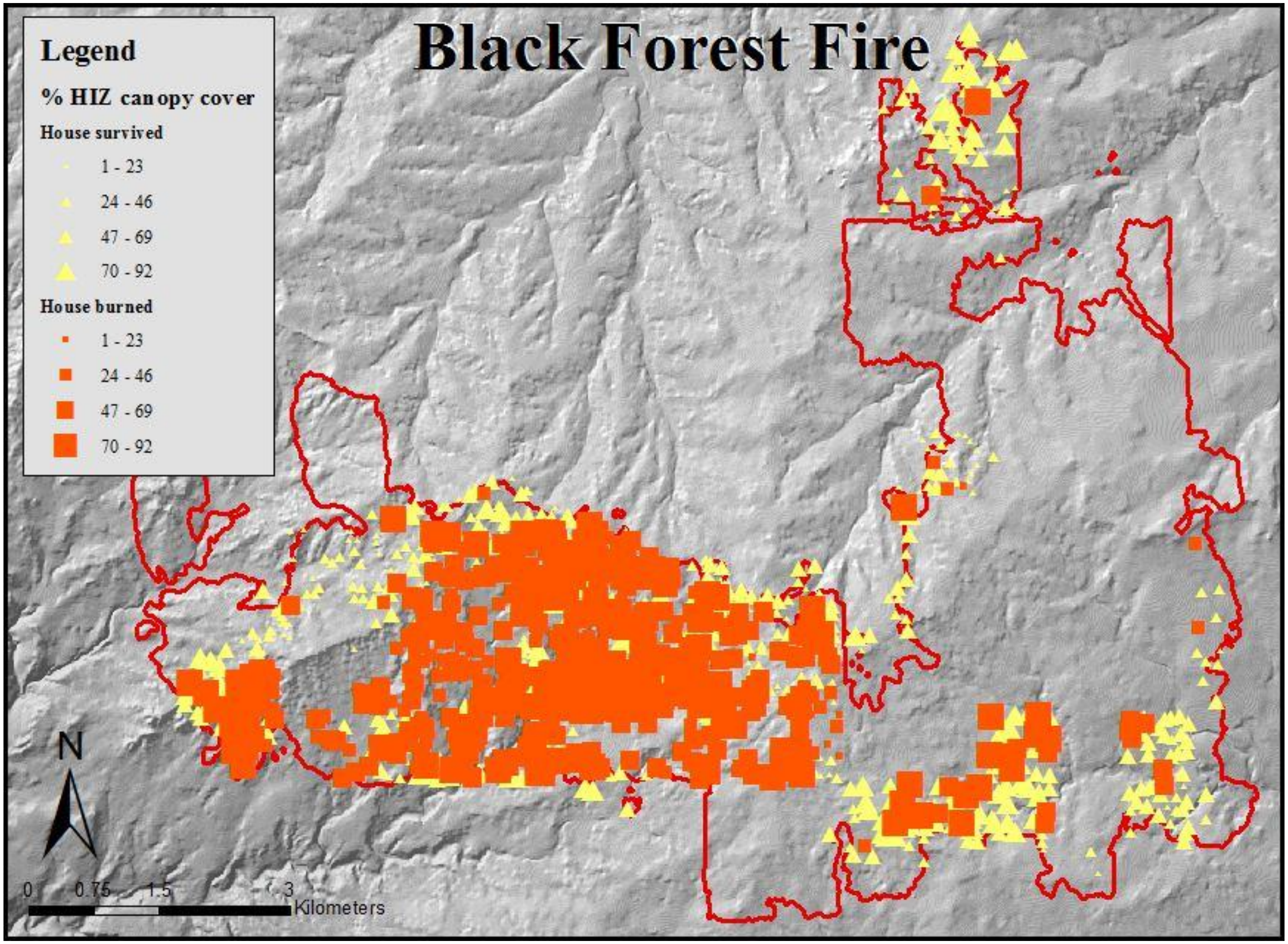
Appendix F: High Park Fire – % HIZ Canopy Cover Inset Map #5



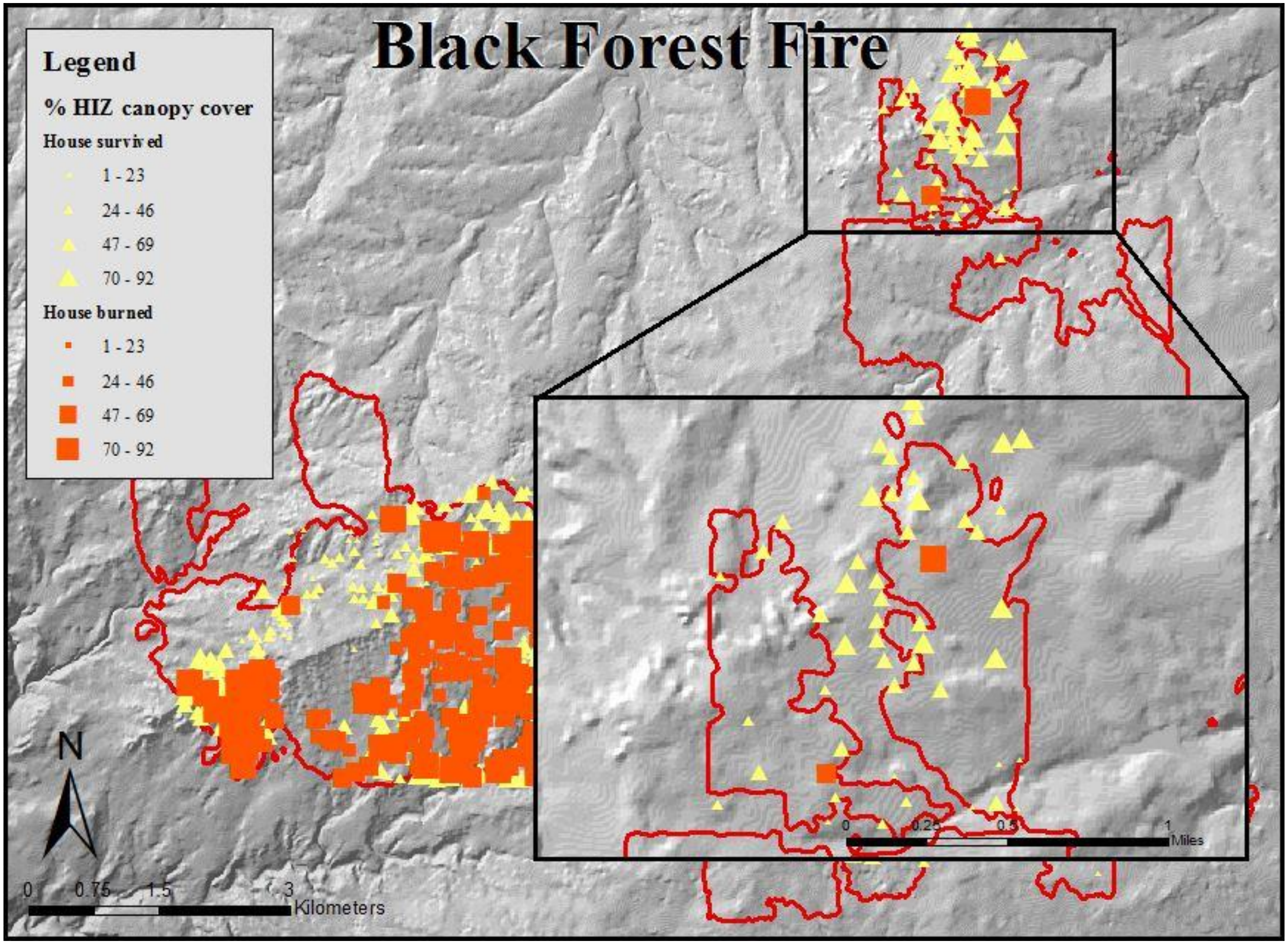
Appendix G: Canyon Creek Complex – % HIZ Canopy Cover Map



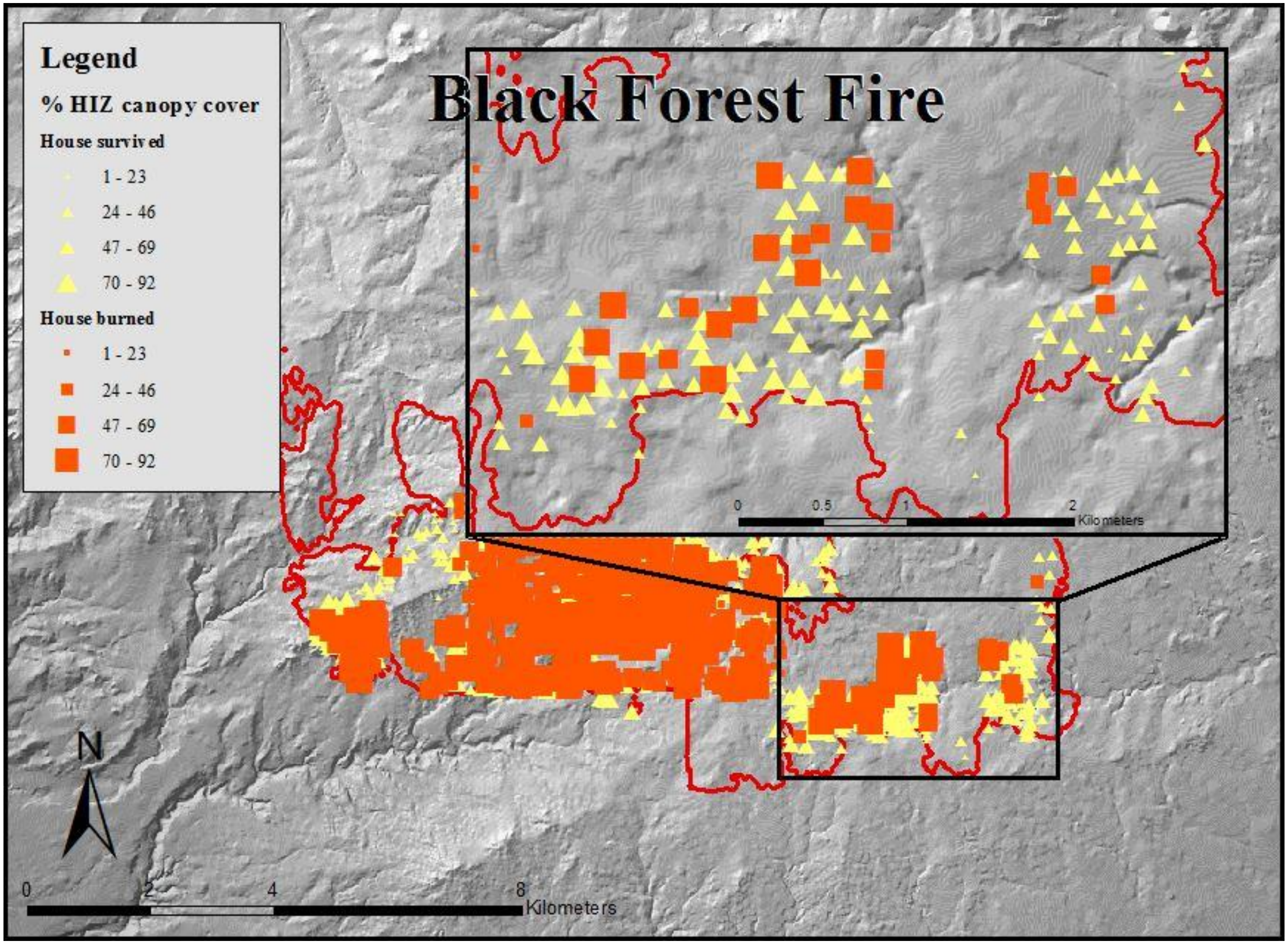
Appendix H: Black Forest Fire - % HIZ Canopy Cover Overview Map



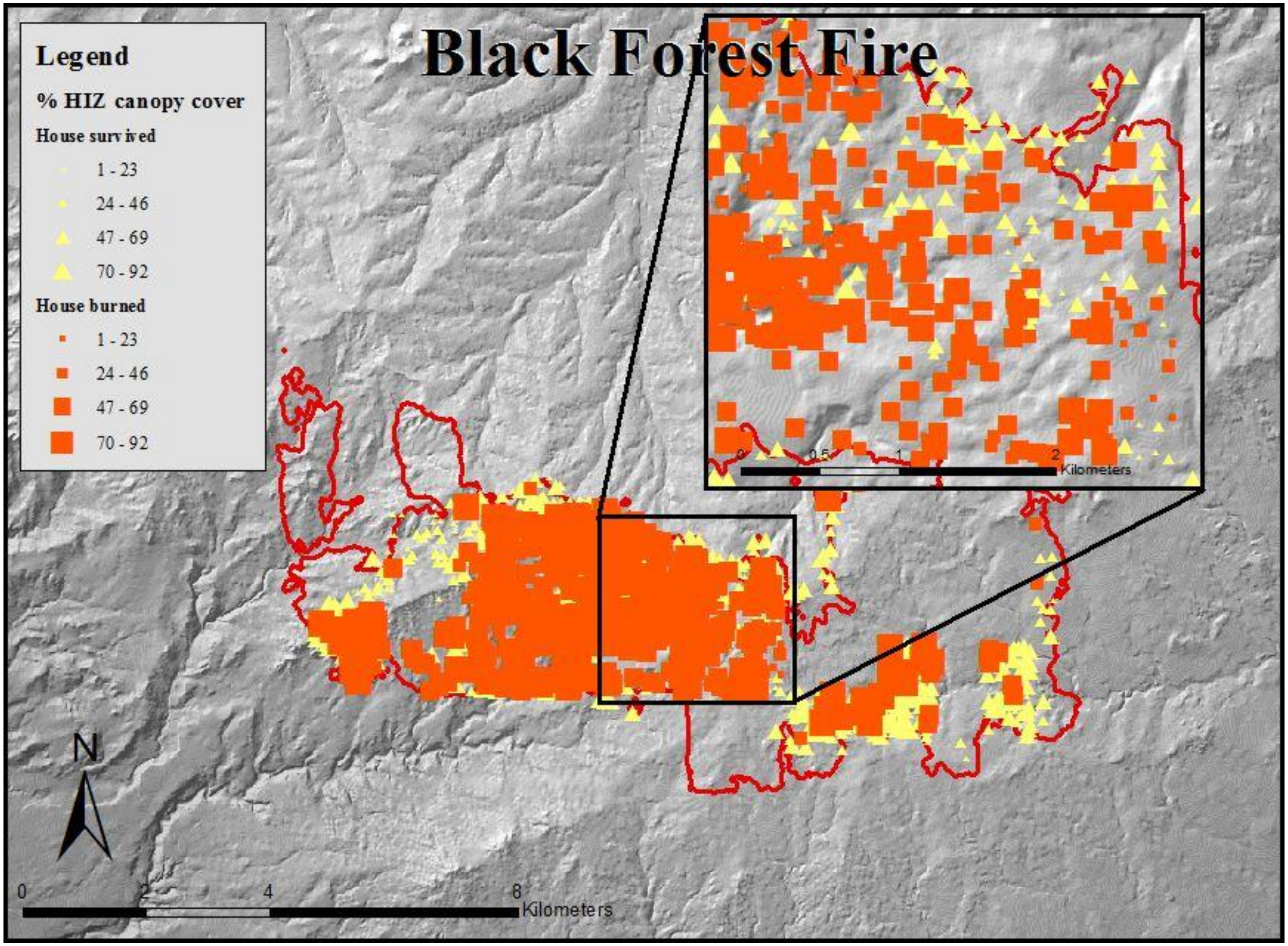
Appendix I: Black Forest Fire – % HIZ Canopy Cover Inset Map #1



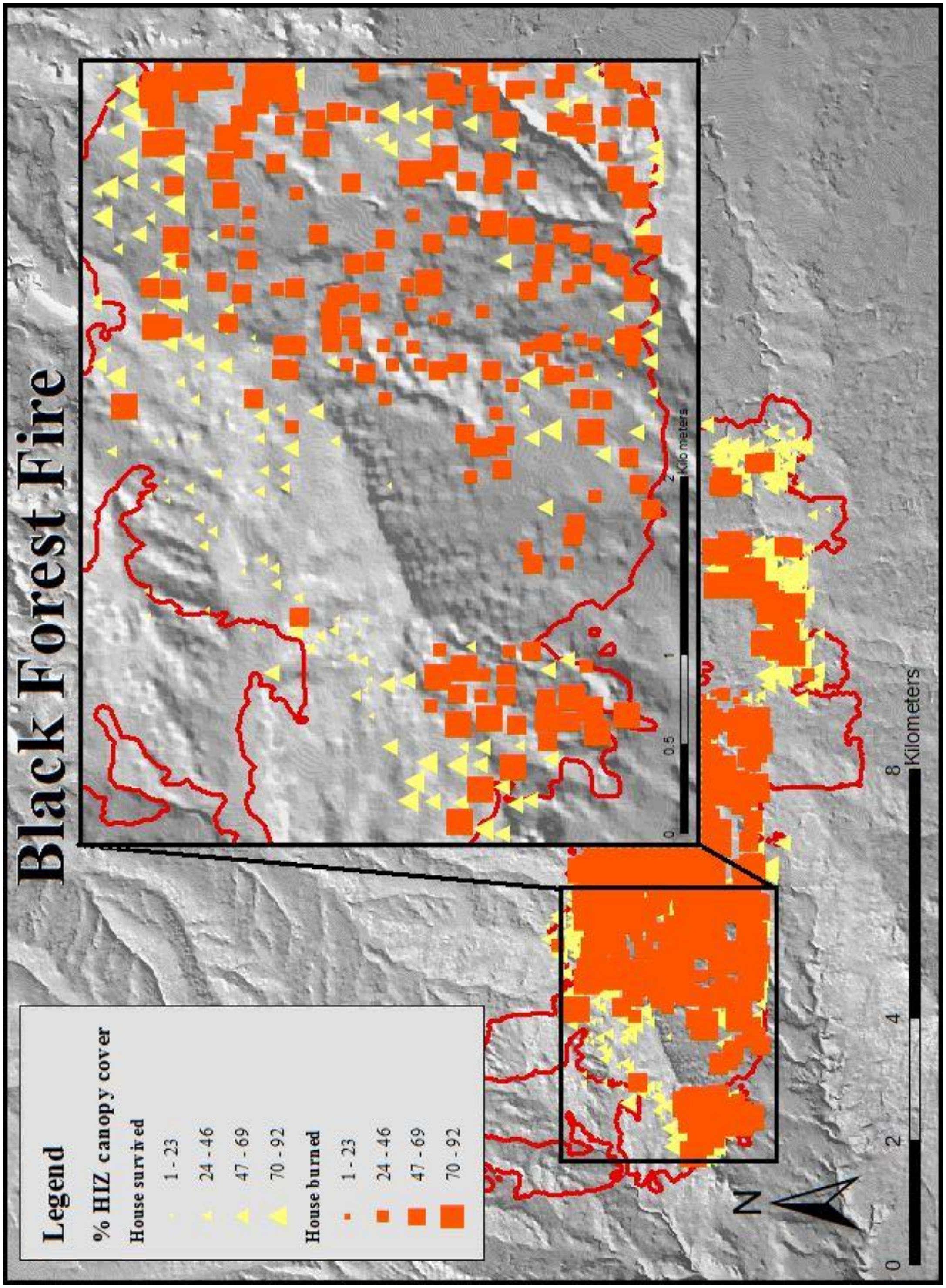
Appendix J: Black Forest Fire – % HIZ Canopy Cover Inset Map #2



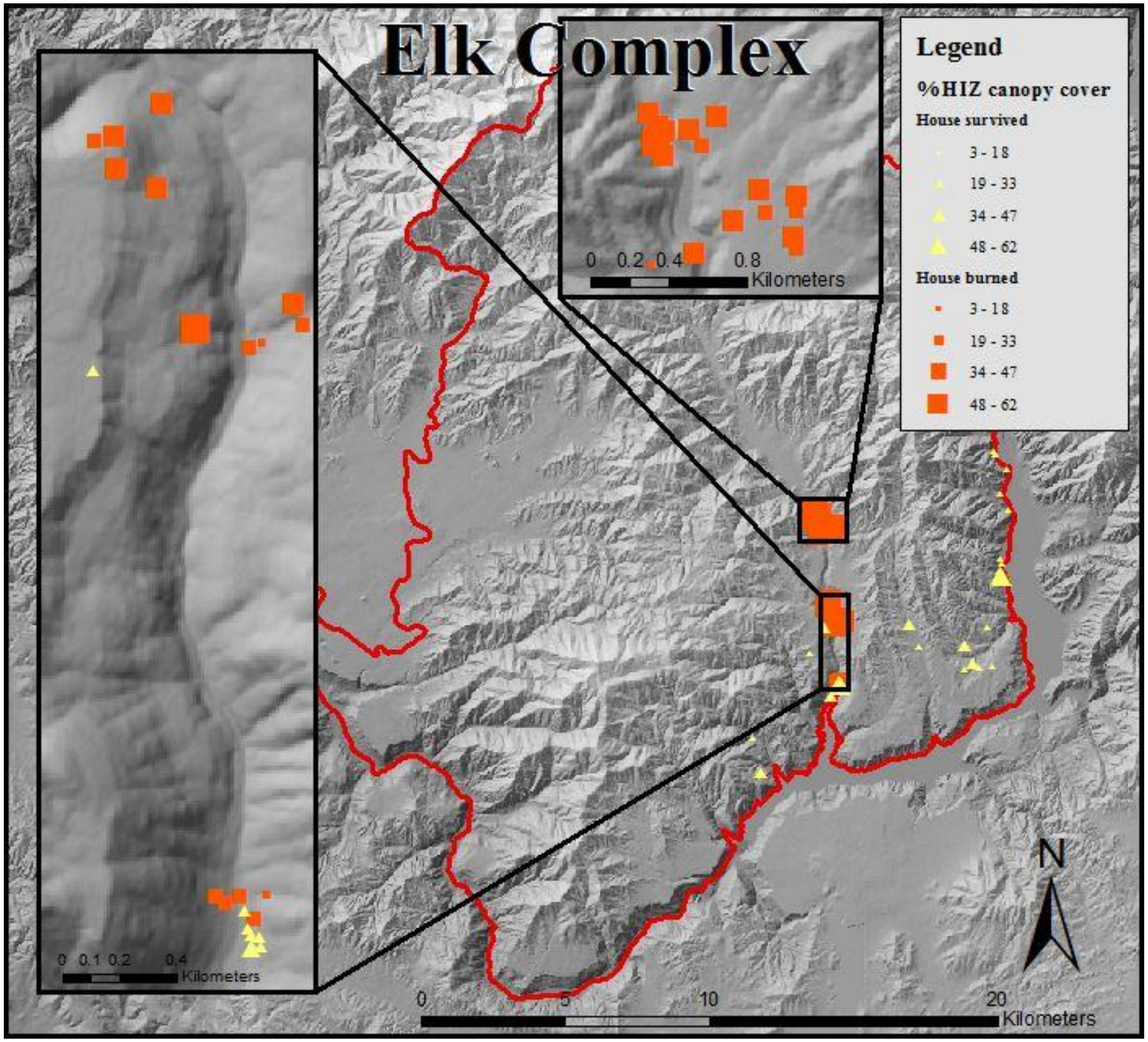
Appendix K: Black Forest Fire – % HIZ Canopy Cover Inset Map #3



Appendix L: Black Forest Fire – % HIZ Canopy Cover Inset Map #4



Appendix M: Elk Complex – % HIZ Canopy Cover Map



Appendix N: Taylor Bridge Fire – % HIZ Canopy Cover Map