DISSERTATION

MAPPING VALUES AT RISK, ASSESSING BUILDING LOSS AND EVALUATING STAKEHOLDER EXPECTATIONS OF WILDFIRE MITIGATION IN THE WILDLAND-URBAN INTERFACE

Submitted by

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ABSTRACT

MAPPING VALUES AT RISK, ASSESSING BUILDING LOSS, AND EVAUALTING STAKEHOLDER EXPECTATIONS OF WILDFIRE MITIGATION IN THE WILDLAND-URBAN INTERFACE

The Wildland-Urban Interface (WUI) is an area where residential development extends into undeveloped land. When WUI development occurs in hazard-prone fire-adapted ecosystems, wildfires can have detrimental impacts on human communities by destroying buildings and infrastructure. Wildfires that cause substantial building loss are known as WUI disasters because of their high social and economic costs. WUI disasters tend to occur when wildfires ignite under extreme burning conditions and threaten a large number of homes in hazardous conditions relative to firefighting resources. This combination of factors can lead to significant home loss. WUI disasters annually result in billions of dollars in fire suppression costs and destroy thousands of homes Governments, land managers, and effected stakeholders respond to this threat in numerous ways as they attempt to mitigate the impacts of wildfires and reduce losses in WUI communities.

Although wildfire mitigation efforts emphasize the removal of nearby flammable vegetation and the use of nonflammable building materials, one of the critical steps involves developing a map of communities and buildings at risk in the WUI. Despite broad-scale mapping efforts, most WUI maps do not identify building locations at sufficiently fine scales to estimate fire exposure and inform wildfire planning. Defensible space is promoted as the most effective way to reduce home ignition; however, questions remain surrounding its interactions with fire

response, and its efficacy under the wide range of potential fire behavior to which homes could be exposed. This dissertation sought to realize three goals: first, it examined the potential of new technologies to map the WUI and the buildings within it at fine scales; second, it evaluated how well existing WUI mapping efforts capture the pattern of building loss observed during WUI disasters; and third, it examined stakeholder perspectives on the efficacy and interactions of defensible space and fire response with regards to protecting homes from WUI disasters.

Chapter two evaluates the ability of Object Based Image Analysis to extract WUI building locations from orthoimagery of the wildland-urban interface by testing accuracy and error at multiple scales. I found the approach can extract building locations with high rates of accuracy, and minimal user input. Extracting building locations using this approach can lead to comprehensive datasets of building locations in the WUI, which can be used to create more detailed maps of buildings exposed to wildfires. Such maps have utility for risk mapping, fuel treatment prioritization, and incident management, and can lead to a better understanding regarding the spatial patterns of home loss.

Chapter three leverages building location data to quantify the impacts of WUI disasters and evaluate the accuracy of WUI maps. I compare how well existing polygon-based SILVIS WUI maps and point-based WUI maps capture the pattern of building loss and assess building loss in relation to the core components of the WUI definition. Findings can be used to improve existing WUI maps, create point-based WUI maps from building location datasets, identify which homes are most in need of defensible space, and refine risk mapping and identification of wildfire exposure zones.

Finally, chapter four assesses stakeholder perspectives regarding the efficacy of defensible space and its interactions with fire response with regards to the stakeholders' ability to protect homes from WUI disasters. This is related to the prior mapping efforts because it speaks to the ways stakeholders co-manage wildfire risk with fire protection authorities, and the actions they take to protect threatened homes mapped using the methods evaluated in chapters one and two. These qualitative methods suggest a wide range in expectations of defensible space efficacy, both in theory and in practice. It is likely that numerous factors reduce the perceived and actual efficacy of defensible space.

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CHAPTER 1: INTRODUCTION

1.1 Introduction

The Wildland-Urban Interface (WUI) is defined as: areas where buildings and other human infrastructure are located within or adjacent to wildland vegetation (Stewart et al. 2009). Due to population growth and urban land expansion, the extent of the WUI has been increasing around the world (Theobald & Romme, 2007), with the greatest growth occurring across North America (Seto et al. 2011). While the WUI presents a number of challenges to land managers, including the introduction and spread of invasive species, and the loss of wildlife habitat (Alavalapati et al., 2005), it has also become a central concern for wildland fire policymakers and managers. In the United States, the expansion of the WUI is of particular concern, especially in areas where past land management strategies such as fire suppression, harvesting, and grazing have resulted in increased fuel loading and altered fire regimes, (Radeloff et al. 2018).

Wildfires result in billions of dollars in fire suppression costs and destroy thousands of homes across the U.S. annually (Abt et al. 2009, Alexandre et al. 2016). For example, the 2018 Camp Fire in California destroyed over 18,000 buildings and led to the death of 85 people. Other areas of the U.S., including Colorado and Arizona, have also experienced recent destructive wildfires. The most destructive wildfires in terms of home loss are known as WUI disasters. Cohen (2008) suggested that WUI disasters occur when a specific sequence of events unfolds (Figure 1.1), starting with the ignition of one or more wildfires during extreme burning conditions (e.g., fuels, weather, and topography). Under extreme conditions, a fire can be very intense and spread rapidly, which can prevent successful suppression by initial attack resources.

If the fire spreads into the WUI, large numbers of homes can be simultaneously put at risk of ignition from either the fire front or airborne firebrands. Fire response resources can become overwhelmed in such situations, and numerous homes can ignite, which then creates a feedback loop that further exacerbates home loss.

"The WUI problem" is the observed and expected home loss associated with wildfires and WUI disaster; the key objective of which is reducing the likelihood of home loss. (Cohen 2008, Calkin et al. 2014). As observed by Calkin et al. (2014), reducing home loss during WUI disasters requires numerous stakeholders to coordinate various strategies around fire prevention, vegetation management, fire suppression, land-use planning, and preparing the home ignition zone. While both the WUI disaster sequence and the WUI problem acknowledge the overlapping social and ecological processes that contribute to home loss, and the role of the various stakeholders tasked with mitigating that loss, neither explicitly accounts for spatial variability and the different ways WUI disasters unfold in different geographies.

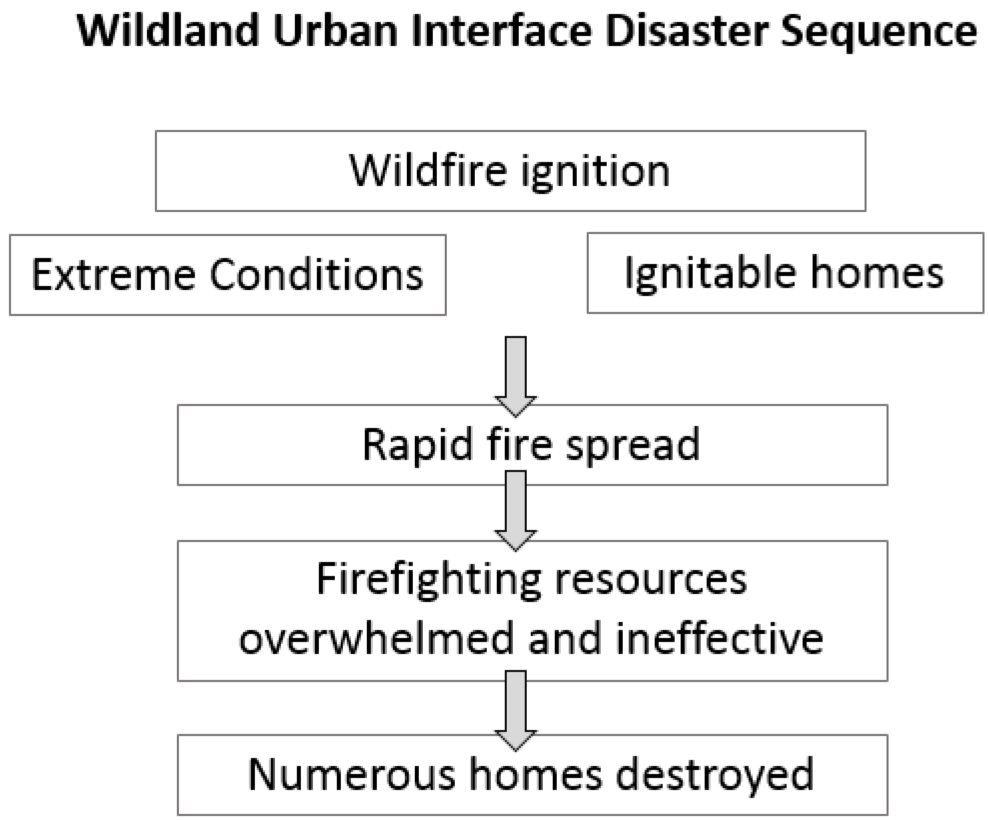

Figure 1.1 The Wildland-Urban Interface Disaster Sequence: Wildfires start during hot, dry, and windy conditions in areas with complex topography which lead to rapid rates of fire spread. When this occurs near residential areas, numerous homes are threatened and begin to ignite, which further increases fire behavior and rates of spread. Increased fire behavior, rapid rates of spread, and numerous igniting homes cause firefighters to become overwhelmed and fire response to be ineffective, which leads to additional home loss. WUI Disaster Sequence diagram modified from Cohen (2008).

To reduce the likelihood of future WUI disasters across different landscapes, WUI communities develop and implement multifaceted community-based wildfire protection strategies. These strategies--which include improving wildfire response capabilities and the implementation of hazardous fuel reduction projects and building defensible space around homes--are designed to mitigate the social and ecological processes that contribute to home loss. The development and implementation of community-based wildfire protection strategies often involve a wide range of stakeholders, including local, state, and federal land and fire managers, homeowners, and community planners. Coordinating wildfire mitigation strategies between stakeholders demands a model of shared risk management (Reams et al. 2005, Brenkert-Smith et al. 2006, Smith et al. 2016). Community-based wildfire protection efforts commonly begin with developing a WUI map, which allows stakeholders to identify at-risk buildings and prioritize areas for mitigation activities (Miller et al. 2016). These mitigation activities may include hazardous fuel reduction projects, which involve the intentional use of silvicultural methods to modify the fuels complex, modify fire behavior, and ultimately minimize the negative impacts of future wildfires (Hoffman et al. 2018). The concept of defensible space, another mitigation strategy, utilizes principles of hazardous fuel reduction treatments and advocates the use of fire-resistant building construction materials to reduce home ignitability. Defensible space leverages contributions from multiple stakeholders, and is thought to be the most effective way to reduce the likelihood of home ignition in the WUI; defensible space reduces home exposure to both heat and firebrands, decreases home ignitability, and provides a safe location for firefighters to take defensive actions (Gill and Stephens 2009). While specific guidelines for the creation of defensible space can vary between jurisdictions, several national programs such as FIREWISE and the National Fire Protection Association promote the practice by providing guidance (Kramer et al. 2018). Developing community-based wildfire protection strategies like defensible space requires coordination and integration among diverse stakeholders; this group includes the researchers who study home loss patterns and mechanisms, land managers who develop defensible space standards, homeowners who implement defensible space, and the firehters tasked with utilizing defensible space and protecting homes.

1.2 Maps as a Key Challenge

Implementing multifaceted community-based wildfire protection strategies presents numerous challenges for the stakeholders tasked with reducing home loss. There are critical questions that need to be answered in order to coordinate planning and mitigation activities: where are at-risk homes, buildings and other assets located in the WUI?; How well do existing WUI mapping methods capture that information?; To what degree do WUI stakeholders have similar or divergent understandings of the factors that contribute to home loss?; And how do stakeholders understand the factors that influence the efficacy of their wildfire mitigation and response activities? One key challenge to answering these questions is the development of WUI maps that can accurately identify areas, homes, and community values likely to be affected by a wildfire, and present this information at a scale fine enough to inform the design and implementation of mitigation strategies (Calkin et al. 2011, Kramer et al. 2018). WUI maps that more accurately capture the likelihood of home loss can improve strategic planning and identify priority areas for hazardous fuel reduction and defensible space projects.

1.3 WUI maps need to account for spatial variability

In order to be useful for developing community-based wildfire protections strategies, WUI maps must account for spatial variability and the different ways WUI disasters can unfold in different landscapes. In other words, WUI maps must provide a visual representation of what and where the WUI is, where values at risk are located, and should at least approximate where loss is likely to occur (Stewart et al. 2007). Since high-resolution data on building loss has been difficulty to gather, the WUI is typically mapped based on a spatial assessment of three core components: housing density, vegetation cover, and proximity to large patches of contiguous wildland vegetation (Radeloff et al. 2005). These three components effectively constitute a geographic theory for how the WUI is conceptualized spatially and have informed our understanding of where values at risk are located. The data contained within WUI maps can help inform the strategic placement of fuel hazard reduction treatments, serve as inputs for quantitative risk assessments, and inform tactical decisions during wildfire incidents (Scott et al. 2013, O'Connor et al. 2016).

1.4 Overview of WUI mapping

There have been numerous efforts to map the WUI and identify at-risk communities and values (Radeloff et al. 2005, Theobald & Romme 2007, Martinuzzi et al. 2015, Scott et al. 2015, Evers et al. 2019). At the national and regional scale, WUI mapping efforts have primarily relied on the WUI definition as described in the 2001 Federal Register, the federal government’s daily journal documenting agency regulations, rules, and executive orders (USDA 2001). WUI maps commonly use Census data and land cover data to determine housing density, vegetation cover, and housing proximity to vegetation (Radeloff et al., 2005; Theobald and Romme 2007; Hammer et al. 2007). Although Census-based maps have proven useful, they have several limitations, including variable precision associated with Census blocks which vary in size, and an increased likelihood of excluding isolated buildings and scattered low-density development when housing density doesn’t meet minimum thresholds employed by the Federal registrar (Bar-Massada et al. 2013; Clark et al. 2009; Platt, 2010). Theobald and Romme (2007) attempted to address some of these limitations through the use of daysemteric techniques, which remove undeveloped land before calculating building density; however, such approaches still suffer from the modifiable areal unit problem, which introduces a statistical bias by aggregating point-based data into zones of varying sizes (Openshaw 1984). Further, Census data only counts housing units and does not include outbuildings and auxiliary structures that represent additional values at risk. Even if the potential biases associated with the use of Census data were overcome, this data does not identify the locations of individual buildings and so is still of limited utility for fine-scale fire planning and operations.

1.5 Point-based WUI maps

To overcome the limitations of Census and land cover data, managers can create point-based WUI maps that identify buildings and other values at risk in the WUI. Point-based WUI maps can be developed using a variety of manual or machine learning approaches. Manual mapping approaches include digitizing building footprints from municipal records or aerial imagery, collecting building locations with GPS units, or using building location proxies such as addresses or parcel centroids (Lowell et al. 2010; Platt, 2010; Calkin et al. 2011). Although these approaches offer several advantages over Census data, digitizing buildings can be time intensive, collecting GPS data is not feasible over large extents, and parcel centroid data may not accurately identify the location of buildings on large parcels.

One of the most promising machine learning methods for developing point-based WUI maps is Object Based Image Analysis (OBIA) (Platt 2014). OBIA approaches take advantage of recent advances in computer technology, earth observation sensors, statistics, and Geographic Information Systems (GIS) to extract discrete objects, such as buildings, roads, and developed areas from high-resolution imagery. OBIA methods attempt to identify discrete objects by examining the spatial and spectral associations of groups of pixels with unique characteristics (e.g., shape, color, reflectance, texture) (Hay and Castilla, 2006). OBIA methods can be classified as either automated or semi-automated, depending on the level of human involvement. Automated OBIA approaches can be more efficient because they do not require a human interpreter, though they do require the development of image processing algorithms. Semi-automated OBIA approaches utilize automated image processing algorithms as a first pass to identify the points of interest, followed by human interpretation for improved quality control. Semi-automated approaches can increase accuracy and can take less time than either manual or automated approaches—the additional time for human interpretation is often less than the time required to refine automated algorithms for a unique application. Point-based WUI maps have primarily been developed over smaller spatial extents (Bar-Massada et al. 2013; Lampin Maillet et al.2009, 2010). However, the availability of new imagery and processing ability allows this approach to be scaled up. Object Based Image Analysis and the Point-based WUI maps can identify specific building location points, so they have the potential to increase the functionality and accuracy of WUI maps relative to Census-based WUI maps.

1.6 WUI maps should be based on likely home loss

Point-based maps potentially offer advantages over Census-based maps, but if they are to be used to identify homes and buildings at risk of ignition, they should still be based on empirical evidence of wildfire-induced home loss (Stewart 2007). Few if any studies have analyzed the accuracy of WUI maps, including how well they capture patterns of home loss, where they may be omitting loss, and where they include buildings with a low likelihood of loss. Although several Census-based WUI mapping efforts have employed sensitivity analyses to examine the influence of modifying WUI components (Building density, vegetation cover, and proximity to areas of contiguous vegetation) (Radeloff et al. 2005; Stewart et al. 2007), it is still unclear how adjusting individual WUI component parameters influences WUI map accuracy and ability to identify at-risk buildings. To solve "the WUI problem," we must assess how well WUI maps identify where loss is and is not likely. Assessing and improving WUI map accuracy can help stakeholders develop a shared understanding of where values at risk are located, which can in turn inform various community-based wildfire protection strategies. If calibrated with patterns of loss, point-based WUI maps are particularly useful for estimating the number of homes at risk of igniting during a wildfire, and as inputs for fine scale risk assessments, Point-based WUI maps can also be paired with fire behavior models to estimate wildfire exposure for individual buildings (Scott et al 2013).

1.7 The Challenge of Coordination

A second key challenge of implementing multifaceted community-based wildfire protection strategies stems from the fact that mitigating wildfire risk requires coordination of mitigation and response strategies across multiple stakeholders (Calkin et al. 2014). Because the success of mitigation and response strategies in the WUI are codependent, stakeholders should ideally have a shared understanding of the objectives of and expectations for the wildfire protection strategies they implement (Cheng and Becker 2005: Champ et al. 2012). For example, firefighters often help homeowners implement defensible space activities, or provide guidance on how to do so based on local conditions (Smith et al. 2016). Reciprocally, if a sufficient number of homeowners in a neighborhood implement defensible space, it may assist the firefighters who are tasked with protecting homes there. Due to the codependence between mitigation and fire response, it is essential that stakeholders not only coordinate actions, but recognize how that coordination influences efficacy. (Moritz et al. 2014: Smith et al. 2016: Paveglio et al. 2016: Madsen et al. 2018). In order to effectively coordinate actions, stakeholders with different priorities, levels of risk tolerance, and resources at their disposal need to align their understandings of WUI disasters and the expectations of fire response and defensible space.

1.8 WUI Stakeholders' Understanding of Risk and Mitigation

There have been numerous efforts examining how WUI stakeholders understand wildfire risk, and the efficacy of individual mitigation efforts (Brenkert-Smith et al. 2006; Martin et al. 2007; Absher et al. 2013; Olsen et al. 2017), yet numerous gaps remain. The literature suggests that a homeowner's perceived defensible space response efficacy, (i.e., the belief that their actions effectively reduce the likelihood of home loss), is one of the more important prerequisites for wildfire mitigation (Fried et al. 1999; Martin et al. 2007; Hall & Slothower 2009). In general, a homeowner's willingness to implement defensible space is positively linked to their belief that these actions will be effective. Although most stakeholders have generally positive view of mitigation efficacy (Absher et al. 2013), numerous homes have been lost despite mitigation efforts in a number of recent WUI disasters such as the Black Forest Fire in Colorado and the Thomas Fire in California (Pikes Peak Wildfire Prevention Partners 2014; Guerin 2017). Some empirical studies have also indicated defensible space and fire response efforts have not consistently protected homes (Cohen and Stratton, 2008; Graham et al. 2012; Syphard et al. 2014). Despite the evidence that defensible space does not guarantee home protection, many WUI homeowners still have high expectations of defensible space and believe firefighters will be able to respond to their home and provide adequate structure protection (Brenkert-Smith & Champ 2011, Meldrum et al. 2015). Due to the codependence between fire mitigation and fire response, and the fact that both are often deployed together as part of community-based wildfire protection strategies, there remains a need to assess WUI stakeholder perspectives on the efficacy of and interactions between fire mitigation and fire response.

1.9 Bridging the Knowledge Gaps

The overall goal of this research is to advance the practice of how the WUI is mapped and determine why and how stakeholder perspectives on wildfire risk and the efficacy of wildfire mitigation align or diverge from one another. This dissertation takes a broad interdisciplinary and spatially based approach to explore these interrelated aspects of the WUI problem. Chapter Two evaluates the accuracy of using remotely sensed imagery and OBIA techniques for detecting individual buildings within the WUI. It examines the influence of OBIA methods on extraction accuracy and quality and assesses how error and accuracy are related to the distance between extracted buildings and control building footprints. Chapter Three investigates the occurrence and location of WUI disasters in the continental USA and compares the extent to which existing Census-block-based WUI mapping methods capture the pattern of building loss relative to point-based WUI maps. This comparison utilizes Incident Status Summary Reports from the National Wildland Fire Coordinating Group, WUI maps, and point-based datasets of buildings affected by WUI wildfire disasters. Chapter Four uses qualitative methods and interviews with WUI stakeholders to explore the range of WUI stakeholder understandings and beliefs around defensible space and fire response. The chapter illustrates similarities and deviations between (a) how stakeholders defined the intended purposes and outcomes of various mitigation and response strategies, (b) how stakeholders described the relationship between mitigation and response strategies, and (c) how stakeholders articulated the efficacy of these strategies in relationship to environmental factors that contribute to WUI disasters (e.g., drought, quality of mitigation efforts in neighborhood, geography). This qualitative chapter provides context for the earlier chapters, pairing an improved understanding of where values at risk are located, with a better understanding of the perceived effectiveness of the wildfire protection strategies implemented by communities. Taken together, the spatial-analytical and social science components of this dissertation combine to improve our understanding of where values at risk are located in the WUI and improve our understanding of the perceived effectiveness of the wildfire protection strategies implemented by communities. Chapters two, three, and four are each written as a stand-alone article for peer-reviewed journals.

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CHAPTER 2: HIGH RESOLUTION MAPPING OF DEVELOPMEMT IN THE WILDLAND URBAN INTERFACE USING OBJECT BASED IMAGE EXTRACTION

2.1 Introduction

The Wildland-Urban Interface (WUI) is described as the geographic area where human development encroaches upon and intermixes with wildland vegetation (Stewart et al., 2009). Over the last several decades, the spread of development into wildlands has expanded the extent of WUI across the United States (Radeloff et al. 2018), resulting in increased concern related to land use planning, habitat conservation, ecosystem services provided by forests, and community protection from wildfire hazards. This study primarily examines the WUI in the context of wildfire hazard management. Of particular concern to many land managers and national policy-makers over the last decade has been the increase in the number of wildfires at the WUI, which has been attributed to the buildup of wildland fuels, climate change, and increasing development (Keeley et al., 1999; Westerling et al., 2006; Theobald and Romme, 2007). The increased number of WUI fires have resulted in greater numbers of firefighter fatalities, home losses, and federal expenditures (Mell et al., 2010; Gude et al., 2013), leading to policies that highlight the need for improved land use planning, community scale fire mitigation, and effective fire response. One tool that has been identified as a key to improving WUI wildfire management, planning, and response are detailed maps that identify building locations and other community values at risk (Calkin et al., 2011).

At the national scale in the United States, WUI mapping efforts that facilitate regional and temporal comparisons have been conducted using Census block data because of their standardized methodology and widespread availability (Radeloff et al., 2005; Theobald and

Romme 2007; Hammer et al., 2007). However, due to the conversion of point to zonal data in the development of Census data, Census based maps have several limitations, including variable precision across space, and an increased likelihood of excluding isolated buildings and scattered low density development (Bar-Massada et al., 2013; Clark et al., 2009; Platt, 2010). Theobald and Romme (2007) attempted to address some of these limitations through the use of daysemteric techniques which remove undeveloped land prior to calculating building density; however, such approaches still suffer from the modifiable areal unit problem, which introduces a statistical bias by aggregating point based data into zones of varying sizes (Openshaw and Openshaw, 1984). Even if potential biases associated with the use of Census data were overcome, these approaches are still limited for fine scale fire and emergency service planning and operations because they do not provide spatial location data for values at risk at an appropriate scale for many fire management applications, nor do they include other outbuildings and auxiliary structures that represent additional values at risk in the WUI (Theobald and Romme, 2007).

Alternatively, WUI maps that include the spatial locations of buildings can be developed through several manual approaches including digitizing building footprints from municipal records or aerial imagery (Lowell et al., 2010), collecting building locations with GPS units (Calkin et al., 2011), or using building location proxies such as addresses or parcel centroids (Platt, 2010; Calkin et al., 2011). The increased spatial detail and ability to identify isolated buildings and low-density development by using these approaches avoids several weaknesses of Census based WUI maps (Calkin et al., 2011; Bar-Massada et al., 2013). Furthermore, since building-based WUI maps are often derived from frequently updated remotely sensed or aerial imagery, they provide additional temporal resolution compared to Census based maps. The increased spatial and temporal data provided by building-based WUI maps makes them ideal tools for many wildfire management applications, including: community-scale wildfire planning, fuel treatment prioritization, suppression resource allocation decisions, and post wildfire home destruction studies during wildfire incidents (Theobald and Romme, 2007; Platt, 2010; Maranghides and Mell, 2011; Syphard et al., 2012; Bar-Massada et al., 2013, Alexandre et al., 2015). Building-based maps can also provide the level of detail required for other land management and emergency service applications (Bar-Massada et al., 2013). Despite these advantages, building-based WUI maps can have limited spatial extents due to the time and effort required for development, and can potentially reduce accuracy if created from parcel centroids or address data (Platt, 2012). Furthermore, if aggregating data at broader scales, the use of multiple sources can lead to incompleteness, lack of standardization, and methodological uncertainty (Lowell et al., 2010). However, newer technologies and standardized techniques that can process data over large spatial extents hold promise for overcoming some of the current limitations for producing and maintaining building-based WUI maps.

Advances in computer technology, earth observation sensors, and Geographic Information Systems (GIS) sciences over the last several decades have led to the development of Object Based Image Analysis (OBIA) methods. These methods include both automated and semi-automated methods, and utilize remote sensing, GIS technology, high-resolution imagery, and image classification algorithms to extract discrete objects, such as buildings, roads, and developed areas.

As opposed to traditional remote sensing approaches which classify individual pixels based on their spectral signatures alone, OBIA methods attempt to identify discrete objects by examining the spatial and spectral associations of groups of pixels with unique characteristics (e.g., shape, color, reflectance, texture) (Hay and Castilla, 2006). Object Based Image Analysis methods are being used with increasing frequency for a variety of natural resource management applications (Blaschke, 2010; Falkowski et al., 2009; Sofia et al., 2014,) and in urban development assessment (Freire et al., 2014; Tiede et al., 2010; Huang et al., 2014; Han et al., 2015). While OBIA methods have been used to map the general pattern of WUI development (Platt, 2012), and building locations in other areas (cite Tiede et al., 2010), OBIA has yet to be used or evaluated for its ability to extract specific building locations across large and diverse WUI landscapes, nor has it been evaluated against a municipally produced control dataset. Object Based Image Analysis methods have the potential to advance WUI mapping by improving the efficiency of creating highly detailed building-based maps across large spatial extents while providing a consistent methodology and accuracies similar to human interpretation (Lang, 2008). Automated OBIA approaches can be more efficient because they do not require a human interpreter, but image processing algorithms have to be developed and accuracy can sometimes be less than desirable. Semi- automated OBIA approaches combine automated image processing algorithms followed by human interpretation for improved quality control. Semi-automated approaches can increase accuracy and confidence in data and can take less time than either manual or automated approaches, because the additional time for quality control is often less than the time required to refine algorithms for unique applications. Ultimately, the strengths and weaknesses of different approaches will vary for different applications, and are influenced by the characteristics of the objects of concern, their pattern and prevalence on the landscape, image quality, spectral resolution, and environmental conditions (Turner and Gardner, 1991).

The objective of this study is to evaluate the potential for using an OBIA approach for the detection of individual buildings within the WUI. This is accomplished by comparing the accuracy and overall quality of extracted buildings to a county maintained building footprint control data. Specifically, this study examined: (1) the influence of semi-automated and automated OBIA methods on extraction accuracy and quality, (2) how error and accuracy is related to the distance between extracted buildings and control building footprints, (3) the influence of environmental characteristics, including topography and vegetation on building detection, and (4) specific errors that occurred during the extraction process and possible reasons they occurred. I conclude with a discussion of potential applications, limitations, and future areas of research related to using OBIA methods in WUI mapping.

2.2 Methods

For this study, I choose four counties (Larimer, Boulder, Gilpin, and Clear Creek) in northern Colorado, USA. These four counties contain a large area of WUI (Radeloff etal.,2005), that span a diverse range of land uses, terrain, Vegetation types, housing densities, and patterns of development, likely representative of WUI conditions across the western United States. This area spans elevations ranging from 1,500 to 2,800 meters, and includes multiple vegetation types including short grass prairie, shrublands, dry and mesic conifer forests commonly found in the Rocky Mountains of the Western United States. Home density in our study area varied from 3 to 170 buildings per km2, spanning a rural/urban gradient that encompasses interface, intermix, and occluded communities. In addition, these four counties had building footprint data that was manually digitized from high-resolution imagery and updated using building permit data. Within these four counties I randomly selected ten 3.75 by 3.75 minute quarter quadrangles (approximately 5.28 km by 6.94 km), and clipped the corresponding county building footprints (Fig. 2.1). Across the ten randomly selected quadrangles there were a total of 12,758 building footprints, at an average density of 35 buildings per square kilometer. The least developed quadrangle contained 101 building footprints and the most developed contained 6,282 building footprints. For each of the ten quadrangles, I also downloaded the corresponding 4-band (red, green, blue, and near infrared bands) multispectral National Aerial Image Program (NAIP) imagery tiles. The NAIP imagery used in this study was taken in 2013 and made available to the public in 2014. I utilized NAIP imagery in our study because it is a freely available standardized product for the western United States, has a fairly fine scale resolution (0.5 to 1.0 m), and has been successfully utilized in other OBIA applications (Garrity et al., 2008; Smith et al., 2008). I used Feature Analyst software (Textron Systems 2015), a third party extension for ArcGIS Desktop (ESRI, 2011), to extract individual building locations from the NAIP imagery tiles, corresponding to our ten randomly selected quadrangles. Feature Analyst is a third party extension for ArcGIS Desktop (ESRI, 2011) that uses a customizable semi-automated machine learning classification approach (Opitz and Blundell, 2008) to extract individual features from imagery. This software was chosen in part due to its ease of use, which is an important consideration for fire and emergency service professionals whom are developing individual-based WUI maps.

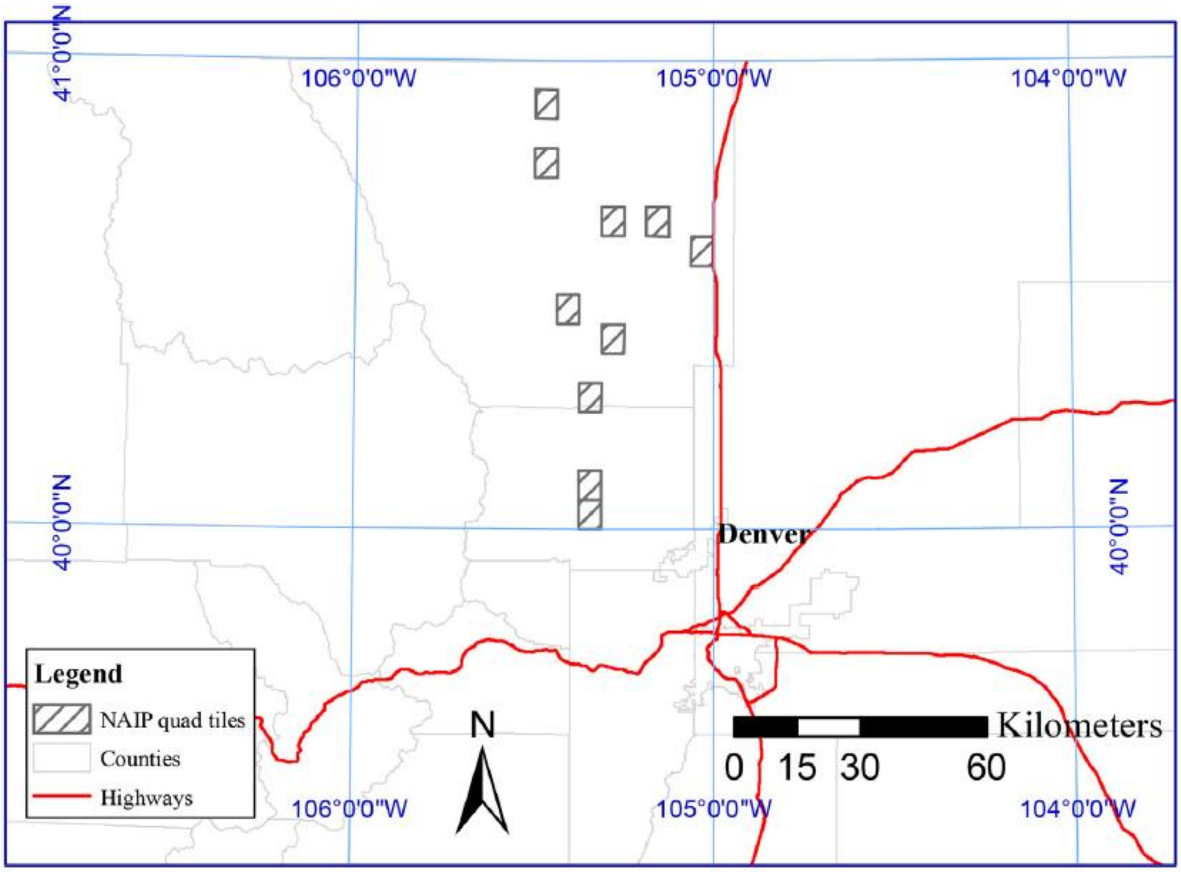

Figure 2.1. Basemap of the study area and the ten randomly selected National Aerial Image Program (NAIP) quadrangles used in the evaluation.

To initialize the OBIA processes, I digitized an initial training set of 5–10 representative building footprints in each NAIP image tile that captured a range of building roof colors, sizes, shapes, shadows, and spatial associations present. I then input the training set along with default input parameters to extract an initial set of objects from each image. For all semi-automated iterations, I used the default input parameters for manmade objects (including buildings), all four bands present in the NAIP imagery, a bulls-eye representation, pattern and a 30-pixel window. The default pattern was used to assist with reproducibility and help ensure the extraction could utilize both the shared and unique characteristics of the training set features to find similar objects in the imagery. Opitz and Blundell (2008) provide a more detailed description of how objects of concern guide the selection of input parameters in Feature Analyst. The dataset resulting from the initial extraction included those training set buildings I had originally identified plus additional features that shared similar spatial and spectral characteristics.

Following the initial feature extraction processes, I created a correction dataset by randomly selecting four to six developed and undeveloped areas in each tile (representing approximately 25% of the total area) and identified ten to twenty correctly and incorrectly identified features. This data was then used to supplement the original training set by refining the spatial and spectral characteristics of the buildings during a second processing iteration. After reviewing the extracted features from the second iteration an additional correction dataset was developed and a third iteration was performed. This processes was repeated an additional time for a total of four semi-automated iterations. After extracting building locations from the four semi-automated iterations, I created the fifth dataset by visually inspecting the results of the fourth iteration and manually added any missed building and removed any incorrectly identified objects. Fig. 2.2 highlights this iterative process and shows example outputs from the first, second, and manual iterations. Depending on quality requirements for a particular application, users can conduct different levels of quality control on the final dataset by spending more or less time correcting and adjusting features to improve accuracy. Depending on the chosen amount of quality control, this process is likely less intensive than traditional manual digitizing because of its ability to focus the user on areas that require additional attention. In our process, the rapid manual scan of a single quadrangle took about 10 minutes as compared to the 30 minutes I estimate it would have taken for traditional manual digitization. The extracted feature polygons from each of the five iterations were converted to centroids to simplify further analysis, reduce computational requirements, and minimize data storage.

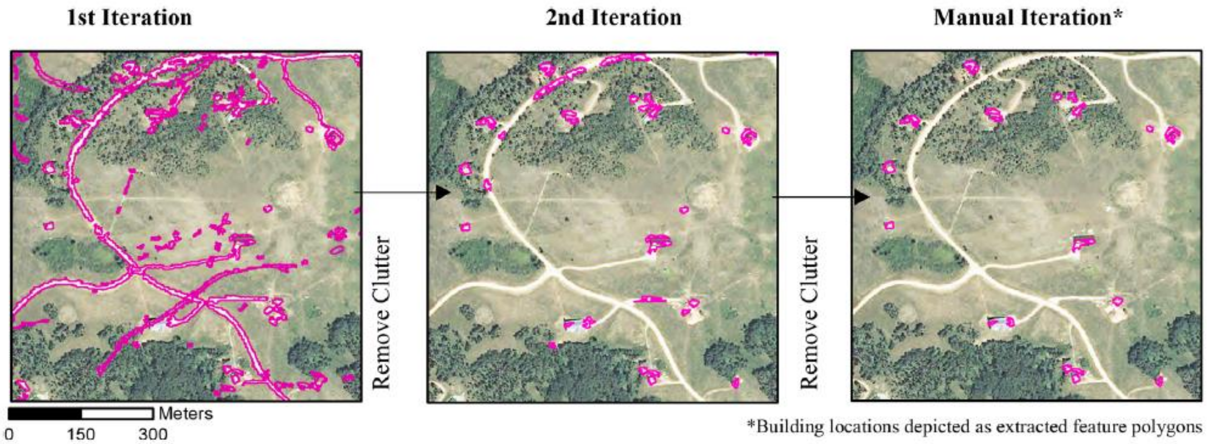

Figure 2.2. Extracting buildings in the wildland-urban interface using an object based image analysis. The evaluated method uses an iterative process that starts with a user defined training set and user defined algorithms to produce an initial dataset of objects interpreted as buildings (pink polygons). It then uses manual intermediate steps to identify a secondary training set of correctly and incorrectly identified objects to refine object detection algorithms for subsequent outputs. Lastly, a user can conduct quality control by manually adding missed buildings or removing incorrectly identified buildings in the final dataset.

For each of the five data sets I calculated the distance between the edge of each control building footprint and the nearest extracted feature centroid, then for each extracted feature centroid I measured the distance to the edge of the nearest control building footprint polygon; separation distances were then assigned to control and extracted feature datasets respectively. The separation, or buffer distances were used to determine accurately identified buildings, missed buildings, and incorrectly identified objects. Accurately identified buildings or true positives (TP) were those control building footprints that had at least one extracted feature centroid within a selected buffer distance. Omitted errors or false negatives (FN) occurred when control building footprints that did not have at least one extracted feature within the selected buffer distance. Commission errors or false positives (FP) were those extracted feature centroids that did not fall within the selected buffer distance around the control building footprints. Fig. 2.3A provides an example of building footprint polygons, associated extracted features, and their separation distances. In addition to estimating the accuracy, omission and commission errors I also estimated an overall Quality Index (Eq. 1), which cumulatively accounts for accurately identified features, commission errors, and omission errors providing a relativized index of agreement ranging from 0 for complete disagreement to 1 for perfect agreement (Heipke et al., 1997).

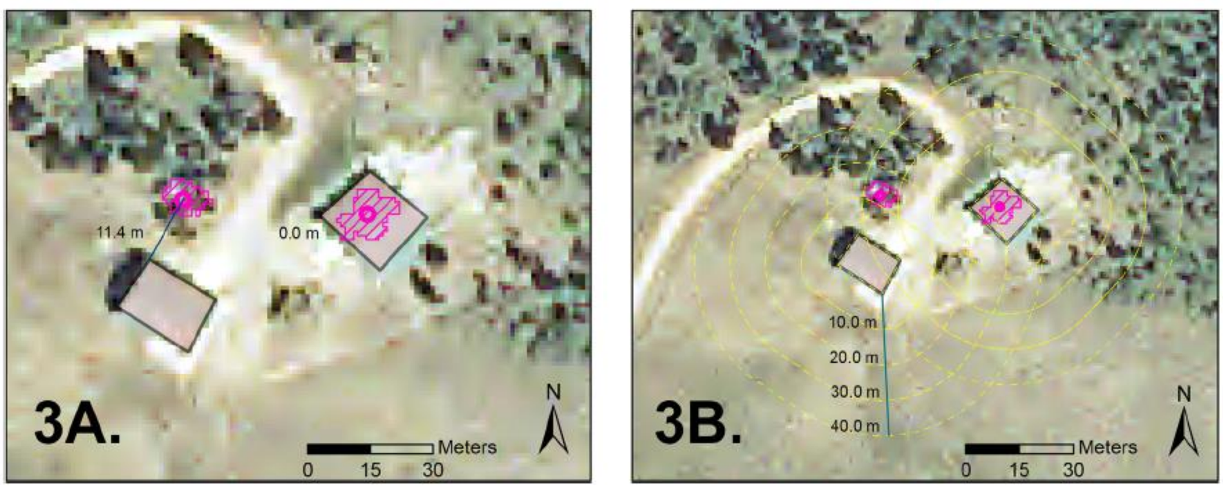

Figure 2.3. (2.3A) Separation distance between the control building footprint (solid polygon), and the extracted feature centroid (circle within hatched polygon used to identify accurately identified features and extraction errors. (2.3B) Buffers around control building footprints (solid polygon) are used to assess agreement with extracted feature centroid (circle within hatched polygon) at different scales.

$$\text{Quality Index} = TP/(TP + FP + FN) \quad (1)$$

For each iteration I calculated accuracy, error (omission and commission), and Quality Index (Fig. 2.4) using a representative 30 m buffer distance because it maintains both high levels of accuracy and contains an appropriate level of detail relative to most fire management applications (Calkin et al., 2011).

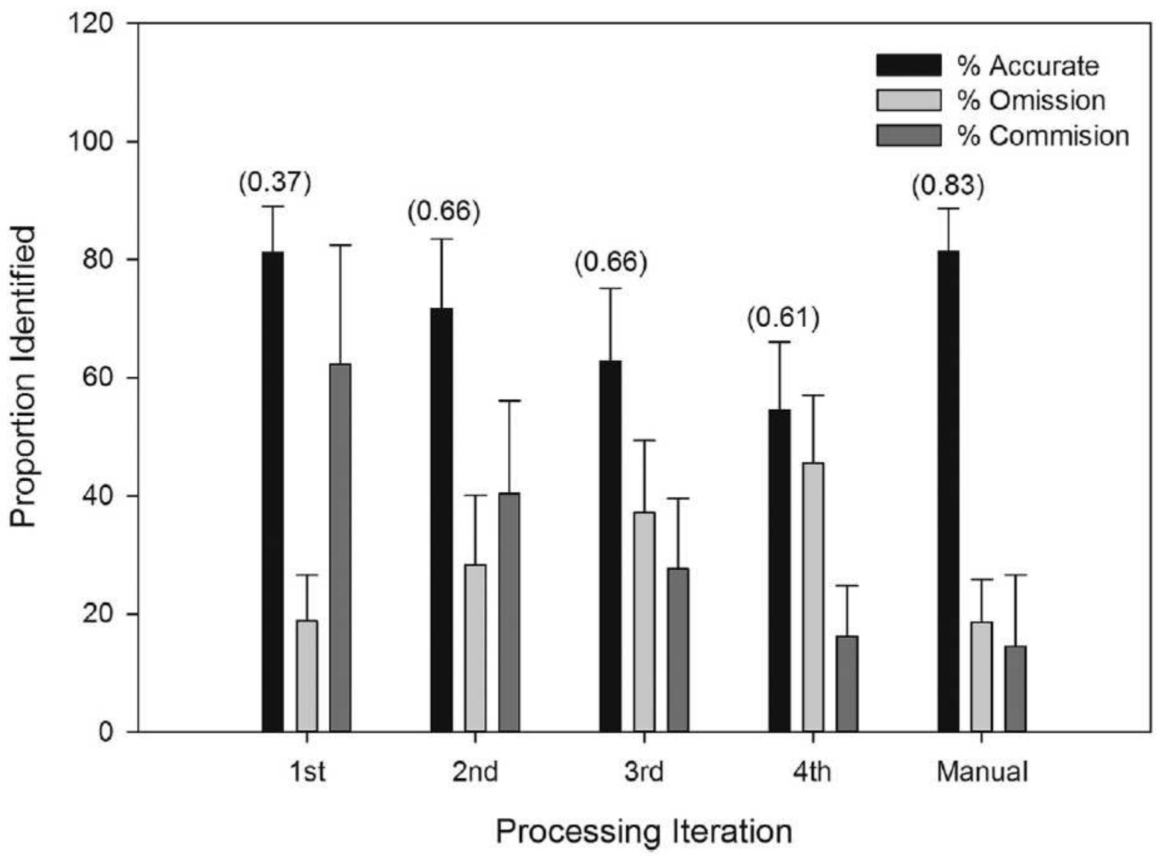

Figure 2.4. Accuracy, omission error, and commission error between control buildings and extracted features during each iteration of the Object Based Image Analysis extraction. The error bars represent the 95th confidence interval between samples, and the composite quality index is shown in parenthesis above the error bars.

After determining which dataset had the highest Quality Index, I examined the effect of different buffer distances (0, 10, 20 30, 40, 60, 80, 100 m) that span a range of suggested precisions in fire management on accuracy and errors (Calkin et al., 2011). This scale of analysis as depicted in Fig. 3B is important because specific applications will have different requirements. For example, an emergency evacuation may need to locate homes to within 50 meters to know where to send emergency service personnel, while a land manager wanting to estimate how many homes would be protected by a community fuel break may only need to locate homes to with 100 meters. Evaluating multiple scales allowed a building to be considered accurately identified using a large buffer distance, but register as an omission error using a smaller buffer distance. In Fig. 3B, the building on the left (with the nearest extracted centroid 11.4 m away) would be considered accurately identified using a 20 meter buffer, but if using a 10 meter buffer, the building would be considered an omitted feature, and the extracted feature (11.4 m away) would then be considered a commission error. The building on the right would be considered accurately identified at all buffer distances. After assessing the influence of buffer distances on extraction accuracy and overall quality, I examined how broad scale environmental factors influenced the extraction.

Lastly, I examined the influence of building size, building density, vegetative properties, and topographic characteristics on extraction accuracy. The effect of building size on accuracy and error was estimated by classifying building sizes into 25 m^2 bins from 0 to 275 m^2 and larger, and then calculating the accuracy for each group using a 30 m buffer distance. To assess the influence of building density, vegetative properties, and topographic characteristics on accuracy I estimated the building density, vegetation type, canopy cover, fuel type, slope, aspect, and elevation, for each of the control building footprints. Local building density was calculated for each extracted feature in the control dataset using a circular 500 m neighborhood. All other variables were sourced from the 2011 National Elevation Database (30 m resolution; Homer et al., 2015) and data from the LANDFIRE Project (Rollins, 2009). The range in accuracies within classes for each environmental characteristic were compared against each other and analyzed for trends and variability.

Finally, I attempted to qualitatively identify the causes of omission and commission errors by randomly sampling 10% of the errors and noting the probable cause of each error. These descriptive error classifications are presented in the discussion along with the other methodological, control data, and imagery related limitations.

2.3 Results

I found that all iterations correctly identified greater than 50% of all buildings using a 30 m buffer distance, with the initial semi-automated iteration achieving the greatest overall accuracy (Fig. 2.4). Although the 1st iteration had the greatest overall accuracy, and accordingly the lowest omission error, this data set also had the highest commission error and a lower overall quality index (0.37). Commission errors decreased with subsequent iterations, while the quality index varied between 0.61 and 0.66 for subsequent iterations (Fig. 2.4). The incorporation of a rapid manual iteration resulted in 81% of all homes being correctly identified, and omission and commission errors of 19 and 15% respectively. The Quality Index was greatest following the inclusion of a manual iteration to 0.83. Suggesting, that the inclusion of a rapid manual iteration results in the best overall performance.

I found that the overall accuracy, and Quality Index were positively related to buffer distance, while both omission and commission errors were negatively related to buffer distance (Fig. 2.5). At the 0 m buffer distance overall accuracy, omission error, commission error and the quality index were 50.1%, 49.9%, 34.1%, and 0.46 respectively. For the largest buffer distance evaluated (100 m), the overall accuracy (95.3%) and quality index (0.96) were the greatest while omission error (4.7%), commission error (3.1%) were the smallest. In addition to increased overall accuracies and quality, I also found decreased variability between the ten randomly selected quadrangles at larger buffer distances.

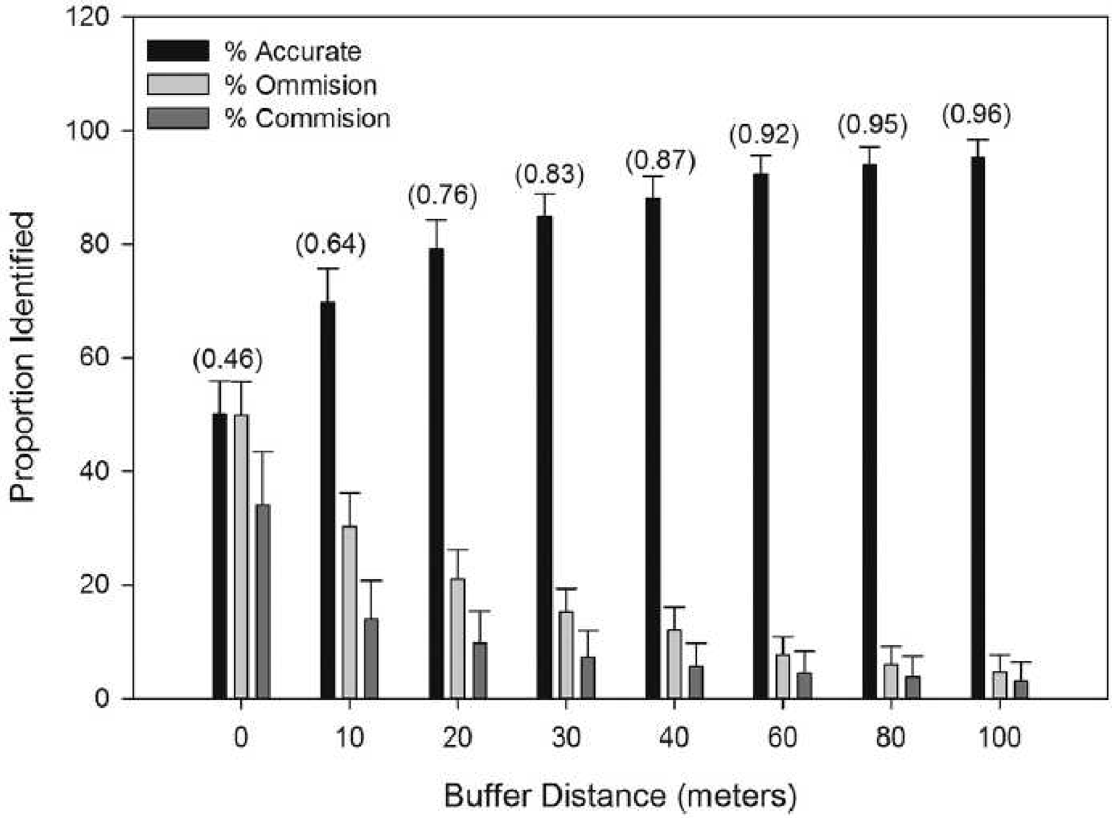

Figure 2.5. Accuracy, omission error, and commission error between control buildings and extracted features produced from the final manual iteration. The error bars represent the 95^{th} confidence interval between samples, and the composite quality index is shown in parenthesis above the error bars.

Our results also indicated that that extraction accuracy varied by building size (Fig. 2.6). In general, overall accuracy was positively related to building size, with the two smallest size classes (less than 50 m^2) having accuracies around 70% and larger buildings (greater than 150 m^2) having accuracies of over 90%. With the exception of canopy cover, which I observed to have reduced our ability to extract buildings, and in turn decreased our accuracy, I found no discernable trends in terms of accuracy, omission and commission errors related to any of the other landscape scale characteristics I tested for including; building density, slope, aspect, elevation, and vegetation type.

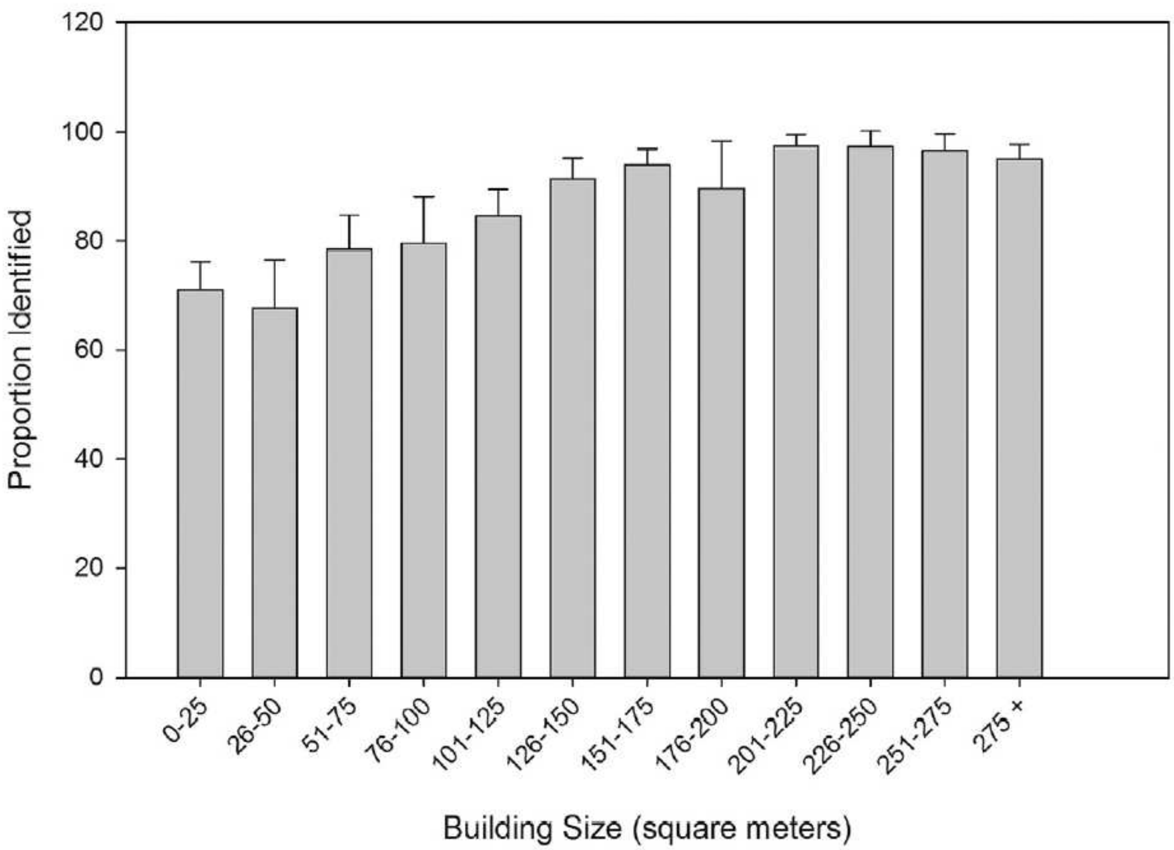

Figure 2.6. Extraction accuracy for different building sizes, classified into $25m^2$ bins, using a representative 30m buffer.

2.4 Discussion

The objective of this study was to assess a semi-automated Object Based Image Analysis (OBIA) approach that utilizes 4-band multispectral National Aerial Image Program (NAIP) imagery for the detection of individual buildings within the WUI in Northern Colorado. I evaluated this approach through comparisons with county maintained building footprint control data and additional analyses of the effects of buffer distance, and the topographic and building characteristics on the accuracy and quality of building extraction. Our results indicated that all iterations correctly extracted at least 50% of all buildings, with a 30 m buffer distance, but that overall quality and accuracy were greater when at least two iterations were included. Our results also indicated that extraction accuracy and quality are dependent upon the selected buffer distance. Although there are no accepted standards for an appropriate buffer distance in WUI mapping, Calkin et al. (2011) suggested that 100 m would be appropriate for most fire management applications. Given this buffer distance, our manual dataset had a Quality Index of 0.96, accurately identified 95% of all buildings, and had omission and commission errors below 6%. These results suggest that the inclusion of a manual iteration results in improved quality and accuracy (Freire et al., 2014). Our efforts also show that for mapping buildings in our WUI study area, the semi-automated process can achieve similar accuracies as reported for traditional digitization efforts (Lowell et al., 2010), but with reduced effort. These findings indicate that the use of an OBIA approach holds promise for developing detailed building-based WUI maps across broad scales in support of fire and emergency service operations and planning.

In addition to assessing the overall accuracy and quality of the OBIA approach I also investigated the causes of omission and commission errors. The causes of these two types of errors are important to understand if building-based maps are to be used in operational planning during wildland fire events as these errors could impact the strategic use of resources as well as tactics and strategies during the event. Visual inspection of omission and commission errors indicate that both the selected buffer distance and the size of the target building influenced the overall errors. In cases where a short buffer distance was chosen, buildings that were in close proximity to accurately extracted features were common among the omission errors I subsampled. The final building extraction also omitted a disproportion- ately high number of small outbuildings and non-residential building, which were sometimes partially obscured by overhanging vegetation. Lowell et al. (2010) also noted the challenge of identifying small buildings obscured by vegetation while digitizing buildings in the WUI. During our final manual iteration, I were I were able to visually locate many of these smaller buildings; however, decreased accuracies should be expected in areas with dense continuous canopy cover. Commission errors were generally associated with the extraction of natural features such as rivers, and rock outcroppings, and features of the built environment such as roads, vehicles, and shadows. Commission errors that were associated with the natural environment were often caught and removed during the first and second semi-automated iterations. However, errors associated with the built environment often persisted through the semi-automated results and were removed during the final manual iteration. Most of the omission and commission errors that remained following the manual iteration were often in close proximity (< 100 m) to accurately extracted buildings. Given that the majority of omission and commission errors occurred within a relatively close proximity to the built environment and other buildings, these errors would likely have little impact on most fire and emergency management applications.

I identified several cases where omission and commission errors were associated with the control data set I used. For example, I identified several omission errors that occurred in partially constructed subdivisions where the control dataset indicated there was a building, but there was no building present in the imagery. Rutzinger et al. (2006) suggested this type of error could be due to temporal scale mismatches inherent in datasets created at different times. While this could be partially mitigated by regularly extracting buildings from the most recently acquired imagery, these errors suggest the potential for decreasing accuracy over time as new buildings are constructed, a temporal limitation inherent in all static geospatial data that represents physical features in dynamic systems. I also found some commission errors resulting from buildings which appeared to have been accurately extracted from the imagery, but were missing from the control dataset. In these cases, it is likely that the county maintained control dataset contained errors and did not fully account for all buildings within its jurisdiction. This could have occurred if a landowner did not apply for a building permit before starting construction, or through a user introduced error while maintaining or updating cadastral data.For any particular fire and emergency management application, it is critical that practitioners clearly identify accuracy and quality requirements, the appropriate buffer distance, and understand the potential implications of omission and commission errors to ensure that any building-based WUI map is appropriate for their specific need. For example, building-based WUI maps that are to be used for community evacuation planning might be more accepting of omitting smaller nonresidential buildings (Lowell et al., 2010), but for other applications this might have important implications. Recent research has indicated that small outbuildings within the home ignition zone of larger residential buildings can act as ignition sources (Cohen, 2000; Maranghides et al., 2015). Depending on the specific application, this study indicates that OBIA approaches hold potential to map individual buildings in similar WUI environments at scales appropriate for many wildfire management and planning related applications.

Although our OBIA approach can extract individual buildings within the WUI with a high level of accuracy, further research could identify additional ways to improve overall accuracy and quality while reducing the need for the manual iteration. As suggested by Blaschke (2010), these improvements might be achieved through advances in different components of the OBIA process such as improvements to image quality, image segmentation, and spectra discrimination. Higher resolution imagery such as 0.5 m NAIP, and 8-band World View II or III imagery with 0.4–2.0 m resolution and additional spectral bands is becoming more widely available and could present a first step in improving OBIA segmentation for differentiating objects on the landscape. Combining advances in image quality with more advanced image segmentation algorithms, such as artificial neural networks, fuzzy set methods, and support vector machines hold potential to further improve OBIA discrimination and the resulting data accuracy (Blaschke, 2010; Hay and Castilla, 2008). Though this study utilized ArcGIS and Feature Analyst software, open source GIS platforms, and other remote sensing product with similar or improved resolution and spectral discrimination may be able to produce similar results. Going beyond identifying the location of buildings centroids, future work may be needed to assess the ability of OBIA methods to assess the degree of overlap between the extracted polygon features and control building footprints, or identify other objects in or characteristics of the WUI environment. For example, OBIA also holds the potential to accurately characterize fine scale environmental features that contribute to the wildfire hazard such as fuel heterogeneity around homes; combining bands into normalized Difference Vegetation Index (NDVI) holds potential to more effectively identify vegetation. As improvements to image resolution and processing ability facilitate the widespread use of OBIA for extraction of different types of features, accuracy assessments should continue to incorporate appropriate object based evaluations that differ from traditional pixel based sampling strategies (Radoux et al., 2008).

Further, additional research should be done evaluating accuracy, error and overall quality in different settings and locations, utilizing different software, imagery, and algorithms, using solely automated extractions without manual input, different satellites, and imagery of varying resolutions, the effect of different image band combinations, and the relative contributions of unique bands. Additionally, alternative technologies such as LiDAR, with its ability to penetrate forest canopy, may be able to overcome some limitations of OBIA approaches, and would aid in building identification in areas with heavy canopy cover. Integrating OBIA produced datasets of building locations with LiDAR, cadastral, or other environmental data such as parcels, roads, vegetation, or fuel hazard assessments could further improve both data quality and utility for community planning or other wildfire management applications, leading to a more comprehensive understanding of the spatial arrangement between buildings and their surroundings in coupled social environmental systems.

2.4_Conclusion

Through our evaluation I demonstrate that OBIA can successfully extract buildings from diverse WUI landscapes while achieving high accuracies at buffer distances appropriate for most fire management application. The approach overcomes the costly and labor intensive nature associated with building-based digitization, as well as the lack of detail and incomplete building counts associated with some zonal based WUI mapping efforts. Our study which has evaluated an OBIA approach that provides some of the first applications of OBIA in the Wildland-Urban Interface that both extract highly detailed building locations, and demonstrates applicability for wildfire management applications. Though the evaluation of the OBIA approach has identified several limitations in need of future study, it still holds potential for contributing to a more complete assessment of hazards, exposures, and vulnerabilities in the WUI when detailed data is unavailable. Leveraging OBIA produced dataset of building locations with other landscape scale datasets can deepen our understanding of the specific pattern of development as well as its implications for wildland fire exposure, which could be used to inform land use planning, hazard assessment, and wildfire management.

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CHAPTER 3: BUILDING LOSS IN WILDFIRE DISASTERS IN RELATION TO CORE COMPONENTS OF THE WILDLAND-URBAN INTERFACE DEFINITION

3.1 Introduction

The rapid development and expansion of the wildland-urban interface (WUI) in areas with highly flammable vegetation has significantly increased the potential for building loss during wildland fires (Theobald and Romme 2007; Platt et al. 2011, Syphard et al. 2013, Hass et al. 2014, Radeloff et al. 2018). Recent wildfire losses in the United States, Australia, and Spain highlight the global nature of this phenomenon (Gill et al. 2013). Globally, wildfires have occurred in wildland-urban interface areas, rural communities, suburban communities, and have even spread into urban areas that were considered low risk (Syphard and Keeley 2019). In the United States, there are currently an estimated 1.7 million residences in the WUI and in other areas that are at high or extreme risk of wildfire (Corelogic 2019). This potential for wildfire-caused home loss, with its often-devastating impacts for communities, has been described as the WUI problem (Cohen 2008).

Wildfires that cause substantial building loss are known as WUI disasters (Cohen 2008). Many WUI disasters follow the same sequence of events (Figure 1). The presence of large numbers of threatened homes relative to firefighting resources reduces the efficacy of fire suppression, which leads to more home loss (Cohen 2008, Calkin et al. 2014). Increased fuel loading in fire-adapted ecosystems due to historical fire suppression practices (Cohen 2008) and increased residential development due to an expanding WUI (Hammer et al. 2009) both exacerbate the WUI problem and increase the potential for future home loss and WUI disasters. Although the exact number of WUI disasters is unknown, these events likely represent only a small subset of the total number of wildfires that ignite annually (Short 2014). The proposed solutions to address the WUI problem and reduce WUI disasters focus on reducing the likelihood of home loss in WUI areas affected by wildfires (Calkin et al. 2014; Smith et al. 2016). Understanding when and where WUI disasters are likely to occur and how community characteristics influence their impacts are both critical steps for reducing wildfire risk (Paveglio et al. 2014). Buildings are the fundamental unit of the WUI problem (Cohen 2008, Calkin et al 2014), and accordingly, land managers tasked with reducing wildfire risk require accurate maps of the WUI and the homes within to understand where loss is likely to occur and estimate the number of buildings at risk (Bar Massada et al. 2013). Accurate WUI maps can be used by managers and researchers to identify at-risk assets, inform quantitative wildfire risk assessments, prioritize strategic planning efforts, and implement wildfire mitigation efforts (Jakes et al. 2007; Calkin et al. 2010; Scott et al. 2013).

WUI mapping efforts in the US are commonly based upon the US Federal Register definition of the WUI communities (Federal Registrar 2001), which suggests that the WUI includes areas where buildings are within or adjacent to wildland vegetation. It further differentiates two subtypes within the WUI based on the housing density and home proximity to wildland vegetation: (1) intermix, where housing units are dispersed among wildland vegetation, and (2) interface, where housing units are adjacent to wildland vegetation. Several different WUI maps have operationalized this definition (Wilmer and Aplet 2005; Theobald and Romme 2007; Martinuzi et al. 2015; Radeloff et al. 2005, 2018). The number of at-risk housing units present and the total extent of the WUI estimated by each map are sensitive to the data inputs, scales of analysis, and thresholds selected by map developers (Stewart et al. 2007; Radeloff et al. 2005, Bar-Massada et al. 2013). The SILVIS WUI maps made available by the University of Wisconsin SILVIS Lab have emerged as the most widely used WUI maps in the United States

(Radeloff et al. 2005, 2018). For example, a presidential executive order in 2016 directed federal wildfire mitigation and planning efforts to use SILVIS WUI maps or their equivalent when determining wildfire risk (Federal Register 2016). SILVIS WUI maps rely on Census block housing units and wildland vegetation extents extracted from land cover data to classify WUI areas and differentiate WUI subtypes based on three specific components: housing unit density, vegetation cover, and proximity to large patches of contiguous wildland vegetation (Radeloff et al. 2005). While managers and researchers often use the SILVIS WUI map to estimate the number of at-risk housing units and communities at risk in the WUI, Census-based maps are often insufficient for fine-scale applications such as wildfire incident response maps or neighborhood-scale planning. Managers have questioned the utility of SILVIS WUI maps for wildfire planning and response due to the relatively coarse spatial scale of Census blocks, and because they do not explicitly consider fire behavior (Calkin et al. 2011, Bar-Massada et al. 2013).

Recently, development is increasingly mapped at finer resolutions, often at the scale of individual building locations. Using individual building locations addresses a fundamental limitation of Census-based WUI maps: the uncertainty of housing unit locations within Census blocks, which vary in spatial resolution. Fine resolution building data, or point-based data, is essential for identifying at-risk buildings because fire behavior, fire response, and other critical factors can vary at fine spatial scales not well-captured by Census blocks (Theobald and Romme 2007, Miller and Ager 2013). While at one time, fine-scale data was only available for limited extents (Bar Massada et al. 2013), recent developments in remote sensing technology have allowed new approaches to proliferate (Blaschke 2010). Point-based building location data is now available across larger extents through commercial vendors and open data archives (Leyk and Uhl, 2018 Microsoft, 2018). In addition to facilitating more detailed analysis, fine-scale building location data can be scaled up and summarized for Census blocks or any other political unit. For example, at one end of the spectrum, at-risk building locations can be used to inform structure protection plans during wildfire incidents, or to help fire departments plan neighborhood evacuations. On the other end, the federal government can use the same at-risk building location data summarized at the county or state level to conduct regional risk assessments, prioritize fire response resources, or adjust regional funding allocations (Calkin et al. 2010; Bar Massada et al. 2013). With these advances in technology a single dataset of at-risk buildings, the fundamental unit of the WUI problem, can be used in various applications and provide consistency across multiple scales (Calkin et al. 2014; Bar-Massada et al. 2013).

In order to create useful WUI maps, point-based building location data must be paired with point-based WUI mapping frameworks (Bar-Masada et al. 2013). Point-based WUI maps should calculate WUI components (housing unit density, vegetation cover, and proximity to large patches of contiguous wildland vegetation) at appropriate scales and must be consistent with existing WUI mapping products to avoid confusion (Stewart et al. 2007, Bar-Massada et al. 2013 Alexandre 2015, Syphard et al. 2016). Further, and regardless of whether WUI maps use individual building locations or Census blocks as inputs, WUI maps seeking to identify at-risk buildings should be validated against observed patterns of loss (Stewart et al. 2007); such validation is critical for assessing the accuracy of WUI maps. Validating maps using observed patterns of loss can advance our understanding of where home loss occurs and how we spatially conceptualize the WUI (Calkin et al. 2011; Bar-Massada et al. 2013, Caggiano et al. 2015; Scott et al. 2015). To date, and despite a call for this need, there has been no systematic assessment of how well either point-based or Census-based WUI maps capture the potential for home loss (Stewart et al. 2009; Scott et al. 2015).

Related to this need are several critical questions: How many homes have been burned in WUI disasters? Where are at-risk homes, buildings, and other assets in the WUI located? And lastly, how well do existing Census-based WUI mapping methods and emerging point-based WUI mapping methods capture patterns of building loss observed in wildfires? Pursuant to these questions, the research presented herein sought to fill this knowledge gap to advance our understanding of the WUI problem as a spatial phenomenon. This study seeks to (1) document the occurrence of WUI disasters, (2) assess building loss in relation to the three core components of the WUI, as defined by the Federal registrar (housing unit density, vegetation cover, and proximity to large patches of contiguous wildland vegetation), each calculated at multiple scales, i.e., WUI component-scale combinations, and (3) compare how well SILVIS WUI maps and point-based WUI maps capture patterns of loss observed in WUI disasters.

3.2 Methods and Data Acquisition

Both spatial and non-spatial datasets were used in several complementary analyses to identify WUI disasters and examine patterns of building loss within those disasters. Herein is a brief summary of methods, while a more detailed description of data sources and methods for each specific analysis is provided below. First, I queried the National Wildfire Coordinating Group Wildfire Incident Status Summary Report, referred to as ICS-209 (National Wildfire Coordinating Group, 2020), to identify individual wildfires and associated building loss. WUI disasters were identified by including only those wildfires that reported more than fifty destroyed buildings, similar to the thresholds used by others (Cohen 2008, Calkin 2014). I then acquired fire perimeters to spatially map each WUI disaster. Next, I examined how well SILVIS WUI maps and point-based WUI maps captured patterns of building loss. This involved utilizing multiple geospatial datasets of building location points affected by and adjacent to WUI disasters, which became the foundation for subsequent analysis. Using spatial overlays, each building location was attributed with fire name, burn status (burned or unburned), Census block housing unit density, and SILVIS WUI type (Radellof et al. 2005, 2018). After calculating building density values, and using the National Land Cover Database (NLCD; Yang et al. 2018) to calculate vegetation cover percent and proximity to vegetation distances, a point-based WUI type was determined for each building location based in WUI component values. Building density, vegetation cover percent, and distance to vegetation were each calculated at multiple scales following the framework proposed by Bar-Massada et al. (2013). Figure 3.1 provides an overview of the spatial datasets used in this analysis using building locations within and adjacent to the 2012 Waldo Canyon Fire as an example.

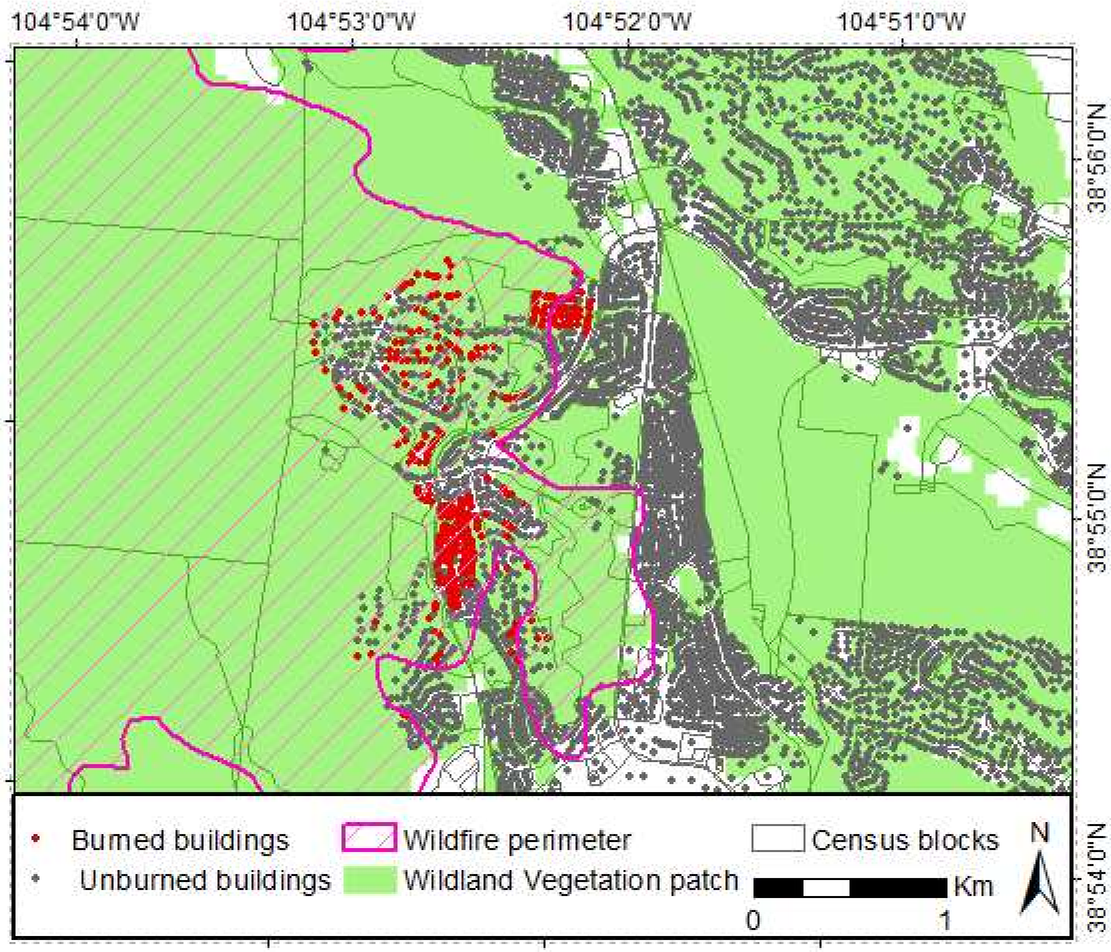


Figure 3.1. An example of the spatial datasets used in our analysis, including fire perimeters, wildland vegetation, SILVIS WUI, Census Blocks, and building locations using the 2012 Waldo Canyon Fire in Colorado. Each building location was assigned burn status and attributed with information from layers derived from the above data, including building density, percent vegetation cover, and distance to vegetation.

3.2.1 Identifying WUI disasters using the ICS-209

I started the analysis by querying annual ICS-209 databases from 2000-2018 to identify wildfires and associated building loss for each. Individual ICS-209 reports capture daily incident-specific information on incident type, fire size, percent containment, significant events, resource needs, and the cumulative number of threatened and destroyed structures (National Wildfire Coordinating Group 2020). From 2000-2014 the ICS-209 reported total structures destroyed, but in 2015, ICS-209 began to differentiate structure type (primary residential, outbuilding, commercial), and created an additional category for damaged buildings. I used total structures destroyed from 2000-2014, and single-family residential structures destroyed from 2015-2019 as a proxy for building loss in the first analysis. This change in data reporting introduces a small bias, the majority of structure loss reported in earlier ICS-209 reports were single-family residential structures which aligns well with the spatial building location datasets described below. Wildfires identified in the ICS-209 were then sorted based on the magnitude of building loss using a threshold of 50 destroyed buildings. This threshold focused analysis on the most destructive wildfires and is generally consistent with, yet slightly lower than, the thresholds used by others to identify WUI disasters (Cohen 2008, Calkin et al. 2014). Use of a slightly lower threshold helps account for potential errors in the ICS-209, including misreported structure loss (Katuwal et al. 2017).

The final fire perimeter for each WUI disaster identified in the ICS-209 database was identified using data from either the Monitoring Trends in Burn Severity (MTBS) (Eidenshink et al. 2007), or the Geospatial Multi-Agency Coordination program (GeoMAC) (Walters et al. 2011). Because perimeters for the 2008 Parker Road Fire, the 2013 Carolina Forest Condo Fire, the 2016 Glendale fire, the 2017 NEU Wind Complex, and the 2017 County Road 630 E were not included in these databases, they were removed from all subsequent spatial analysis.

3.2.2 Building location data

I acquired building location data for 70 of the 91 WUI disasters identified in the ICS-209 by querying and merging four distinct point-based building location datasets. First, building location data was acquired for 44 fires from a spatial dataset of burned and unburned buildings created by visually digitizing buildings and evaluating building burn status from high-resolution pre- and post-fire Google Earth imagery from 2000 through 2013, produced by Alexandre et al. (2016). Second, building location data was acquired for 15 fires from the California Department of Forestry and Fire Protection (CalFire) as part of their Damage Inspection Report Program (DINS) (CalFire 2020). This dataset is produced from door to door damage inspections collected by CalFire staff with GPS-enabled tablets during and after wildfire incidents but is only available for a limited set of recent fires in California starting in 2013. The CalFire data collection process, data attributes, and limitations are further described in Syphard and Keeley (2019). To our knowledge, no other state maintains a similar dataset. Third, building location data was acquired for 11 fires identified in the ICS-209 analysis that were missing building location data from other sources. For these fires, missing effected buildings were digitized and burn status (burned or unburned) was determined using pre- and post-fire Google Earth imagery using similar methods as described in Alexandre et al. (2016). The fourth building location dataset used in this analysis was the Microsoft structure footprint dataset (2018). This dataset allowed us to augment the CalFire data by identifying missing building locations within fire perimeters. It also allowed us to identify adjacent buildings within 2400 meters of each fire perimeter to reduce edge effects when calculating building density. The Microsoft dataset was generated using the RefineNet convolutional neural network for semantic segmentation followed by a polygonization process to identify building footprints form high-resolution satellite images collected roughly around 2015 (Lin et al. 2017; Microsoft 2018). While the exact build date of a specific structure is challenging to determine from the Microsoft data, the building locations have a reported accuracy of 99.3% accuracy with respective rates of commission and omission of 0.7% and 6.5%, when assessed against the source imagery (Microsoft 2018). For this study, the centroid locations of the footprint polygons were used to match the other building datasets.

For the remaining 21 WUI disasters, building location data was not obtained because of limited pre- and post-fire image availability (6 wildfires), or excluded due to insufficient data (15 wildfires). Fires missing imagery included older fires such as the 2002 Hayman in Colorado and the 2004 Bear Fire in California (which lacked high-resolution imagery at the time of the fire), and recent fires such as the 2018 Roosevelt Fire in Wyoming, and the 2018 Spring Creek fire in Colorado (which lacked publicly available post-fire imagery as of January 1st, 2020). Other fires such as the 2003 Padua Fire and the 2007 Ham Lake Fire were excluded due to insufficient building location data. For example, the ICS-209 reported the 2003 Padua Fire destroyed 60 buildings, but the corresponding spatial dataset of building locations only included 22 burned building location points. Fires where ICS-209 reported greater than 50 burned buildings, but the spatial data had less than 50 burned buildings, were included in the initial ICS-209 analysis but excluded from subsequent building location analyses evaluating Census-based and point-based WUI map accuracy. Fires with missing or insufficient building location data occurred in states that were generally well represented by other fires, allowing us to assume that the missing fires will not bias our results.

3.2.3 SILVIS WUI map accuracy capturing building loss

To assess the proportion of home loss associated with the SILVIS WUI categories, each building location point was assigned its SILVIS WUI type and Census block based housing unit density (Radeloff et al. 2018). For each WUI disaster, I calculated the total number of exposed buildings, the total number of burned buildings, the proportion of building loss, and the total number of adjacent buildings (within 2400 meters) in each SILVIS WUI type. The total number of buildings and proportion of loss between WUI and non-WUI buildings, as well as among the WUI types (interface, intermix, low density vegetated, high density non-vegetated), were assessed for both individual fires and the dataset as a whole.

3.2.4 Determining WUI type for point-based data

Values for each of the three WUI components (housing unit density, vegetation cover, and proximity to large patches of contiguous wildland vegetation) were calculated at multiple scales for each building location. This follows the framework proposed by Bar-Massada et al. (2013), herein we refer to these as WUI component-scale combinations. For example, building density was calculated using the density of building locations measured at different neighborhood sizes ranging from 100 to 2,400 m in 100-m increments. Similarly, percent vegetation cover was calculated after reclassifying the 2011 NLCD data (Yang et al. 2018) to delineate wildland vegetation using forest, shrub/scrub, grassland, wetland, and open space categories. Percent of vegetation cover surrounding each building was calculated using focal areas in 100-m increments from 100 to 2,400 m. To identify proximity to contiguous patches of wildland vegetation, a single binary morphology shrink and expand algorithm (ESRI, 2011) was applied to the national NLCD wildland vegetation data. This removed isolated pixels of vegetation and generalized edges. The resulting data were converted to polygons from which patch size was measured. Five different layers of wildland vegetation were created with minimum patch sizes of 0.2, 0.4, 1.25, 2.50, and 5.0 km^2, and then the distance to vegetation was measured for each building location using the approach outlined by Chen and McAneney (2004).

I used logistic regression to assess the relationship between building burn status and WUI component at different scales after first conducting indicator kriging with semivariogram analysis to determine the distance at which burn status was correlated between adjacent building locations (Solow 1986; Curran 1988). This resulted in correlative models, whose fit was then assessed using the area under the curve (AUC) for each receiver operating characteristic plot (Fawcett 2006) and p-values to assess predictor significance. WUI component- scale models and AUC results were used to determine which scale had the highest predictive performance for each WUI component. Then the study employed and tested a multivariate logistic regression using the most predictive scale for each of the three WUI components to determine if using all three components increased our ability to predict building loss as compared to the individual components.

Results from the best performing WUI component-scale combinations were also used in a heuristic approach by visualizing relationships between building loss and WUI components using histograms and cumulative distribution functions. The study assessed how building loss was distributed across the range of values for each WUI component (building density, percentage of vegetation cover, and proximity to wildland vegetation). The study employed the framework presented by Bar-Massada et al. (2013) to determine the point-based WUI type for each building location, but instead of calculating all three WUI components at a single scale, it calculated building density, vegetation cover, and distance to vegetation at the most predictive scale for each component. Finally, the study assessed how well the point-based WUI map captures the pattern of loss in WUI and non-WUI categories compared to the results from the Census-based SILVIS WUI mapping approach.

3.3 Results

3.3.1 ICS-209 WUI disasters

Between 2000 and 2018, the ICS-209 data reported 2,777 wildfires that burned at least one building, and cumulatively burned 56,783 buildings (Table 3.1). The study identified 91 WUI disasters, fires that burned more than 50 buildings, which were responsible for 83% of all building loss reported in the ICS-209 database. Geographically, the WUI disasters were distributed primarily across the western United States (Figure 3.2). Over half of the WUI disasters occurred in California (51%), followed by Texas (10%), Colorado (7%), and New Mexico (6%). On average, there were five WUI disasters and 2,433 buildings lost per year (Figure 3.3); however, there appears to be an increase in the number of WUI disasters per year through time.

Table 3.1. The number and percent of wildfires and building loss reported in the Incident Status Summary Reports (ICS -209) between 2000 and 2018.

Buildings lost per wildfire	Number of wildfires		Number of buildings lost	
	Total	*%*	*Total*	*%*
>1000	9	0.3	31,321	55.2
400-1000	8	0.3	3,837	6.8
101-400	46	1.7	8,741	15.4
51 - 100	45	1.6	2,685	4.7
1 - 50	2,669	96.1	10,199	18.0
Total	**2,777**		**56,783**	

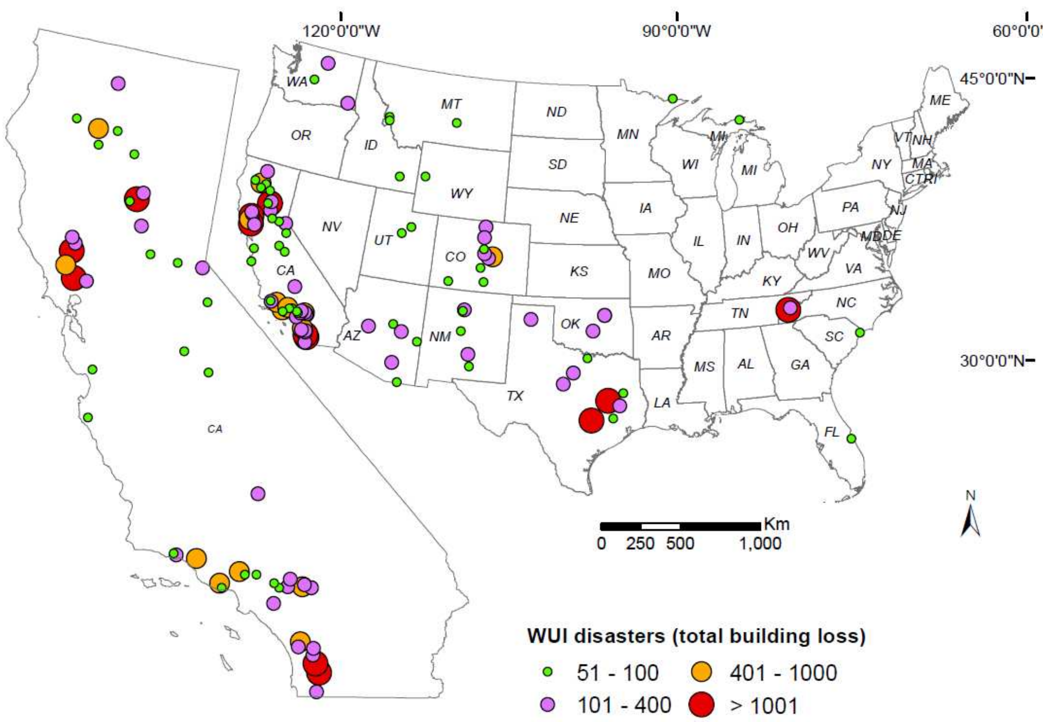
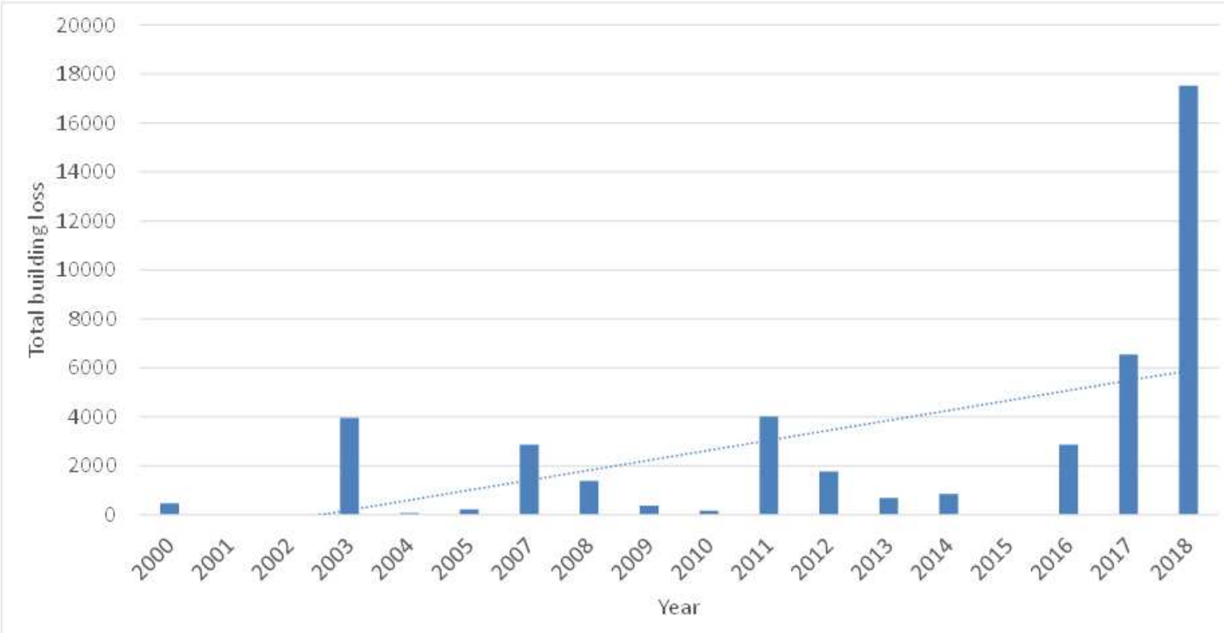
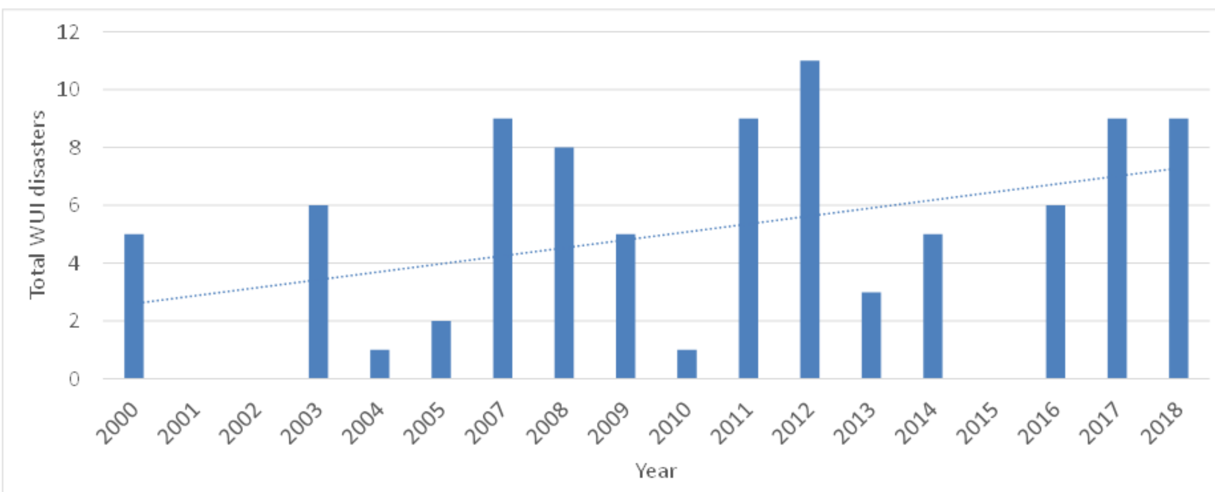


Figure 3.2 The spatial distribution and magnitude of wildland-urban interface (WUI) disasters in the continental US from 2000-2018.



(3A)



(3B)

Figure 3.3 (3.3A) WUI disaster annual building loss from 2000 to 2018 in the United States, and (3.3B) total WUI disasters from 2000 to 2018 in the United States.

3.3.2 Building loss by SILVIS WUI type

The composite building location dataset created by merging the four point-based building location datasets contained 987,430 total buildings within and adjacent to fire perimeters. This included 135,416 buildings that were affected by wildfires and within fire perimeters, of which 53,786 were burned. The minimum, median, and maximum number of burned buildings per fire were 51, 194, and 18,831, respectively. California's 2018 Camp Fire was responsible for 35% of the total building loss in our dataset. The SILVIS WUI maps captured 86% of burned buildings in areas classified as WUI interface (16,009 buildings) and intermix (30,441 buildings) (Table 3.2). The remaining 14% of burned buildings were located in areas classified as non-WUI, either areas with vegetation and low building density, or areas with no vegetation and medium or high building density. 12% of burned buildings were in areas where building densities were less than 6.17 buildings per km^2, the threshold used to distinguish WUI from non-WUI in the SILVIS WUI map. The percentage of home loss varied from 20% to 48% in non-WUI areas and 36% to 45% for interface and intermix areas. Non-WUI areas with no vegetation and medium to high building density experienced the highest rates of loss at 48%.

There was considerable variability among individual WUI disasters in terms of how home loss was distributed between SILVIS WUI categories (Figure 3.4). Figure 3.4 displays building loss in WUI and non-WUI land use types for the 30 most destructive WUI disasters. In total, 42 of 70 WUI disasters experienced 80% or more of their losses in WUI interface or intermix categories, but 12 WUI disasters had more than 50% of their loss occur in non-WUI areas. 9% of the WUI disasters in this study resulted in losses in high-density non-WUI areas, while 90% experienced losses in low-density non-WUI areas. Our results show that non-WUI building loss occurs both in areas with wildland vegetation and very low housing density, as well as in areas with medium or high housing density but without wildland vegetation.

Table 3.2: Total number of buildings and burned buildings by SILVIS WUI type for wildland-urban interface (WUI) disasters from 2000 to 2018 calculated using the SILVIS Wildland-Urban Interface categories.

Wildland-Urban Interface Land Use Categories			Total affected buildings (%)	Burned affected buildings (%)	Affected building loss rate (%)	Total buildings adjacent to wildfires (<2,400 m)
WUI		**Sum:**	**113,083**	**46,450**		**779,052**
			84%	***86%***	***41%***	***79%***
	Interface		44,913	16,009		*553,847*
			33%	*30%*	*36%*	*56%*
	Intermix		68,170	30,441		*225,205*
			50%	*56%*	*45%*	*23%*
Non-WUI		**Sum:**	**22,333**	**7,336**		**208,378**
			17%	***14%***	***33%***	***21%***
	Vegetation & no housing		4,089	819		*12,532*
			3%	*2%*	*20%*	*1%*
	Vegetation & very low housing density		12,107	3,880		*39,009*
			9%	*7%*	*32%*	*4%*
	No vegetation & low and very low housing density		2,719	986		27,347
			2%	*2%*	*36%*	*3%*
	No vegetation & medium and high housing density		3,418	1,651		129,490
			3%	*3%*	*48%*	*13%*
		Total:	**135,416**	**53,786**		**987,430**

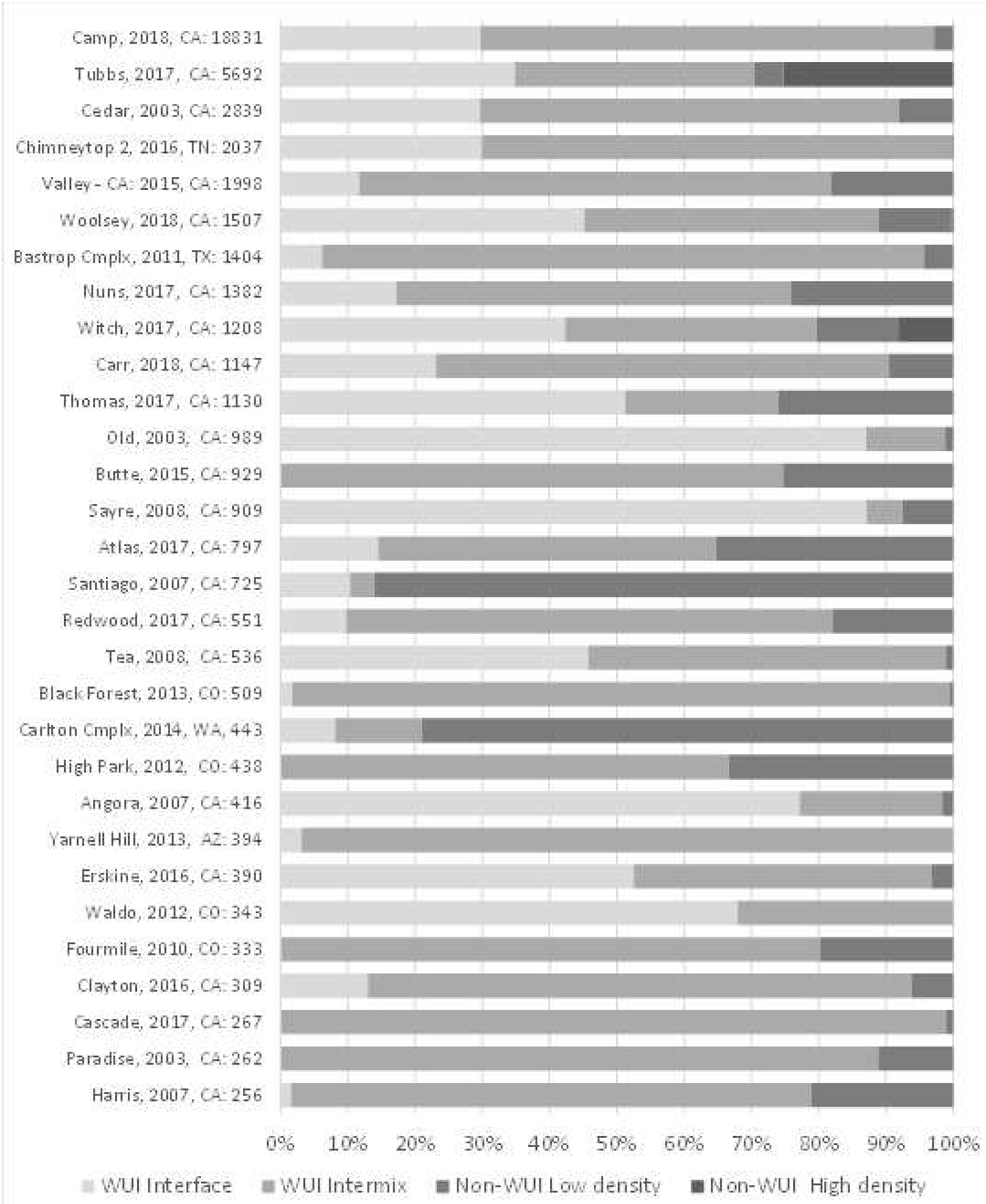


Figure 3.4. Percent of building loss in wildland-urban interface (WUI) and non-WUI land use types for the 30 most destructive WUI disasters. Data is sorted by most to least destructive, with fire name, year, state, and total building loss.

3.3.3 Building loss by WUI component

Burn status was not well correlated between neighboring buildings at distances greater than 1 meter. Results from indicator kriging and semivariogram analysis documented sample independence between point-based building locations, with a range, sill, and nugget of <0.01m, 0.002, and 0.14, respectively. Logistic regression results indicate that home loss was most correlated with building density when calculated at 1,000 m, vegetation cover percent when calculated at 100 m, and distance from vegetation when calculated at a minimum patch size of 2.5 km^2. These best-performing WUI component scale combinations had AUC and P-values of 0.613 and <0.005, 0.547 and <0.005, and 0.547 and <0.005, respectively. Low AUC results suggest poor model fit for individual WUI component scale combinations. Building density AUC values tended to increase with the neighborhood size used up to 1,000 meters, and then decreased at larger neighborhood sizes. Vegetation cover AUC values were highest at 100 m and declined with increasing neighborhood size. The relationship between building loss and distance to wildland vegetation patches calculated using multiple patch sizes were similar to one another, with the 2.5 km^2 patch size having the highest AUC value. A multivariate logistic regression using the three best performing WUI component-scale combinations improved model performance (AUC= 0.65) and was also significant (p-value < 0.00001).

A visual analysis of histograms and cumulative frequency distributions of building loss and WUI component values provide further insight. Our results indicate that building loss during WUI disasters occurs across a wide range of building densities from 0.3 to 960 buildings per km^2, a wide range of vegetation cover percentages from 0 to 100, and a wide range of distances from vegetation from 0 to 843 m. Despite loss occurring across a wide range of each WUI component, the majority of building loss occurred in areas with low building density, high vegetation cover, and within close proximity to large patches of wildland vegetation (Figure 3.5). Although all WUI disasters experienced building loss at low densities, <100 buildings/km^2, only 2.7% of burned buildings occurred at densities <6.17 buildings per km^2 (the housing density threshold used to differentiate WUI from non-WUI areas in the Census-based SILVIS WUI maps). While only nine WUI disasters experienced building loss at densities greater than 500 buildings/km^2, these disasters accounted for 20.5 percent of all building loss. Ten percent of burned buildings occurred in areas with less than 25% vegetation cover. In comparison, 80% of building loss occurred in areas with 50% or more vegetation cover, the threshold SILVIS WUI uses to distinguish WUI-Interface from WUI-Intermix. Fourteen fires experienced building loss in areas with less than 25% of vegetation cover. Building loss occurred across a range of distances from wildland vegetation. Eighty percent of all burned buildings were located within wildland vegetation (0 m distance), and 95% of burned buildings occurred within 100 m. Seven WUI disasters resulted in building loss at distances greater than 300 m from wildland vegetation and only California's 2017 Tubbs Fire observed building loss further than 500 m from large patches of wildland vegetation.

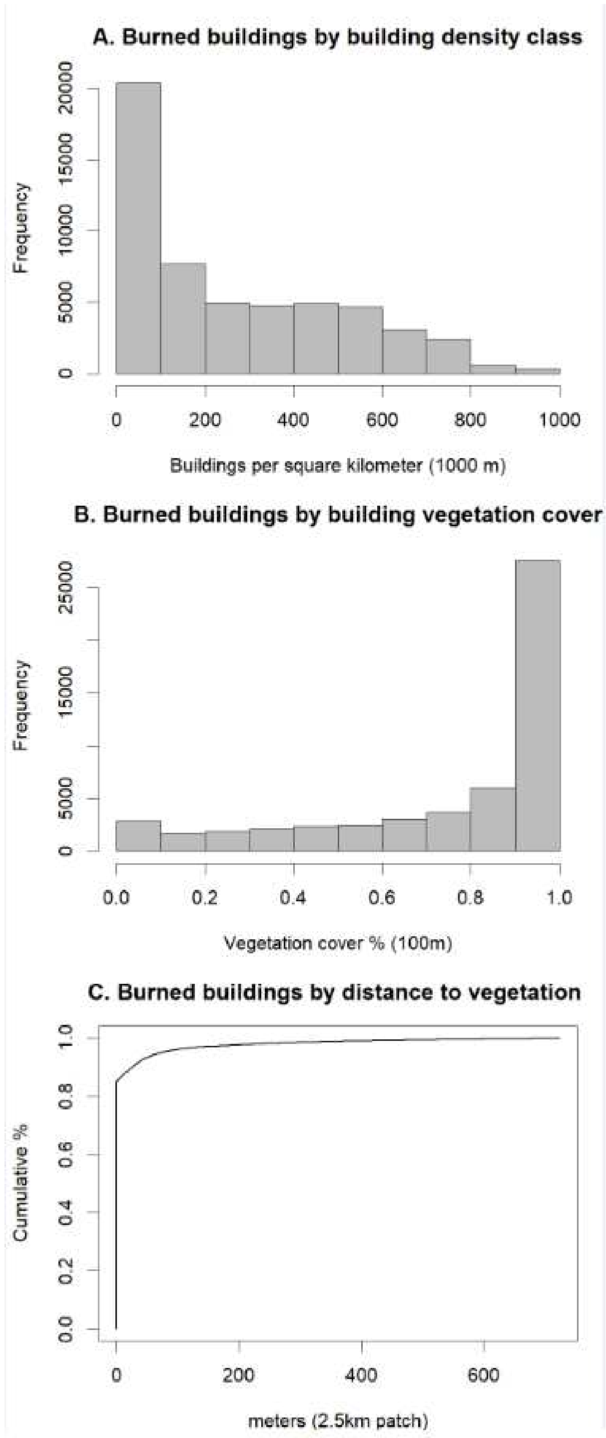


Figure 3.5. Building loss by WUI components (3.5a) histogram of building density calculated with a 1,000-meter neighborhood size, (3.5b) histogram of vegetation cover within 100 m, and (3.5c) cumulative distribution of building loss by distance to 2.5 km^2 or larger patches of wildland vegetation.

3.3.4 Building loss by point-based WUI type

Each building's point-based WUI type was determined by using the WUI component values from the previous analysis. Point-based WUI maps captured 97% of burned buildings in areas classified as either WUI interface (20%) or WUI intermix (77%) (Table 3.3). The remaining 3% of burned buildings were located in areas classified as non-WUI, primarily in areas with vegetation and low building density. Using the 1,000 m neighborhood size to calculate building density resulted in only 3% percent of burned buildings in areas where building densities were less than 6.17 buildings per km^2, the threshold used to distinguish WUI from non-WUI in the SILVIS WUI map. The percentage of home loss for WUI and non-WUI categories varied from 31% to 43% percent in non-WUI areas and 36% to 45% for interface and intermix areas. WUI intermix areas experienced the highest rates of loss at 43%.

Table 3.3. Total buildings and building loss by wildland-urban interface (WUI) type created using a point-based WUI mapping method and the best performing WUI component and scales, Building density and percent vegetation cover were measured in 1000 m and 100 m neighborhoods, respectively, and distance to wildland vegetation was measured using a 300 acre minimum patch size and maximum distance of 850 m.

Wildland-Urban Interface Land Use Categories			Total affected buildings	Burned affected buildings	Affected building loss rate	Total buildings adjacent to wildfires (<2,400 m)
			(%)	*(%)*	*(%)*	
WUI		**Sum:**	**130,636**	**52,307**		**907,923**
			96%	***97%***	***40%***	***92%***
	Interface		32,727	10,815		514,241
			24%	*20%*	*33*	52%
	Intermix		97,909	41,492		393,682
			72%	*77%*	*43%*	*40%*
Non-WUI		**Sum:**	**4,780**	**1,479**		**79,507**
			4%	***3%***	***31%***	***8%***
	Vegetation & no housing		-	-		-
			-	-		-
	Vegetation & very low housing density		4,534	1,424		16,795
			3%	*3%*	*31%*	*2%*
	No vegetation & low and very low housing density		246	55		2,769
			<1%	*<1%*		*<1%*
	No vegetation & medium and high housing density		-	-		59,943
			-	-	-	*6%*
		Total:	**135,416**	**53,786**		**987,430**

3.4 Discussion

This study sought to document the occurrence of WUI disasters, assess building loss in relation to the three core WUI components, and compare how well SILVIS WUI maps and point-based WUI maps capture patterns of loss observed in WUI disasters. By quantifying the magnitude of the WUI problem and evaluating the accuracy of WUI maps, this study advances our understanding of the WUI problem and WUI disaster sequence spatial phenomenon. Study findings have implications for local and national WUI mapping and wildfire planning efforts. There were 91 wildfires in the United States between 2000 and 2018 that burned more than 50 buildings (classified as WUI disasters). These WUI disasters are the most destructive wildfires in the United States in terms of building loss, but represent only a small fraction of the estimated 1.4 million wildfire ignitions (Short 2014), and of the 2,771 wildfires that burned at least one building during our study period. WUI disasters were concentrated in California, Colorado, Texas, and Arizona. The number of WUI disasters and associated building loss has been increasing since 2000. However, there was considerable year-to-year variation, with extensive losses in 2017 and 2018 heavily influencing the overall trend. Numerous factors likely contribute to the increasing number of WUI disasters and total building loss, but the expansion of WUI development, climate change, and historical land management practices are probably key drivers of this trend (Westerling et al. 2006, Cohen 2008, Radeloff et al. 2018, Mueller et al. 2020).

This study defined WUI disasters as those wildfires burning more than 50 buildings, but WUI disasters have no formally agreed-upon definition. Cohen suggested 100 burned buildings was an appropriate threshold (2008), but I lowered that to capture more loss and account for reporting errors. A visual inspection of the data summarized in Figure 3.4 suggests the 50-building threshold likely biased results. Had the study kept Cohen's threshold of 100 burned buildings, the proportion of interface loss relative to intermix loss would have likely been higher;

if I had further lowered the threshold, or examined all fires that resulted in any amount of building loss, the proportion of interface would have likely been lower. Future research that investigates the sensitivity of WUI disasters' home loss thresholds would be useful in furthering our understanding of the spatial nature of home loss, and could help synthesize findings from disparate post-wildfire home loss case studies.

Point-based WUI maps and Census-based SILVIS WUI maps respectively classified 97.0 and 86.4 percent of all buildings lost in WUI disasters as being in either the WUI interface or intermix. The SILVIS WUI maps capture ratio indicates that despite the coarse resolution of SILVIS WUI data, these maps are effective, identifying a majority of WUI disasters home loss as occurring in the WUI. The SILVIS WUI mapping methods are transparent and easy to replicate with publicly available data (Radeloff et al. 2018). Census and land cover data collection efforts are both well documented and routinely collected, allowing managers and researchers to account for temporal changes in WUI development (Hammer et al. 2009, Wickham et al. 2017). Both the demonstrated utility of the SILVIS WUI maps and their acceptance as a standard in federal regulations suggest they will continue to serve an essential role at a national scale, and for many broad-scale WUI mapping efforts that do not require specific building locations. That said, point-based WUI mapping methods can better capture building loss relative to Census-based maps. Further, their ability to include specific locations of at-risk building locations and exclude low-risk buildings offers additional advantages for multiple applications, and more closely aligns with our conceptual understanding of the WUI problem as one whose fundamental unit is the home (Cohen 2008, Calkin et al 2014; Scott et al. 2015).

Our finding that building loss mostly occurs in areas with low building densities and high vegetation cover supports previous findings (Syphard et al. 2012, Alexandre et al. 2016, Kramer et al. 2019). Higher losses in more rural intermix environments with more vegetation may be due to multiple factors: continuous vegetation providing more potential for fire spread and home ignition, lower fire response capacity, the relative inaccessibility of dispersed homes, or incident managers' choices to direct resources to areas with higher-density clusters of homes (Clark et al. 2016). However, 20.5% of building loss occurred in areas with >500 buildings per km^2, and 5.2% of building loss occurred in areas with both >500 buildings per km^2 and less than 25% vegetation cover; this suggests that home loss in urban environments may result from a set of factors unique to that environment, possibly including unique construction material, landscaping, and home arrangements and proximity which facilitate home-to-home fire spread. Observations that building loss occurs in high-density areas supports findings from other studies that have reported building loss in urban environments (Maranghides 2015, Kramer et al. 2019, Syphard and Keeley 2019) and helps quantify the magnitude of this phenomena. In urban unvegetated environments, our results also show that building loss declined rapidly with increasing distance from vegetation. All building loss in the study occurred within 850 m from 2.5 km^2 patches of wildland vegetation, and less than 5% of building loss occurred at distances exceeding 100 m. While study design and building loss data could not identify the role of fire response or specific home ignition mechanisms, this finding aligns with the research suggesting embers are the leading cause of building ignition (Cohen 2010). Embers rarely travel further than a few hundred meters (Koo et al. 2010), and buildings at the edge of building clusters, being closer to wildland vegetation, are more likely to ignite than interior buildings (Alexandre et al. 2015). Further, logistic regression results can inform the scales at which WUI components should be calculated for point-based WUI maps. While WUI components' generally low AUC values indicate that individual WUI components have poor correlation with burn status, users can select appropriate scales to calculate WUI component values and thresholds based on their own needs or risk aversion. A future direction of this work could involve developing point-based WUI maps that integrate additional fine-scale data, including fuel conditions, topography, fire behavior predictions, fire response capacity, distance to neighboring buildings, building construction, and mitigation efforts, all to better estimate wildfire hazard for specific assets in ways not possible with Census-based data (Stewart et al. 2007).

Our findings related to how building loss is distributed across a range of building densities, percent vegetation cover and distance to large patches of wildland vegetation could potentially improve how the WUI is mapped when using point-based data, and at the same time help identify appropriate mitigation strategies for different environments. The fact that all building loss occurs at distances substantially less than the 2400 m used in other WUI mapping efforts (Radeloff et al. 2005, 2018) suggests this threshold could potentially be altered for WUI maps that seek to identify at-risk buildings. The 2400 m distance threshold used in the SILVIS WUI maps may be appropriate for Census-based WUI maps, but our results suggest a more conservative distance threshold could be used for point-based WUI maps. Reducing the buffer distance threshold to 850 m or shorter would focus attention on buildings with the highest risk of ignition while removing buildings at low risk. Using the results from this analysis to adjust WUI buffer distance could help tailor mitigation efforts, improve fine-scale spatial risk assessments, refine estimates of values at risk, and better identify community wildfire exposure zones (Maranghides and Mell 2012; Scott et al. 2013; Ager et al. 2019). Furthermore, documenting losses across a range of building densities and vegetation cover percentages suggests the need to identify specific ignition mechanisms and customize wildfire mitigation techniques for different environments. In areas between 100 and 850 m from wildland vegetation, buildings may still be at risk of igniting, but exposure in this zone is likely due to features of the built environment as opposed to areas of contiguous wildland vegetation. In areas where wildland hazardous fuel reduction projects are not feasible, there may be a benefit to removing flammable landscaping and implementing building hardening techniques. Our results, which describe the pattern of loss in different environments, underscore the need to develop and implement distinct mitigation techniques across a range of building density, vegetation cover, and community types, including some areas not traditionally considered at risk (Maranghides and Mell 2012, Evers et al. 2019).

Detailed maps of at-risk structures can also improve community-based local land-use planning and wildfire mitigation efforts (Calkin et al. 2011; Mell et al. 2010; Evers et al. 2019). For example, it would be helpful for communities considering wildfire-related land-use policies and building codes to understand which buildings are at heightened risk of igniting during a wildfire. Local governments have faced calls to both limit residential development in fire-prone areas in the WUI, and enact building codes that require defensible space or fire-resistant construction for at-risk homes (Miller et al. 2018). In response to these calls, communities may restrict residential development or require homeowners to mitigate wildfire risk--these measures either limit the local tax base, or impose financial burdens on residents. While in the past, it has been challenging to identify at-risk homes, detailed point-based WUI maps that can accurately identify at-risk homes while excluding low-risk homes can inform which strategy or combination is preferable for a given community. Understanding the implications of limiting growth or requiring mitigation for either existing homes or future development is critical for informing local governance (Paveglio et al. 2013; Calkin et al. 2014; Smith et al. 2016). Further, detailed

WUI maps comprised of at-risk structures enables more in-depth discussions about how communities and property owners can mitigate risk. WUI communities can use results from point-based maps to target individual buildings for nuanced mitigation efforts that take into account local knowledge about the building's immediate surroundings, property access, construction materials, and vegetation cover on the property. The knowledge from detailed WUI maps reduces the uncertainties that WUI residents and communities need to navigate, including how homes and vegetation are co-located within a Census block. In addition to their benefits at fine scales, point-based maps can also be summarized at the Census block or county level, so they can also be used for national planning and mapping efforts (Calkin et al. 2011). The flexibility of point-based WUI maps overcomes a key limitation of Census-based maps, which are sufficient at a national scale, but often insufficient for local applications such as wildfire incident response or neighborhood evacuation planning (Bar Massada et al. 2013).

Point-based maps also have additional benefits at national scales. Their improved spatial resolution relative to Census blocks can better estimate community wildfire exposure, refine estimates of values at risk, and inform regional land management budget allocations tied to home exposure (Scott et al. 2015; USDA 2015; Ager et al. 2019). Findings that building loss primarily occurs in areas with low building density and within 850 m from wildland vegetation are particularly informative in light of previous WUI sensitivity analysis (Radeloff et al. 2005, Stewart et al. 2007). This literature has examined how adjusting WUI component parameters would change the number of homes and spatial extent of the WUI intermix and interface areas. For example, shrinking the WUI buffer distance would reduce the number of homes and spatial extent of the WUI interface, while reducing building density threshold would increase the number of homes in the WUI intermix.

Our findings suggest that not only do point-based WUI maps better capture homes at risk of igniting during a fire, but they also include more homes with marginal building densities relative to Census-based maps due to the scale at which density is calculated. Many building points have building densities > 6.17 homes per km^2 when calculated using a 1000 m neighborhood, but < 6.17 homes/ per km^2 when calculated at the Census block scale. This results in increasing the number of WUI intermix homes and expanding the spatial extent of the WUI intermix by using point based WUI maps. Additionally, excluding homes further than 850 meters from wildland vegetation, where we have not observed home loss, would reduce the number of homes in the WUI interface and shrink its spatial extent. These adjustments could have significant implications for informing land management decisions. Expanding the WUI intermix and shrinking the WUI interface could influence funding allocations tied to the number of at-risk WUI homes present in a landscape. Expanding how and where the intermix is represented in WUI maps could also impact land management agencies whose hazardous fuel reduction efforts are often tied to WUI community protection objectives (Schoennagel et al. 2009). Additional research could investigate the potential implications these adjustments may have for different states and regions depending on their unique patterns of residential development and mix of WUI interface and WUI intermix.

In conclusion, study results indicate that point-based WUI maps can improve our understanding of where building loss occurs during WUI disasters, and can more accurately identify at-risk buildings relative to existing Census-based mapping. In documenting the pattern of home loss relative to the standard WUI mapping components (building density, vegetation cover, distance from vegetation), this study also improves our understanding of the WUI problem as a complex spatial phenomenon. Although the WUI is the fastest-growing land-use type in the United States (Radeloff et al. 2018), our results suggest building loss is spatially variable and is not equally distributed throughout interface, intermix, and WUI adjacent areas. Though this variation needs to be explored further, findings herein undoubtedly have important implications for both land-use planning and wildfire management. Findings improve our ability to understand the historical pattern of loss and the potential for loss in the future, which will become increasingly important as the WUI expands, and the number of at-risk buildings increases.

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CHAPTER 4: STAKEHOILDER EXPECTATIONS OF DEFENSIBLE SPACE AND FIRE RESPNSE IN THE WILDLAND-URBAN INTERFACE

4.1. Introduction

Fires in the Wildland-Urban Interface (WUI) pose a serious threat to communities around the globe, and often result in considerable economic, environmental, and social losses. Although the potential impacts of wildland fires on human communities have been recognized since the 1970's (Butler 1974), the cost, frequency, and severity of WUI disasters (i.e. wildfires occurring in residential areas result in numerous homes being destroyed), have been increasing over time (Cohen 2008). Federal expenditures on wildland fires within the U.S., for example, rose to 48 percent of the 2015 United States Forest Service's 2016 budget as compared to 16 percent in 1995 (USDA 2015). This increase has been partially driven by the need to protect private property located within the WUI (Ellison, Mosley, and Bixler 2015). Additionally, the increased severity, frequency and cost of WUI wildfire incidents has been linked to changes in wildland fuels, climate, and urban development patterns (Hammer, Stewart, and Radeloff 2009; Platt et al. 2011; Hass, Calkin, and Thompson 2014). These factors are expected to persist into the foreseeable future, thereby intensifying the impacts of wildfires in the WUI (Gude, Rasker, Van den Noort 2008; Westerling et al. 2006).

Increased concerns over heightened potential for WUI disasters have prompted to communities to develop multifaceted wildfire protection strategies, such as reducing combustible vegetation within forests and grasslands and improving the response capacities of local fire protection agencies (Vaske 2006; Jakes et al. 2007). The creation of *defensible space*, a mitigation activity that reduces the ignitability of homes by hardening the structure utilizing fire resistant building materials and removing combustible material and vegetation from the area surrounding homes, is often touted as the most effective strategy for increasing the survivability of structures located in the WUI (Cohen 2000; Calkin et al. 2014). While a homeowners decision to implement defensible space are shaped by numerous factors, as discussed further below, mitigation efforts and fire response are a community issue rather than an individual issue, so it is important to also understand the perspectives of other stakeholders involved with wildfire mitigation and protection in WUI communities. This study seeks to examine how different stakeholders understand defensible space and the factors that influence home loss during WUI disasters.

Within the WUI, various government, nongovernment, and community stakeholders co-manage wildfire risk. Each is responsible for implementing distinct yet overlapping aspects of community protection measures such as those noted above. While homeowners are primarily responsible for implementing defensible space around their homes (Schoennagel et al. 2009), they often receive financial or technical support from mitigation specialists hired by local governments or community organizations (Renner, Reams, and Haines 2006). Specific examples of the ways homeowners might create defensible space include cutting down trees within a certain distance of their residence, regularly mowing grass, moving stacks of firewood away from their home, forest raking, cleaning leaves and pine-needles from gutters, installing metal or slate roofs, attaching wire mesh around attic or soffit vents to keep embers out of the home, and/or removing ladder fuels such as brush that enable fires creeping on the ground to climb into the crowns of trees. Firefighters are often involved with those same efforts, and are often called on as technical specialists to help design community scale mitigation projects and assist homeowners wishing to implement defensible space around their homes (Brenkert-Smith

2011). Further, firefighters are often called upon to protect communities when threatened by wildfires, and incorporate mitigation projects into fire response strategies and utilize defensible space when protecting homes in need (Maranghides and Mell 2011). Moreover, because the success of mitigation and fire response strategies in the WUI are codependent, it is essential for stakeholders to recognize that efforts to reduce the risk of wildfire and home loss in the WUI are impacted by the degree that efforts are holistically coordinated throughout a community (Moritz et al. 2014; Smith et al. 2016; Paveglio, Abrams, and Ellison 2016; Madsen, Haynes, and McCaffery 2018). In this way, managing WUI fire risk is a co-management problem.

One of the critical aspects of ensuring effective co-management of multifaceted WUI wildfire risks is to ensure stakeholders (including homeowners, firefighters, and mitigation specialists) have a common understanding of the problem and its solutions (Cheng and Becker 2005, Champ, Brooks, and Williams 2012). Stakeholder understandings of the factors that lead to wildfire disasters and home loss are important because they influence mitigation actions and priorities (Olsen et al. 2017). For instance, some homeowners might prioritize vegetation removal, while others might emphasize structure hardening (Vaske 2006), techniques that reduce the potential for firebrands and embers to ignite homes. Similarly, some wildfire experts might understand defensible space differently according to how will it is likely to perform under different fire conditions. The lack of common understanding can lead to different conclusions about appropriate actions. Indeed, differentiating the ways stakeholders understand the implications of mitigation and response activities and how WUI disasters unfold could have particularly powerful impacts on a community’s ability to coordinate risk mitigation efforts effectively.

There is a substantial body of research that has characterized homeowner understandings, motivations and challenges associated with implementing defensible space (Brenkert-Smith, Champ, and Flores 2006; Martin, Bender, and Raish 2007; Absher, Vaske, and Lyon 2013; Olsen et al. 2017). Specifically, homeowner's belief that mitigation actions will be effective is a prerequisite for action (Fried, Winter, and Gilless 1999; Martin, Bender, and Raish 2007; Hall and Slothower 2009). This concept, termed *response efficacy* within sociological theory, explains how people perceive and respond to threats (Rogers 1975). In the context of specific wildfire mitigation actions considered by homeowners, Absher, Vaske, and Lyon (2013) found that homeowners thought installing a fire-resistant roof and removing dead limbs, leaves, and other flammable debris adjacent to homes were among the most effective actions they could take to improve the likelihood of home survival.

Although homeowners generally believe defensible space is effective, recent WUI fires such as the Fourmile Canyon and Black Forest Fires in Colorado and Thomas Fire in California have confounded homeowners, mitigation specialists, and wildfire researchers because numerous homes were lost despite mitigation efforts (Pikes Peak Wildfire Prevention Partners 2014; Southern California Public Radio 2018, Lasky 2018). Lending credibility to these non-peer reviewed observations, several recent studies have demonstrated that the public sometimes questions the efficacy of defensible space (Brenkert-Smith 2011), while other studies have indicated defensible space practices have not consistently protected homes in some WUI communities (Cohen and Stratton, 2008; Graham et al. 2012; Syphard, Brennan, and Keeley 2014). These studies illustrate that reducing fuel loading immediately around a home does not always lead to home survival because home survivability is also dependent on factors such as fire exposure, ignition sources, home construction materials, and firefighter actions. It is unclear how homeowners and other stakeholders understand how these factors interact to facilitate home survival in some cases and inhibit it in others.

The research on human dimensions of wildfire and mitigation efforts has largely focused on homeowner perspectives with minimal accounting for other stakeholder groups, and has largely assessed perspectives of wildfire risk and defensible space without accounting for firefighter response (McCaffery et al. 2013). However, it is important to understand how first responders understand their roles and responsibilities (Madsen, Haynes, and McCaffery 2018), and how the public perceives the efficacy of fire response (Paveglio, Abrams, and Ellison 2016), because fire response tactics can influence home survival, and perceptions of the efficacy of fire response may influence the mitigation actions of homeowners. At least two studies illustrate potentially important differences in how stakeholder groups understand defensible space and factors that influence home loss. After the 2010 Witch Fire, Maranghides and Mell (2011) discovered that homeowners attributed home survival to their own mitigation actions without acknowledging firefighter response, while firefighters attributed home survival to the actions they took to protect homes. Similarly, Meldrum et al. (2015) found that homeowners in northern Colorado considering mitigation were likely to perceive a reduction in risk due to their own mitigation efforts, while firefighters assessed a home's risk relative to their ability to access and protect it. These comparative studies indicate there is tension between how different stakeholder groups perceive the roles and efficacy of defensible space and firefighter response. Since homeowner and wildfire professional groups both have critical roles interacting with one another to co-manage and forge effective community protection efforts, divergent understandings of defensible space and fire response are potentially problematic.

The WUI Disaster Sequence Theory (WDS) provides an integrated framework from which to understand defensible space, fire response and home loss during WUI disasters (Cohen 2008, Calkin et al. 2014). Two especially valuable features of the WDS framework are that it has been empirically derived from commonalities observed across multiple large wildfires with significant home loss, and that it accounts for the systematic, multiscale, and contingent processes by which variables such as fire behavior, extreme weather conditions, ignitable homes, and fire response interact with one another (see Figure 7). According to WDS, WUI disasters begin with the ignition of a wildfire under extreme environmental conditions (e.g., severe drought preceding ignition and hot, windy weather) in an area with numerous highly ignitable residential homes. Under these conditions wildfires spread rapidly and threaten numerous homes simultaneously, which overwhelms fire suppression resources and exacerbates home losses. While not explicitly included in the WDS, defensible space and mitigation efforts affect home ignitability and fire behavior, and are important for facilitating fire response, and mitigating WUI Disasters. The WDS attends to the interrelated processes that unfold within WUI disasters, which adapted for use as an analytical tool for studying stakeholder perspectives regarding the relationships between social and environmental interactions and home loss during wildfires. I sought to use the WDS as a framework to assess different WUI stakeholders understanding and beliefs around defensible space and fire response. Loosely following the WDS components identified by Cohen, I identified three key variables in WUI Disasters to focus our study: 1) how extreme fuels weather and topography lead to extreme fire behavior; 2) factors that influence ignitability of residential homes during extreme fire events; and 3) firefighter response. I sought to understand stakeholder perspectives on these three variables and their interactions during WUI disasters.

4.2 Methods

To better understand stakeholders' perspectives of how these variables interact, I interviewed participants from each stakeholder group. I developed a semi-structured script that solicited responses about wildfire risk, home ignitability, fire response, and defensible space. This allowed us to identify the range in how stakeholders understand and consider the relationships between these variables. I solicited participation from multiple stakeholder groups and acknowledge a potential self-selection bias from participants who volunteered for our study. As such, our findings are exploratory and may not be representative of the broader WUI population. Caution should be taken if findings are to be generalized beyond our interview participants and study area.

I identified three study communities, Evergreen, Genesee, and Larkspur, all in the Upper South Platte Watershed 20 miles southwest of Denver, Colorado. These communities were selected because they are all in a watershed that has experienced multiple large fires in the last 20 years and have recently formed The Upper South Platte Partnership (USPP), a collaborative group composed of government, nongovernment, and community stakeholders. The USPP seeks to implement actions consistent with the National Cohesive Wildland Fire Management Strategy (restoring fire adapted landscapes, promoting fire adapted communities and improving fire suppression efficiency) (Huayhuaca 2016). Each community has a fire protection district responsible for wildfire suppression that actively engage in community risk mitigation activities and residential defensible space programs. A secondary goal of this study was to provide the USPP with baseline information about the current state of wildfire awareness among homeowners and wildfire professional populations in the watershed.

Within the three communities, I randomly solicited interview participants from stakeholder groups that included homeowners, firefighters, and wildfire mitigation specialists. In each community, I selected the first six residents and first six firefighters to respond to our solicitation. Residents were solicited using mailings and postings in community newsletters, and firefighters were solicited through flyers posted in fire stations and fire district email distribution lists. Additionally, six mitigation specialists were solicited through the Front Range Round Table, a regional forestry working group (Cheng et al. 2015). In the fall of 2015, I conducted 42 semi-structured interviews with 45 individuals, as three interviews were conducted with multiple members of a household. Interviews were conducted at locations chosen by respondents. Homeowners were often interviewed at their residences, which provided researchers with an opportunity to observe their mitigation efforts in person. Firefighters and mitigation specialists were interviewed at fire stations and offices respectively. This process resulted in 1,916 minutes of audio recordings which were later transcribed for analysis.

To identify prominent themes within the dataset, I utilized an iterative process of coding and analysis (Spinuzzi 2013). I began by assigning starter codes derived from Cohen's WDS, open codes that corresponded to unexpected or emergent topics, and axial codes associated with relational trends between starter and open codes. In the results section below I present exemplars that illustrate the range in perspectives for each theme. I also account for and discuss intra- and inter-group variability in stakeholder group perspectives.

4.3 Results and Discussion

In the results section below, I present and discuss our most significant findings. In each subsection, I introduce a significant theme from the dataset, before describing the range of stakeholder perspectives on the theme and offering quotes that exemplify noteworthy stances on the issue. Readers will also find discussion regarding about the ways perspectives align with the WDS framework and current fire science. Last, I discuss the implications of our findings for management, outreach, and future research.

4.3.1 Home ignitability and emphasis on Mitigation Activities

All participants, regardless of stakeholder group, expressed an understanding of how extreme fuel topography, atmospheric conditions, and ignitable homes set the stage for WUI disasters. However, I found variation in stakeholder understandings of and priorities for defensible space mitigation efforts. While discussing how mitigation can reduce home ignitability, I found some stakeholders responses spanned a continuum. Some placed a greater emphasis on vegetation removal, others focused on structural hardening, and still others placed equal importance on both. Table 4.1 presents the results of our coding as it relates to home ignitability and participant emphasis on common mitigation activities which I organized and coded into three categories. It is important to note that while many participants emphasized various mitigation activities, they also often qualified their statements by describing various limitations that could impede their efforts to reduce home ignitability.

Table 4.1 Stakeholders place different emphasis on defensible space mitigation activities. Presents the coding scheme illustrating the range of stakeholder positions regarding defensible space, home ignitability and limitations thereof. Participants were classified into categories according to their dominant perspective and distinguished by stakeholder type and study community. **Legend:** EH: Evergreen Homeowner, EF: Evergreen Firefighter, GH: Genesee Homeowner, GF: Genesee Firefighter, LH: Larkspur Homeowner, LF: Larkspur Firefighter, MS: Mitigation Specialist

Table 1: Stakeholders place different emphasis on defensible space mitigation activities

	Coding Categories			
Participant Groups	Heavier emphasis placed on vegetation removal	Equal emphasis placed on vegetation removal and structural hardening	Heavier emphasis placed on structural hardening	Vegetation removal and structural hardening efforts vary year-to-year based on fire behavior, economic, and/or seasonal factors
Homeowners from Community One	EH1, EH2, EH3, EH4	EH6	EH5	EH1, EH2, EH3, EH4, EH5, EH6
Firefighters from Community One	EF6	EF1, EF2, EF3, EF5	EF4	EF1, EF3, EF4, EF5, EF6
Homeowners from Community Two	GH1, GH2	GH3, GH4, GH5, GH6		GH2, GH3, GH4, GH5, GH6
Firefighters from Community Two	GF2, GF6	GF1, GF3, GF4, GF5		GF1, GF2, GF3, GF4, GF5, GF6
Homeowners from Community Three	LH1, LH2	LH3, LH4, LH5, LH6		LH1, LH2, LH3, LH4, LH5, LH6
Firefighters from Community Three	LF2, LF6	LF1, LF3, LF4	LF5	LF1, LF2, LF3, LF4, LF5
Mitigation Specialists		MS5	MS1, MS2, MS3, MS4, MS6	MS1, MS2, MS3, MS4, MS5, MS6

4.3.1.1 Greater emphasis on vegetation

I found 13 of 42 participants placed a greater emphasis on vegetation removal activities with little or no discussion of structural considerations. More specifically, participants in this group tended to emphasize mitigation activities such as removing trees, cutting tree limbs, and mowing grass in the area immediately surrounding the home. When asked about mitigation priorities, for instance, a Firefighter Evergreen responded:

> *Creating at least a 30-foot barrier zone around your house without a lot of heavy fuels. Removing trees back away from the house, removing the limbs that are overhanging and touching your roof. That would be the number one thing I'd work on. Number two would be removing ground fuels that are around the house, tall, dried, cured grasses that come right up to your house.*

Note how in this excerpt the interviewee described two different types of vegetation removal and placed emphasis on the area immediately surrounding the home as the two most important steps in a mitigation strategy.

4.3.1.2 Greater emphasis on structural hardening

A small number of respondents (8 of 42 participants; 5 of 6 mitigation specialists), prioritized structural considerations. It's also noteworthy that no participants in the Genesee participant group placed a greater emphasis on structural considerations. Participants in this group stressed structural hardening, while often referencing embers as the most common source of home ignition. As one Larkspur firefighter observed:

> *I need to manage the fuels further out but if you don't take care of the house first, harden it from embers, have your non-combustible all around it, all that good work with fuels out further may be for not. You're wasting your money and you're wasting your time. Start with the house, work your way out.*

Among our different respondent groups, the mitigation specialists consistently emphasized structural considerations over vegetation removal, a homogenous trend that was not observed within the other stakeholder groups. Indeed, the majority of participants did not emphasize structural considerations over vegetation removal, and even those who said they were equally important still spent the majority of our interview speaking about vegetation removal. Mitigation specialists were far more likely to justify their focus on the home by referencing findings from current fire science that suggests the importance of structural hardening to prevent ember intrusion and ignition (Cohen 2000; Quarles et al. 2010).

This suggests that some homeowners may not recognize that structural hardening is an especially valuable action for preventing home ignition from ember intrusion. The divergent emphasis stakeholders placed on various components of defensible space suggests that the groups may have different understandings of home ignition mechanisms, and which actions are most effective in preventing home loss. In fact, several mitigation specialists readily acknowledged this disconnect, noting this discrepancy might stem from past community outreach practices that stressed vegetation removal:

> *When I first came in it was defensible space vegetation only, then as I started to learn how homes ignited ….I started looking more at the home and the vegetation. But when I started it was all veg. it's still kind of all I can do, but the message now is different than when I started.*

This description from a mitigation specialist demonstrates that wildfire protection community outreach efforts, which initially stressed vegetation removal, have evolved over time. Although our data suggests disconnects currently exist, new messaging now includes more holistic approaches that emphasize the role of structural hardening for mitigation.

4.3.1.3 Equal Emphasis

Half of our participant statements reflected a more balanced approach, considering both vegetation removal and structural modifications as key elements of a mitigation strategy (21 of 42 participants). Statements coded in this category include those where participants found placed equal emphasis on vegetation and structural activities, sometimes because they found it difficult to prioritize one over the other. For instance this Evergreen firefighter observed:

> *I lean towards everything is equally important, trees trimmed, gutters cleaned, I think it is all important, one little thing can help you and one little thing can hurt you.*
>
> *I think the Black Forest fire was probably the most that shaped my experience with defensible space, just because I saw fire interact with what people did on the property. ...So defensible space, to me, always means tree thinning, fuel reduction, but with that also includes the little things like cleaning your gutters, making sure the grass is cut around your house so the fire doesn't get to that structure specifically…. Meshing under decks, building materials, then from there what do they have around their house as far as fuels go.*

A notable difference between these exemplars is in the details of their justification. While the first makes a general statement and is reflective of the level of detail expressed in many homeowner understandings, the later quote is more detailed. In the second quote the firefighter from Genesee drew from first-hand experience and observations from a recent fire regarding how specific mitigation activities impacted home survivability during the Black Forest Fire. This more nuanced understanding take into account a range of activities and interactions which cumulatively influence home loss and in doing do can help prioritize actions in more meaningful ways.

4.3.1.4 Limitations of mitigation activities

One final pattern I want to draw attention to is that most participants indicated that mitigation activities have limitations and thus would only be effective in some instances. In fact, many participants appeared to express uncertainty about which aspects of mitigation they should emphasize because fire behavior is unpredictable. Moreover, participants indicated that lack of aggressive mitigation on behalf of some homeowners reduced the overall effectiveness of mitigation efforts at the community scale. Across stakeholder groups, participants noted that the lack of high quality mitigation, often described as “stand alone,” could hinder the overall success of protection efforts enacted within a community. According to one firefighter:

> *Some people think they have [implemented defensible space], but they haven't met any meaningful mitigation standard…I think that there's probably less than 10% in my neighborhood that have actually met the standards that the Colorado State Forest Service has put out on the web… based on Firewise.*

These statements suggest a potential divide between theory and practice. While defensible space is regarded as an effective mitigation strategy in theory, in practice it may be compromised, and enacted in ways that reduce the efficacy of protection efforts given uncertainties associated with fire behavior and variable quality. Indeed, some respondents perceived that homeowners within a community may not be consistently implementing mitigation activities in ways that align with state recommendations, a similar finding to that of Penman et al. (2016). Stakeholders may also believe that mitigation projects, while generally helpful, will not effectively protect homes during extreme conditions when most home loss occurs: According to one mitigation specialist:

> *Fuel treatments in general I think are probably best geared to deal with the seventy-five percentile and below fire. Waldo Canyon [Fire], fairly sparse vegetation, a hundred plus percentile because of the wind element. The homes became the fuel. When you talk about effectiveness you have to be very careful to frame that within what percentile of fire behavior…..You need to do this, but if the fire behavior passes this threshold, all bets are off.*

While only a minority of participants explicitly expressed these critiques, if more widely held they could account for some variance in the levels of emphasis stakeholders placed on vegetation removal and structural hardening. These perspectives highlight discrepancies among different stakeholders’ understanding and beliefs about defensible space effectiveness and efforts to reduce home ignitability. This has important implications for managers who are tasked with designing effective community outreach and implementing effective protection measures in coordination with other stakeholders. Acknowledging critiques regarding the lack of defensible space at the community scale and limitations of fuel treatments for protecting individual homes, can help prioritize actions, set goals and align expectations regarding the efficacy of mitigation efforts.

4.3.2 Expectations of fire response

The WDS suggests that fire response is a critical component of community protection, as WUI disasters tend to occur after fire response becomes ineffective. Our work indicates that regardless of stakeholder group, all participants acknowledged the importance of firefighter response, and most suggested they relied on firefighters to protect homes during WUI disasters. However, despite its perceived importance, I found participants held a range of beliefs regarding the role of fire response, its purpose and interactions with defensible space, and expectations about its effectiveness. I found participants perspectives on fire response fell into three categories, 1) defensible space was designed so that firefighters would protect threatened homes; 2) defensible space facilitates response when firefighters are available but also reduces home ignitability independent of response; and 3) defensible space should be designed to allow homes to survive independent of firefighter intervention. Table 4.2 presents the results of our coding as it relates to understandings of fire response, classifies each participant into one of three main categories, and notes those who discussed its limitations. One common trend across stakeholder category was that participants hedged their views regarding expectations of fire response by noting various factors and conditions that could limit its effectiveness. The three dominant viewpoints, and the ways participants hedged their expectations of fire response are discussed below.

Table 4.2. Stakeholders have different understandings regarding the role of fire response and how it relates to defensible space. This presents the coding scheme illustrating the range of stakeholder positions regarding the role of fire response and how it relates to defensible space. Participants were classified into categories according to their dominant perspective and distinguished by stakeholder type and study community. **Legend.** EH: Evergreen Homeowner, EF: Evergreen Firefighter, GH: Genesee Homeowner, GF: Genesee Firefighter, LH: Larkspur Homeowner, LF: Larkspur Firefighter, MS: Mitigation Specialist

Table 2: Stakeholders have different understandings regarding the role of fire response and how it relates to defensible space.

	Coding Categories			
Participant Groups	Firefighters will protect threatened homes	Firefighters protect homes when available but also reduces home ignitability independent of response	Stand alone: Defensible space allows home survival without firefighter intervention	Firefighting response may be limited because of extreme fire behavior or insufficient resources
Homeowners from Community One	EH2, EH3, EH4	EH5, EH6	EH1	EH1, EH4, EH5, EH6
Firefighters from Community One	EF1, EF3, EF6	EF2, EF5	EF4	EF1, EF2, EF3, EF4, EF5, EF6
Homeowners from Community Two	GH1, GH4, GH6	GH2, GH3, GH5		GH2, GH4, GH5
Firefighters from Community Two	GF3	GF1, GF2, GF4, GF5, GF6		GF1, GF2, GF3, GF4, GF5, GF6
Homeowners from Community Three		LH1, LH2, LH3, LH4, LH5, LH6		LH1, LH2, LH3, LH4, LH5, LH6
Firefighters from Community Three		LF2, LF3, LF4, LF5, LF6	LF1	LF1, LF2, LF3, LF4, LF5, LF6
Mitigation Specialists		MS1, MS2	MS3, MS4, MS5, MS6	MS1, MS3, MS4, MS5

4.3.2.1 Firefighters will protect threatened homes

I found 10 of 42 participants felt that defensible space should be designed to increase firefighter's ability to defend and protect homes. This view reflects the belief that home survival depends primarily on firefighter intervention, and any vegetation removal or structural hardening efforts serve to facilitate firefighter intervention. As one homeowner from Evergreen explained:

The aim [of defensible space] from a property's standpoint is to allow the fire department to attack a fire, and save the structure. They've got to have a place to draw a line and fight the fire.

This viewpoint places much of the responsibility for home protection on the firefighters themselves. It doesn't acknowledge that defensible space activities can be designed to inhibit structure ignition independent of firefighter intervention, a common perspective as supported by the findings of Paveglio, Abrams and Ellison (2016). Referencing why homeowners may rely so heavily on fire response, a mitigation specialist observed:

When I first started doing this I really emphasized giving firefighter's room around the home to defend the home, but over time I have changed that message, because in some instances it gives a false sense of "that means firefighters are going to be here". So [now] I give that message and then say "there is not enough fire engines to save every home and you can expect that." … Even the name defensible space implies someone will be there to defend my home."

This explanation suggests that homeowner reliance on defensible space for enabling firefighter protection may be an artifact from earlier messaging that implied firefighters would be present to defend homes. Whereas the previous excerpt illustrates the assumption that defensible space primarily serves to facilitate firefighter intervention, the last excerpt notes the origin and fallacy of this commonly held perspective, and indicates that messaging is evolving to acknowledge the limitations of both mitigation and fire response.

4.3.2.2 Defensible space facilitates response when firefighters are available but also reduces home ignitability independent of response

I found 25 of 42 participants suggested that defensible space serves the dual purpose of reduce fire intensity near the home and facilitating firefighter suppression activities around homes if they were available. This differs from the firefighter-centric viewpoint above and suggests defensible can also help home survival in the absence of firefighters. The quotes below help articulate the viewpoint that both vegetation removal and firefighter response are critical to protecting homes and communities. Firefighters from Larkspur and Genesee respectively noted:

> *I guess goals are cutting or trimming vegetation far enough away from the home that if there is a wildfire that comes through, A, it either slows the wildfire, or B, gives the firefighters that are in there a chance to be able to defend it,..."I've been on fires that vegetation is far enough away from the home to where I could set our hose lines out and let the fire come up to where the vegetation is cut and we're able to extinguish the fire around the home. From a structure protection stand point, I have to make a call where to put our resources. Generally, if I see a group of houses that have ....defensible space .... And it's been mitigated .... We'll make a stand..... It's that combination of fire crews, fire condition, and defensible space [that protects homes].*

These quotes indicate beliefs that home survival is a result of both the defensible space mitigation work homeowners conduct before the fire and the actions of firefighters during a fire, as fire response is related to mitigation levels and quality. In other words, while mitigation activities and firefighter protection efforts are not sufficient by themselves, together they can effectively protect homes. The majority of participants embraced this perspective that defensible space and firefighter intervention act in conjunction to protect homes.

4.3.2.3 Defensible space is designed to allow homes to survive without firefighter intervention I.e. "Stand alone"

I found that 7 of 42 participants believed that defensible space should be designed so that homes can "stand alone" and survive without firefighter intervention. This viewpoint appears to contradict the commonly held understandings that defensible space is designed to work in conjunction with fire response. Several participants thought homes should be designed to this high standard, i.e. aggressive vegetation removal and structural hardening, but also noted that this level of mitigation is rarely achieved in practice, again pointing to the theory/practice divide. They noted the difficulty in designing a home to this standard because ignition potential has to do with the surrounding site conditions, which can be hard to change after the home is built. Indeed, retrofitting the structures with flame and ember resistant building materials is among the most expensive mitigation activities that property owners can undertake, therefore many homeowners may be less likely to carry out this type of mitigation work (Penman et al. 2016). As one firefighter from Evergreen observed:

> *Defensible space needs to be done for standalone. If you're not doing it for standalone then what are you doing it for? .... People that think they've done defensible space and it's not, from my perspective, not nearly good enough. I think you could almost argue in that case 95 to 90% of people have done something, but there's this massive gap between what's enough and effective versus that lower number, which would be good, what firefighters would call standalone.*

Note that this excerpt not only gestures toward the divide between the theory and practice of defensible space but also the range of mitigation quality present in many WUI communities. In other words, while defensible space should be designed to function without firefighter intervention in theory, the failure of many homeowners to effectively implement mitigation activities in practice means the majority of homes in WUI communities may still be heavily reliant on fire response.

4.3.2.3 Limitations of Fire response and high expectations among homeowners

While the three categories above describe a spectrum of stakeholder beliefs and understandings around the role fire response, I found that homeowners had higher expectations of fire response than the wildfire professionals I spoke with. For example, some homeowners thought most of the homes in their neighborhood would be protected if it was threatened by a wildfire. As one Larkspur homeowner explained:

> *Let's assume [the fire district] can get to all of [the homes]. I think if they have a defensible space around their property I think a large percentage of them would be protected.*

This statement reflects a belief that defensible space allows firefighters to effectively protect their homes, which may indicate a lack of knowledge about firefighting resource scarcity during WUI disasters. In a case study of WUI communities, Meldrum et al. (2015) found roughly half of homeowners expected firefighters to protect their home if threatened by a wildfire. Research has found past experience with successful wildfire response reinforces the idea that firefighters can successfully protect homes (Paveglio, Abrams, and Ellison 2016). In contrast, wildfire professionals were more measured in their expectations of fire response. Most of the wildfire professional respondents in our sample thought the majority of homes in their communities would be protected under moderate conditions, but not if fire behavior conditions were extreme or if there weren't enough firefighting resources. Referencing these issues, one Larkspur firefighter noted:

> *The main thing is to get people out of the area and try not to engage because of the topographical features and if I have [extreme] fire behavior, you probably don't want to be in there"..."Obviously I don't have an unlimited amount of resources to protect every home so yeah, it could be a problem. A lot of the standards for us in that environment is to have a truck at every home, I don't have that many trucks. You could run out of resources really fast.*

Compared to that of the homeowner, the wildfire professional's perspective is more nuanced, and references many of the interrelated factors noted in the WDS. It reflects the fact that a firefighter's first duty is protecting the lives of both citizens and other first responders, and then goes on to state that incident size, complexity, and fire behavior all potentially limit fire response. Even if firefighters are able to engage a fire, they may not have enough resources to protect every home. This view positions fire response as uncertain, dynamic, and its efficacy is a result of contingent probabilities. Thus, public and wildfire professionals may harbor divergent views and expectations for fire response that may complicate community protection efforts and increase the risk of WUI disasters by creating inconsistent expectations and actions, ineffective mitigation, and conflicts in WUI communities (Cheng and Becker 2005; Champ, Brooks, and Williams 2012; Paveglio et al. 2015).

4.3.2.4 Homeowners compete for firefighting resources

While many homeowner interviewees had generally high expectations of fire response, some demonstrated an awareness that the scarcity of firefighters means that homeowners compete for these resources. For example, some hoped that because they had implemented defensible space and their neighbors hadn't, their homes might be more attractive to firefighters confronted with decisions regarding which homes to protect. I firefighter from Genesee noted:

> *As a homeowner with a mitigated house, I've got a higher likelihood that firefighters are going to protect my house than my neighbor who doesn't have mitigation.*

This indicates that homeowners may see themselves in competition with other homeowners for fire response and view defensible space as a strategy that would attract firefighters looking for opportunities to safely protect homes. Some firefighters echoed this perspective, indicating that they were more likely to protect homes with defensible space than those without, while others noted the homes they protect depended other factors such as the adequacy and safety of a property's access. In an apparent inconsistency, many homeowners noted their defensible space is designed to be effective with firefighter intervention, while recognizing that fire response capacity may be severely reduced under extreme conditions.

This highlights the important connections between defensible space and fire response. First, understandings and expectations of fire response can influence the ways homeowners implement defensible space. Second, while in some circumstances second defensible space can encourage firefighters to protect one home over another, this may not be true if the number of homes outnumber the number of firefighting resources. As more and more homeowners implement high-quality defensible space, they may increasingly be in competition with each other for a limited number of firefighting resources. Ultimately, if local firefighting capacity does not increase in parallel with defensible space efforts, or defensible space is not designed to be effective independent of firefighter intervention, there will not be enough firefighting resources to protect homes in need.

4.3.2.5 Expectations of fire response influence homeowner mitigation

Regardless of how the dynamics between defensible space and fire response may play out within a particular incident, these perspectives underscore the fact that expectations of fire response influence not only why, but how homeowners implement defensible space. Several participants noted that firefighters can conduct last minute mitigation around homes threatened by a wildfire through a variety of actions, such as moving furniture off the deck, mowing the lawn, or cutting trees. A Homeowner from Larkspur noted:

> *[The fire chief] understands living out here … so I told him, "That tree is 15 feet from the house but I'm not cutting it down just for the eventuality of a fire." That's when he said, "Well, don't worry about it." They would get up here and if*

> *the place needed defending then they could do things like that as a last resort to defending the property.*

This indicates that homeowners may be mitigating less intensely because they expect or have been told that firefighters will perform this mitigation work when their homes are actually threatened. One mitigation specialist observed that fire district leadership occupies a difficult rhetorical position when communicating with tax paying residents:

> *Think about the fire chief. How does the fire chief stand up in his community and say [there is a] good chance that when the fire starts I'm not going to be at your house?*

Perhaps, firefighting resources may be able to conduct last minute mitigation on homes threatened by wildfire when they have sufficient time and resources, but WUI disasters often unfold rapidly and quickly stress limited resources. Expecting fire responders to conduct last minute mitigation work, then, further burdens an already limited resource. Put differently, when homeowners rely on firefighters for last minute mitigation, it increases the workload of firefighters, increasing the likelihood they will become overwhelmed and less effective at the community scale. In this sense inadequate defensible space and high expectations of fire response can create feedback loops, which burden fire response and may exacerbate home loss during WUI disasters.

4.4 Discussion and Implications

Using the Wildfire Disaster Sequence (Cohen 2008) as a conceptual framework, I sought to compare and contrast the perceptions of response efficacy across homeowners, wildfire mitigation specialists, and firefighters. To accomplish this, I performed an in-depth qualitative case study analysis examining what homeowners and wildfire mitigation specialists in three WUI communities expect to be effective regarding wildfire mitigation actions, and compared them with the realities confronted by firefighters' strategies and capacities when responding to WUI wildfires. The findings suggest that: 1) stakeholder expectations about wildfire mitigation actions and firefighter response overlap to a certain extent, but that homeowners' expectations of efficacy exceed those of firefighters due to misconceptions of firefighter capacity; and 2) elevated expectations of homeowners who implement defensible space may inadvertently exacerbate WUI disasters by changing mitigation behaviors and 3) scarce firefighting resources may encourage some homeowners to implement defensible space as a means of attracting firefighters.

Here I outline implications this work has for stakeholders tasked with implementing effective mitigation and response strategies in WUI communities, with an emphasis on what these findings might mean for individuals and organizations responsible for conducting mitigation outreach and assistance for WUI community property owners. Finally, I discuss the implications our study has for researchers interested in examining the social dynamics of the Wildland-Urban Interface, defensible space, and fire response. Our findings underscore the challenges associated with managing and communicating expectations about the effectiveness of wildfire risk mitigation actions, especially given the heightened need for wildfire risk to be "co-managed" by many individuals and organizations (Steelman et al. 2018).

4.4.1 Overlaps and gaps in response efficacy of wildfire mitigation actions: what does "defensible space" really mean?

Our findings highlight that in contrast with current physical science of wildfire and home loss (e.g., Maranghides, Mell citations; Cohen 2008; Quarles et al. 2010), many interviewees did not emphasize or prioritize structural hardening and tended to over-rely on fire response when defining their expectations for defensible space effectiveness. This has implications for management because it suggests some homeowners may not be recognizing the importance of structural hardening or the limitations of fire response. Other homeowners may understand the importance of structural hardening but don't think the investment is worth it. Either way, this results in less effective risk mitigation per the WDS model. Updating mitigation expectations and actions to more closely match the current status of knowledge of physical fire science and fire protection engineering that stresses the role of ember ignitions (Manzello and Foote 2014; Cohen 2008; Quarles et al. 2010) and the limitations of fire response under extreme conditions (Cohen 2008) can help address this disconnect.

The limitations of fire response under extreme conditions suggests the need to incorporate mitigation measures that are effective without firefighter intervention given continued limitations on fire response resources in the face of likely increased frequency of extreme wildfire conditions. This could include techniques such as installing noncombustible material extending five feet out or more from a home's foundation to prevent ignition caused by embers or a creeping surface fire after the main flame front passes (Ramsey and Rudolph 2003; Manzello and Foote 2014). Because this particular mitigation action addresses one of the primary causes of home ignition and does not rely on firefighters being present, it could reduce the likelihood of home loss under a range of conditions irrespective of firefighter actions. Taking such aggressive actions would place WUI homeowners more in a position of co-managing not only their own risk exposure, but the exposure of neighboring properties and fire responders.

Uncertain conditions, poor quality defensible space, and insufficient scale of mitigation all highlight perceived inadequacies of current mitigation efforts that may need to be overcome. Efforts to promote community protection could be improved by conducting community wide property assessments (Meldrum et al. 2015), and encouraging firefighters and homeowners to more openly articulate the limitations and barriers they face, as the financial costs of mitigation actions more aligned with current physical fire science and other concerns (e.g., aesthetics, cost of maintenance, physical ability to implement) impact the types of mitigation homeowners might enact and the levels of response that fire districts can offer. By acknowledging, foremost, the limitations of mitigation and response, stakeholders might identify or define realistic expectations for one another and make more informed decisions about the costs and benefits associated with investing in mitigation activities and fire response infrastructure at individual and community scales.

4.4.2 Response efficacy as a continuous knowledge co-production and co-management challenge

By examining perceptions of response efficacy under a range of conditions commonly experienced during WUI disasters, our findings expands on previous work that suggests homeowners think defensible escape is generally effective (Fried, Winter, and Gilless 1999; Martin, Bender, and Raish 2007; Hall and Slothower 2009. Stakeholders expressed that effectiveness of both defensible space and fire response is reduced with increasingly severe fire behavior commonly associated with WUI disasters. This aligns with findings from post fire case studies that have analyzed empirical factors that contribute to home loss (Cohen 2000; Cohen and Graham, 2008; Graham et al. 2012; Calkin et al. 2014). Our findings provide nuance to these findings. I found that beliefs regarding response efficacy are still variable and dynamic, and depend on an individual's understanding and expectations of fire behavior, home ignition mechanisms, defensible space, and fire response, and the perceived quality and scale of mitigation, all of which feedback to influence mitigation behaviors.

I suggest response efficacy perceptions may be connected to the way messaging surrounding these concepts have evolved over time between stakeholder groups. In fact, our research builds from many prior social science research efforts on wildfire mitigation and defensible space as it considers the perspective of multiple groups involved in co-managing wildfire risk (Williams et al. 2012). Closing the response efficacy perception gap can benefit from attributes associated with successful co-management in other natural resource contexts (Berkes 2009), specifically, the continuous co-production of knowledge involving all groups involved in addressing wildfire risk, from physical and social scientists to homeowners and wildfire mitigation specialists to firefighters representing community, local, state, and federal organizations. In our research, the factors that lead to variations in perceived response efficacy within and between groups suggests that co-managing wildfire risk to WUI communities is not just about implementing one-and-done hazard reduction actions, but, perhaps more importantly, is about constantly managing expectations regarding the effectiveness of those actions under a range of conditions. This is especially true in light of a growing body of research that demonstrates that even homes with defensible space can burn under certain conditions (Cohen and Stratton, 2008; Graham et al. 2012; Syphard, Brennan, and Keeley 2014), which are increasingly likely to occur in Colorado, the American West, and globally (Westerling et al. 2006; Gude et al. 2008; Moritiz et al. 2014).

Despite the prevalence of this research, our findings suggest persistent gaps between the theory and practice about defensible space and its perceived efficacy and wildfire risk across WUI stakeholders. Definitions of defensible space, including, what it is, how it works, under what conditions it is designed to be effective, and how it is connected to fire response have not been consistent over the past twenty years. Consequently, some stakeholders work from the position that the success of defensible space hinges on firefighter presence, whereas others believe that defensible space can or should be designed to help homes survive wildfire independent of firefighter intervention. These positions are in tension with one another, in part because these groups do not have forums and processes for sharing, deliberating, and evaluating constantly evolving scientific and experiential knowledge about response efficacy. Making progress in altering and or aligning 'response efficacy' belief systems concerning defensible space isn't just about changing wording, marketing, and communication, but may need to involve more intensive social process through which WUI community residents, wildfire mitigation specialists, firefighters, and wildfire researchers continuously engage in co-producing actionable knowledge (Moritz et al. 2014; Smith et al. 2014). Collectively generating and making sense of evolving scientific and experiential knowledge about all of the factors affecting home loss in WUI disasters may led to more effective multifaceted wildfire protection strategies.

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CHAPTER 5: CONCLUSION

While both the WUI disaster sequence and the WUI problem acknowledge the role of the various stakeholders and the overlapping social and ecological processes that contribute to home loss, neither explicitly accounts for spatial variability and the different ways WUI disasters unfold in different geographies. The overall objective of this research was to further our understanding of WUI disasters by addressing two key challenges related to this need. The first challenge centered around utilizing spatial data and spatial-analytical tools to better understanding the spatial arrangement of homes in the WUI and the pattern of home loss resulting from WUI disasters. The second challenge involved developing a common understanding between WUI stakeholders regarding the effectiveness of strategies employed before and during WUI disasters, with a focus on wildfire mitigation, defensible space, and fire response efforts. Both research efforts were carried out to inform wildland fire-related policy, risk mapping, fire response, and wildfire mitigation efforts. The conclusions and knowledge gained from this research hold the potential to reduce the likelihood of home ignition, and can directly impact how WUI communities co-manage wildfire risk. Further, findings, contributions, and implications of each chapter, as well as the key themes apparent across chapters highlight additional opportunities for future research.

5.1 Using OBIA to Increase Efficiency and Accuracy

After the introduction, which introduced the key challenges and situated this effort within the broader literature, chapter two explored the possibility of improving point-based WUI mapping efforts. It evaluated the ability of a supervised Object Based Image Analysis approach (OBIA) to identify and extract individual buildings in the WUI using several spatial datasets and imagery sources. It tested accuracy, as well as omission and commission errors at multiple scales and for different building sizes, and evaluated the efficiency of different workflows with different degrees of automation and user input. The overall accuracy and quality of our approach was positively related to buffer distance, with accuracies ranging from 50% to 95% for buffer distances from 0 to 100m. Our results also indicate that building detection was sensitive to building size, with smaller outbuildings (footprints less than 75m^2) detected at rates below 80% and larger residential buildings detected at rates above 90%.

Overall, the findings indicate OBIA methods can extract individual buildings in the WUI with high spatial resolution and with high degrees of accuracy. This method's ability to improve fine-scale WUI mapping efforts across large extents facilitates the development of WUI maps by identifying specific buildings likely to be affected by a wildfire. Stemming from this research effort, a building location dataset for Colorado was developed; this dataset is now available for use by local, state, and federal land managers and other researchers. The resulting dataset has helped incident management teams develop structure protection plans for multiple wildfires, including the 2017 Hayden Pass Fire that threatened several communities. The data was also used by the Upper South Platte Partnership--a regional forestry collaborative—to develop fire district response maps and prioritize fuel treatment locations.

This work builds on and exists between the body of literature that tests and evaluates remote sensing technologies (Hay & Costilla 2008), and the literature that maps values at risk in the WUI at fine scales (Lowell et al. 2010, Calkin et al. 2011, Bar-Massada et al. 2013). It evaluated the ability for OBIA methods to extract individual building locations; this is a very specific application of OBIA methods, but one with potentially numerous implications for WUI mapping and wildfire management. This work indicates possible avenues for future applied research. As remote sensing technology improves, there will continue to be a need to evaluate the accuracy and efficiency of new imagery processing approaches for different purposes, including the ability to extract WUI building locations. Using the approach employed herein, efforts could also track WUI development over time by extracting building locations from vintage imagery (Platt et al. 2011). Paring such temporal data with fire models, or results of post-fire case studies could provide insight as to how the wildfire risk profile of buildings in the WUI is changing over time (Syphard et al. 2013), how it is predicted to change in the future in light of other disturbances (Liu et al. 2015, Syphard et al. 2019), or how it varies spatially between different regions (Alexandre et al. 2016, Syphard & Keely 2019).

5.2 Quantifying Spatial Distribution of Home Loss

Chapter three quantified the spatial and temporal distribution of WUI disasters and associated building loss. It investigated patterns of building loss in wildfire disasters using both spatial and non-spatial datasets, including Incident Status Summary reports, multiple datasets of burned and unburned building locations, landcover, and fire perimeters. After documenting the occurrence of WUI disasters, it evaluated the ability of point-based and polygon-based WUI maps to capture building loss. It then employed heuristic approaches to assess patterns of building loss relative to the range of values for individual WUI components (building density, vegetation cover, and proximity to wildland vegetation). Using building locations to examine the frequency and distribution of WUI disasters and associated home loss builds on chapter two. The findings from chapter three can inform multifaceted community-based wildfire protection strategies by assessing buffer distances used to estimate wildfire exposure, quantifying loss in interface and intermix areas, and by developing maps with specific locations of at-risk buildings likely to be affected by wildfires.

In the United States between 2000 and 2018 there were 91 wildfires that each burned more than 50 buildings: we classified these as WUI disasters. These fires cumulatively burned 56,783 buildings. Across all fires, Census-based mapping approaches classify 86% of building loss in WUI areas (56% intermix and 30% interface), with 14% of building loss occurring outside of the WUI. Point-based WUI maps classified 97.0 percent of all buildings lost in WUI disasters as being in either the wildland-urban interface or intermix. Using Census-based mapping methods, most non-WUI losses were identified in either areas of vegetation and low housing density (9%), or non-vegetated areas with high housing density (5%). Individually, twelve fires experienced a majority of loss (>50%) in non-WUI categories. Results from the point-based analysis indicate losses primarily occurred in areas with low building density, high vegetation cover, and short distances to wildland vegetation, but also indicate that building loss occurs across a wide range of building densities (0.3 to 960 buildings per km^2) and vegetation covers (from 0 to 100%), and up to 850 m from large patches of continuous vegetation. For point-based maps, WUI components are best measured at fine scales, and doing so can more accurately capture building loss relative to Census-based approaches. Reducing WUI buffer distances used to calculate proximity to wildland vegetation can improve point-based WUI maps by excluding buildings at low risk of igniting during a wildfire (greater than 850 m from wildland vegetation). By assessing how well WUI mapping methods capture building loss, we can refine mapping techniques to exclude buildings at low risk and focus attention on buildings at higher risk. This has multiple implications for wildfire management, where managers must identify high risk areas and prioritize funding and planning efforts.

5.3 Implications of this Research and Future Research Opportunities

By identifying WUI disasters, the patterns of building loss within fire perimeters, and the ability of WUI maps to capture that loss, this analysis builds from bodies of literature that examine patterns of building loss in WUI disasters (Cohen & Stratton 2008, Graham et al.2012, Maranghides 2015), and the literature that examines how modifying WUI mapping protocols affect estimates of values at risk (Radeloff et al. 2005, Stewart et al. 2007, Bar-Massada et al. 2013). This work develops new estimates of WUI disaster thresholds, and uses empirical patterns of loss to refine WUI buffer distances. These advances are critical for land management agencies tasked with mapping the WUI. Managers require maps that accurately identify homes at risk for multiple applications, including quantitative risk assessments and structure protection plans. These findings also contribute to the literature by proposing home loss thresholds that can be used to define WUI disasters, and presenting a framework that can be used to track whether wildfire impacts on WUI communities worsen over time (Cohen 2008, Calkin et al. 2014). The analysis that relates building loss to building density, vegetation cover, and proximity to vegetation contributes to literature that examines the efficacy of policy decisions and mitigation activities for reducing risk of home loss (Cohen 2000, Miller et al. 2016).

Further research could conduct sensitivity analyses to examine how changing buffer distances changes estimates of values at risk in the WUI created from point-based maps (Bar-Massda et al. 2013). It could also examine regional differences in the total number of WUI buildings or total extent, or explore how higher resolution vegetation data could further refine estimates of buildings at risk. This work could have important implications for prioritizing hazardous fuel reduction efforts, and working with communities to develop more nuanced understandings of risk and the efficacy of mitigation.

Excluding those buildings beyond several hundred meters from wildland vegetation that are at low risk of ignition, and updating buffer distances to refine estimates of values at risk can improve WUI maps and inform quantitative wildfire risk assessments (Scott et al. 2013). Findings can also help identify areas where county building codes, defensible space, and use of fire-resistant building materials can most effectively reduce building loss (Maranghides and Mell 2012), and help prioritize fuel treatment locations for managers (Addington et al. 2020). At a national scale, managers could track whether WUI disasters and/or associated building loss is increasing over time. This would complement other efforts to track increases in suppression costs, insured losses, wildfire severity, or loss in ecosystem services (USDA 2015).

5.4 Gaining Qualitative Understanding of Stakeholder Expectations

Chapter four compliments the spatially-based approaches in chapters two and three using a more social science based and qualitative approach to understand differences in stakeholder expectations of wildland fire mitigation. Specifically, it focuses on defensible space and fire response during wildfires. It examines the efficacy of defensible space mitigation and fire response activities, as well as the interactions between the two, and the general uncertainty surrounding wildfire, fire mitigation, and fire response. My results indicate that perceived efficacy of defensible space was influenced by numerous factors, including the quality of defensible space, scales of mitigation, firefighting resources, and potential fire behavior. Perceived efficacy depended on how stakeholders saw the purpose of defensible space, i.e., whether defensible space was meant to facilitate firefighter intervention or enable a home to stand alone and survive without intervention. Numerous participants thought defensible space mitigation would mostly be ineffective against large wildfires, because (1) mitigated homes were the minority in many neighborhoods, and (2) the defensible space as implemented for the majority of mitigated homes was of poor quality. These findings demonstrate WUI stakeholder understandings of the social and ecological processes that unfold during WUI disasters, and how those factors that can either mitigate or exacerbate building loss. This study also underscores the degree to which wildfire risk is co-managed by various stakeholders and the different agencies and understandings stakeholders each has over specific mitigation and response activities.

This work builds off a large body of literature that focuses on WUI stakeholder perspectives on wildfire risk (McCaffery et al. 2013). It contributes to these efforts by examining the differences in risk perceptions between groups and the interactions between fire mitigation and fire response that complicates the perceived efficacy of stakeholder actions (McCaffery et al. 2008, Meldrum et al. 2015). Future research is needed to examine why homeowners have high expectations of wildfire mitigation before a fire occurs, but complain of mitigation and response efficacy in a fire's aftermath (Guerin 2017, Lasky 2018). These findings about the intricacies and interrelated nature of mitigation and response can align stakeholder expectations regarding home ignition by examining the interactions between the two. They articulate the need to acknowledge our differing confidence in mitigation and fire response, and the range of conditions under which either are likely to be effective. Aligning expectations can help diffuse contentious interactions between different WUI stakeholders tasked with co-managing wildfire risk by addressing interrelated nature of wildfire mitigation and response (Paveglio et al. 2015).

Conclusion

In all, my work has led to a better understanding of WUI disasters as spatial phenomena. It has developed and evaluated new techniques that are capable of quantifying changed in WUI development at fine spatial and temporal scales, and allow more accurate mapping of buildings and values at risk in the WUI. It also allows for a more nuanced understanding of stakeholder perspectives on wildfire risk, and how mitigation and response work together. While wildfires and the problems they bring with them will surely grow in the future, gains will come from evaluating new technologies and mapping approaches and working with a diverse range of stakeholders, researchers, managers, and practitioners to co-manage wildfire risk. The solutions to wildland-urban interface related problems are best achieved using interdisciplinary approaches that account for multiscale ecological and social complexities, and that focus on stakeholder-driven questions. I am optimistic that my work and other applied research in this vein can facilitate effective wildfire management at appropriate scales, and encourage communities to live well with fire.

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