The Thesis committee for Holly Muree Bonine

Certifies that this is the approved version of the following thesis:

Understanding Wildfire Hazards in the Eastern Edwards Plateau

APPROVED BY

SUPERVISING COMMITTEE:

Supervisor: ______________________________

Sarah Dooling

____

Mark Simmons

Understanding Wildfire Hazards in the

Eastern Edwards Plateau

by

Holly Muree Bonine, B.S.

Thesis

Presented to the Faculty of the Graduate School

of the University of Texas at Austin

in Partial Fulfillment

of the Requirements

for the Degree of

Master of Science in Community and Regional Planning

The University of Texas at Austin

August 2013

Understanding Wildfire Hazards in the

Eastern Edwards Plateau

by

Holly Muree Bonine, MSCRP

The University of Texas at Austin, 2013

Supervisor: Sarah Dooling

ABSTRACT

Trends indicate that wildfires have become larger and more intense over the past few decades. Experts suggest this is due to multiple factors including long-term shifts in land use that disrupt the balance of fuels and fire regimes. Research predicts that climate change will exacerbate this trend but will do so in spatially variable ways across the globe, causing increases in fire activity for

some regions and decreases for others. In the United States, increased wildfire activity combined with the rapid expansion of residential development in fire-prone land necessitate billions of dollars in suppression efforts every year to protect human lives and property. The confluence of these issues has catalyzed momentum for communities to actively participate in mitigation at the local level. Yet, the precursor to developing effective solutions is to understand the unique environmental and social components of wildfire hazards at local and regional scales and how these components influence the deleterious impact of fire.

This thesis takes a case study approach to understanding and communicating wildfire hazard potential in the Edwards Plateau ecoregion of central Texas. Wildfire simulations were conducted at the regional scale to quantify the magnitude of predicted fire behaviors under various spatial and temporal conditions. Simulations were also conducted within two focal communities to illuminate how patterns of wildfire susceptibility overlap with residential development. Finally, an investigation was made into the emergency response infrastructure and mitigation strategies adopted by each of the focal communities.

As a result of simulations under drought conditions, forty-four percent of the study area exhibited flame lengths over eleven feet and ninety-six percent of the tree canopy exhibited crown fire activity. Simulations also revealed an increased potential for crown fire activity and extreme flame lengths along the heavily-populated Balcones Escarpment. Third, physical forms of communities appeared to influence the spatial distribution of burn susceptibility. Finally, the infrastructure and practices of the surrounding region impacted community resilience to wildfire hazards. While these findings are specific to the eastern Edwards Plateau, they showcase how mixed methods can be used to build a comprehensive wildfire hazard assessment for a community.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ACRONYMS

ANCOVA	Analysis of Covariance
CWPP	Community Wildfire Protection Plan
ESD	Emergency Services District
FB	Fire Behavior
ISO	Insurance Services Office
MTT	Minimum Travel Time
NIFC	National Interagency Fire Center
NOAA	National Oceanic and Atmospheric Administration
NWCG	National Wildfire Coordinating Group
RAWS	Remote Automatic Weather Station
RSG	Ready, Set, Go!
USDA	United States Department of Agriculture
WUI	Wildland Urban Interface

GLOSSARY OF TERMS

ADAPTATION:	The process or action undertaken by a system in order to better cope with future hazards resulting from global change.
BIOPHYSICAL VULNERABILITY:	A system that physically occupies a hazard zone.
COMMUNITY:	Groups of individuals that share some jurisdictional boundary as well as a set of resources and infrastructure.
HAZARD:	A disturbance that has the potential to cause harm or damage to a system.
RESILIENCE:	The ability of a system to respond and recover from a hazard.
SOCIAL VULNERABILITY:	The sensitivity of a community to loss or damage from a hazard, tempered by the characteristics, infrastructure, and practices within that community.

VULNERABILITY:	The condition of a system that is susceptible to loss or damage measured at a static point in time or produced through many mechanisms as material conditions of being vulnerable are translated through a recursive process.
WILDFIRE:	Unplanned fires that burn in natural areas such as forests, shrub lands, grasslands, or prairies.

CHAPTER 1: INTRODUCTION

1.1: STATEMENT OF THE PROBLEM

Images of residential neighborhoods pinned behind a backdrop of catastrophic wildfires have been all too common in the United States media since the beginning of the twenty-first century. Many sources confirm that this publicity is the result of a veritable trend toward larger, more intense wildfires occurring in areas where residential development and fire-adapted landscapes merge. Moreover, numerous federal, private, and academic institutions are predicting that this trend will continue as a consequence of human-altered fire regimes, climate change, and the continued expansion of communities into areas prone to wildfire activity. Practical solutions are critical to saving lives and property from future harm. Yet the complex interaction of ecological and social factors that make communities susceptible to harm is not universal. Instead, the heterogeneity of fire-adapted ecosystems and the diverse character and practices of each community require the development of unique solutions to meet their needs.

Reports from the National Interagency Fire Center (NIFC) indicate that the area of land that burns every year during wildfire events has been increasing since 1980 (Figure 1.1). Simultaneously, NIFC reports show that the number of fires per year has not increased indicating that the increased burned area is a result of larger fires rather than more frequent fires (NIFC 2009). Of equal concern is that these larger fires are materializing despite increased federal, state, and local funding to suppress them (Stephens and Ruth 2005, NIFC 2009). The suppression cost in 2012 of federal agencies alone was just under two billion dollars, over double the amount spent in 1994, and almost four times the cost in 1990 (Figure 1.2) (NIFC 2013a).

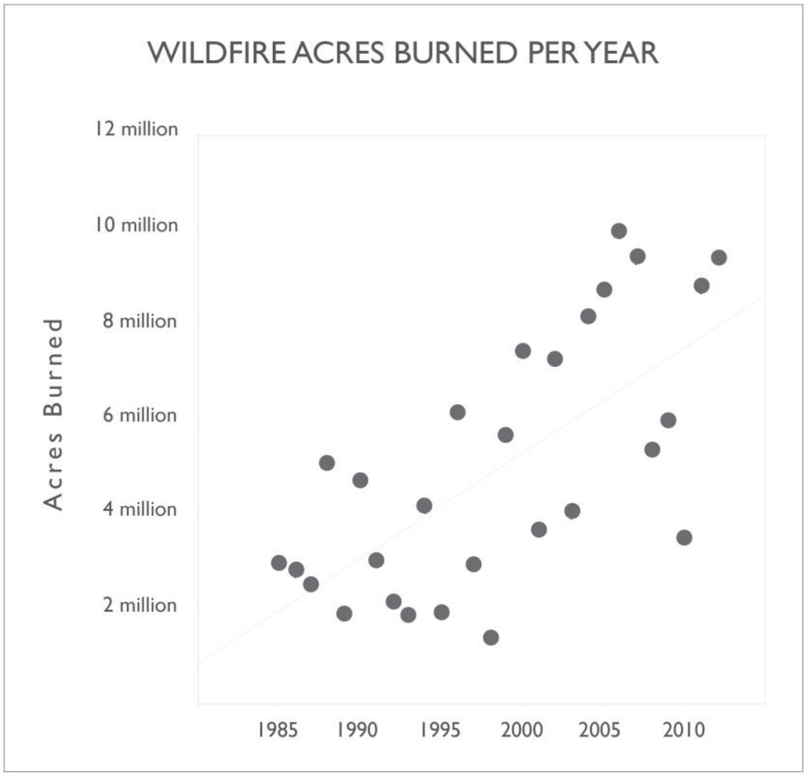

Figure 1.1: The annual area burned during wildfire events (NIFC 2013).

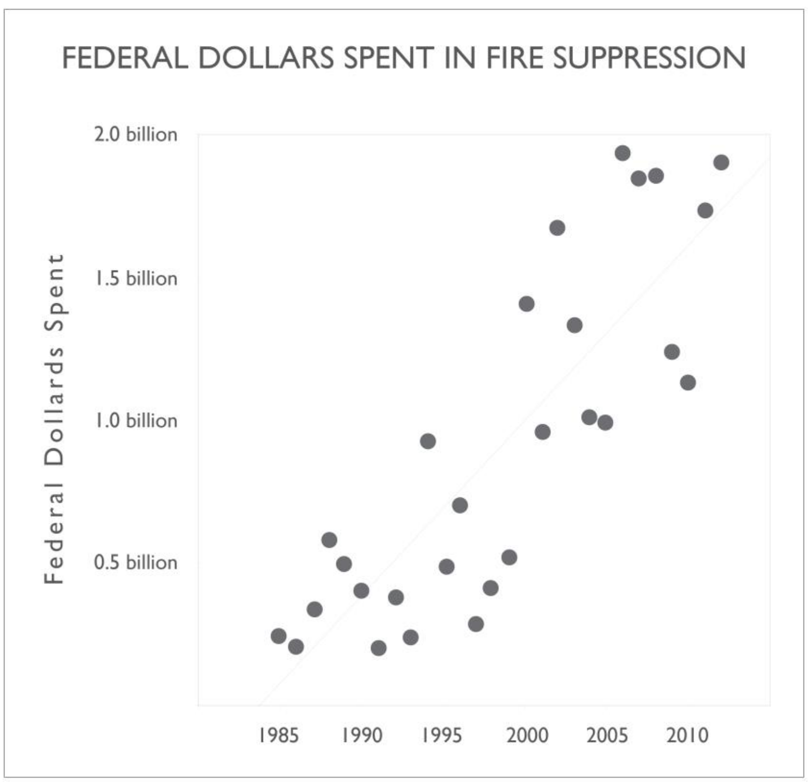

Figure 1.2: Annual dollars spent to suppress wildfire events (NIFC 2013).

Considerable research conducted by government, academic, and private institutions has been dedicated to investigating the larger fires of the twenty-first century. The general consensus across disciplines is that the occurrence of larger wildfires is due to an inextricable partnership between fire exclusion, climate change, and fuel abundance, which results in drastically variable outcomes across geographies (Stephens and Ruth 2005, Westerling et al. 2006, Headwaters Economics 2009, NIFC 2009, Moritz et al. 2012, USDA Forest Service 2013). Natural fire regimes, the cycle of fire to which plant and animal species have evolved in concert and which have shaped and sustained ecosystems since the origin of terrestrial plants on the earth, are being altered dramatically by humans (Bowman et al. 2009). This is mostly through the suppression of fire and changes in land use, but fire regimes are also altered through invasive species and shifts in temperature and precipitation (USDA Forest Service 2013). The accumulation and increased flammability of fuels create the dangerous conditions that we face today, but the degree to which a region experiences increased wildfire activity is geographically-specific. Studies on the relationship between fuel and climate are required at regional or local scales in order to better predict how fire will behave in the future for a given location (Moritz et al. 2012).

Although it is widely accepted that the suppression of fire leads to increased fuel abundance, fire suppression continues to be the dominant practice in order to protect human lives and property, which is the primary federal fire policy agenda (Stephens and Ruth 2005). This necessity is linked to the increase of local residential development in areas that are prone to wildfire activity. These areas, coined the wildland urban interface (WUI) were calculated to contain thirty-nine percent of the housing units in the United States in 2000 and are continuing to grow (Radeloff et al. 2005, Stewart and Radeloff 2012). Increased funding for suppression, a concern of federal agencies and taxpayers alike, has been insufficient in reducing the size of wildfires and the damages that residents in the WUI incur. The National Oceanic and Atmospheric Administration (NOAA) publishes a list of weather and climate related disasters that result in over one billion dollars in damages, a rough metric of extreme national disasters, dating back to 1980. The first wildfire event to show up on that list was in 1991. Since then wildfires have made an increasing appearance (Table 1.1), with six of the past seven years making the list (NOAA 2013). The calculations made by NOAA do not include federal, state, and local suppression costs.

YEARS WILDFIRES MADE THE NOAA BILLION DOLLAR DISASTER LIST

Decade	Years Listed as a NOAA Billion Dollar Disaster	Number of Years in the Decade
1980 – 1989		0
1990 – 1999	1991, 1993, 1994	3
2000 – 2009	2000, 2002, 2003, 2006, 2007, 2008, 2009	7
2010 – Present Day	2011, 2012	2... and counting

Table 1.1: Years wildfires appeared on the NOAA Billion Dollar Disaster List (NOAA 2103).

A review of the NIFC's list of wildfires that burned over one hundred thousand acres in the United States between the years 1997 and 2012 (NIFC 2013b) reveals that large fires typically occur west of the Great Plains. Due to this, the public generally perceives wildfires to be a problem only in western states (Cohen 2008, USDA Forest Service 2013). However a much smaller fire can cause devastating damage to a community. A map published by the USDA Forest Service in 2013 displaying the location of structures lost during wildfire events between 1999 and 2011 confirms that fires are not just a problem in western states (Figure 1.3). Only a few states on the map were free from damage, while other states such as Texas, Oklahoma, Minnesota, and Florida all suffered losses of more than one hundred structures during one wildfire event.

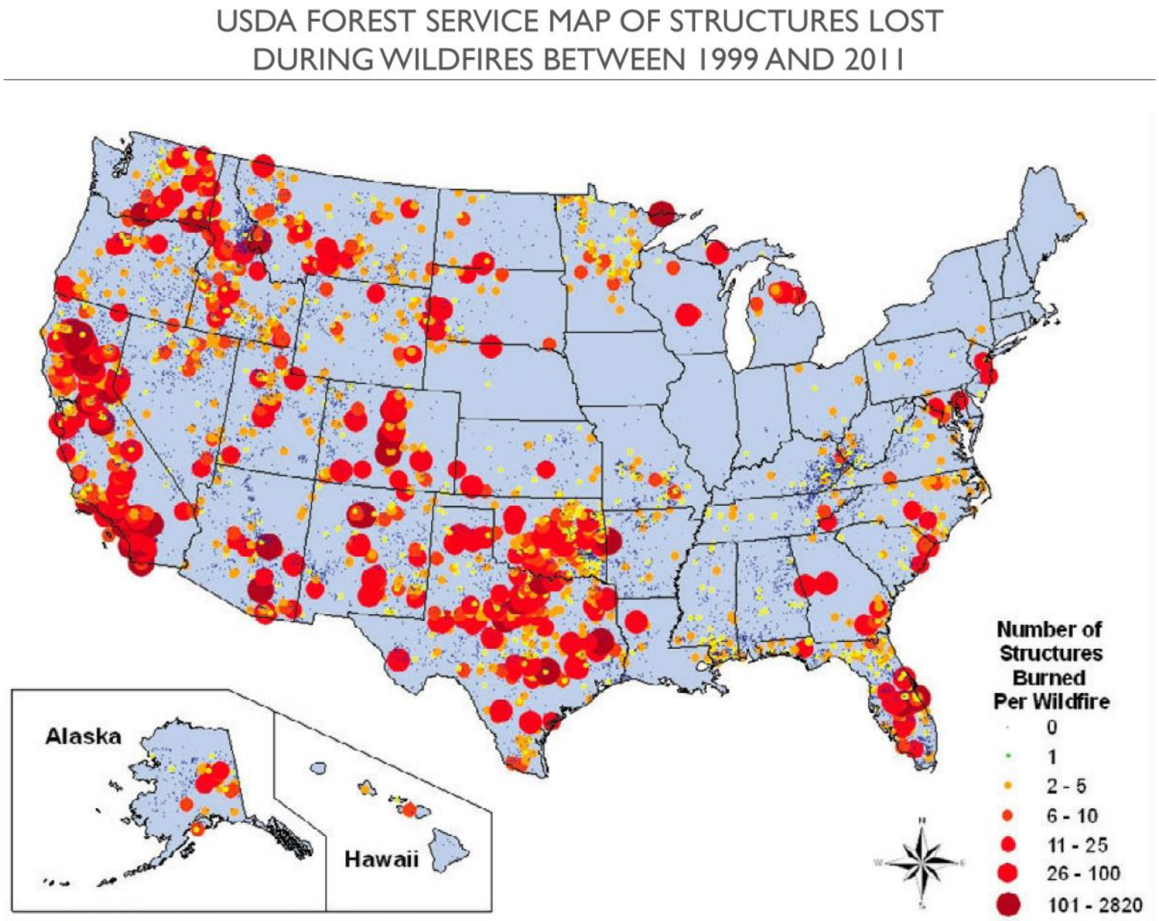

Figure 1.3: Structures lost to wildfire between 1999 and 2011. Published by the USDA Forest Service in 2013.

Given these facts, that wildfires are bigger and more costly, causing more damage in the expanding WUI and affecting much of the United States, there has been a push by policy makers for local governments and citizens to participate in deriving solutions. Partially this is to address the strained federal budget by making local governments shoulder more financial responsibility in suppressing fires and thus incentivizing changes to local development that aim to protect citizens (Stephens and Ruth 2005). However involving local governments and citizens in decision making has additional merits. A nation-wide, or even state-wide, approach to mitigating wildfire cannot realistically meet the needs of the diverse communities it intends to serve. Finding a solution that will help protect a community from damage caused by wildfire events relies foremost on understanding a complex and dynamic interaction of ecological and social elements specific to each locality then developing place-specific strategies to meet the challenge (Cutter and Finch 2008).

1.2: RESEARCH OBJECTIVES

This thesis takes a case study approach to investigating both the ecological and social elements of wildfire hazards in the fire-prone eastern Edwards Plateau ecoregion of central Texas. For the purposes if this thesis, a hazard is defined as a disturbance that has the potential to cause harm or damage to a system. Not all wildfires, as will be discussed in Chapter 2, are considered hazards, for they typically play an essential role in supporting healthy ecosystems.

The primary research objectives are to understand the potential for wildfire hazards in the eastern Edwards Plateau as well as how communities, i.e. groups of individuals within some jurisdictional boundary that share resources and infrastructure, are responding to the potential. Specifically, the research seeks to: i) quantify the expected magnitude of wildfire behavior under various spatial and temporal conditions using simulation modeling, ii) map the susceptibility to wildfire in areas where residential development co-occurs with fire-prone land, and iii) investigate the ways in which communities adopt strategies and develop infrastructure to mitigate potential wildfire hazards.

The results of these objectives are intended to communicate wildfire hazard potential in a way that is meaningful at multiple scales. If solutions are to be derived through the cooperation of local governments and residents, then both entities need to understand how wildfire hazards affect the community as a whole as well as how wildfire hazards affect single neighborhoods. While the outcome of this thesis is specific to the eastern Edwards Plateau, the methods can be easily applied to any community.

1.3: ROADMAP TO THE FOLLOWING CHAPTERS

Chapter 2 begins by outlining the socio-ecological framework for studying environmental hazards that was used to structure this thesis. The framework contains three main components: the hazard, systems occupying the hazard zone, and the resilience and adaptive strategies of systems exposed to the hazard. A background of the environmental controls of wildfire, the WUI, and mitigation tactics are provided. The chapter then concludes with a description of the study area, its landscape, population, and summary of wildfire events in 2011, which was an active fire season for the region.

Chapter 3, the research design chapter, details the three methods used to meet the research objectives. First, the potential for wildfire hazards in the region is explored through fire simulation modeling. Variation in fire behavior that results from moderate and extreme summer weather conditions is tested and the vegetation and topographic characteristics that correlate with more extreme fire behavior are identified. Following this, the investigation continues at a smaller scale by looking at two communities of approximately equal populations: one unincorporated community bordering the Austin city limits; and one incorporated community in the middle of rural Kendall County, the city of Boerne, Texas. The boundaries of these communities are defined by the fire department jurisdictions that serve them. Simulation modeling is used at this scale to determine the spatial distribution of areas susceptible to burning as well as the potential for extreme fire behavior within the jurisdictions. Finally data on how these communities respond to wildfire hazards now as well as the actions they are taking to respond to wildfire hazards in the future are compared.

The results of these three methods are supplied in Chapter 4 and discussed in Chapter 5. Under moderate weather and climate conditions, the predicted fire behavior for the region was mild. However, periods of drought, a gust of twenty mile per hour winds, or a two week interval of dry, hot days all led to substantial increases in the predicted surface and crown fire activity in the simulations. Furthermore, the highest concentrations of crown fire activity and most extreme flame lengths occurred closer to areas inhabited by people along the IH 35 corridor linking the cities of Austin and San Antonio.

Mapping susceptibility to burning in the two focal communities highlighted the importance of urban form in wildfire susceptibility patterns.

Boerne had a smaller, but denser, urban form than the unincorporated community outside Austin. This form correlated with lower burn susceptibilities and lower occurrences of extreme fire behavior. In direct contrast, the community outside Austin had a greater response capacity and greater access to external resources than those available to Boerne.

Overall, this project shows that simulation modeling can be an effective tool in understanding wildfire hazard potential in WUI communities and communicating that potential hazard in metrics that are easy to interpret. Further research into the ignitibility and spread of fires among residential structures as well as the efficacy of property-level fuel management are important future steps in deriving successful mitigation strategies.

CHAPTER 2: BACKGROUND

2.1: INTRODUCTION TO CHAPTER 2

Wildfires, defined by the USDA Forest Service as unplanned fires that burn in natural areas such as forests, shrub lands, grasslands, or prairies (2013), are invaluable to the health of many ecosystems yet simultaneously constitute a threat to the lives and property of people living in the wildland urban interface (WUI). This is the consequence of a two part problem: i) wildfires are larger and more severe due to dramatic human-induced changes in fire regimes, fuel accumulation, and climate change (Bowman et al. 2009, Miller et al. 2009); and ii) a large percentage of housing units are located in the WUI, which necessitates immense budgets for suppression and drains potential funds for preventative mitigation (Stephens and Ruth 2005). The two part problem is best described as a socio-ecological system in which human actions and environmental processes are inextricably linked. Solutions aimed at mitigating these threats require attention to both the ecological and social aspects (Gallopin 2006).

2.2: A FRAMEWORK FOR HAZARDS IN SOCIO-ECOLOGICAL SYSTEMS

Investigations of environmental hazards are common in the research fields of vulnerability, global change, and sustainability and provide useful frameworks for illuminating complex relationships in socio-ecological systems. While scholars from various disciplines tend to disagree on technical definitions and the specific relationship of concepts within the socio-ecological framework, there is general agreement on some basic principles (Brooks 2003, Adger 2006). First there is a hazard to which a system is exposed, which could be a sudden event or gradual environmental degradation. Second there are biophysical elements (people, infrastructure, ecosystem functions, etc.) that are vulnerable to damage or loss as a result of being exposed to the hazard. Third, there is a societal response that tempers sensitivity to the hazard, which can be described as either the ability to cope with hazards, i.e. resilience, or the ability to evolve in the face of rapidly changing natural and human environment that brings about hazards, i.e. adaptation (Adger 2006).

A hazard, defined broadly as a threat to a system (Turner et al. 2003), is viewed as the onset of an event and measured in physical terms such as duration or magnitude. Deeper focus into hazards, though, includes delineating the conditions, both ecological and social, that lead to the hazard onset. These conditions can develop gradually through time as a result of anthropogenic activity or natural processes or come about quickly, such as in shifting weather patterns (Brooks 2003). Deriving meaningful solutions to environmental hazards, especially hazards aggravated by climate change such as wildfire, relies on understanding the conditions that lead to hazards and predicting how those conditions will change in the future.

Vulnerability has been defined in many ways, but the most harmonious definition in terms of wildfire hazards separates vulnerability into two parts. The first part of vulnerability is a measure of what physically occupies the hazard zone (Cutter 1996), in other words, what is in the path of the hazard and will likely result in damage. This can be seen as the biophysical vulnerability (Brooks 2003), and can include anything susceptible to damage such as humans, structures, habitat, livestock, water bodies, bridges, communication networks, etc.

However the proximity to the hazard is not the sole determinant of loss as a result of the hazard (Cutter et al. 2000, Turner et al. 2003), which leads us to the second type of vulnerability, social vulnerability. How sensitive a community is to loss or damage from a hazard is tempered by the characteristics, infrastructure, and practices within that community (Brooks 2003, Adger 2006). This indicates that attributes such as the use of poor building materials, the lack of emergency infrastructure, inadequate access to information and assistance programs, etc. can dramatically alter how vulnerable a system is to hazards (Brooks 2003).

A related but slight variant on social vulnerability is the concept of resilience. Resilience is the ability to of a system to respond and recover from hazards (Cutter et al. 2008). Simply stated, it is the erosion of resilience that leads to greater vulnerability and the buildup of resilience that minimizes vulnerability (Adger et al. 2005). Like vulnerability, resilience can be measured in terms of infrastructure or access to services and support systems, to name only a few factors. Others use demographic characteristics as broad proxies for vulnerability and resilience, indicating that income, age, gender, or ethnicity may correlate with the ability for a community to cope with hazards (Cutter et al. 2000, Cutter et al. 2003). Metrics of vulnerability and resilience are not easily quantifiable or standardized among fields. The appropriate method for measuring these attributes depends on the context of the socio-ecological system of interest (Adger 2006).

The final concept in this socio-ecological framework is the idea of adaptation. Adaptation is the process or action undertaken by a system in order to better cope with the constant metamorphosis of environmental hazards resulting from global change (Smit and Wandel 2006). Like resilience, more adaptation reduces vulnerability. Unlike resilience, it reflects the ability of a system to evolve in conjunction with hazards (Adger 2006). While resilience can be seen as ways of reducing vulnerability to hazards in the present, adaptation reflects the capacity of a community to reduce vulnerability both in the present as well as the future (Smit and Wandel 2006).

Unfortunately, many scholars have observed that strategies aimed at reducing vulnerability to environmental hazards are often neglected until a community is faced with an event. It is not until after a hazard occurs that mitigation is attempted (Adger et al. 2005, Smit and Wandel 2006, Cutter et al. 2008). Yet protecting communities from the increase in wildfire activity as a result of climate change require that adaptive strategies be put in place well before a wildfire occurs. It is critical that communities understand the environmental hazards they face and that mitigation strategies employed address the specific needs of the people and the environment that is affected (Cutter 1996, Cross 2001, Cutter and Finch 2008). The following sections of this chapter discuss current research on wildfire hazards borrowing the three part framework described above: the first section is a synthesis of the causes of wildfire hazards; the second section delineates what is susceptible to damage from wildfire; and the third section outlines mitigation strategies that are known to bolster resilience and adaptation to wildfire hazards.

2.3: WILDFIRE AS HAZARD

Wildfire has existed on earth since the origin of terrestrial plants over four hundred million years ago. Along with climate, fire has been a major force in shaping the ecological communities that persist today (Bowman et al. 2009, Pausas and Keeley 2009). These communities have evolved in conjunction with fire and rely on the essential functions fire provides, such as nutrient cycling, soil conservation, foraging opportunities, and new habitat (USDA Forest Service 2000a, USDA Forest Service 2005). Thus classifying wildfire as only a hazard would be remiss of its merits. Within the boundaries of this thesis, wildfire is only defined as a hazard when it threatens human lives and property or when damage to a natural system outweighs the environmental benefits it receives.

Fire is a component of a dynamic system made up of its interactions with climate and vegetation (USDA Forest Service 2000b, Parisien and Moritz 2009). Climate is widely recognized as a dominant factor in the range and distribution of vegetation that have gradually shifted through time in response to climatic variation (Pearson and Dawson 2003). Weather patterns, interspecies interactions, and the presence of fire have shaped the composition and abundance of vegetation, which then affect how fire behaves. Climate also affects fire behavior by controlling the moisture content of vegetation, influencing its flammability, and contributing to the spread of fire through wind speed and direction. In return, vegetation and fire impact climate through the detention or release of carbon into the atmosphere (USDA Forest Service 2000b).

Fire behavior is typically characterized by metrics of an active fire. Basic descriptions include spread rates, flame lengths, how much energy was released, or whether the fire remained on the surface or spread to tree canopies, resulting in crown fire activity. Crown fire activity is further characterized by passive versus active fire behavior. According to the USDA Forest Service, an active crown fire includes a wall of flames from surface to crown that seem to engulf an entire fuel complex rather than individual trees or small clusters, which is indicative of passive crown fires.

Fire severity, on the other hand, is a measure of how much organic matter was consumed once a fire event is complete. While severity is a culmination of fire behavior and vegetation, it reflects the results rather than the characteristics of a fire (Keeley 2009). Fire regimes are commonly described in terms of return frequency and severity. While it is understood that fire regimes vary as result of fluctuations in climate, vegetation, fire system, broad fire regime classifications have been made that help elucidate how fire is spatially distributed (Figure 2.1). Once anthropogenic activity reached a level that greatly altered vegetation communities and excluded fire from occurring naturally, humans became a major force in modifying fire regimes (Pausas and Keeley 2009). Combined with the prediction that climate change will rapidly bring about new temperature and precipitation patterns as a result of human activity (IPCC 2007), the natural variability of fire regimes will be replaced with even greater uncertainty about global fire patterns (Krawchuk et al. 2009, Bowman et al. 2011).

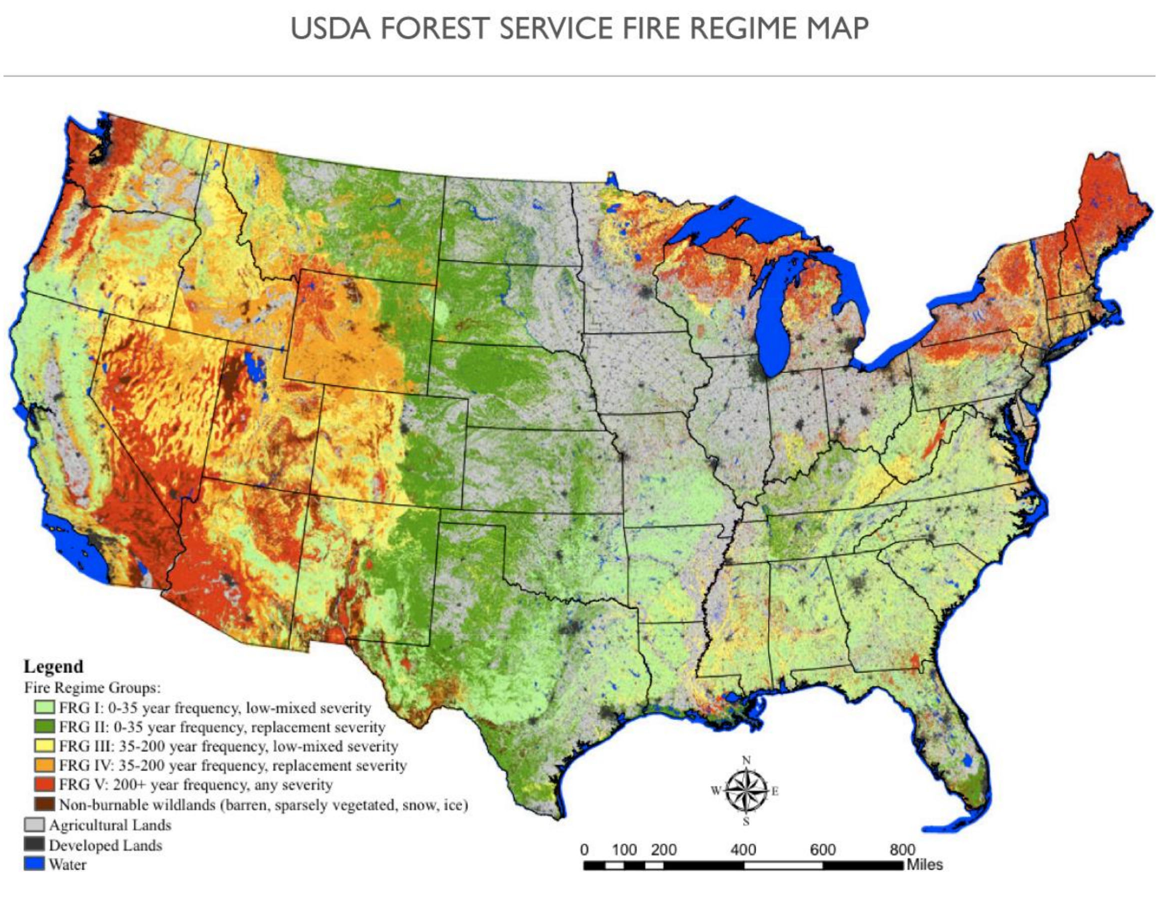

Figure 2.1: Map of fire regimes in the United States. Map obtained from the USDA Forest Service (2013).

How future climate change will impact fire regimes is a subject that has received a lot of attention in the past ten years due to the uncertainty that it brings to our understanding of global fire patterns. Marlon et al. (2009) looked at evidence of fire regime changes in the paleorecord and found that periods of rapid climate change correlated with rapid shifts in fire activity. Research on tree mortality has shown that recent fluctuations in climate have caused increased tree mortality and susceptibility to burning through physiologic stress (Van Mantgem et al. 2009, Allen et al. 2010). Recent climate change, within the past few decades, has also been linked to longer fire seasons (Brown et al. 2004, Westerling et al. 2006), larger fires (Westerling et al. 2006, Flannigan et al. 2009), and higher resulting fire severity (Miller et al. 2009).

These studies all agree that climate change has an impact on fire activity, which promotes the idea that future fire activity as a result of the rapid changes in climate predicted to occur in this century should be a major policy concern (Schroter et al. 2007). What these studies also agree on is that climate-impacted fire activity varies considerably across the globe. A study by Moritz et al. (2012) that predicted future global fire activity using multiple climate change models illustrates this spatial variability. In any given climate model, some areas are predicted to see significant increases in fire activity while others are expected to see decreases in fire activity. This is likely due to climate change impacts on species ranges and distributions over time. However, there is little agreement among the models regarding where these changes will occur. Thus we have evidence that fire activity will change drastically, but no direct indication of where. To ensure that each region understands the range of possible outcomes as a result of climate change, regional studies are required (Moritz et al. 2012).

It is unrealistic to assume that we can ever return to the fire regimes that existed a century ago given the massive amounts of land use change, fire exclusion, and invading species that have occurred. However, we do have the ability to influence fire behavior and severity through managing fuels. Restoring landscapes to reduce fuel loads is widely accepted as a proactive strategy to address future fire uncertainty (Agee and Skinner 2005, Stephens and Ruth 2005, USDA Forest Service 2013). Practices such as mechanical, chemical, or biological (grazing) reduction of vegetation, as well as prescribed burning have been proven to mitigate hazards through reducing surface fuel, increasing the height of live tree crowns, and weeding out highly flammable species while retaining fire-resistant species (Agee and Skinner 2005). Studies have shown that these methods reduce overall tree mortality during unplanned fires (Stephens et al. 2009). They also ameliorate fire behavior, including flame lengths and ignition susceptibility near structures (Finney 2001, Ager et al. 2010).

It has also been shown that the pattern of fuel reduction carried out influences its effectiveness. Optimized patterns of fuel reduction have been proven to protect ecosystems and minimize overall fuel reduction needs (Finney 2008), yet direction for optimizing fuel patterns is highly dependent on place-specific attributes and goals and practical guides for land managers are lacking. Furthermore, fuel management that successfully protects residents in the WUI relies on cooperation among multiple private property owners, which can create barriers to fulfilling fuel management objectives (Fernandez and Botelho 2003). In fact, a study in 2009 by Schoennagel et al. showed that, of the fuel treatments conducted by federal agencies between the years of 2004 and 2008, only three percent were carried out in the WUI. Considering that reducing fuels in the WUI is one the major objectives in the National Fire Plan, three percent appears low. The authors point out that this is due to much of the WUI being under private ownership, which is beyond federal control.

2.4: BIOPHYSICAL VULNERABILITY TO WILDFIRE HAZARDS

Biophysical vulnerability to wildfire hazards is an account of systems physically within the wildfire hazard zone that are susceptible to damage or loss from a fire. In some instances highly severe wildfires can actually cause more harm than help to an ecosystem, especially when the system is undergoing another stress, such as drought or species endangerment. Severe fires can destroy critical species habitat (Miller et al. 2009) or expose large areas of soil to erosion (Benavides-Solorio and MacDonald 2001). Riparian areas typically provide buffers against fire and refuge for animals waiting out the event, however when riparian conditions are overly dry, they can instead act as conduits to spread fire farther (Pettit and Naiman 2007). Ecosystem damage can also affect human infrastructure. For example, the 1996 Buffalo Creek fire in Colorado resulted in two million dollars in flood damage and twenty million dollars in damage to Denver's water supply from large amounts of eroded sediment (USDA Forest Service 2013).

The biophysical vulnerability of greatest policy concern, though, is that of human life and property (Stephens and Ruth 2005). Much of the United States population today is living within the WUI. In 2005, Radeloff et al. mapped the WUI for the United States using US Census housing data from the year 2000 and the definition of what constitutes the WUI as recorded in the Federal Register. According to the Federal Register, WUI contains at least one housing unit per forty acres with no maximum density and is either dominated by wildland vegetation (intermix communities) or is within the vicinity of wildland vegetation (interface communities). Radeloff et al. interpreted this definition to include all census blocks with at least one housing unit per forty acres that are more than fifty percent vegetated or within 2.4 km of a block that is more than seventy-five percent vegetated. The 2.4 km length represents the distance that an ember can travel from a wildfire (Radeloff et al. 2005). Given this definition, the team found that thirty-nine percent of housing units in 2000 were in the WUI, which was found to be a significant increase since 1970 (Figure 2.2) (Radeloff et al. 2005, Theobald and Romme 2007).

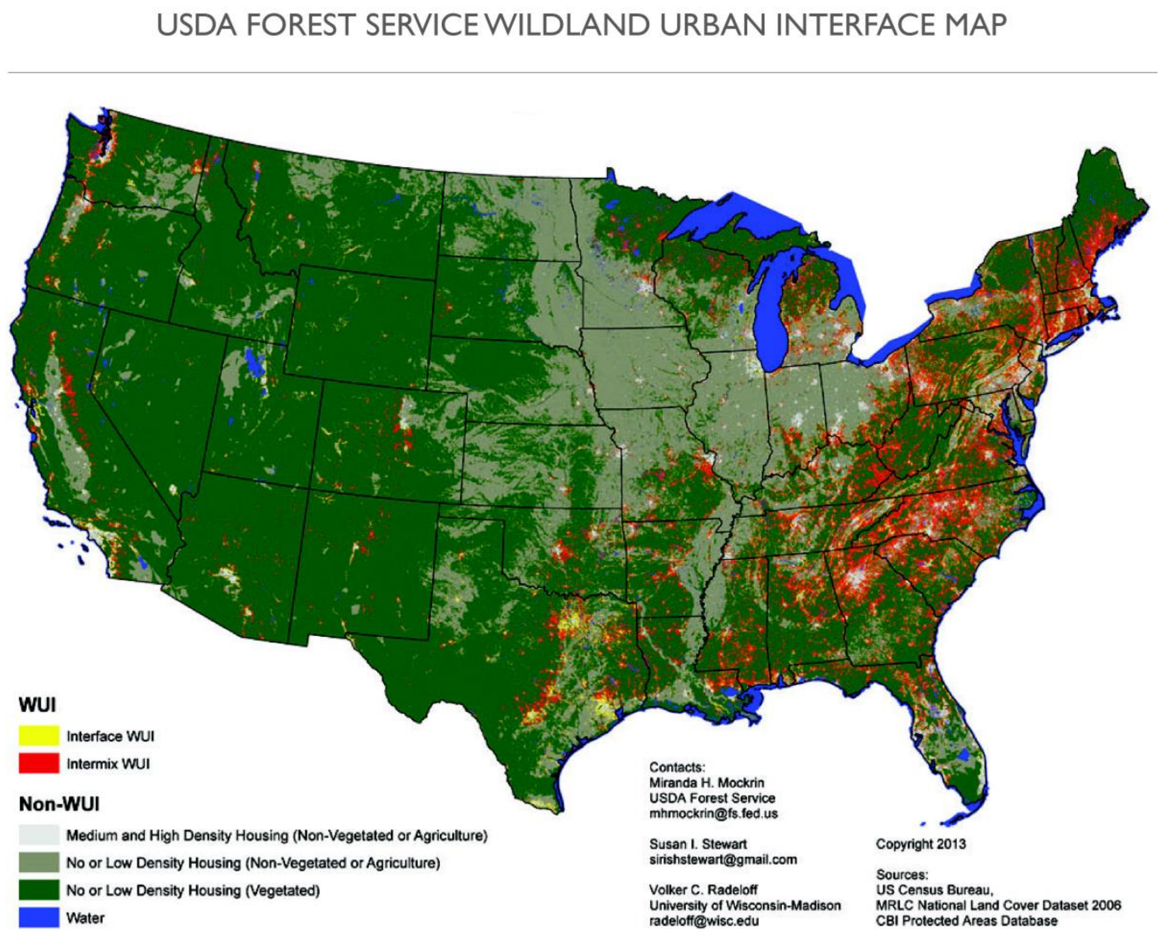

Figure 2.2: Map of the WUI in the United States. Map obtained from the USDA Forest Service (2013).

The reasons for the expansion of the WUI are not well documented, but researchers have attributed it to an affinity that Americans have for rural settings, particularly ones rich in natural amenities (Radeloff et al. 2005). Others suggest that local codes and regulations fail to steer private development away from highly hazardous areas of the WUI (Headwaters Economics 2013). An econometric analysis from 1970 to 2000 conducted by Olmstead et al. in 2012 showed that increases in federal efforts to suppress wildfire in specific federally-managed lands correlated with subsequent increases in development near those lands, which indicates, according to the authors, that federal actions to mitigate hazards inadvertently promoted growth in hazardous areas.

No matter how development patterns change, there will always be some portion of the housing units in the United States that are situated in the WUI. What is important is that each community understands how much of their housing stock overlaps with areas susceptible to wildfire activity so that they can derive solutions that work for them (Paveglio et al. 2009).

2.5: RESILIENCE AND ADAPTATION TO WILDFIRE HAZARDS

Research on how and to what extent communities prepare for potential wildfire hazards shows substantial variation among the communities studied. This variation is attributed to the diversity of residents based on experiences, demographic characteristics, and access to information and resources (Jarrett et al. 2009, Paveglio et al. 2009, Eriksen and Prior 2011). For instance, residents in longer-established communities may have more experience with wildfires and thus been inspired to adapt to future threats, whereas residents of newer communities may not understand the threats they potentially face (Eriksen and Prior 2011). Attitudes, beliefs, and experiences have also been shown to affect the level of community cooperation in carrying out a fuel management plan (Fischer and Charnley 2012). The degree to which a community is organized has been shown to impact how they approach mitigation. Communities with well-defined organization, or communities that organize for the sole purpose of addressing potential wildfire hazards, have shown to be effective in implementing mitigation. Understanding that there is not a one size fits all solution to wildfire hazards is an important concept in designing adaptive strategies that will lead to real benefits in a community (Paveglio et al. 2009).

Based on the growing expense of wildfire suppression, and the fact that many communities are ill-prepared for wildfire hazards, several government agencies have been promoting community awareness and community planning as a way to mitigate future harm. Part of the federal Healthy Forests Restoration

Act of 2003 included the promotion of community wildfire protection plans (CWPP), a planning process that incentivizes communities to assess their risk and establish priorities for mitigation in return for possible grants and fuel management assistance (USDA Forest Service 2013). Research has shown that the process improves the ways that residents communicate within a network and solve problems beyond wildfire protection (Jakes et al. 2007a, Jakes et al 2007b, Paveglio et al. 2009). However, CWPP's have been criticized for not requiring public participation. A CWPP that is conducted without public input fails to encourage communication among residents or measures toward taking personal responsibility (Brummel et al. 2010).

The Firewise program is another strategy that encourages communities to engage in wildfire protection planning but with a focus on informing residents on best practices for their property. Initiated by the National Fire Protection Association in the 1990's, this program certifies communities as “Firewise” based on a set of criteria the community must carry out including an official hazard assessment, a plan that addresses the assessment, an annual public outreach event, and a two dollar per capita annual investment to fund local Firewise initiatives (www.firewise.org). Standards for creating fuel-free buffers around structures, coined defensible space, and using fire-resistant building materials are key tools promoted by the program (USDA Forest Service 2013). Yet, researchers have argued that while property-level mitigation tactics, such as defensible space and fire-resistant building materials, are recognized for their benefit to hazard reduction, they are in great need of more in depth testing (Cohen 2008, Gill and Stephens 2009, Mell et al. 2010).

In 2011, the International Association of Fire Chiefs released recommendations for a wildfire hazard strategy that is intended to blend with CWPP's, Firewise programs, as well as any other local strategies already in place. The program is called Ready, Set, Go! (RSG) and comprises a more comprehensive set of wildfire hazard strategies than the CWPP or Firewise programs alone. It includes multi-level planning, from fire departments to neighborhoods to families, and focuses on both preventative strategies like the Firewise program as well as improved emergency management during a wildfire event (www.wildlandfirersg.org). It is the only program of its kind that emphasizes the need for emergency planning at both the household and community-wide scales.

Resilience to wildfire hazards necessitates incorporating RSG principles. First and foremost, strategies for protecting human life once a wildfire occurs are critical. Notifying residents, having access to adequate emergency staff, and having access to evacuation routes are all ways of building resilience to wildfire hazards. Second, implementing strategies that minimize fire behavior around structures greatly increases the chances that property can be saved. Both of these principles require that the public understands the potential wildfire hazards in their area and how wildfire hazards vary with climate.

Overall, this broad body of wildfire literature highlights an understanding that wildfire hazards will increase as the climate changes and that each year more people will be affected as the WUI expands. The literature also strongly indicate that the degree to which wildfire hazards change will vary dramatically among regions and that taking a regional or community-level perspective on wildfire hazards is the best way to derive effective solutions.

This thesis takes a multi-scaled, case study approach to understanding potential wildfire hazards for a region in central Texas. The eastern Edwards Plateau is known to be prone to wildfire activity, is simultaneously experiencing rapid population growth, and is predicted to experience increased average temperatures and periods of drought as a result of climate change. Through the use of simulation modeling, this thesis looks at the variation in wildfire hazards under mild to extreme weather and climate conditions. This process helps predict the magnitude and location of wildfire hazards for the region as climate change proceeds. The thesis also examines two WUI communities within the region that are each experiencing population growth and are indicative of two types of development that take place in central Texas: regulated growth in incorporated cities, and unregulated growth in unincorporated suburbs. In doing so, the thesis highlights the wildfire hazard potential at the community and neighborhood scales.

2.5: STUDY AREAS

The Edwards Plateau ecoregion is located in central Texas and contains two of Texas' largest cities linked by the IH 35 corridor, Austin and San Antonio (Figure 2.3). Synonymous with the Texas Hill Country, the region is noted for its distinctive hydrologic features created by a karst aquifer system and is prominently delineated by the Balcones Escarpment on the eastern and southern edges. Figure 2.4 shows two maps of the eastern portion of the ecoregion containing the Balcones Escarpment. The shaded relief map, which spans in elevation from three hundred feet above sea level to two thousand feet above sea level, highlights the curved edge of the escarpment at approximately eight hundred feet. Likewise, the tree canopy map shows a denser canopy of juniper-oak woodlands that have established themselves along the highly eroded canyons and separate the region from the Coastal Plains to the east. Moving west, the ecoregion shifts into a savanna that has been experiencing woody species encroachment as a result of overgrazing and fire exclusion. Unlike this eastern portion, the northern and western delineation of the Edwards Plateau ecoregion are not well-defined and have been interpreted differently by multiple sources (Johnson 2013).

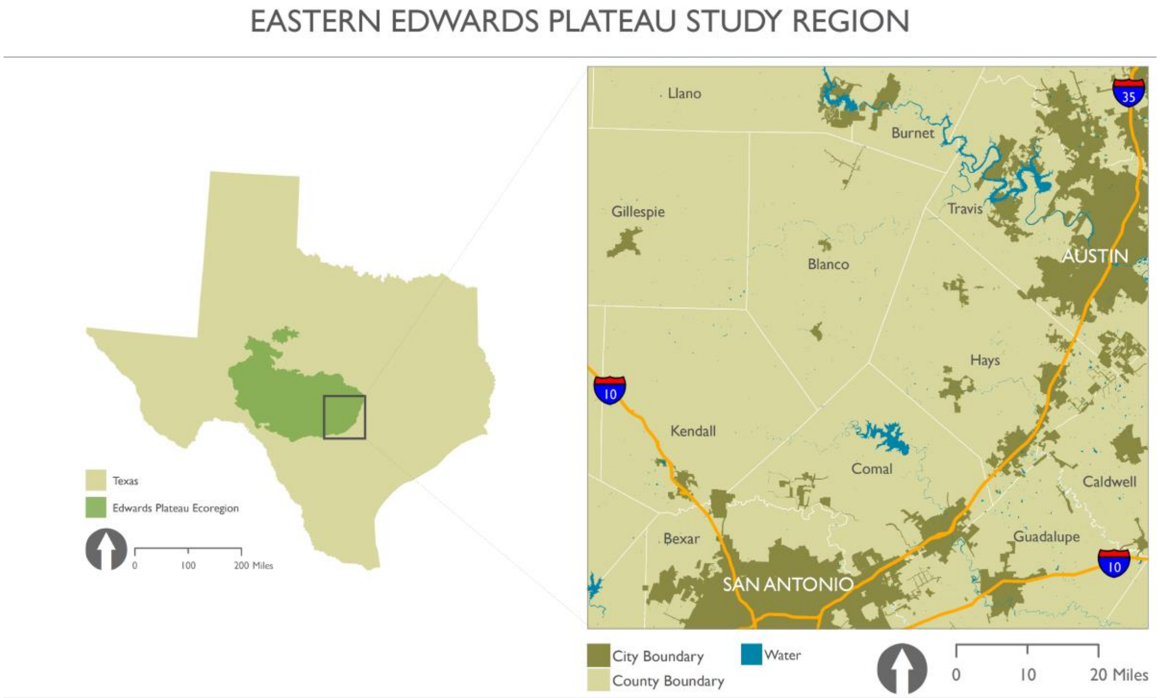

Figure 2.3: Edwards Plateau ecoregion and study extent.

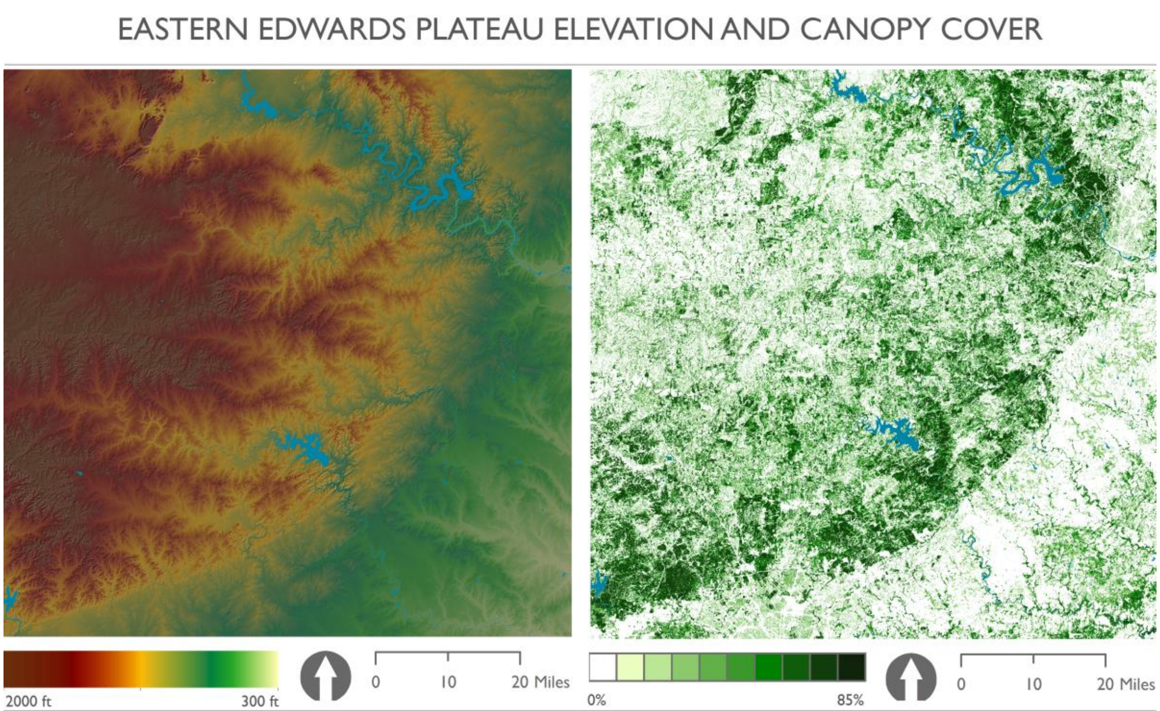

Figure 2.4: Eastern Edwards Plateau elevation (ft) and canopy cover (percentage).

Just as the landscape shifts from east to west, so does the population density west of the IH 35 corridor. The eastern portion of the Edwards Plateau contains the majority of the population in the region due to the growth of Austin, San Antonio, and the cities in between. According to the Texas County Profiles website, the four counties along the IH 35 corridor grew between twenty-three and sixty-one percent from the year 2000 to 2010 (http://www.txcip.org/tac/census/CountyProfiles.php) and are predicted to continue growing between twenty and sixty-four percent between 2010 and 2020 (http://txsdc.utsa.edu/). According to WUI data made available by Radeloff through the Spatial Analysis for Conservation and Sustainability lab at the University of Wisconsin, approximately seventy-seven percent of this region's housing units in 2010 were in the WUI (http://silvis.forest.wisc.edu/) (Figure 2.5).

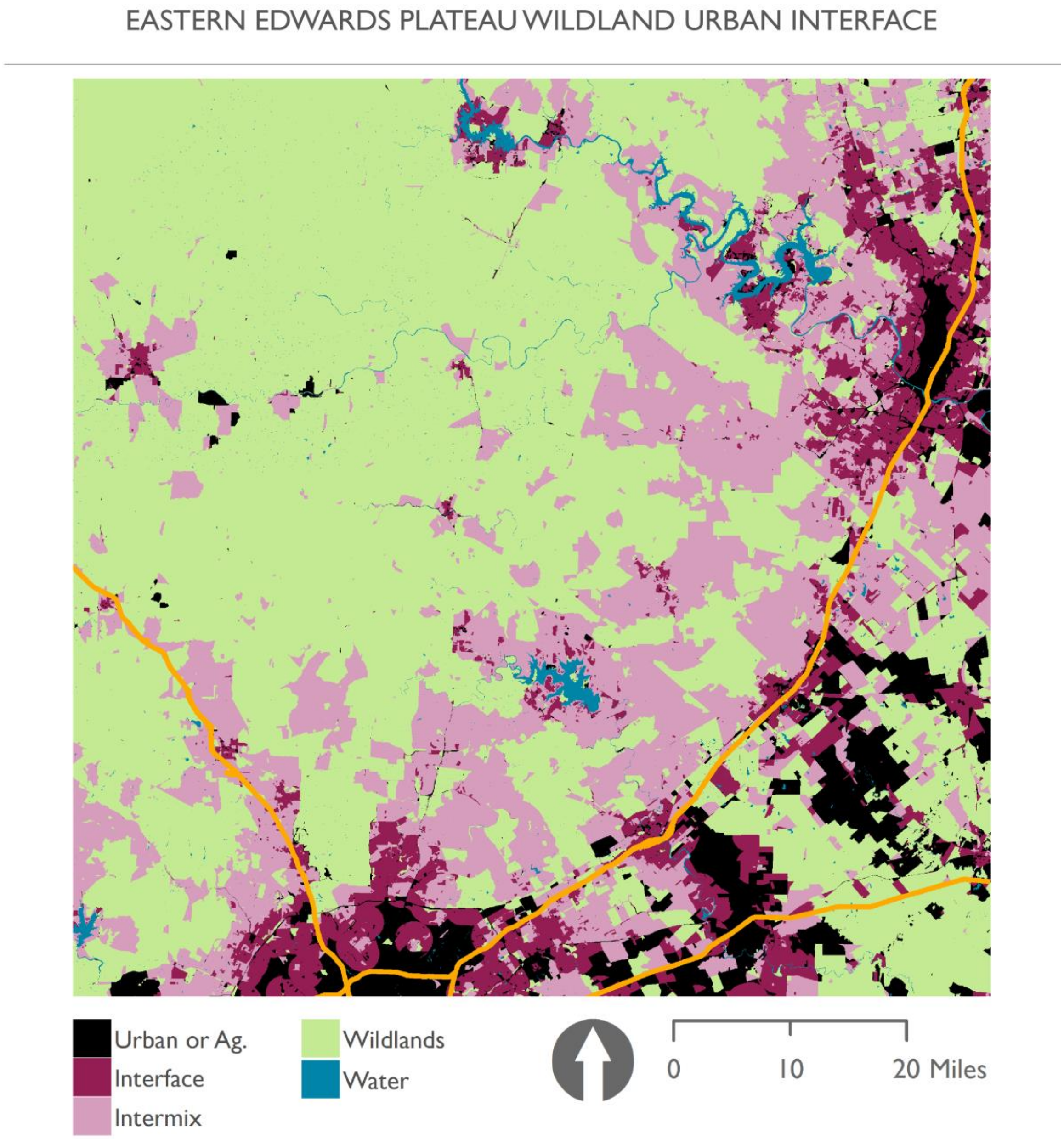

Figure 2.5: WUI of the eastern Edwards Plateau. Data from 2010 US Census and University of Wisconsin.

The year 2011 was an active fire season for Texas. The eastern Edwards Plateau ecoregion experienced numerous fires, most notably the Pedernales fire that burned sixty-five thousand acres (Lee 2012). On the same day as the Pedernales fire, September 4, 2011, a fire in the Steiner Ranch neighborhood west of Austin burned over one hundred and sixty acres and destroyed or damaged over fifty homes (Travis County Fire Marshal's Office 2011). Earlier in the year, the Oak Hill neighborhood in southwest Austin experienced an urban wildfire that burned approximately one hundred acres and destroyed ten homes while damaging another eleven (Lee 2011).

The magnitude of fire behavior during the 2011 fire season is largely attributed to the most severe one-year drought on record for Texas. This fact raises concerns about the potential for wildfire hazards in the near future as predictions indicate that average temperatures and the frequency of drought will increase (Texas A&M Forest Service 2011). According to a Texas climate change study in 2012, average summer temperatures could increase between 2.2 and 4.8 degrees Celsius in central Texas by 2100 and precipitation patterns will be variable but likely lead to more arid conditions (Jiang and Yang 2012).

The recent occurrence of wildfire events, a growing population, and the climate change predictions make the eastern Edwards Plateau an ideal case study for assessing wildfire hazards through a socio-ecological framework. The first objective of this thesis is to quantify the expected magnitude of wildfire behavior under various spatial and temporal conditions using simulation modeling. The spatial variation tested is the gradient of vegetation and topography that exists across the eastern Edwards Plateau extent. The temporal variation tested is a set of eight weather and climate scenarios that range from mild summer conditions to the extreme conditions of September 4, 2011.

The second and third objectives of this thesis require focus on communities within the eastern Edwards Plateau extent. In order to map wildfire susceptibility in WUI areas and investigate mitigation strategies adopted by communities, two smaller extents were selected (Figure 2.6). The first is an area just beyond the Austin city boundary in Travis County, Texas. Outside the city limits emergency protection is provided by emergency service districts, which are authorized by the state to form and collect taxes from their district for the purpose of protecting health and wellbeing of the community (Jarrett and Anchondo 2012). The Travis County emergency service district number three

(ESD #3) forms the boundary of this extent. The Travis County ESD #3 is also called the Oak Hill Fire Department because it used to serve the entire unincorporated Oak Hill community before half of Oak Hill was annexed by Austin in 2000. Now the Oak Hill Fire Department serves the remaining unincorporated neighborhoods of West Oak Hill as well as the unincorporated Barton Creek neighborhood directly north with a total population of almost fifteen thousand individuals in 2010 and a land area of over twenty-six thousand acres. In Texas, county governments have limited authority over growth and development. Thus growth that occurs in unincorporated areas is largely unregulated beyond protecting basic health and safety (Capital Area Council of Governments 2009).

The second study extent is located fifteen miles northwest of the city limits of San Antonio in the small city of Boerne, Texas. Boerne is the county seat of rural Kendall County, Texas and had a population of almost fourteen thousand people in 2010. The Boerne Fire Department provides fire protection services to this population as well as a large land area outside the city limits. For the purposes of this study, the municipal jurisdiction serves as the study area boundary, which is roughly sixty-five hundred acres.

TRAVIS COUNTY ESD #3 AND BOERNE STUDY EXTENTS

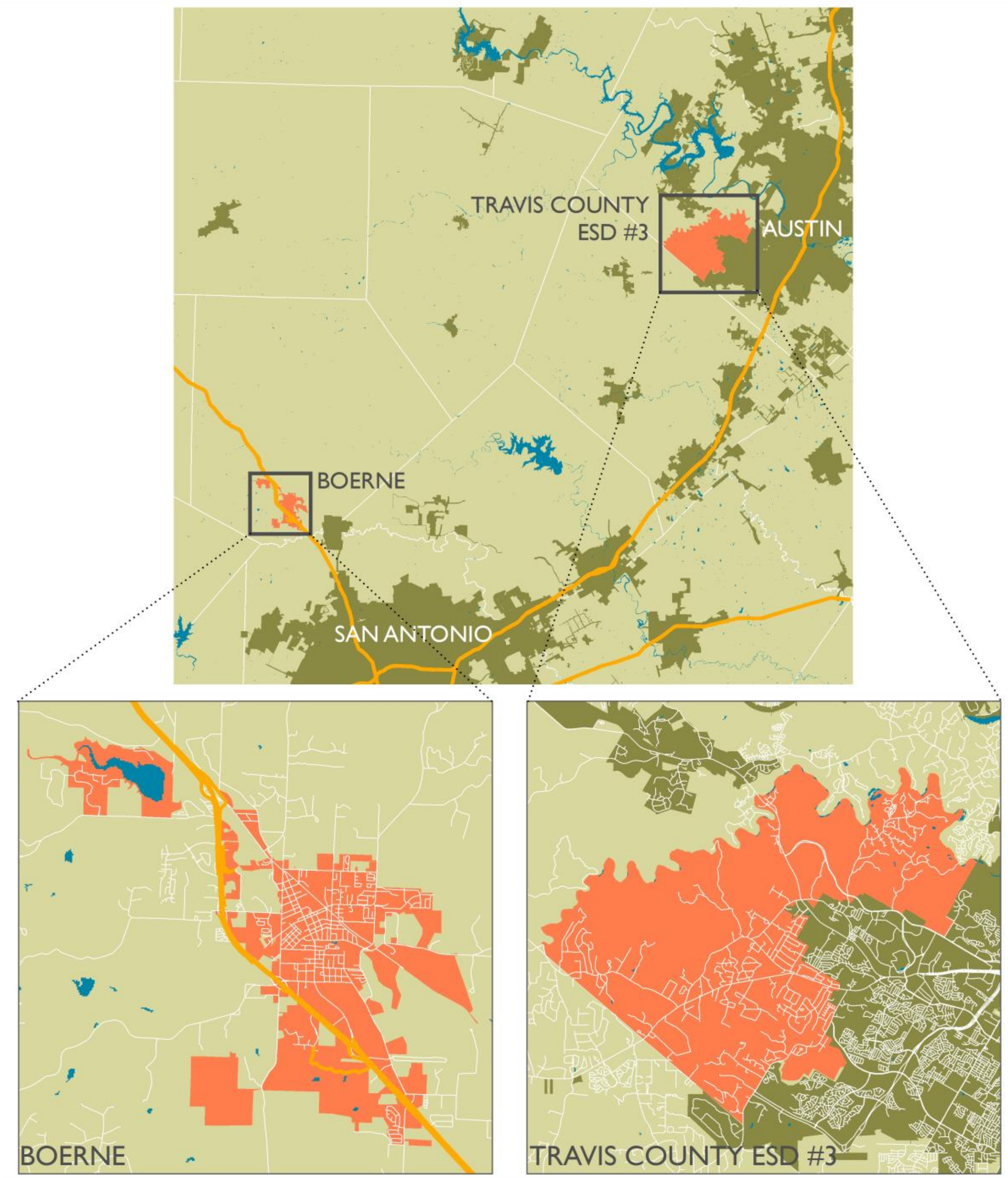

Figure 2.6: Location and population density of Travis County ESD #3 and Boerne study extents.

CHAPTER 3: RESEARCH DESIGN

3.1: INTRODUCTION TO CHAPTER 3

Chapter 3 details the data collection and data analysis used in this thesis. Three methods were employed to investigate wildfire hazards in the eastern Edwards Plateau. Each method is tailored to answer one of three research questions beginning with an examination of fire behavior at the regional scale before narrowing the focus to wildfire hazard susceptibility and mitigation at the scale of the communities served by two fire department jurisdictions, the Travis County ESD #3 and the Boerne City Fire Department. This integrated approach addresses both the ecological and social dimensions of wildfire hazards to not only identify the magnitude and location of potential hazards but also how communities in the eastern Edwards Plateau confront wildfire risk as the regional population continues to expand.

The first research method employs fire simulation software developed by the USDA Forest Service, FlamMap Fire Behavior (FB), to analyze the region's expected wildfire behavior under eight weather scenarios ranging from a mild, calm September day to an overly hot, dry, and windy September day. The second method also uses simulation software developed by the USDA Forest Service but instead focuses on recreating the September 4, 2011 weather conditions at the community scale. The same FlamMap FB software is used with the addition of FlamMap's Minimum Travel Time (MTT) application, which explores the susceptibility to wildfire spread in areas that co-occur with residential development. The third research method compiles and synthesizes information obtained from public records and personal communications on the wildfire response capacity in each of the focal communities as well as any measures instituted by the communities to reduce wildfire hazard potential.

The succeeding sections state the research questions, describe the data collection methods, describe the data analysis methods, and provide a discussion of the assumptions and limitations of each approach.

3.2: RESEARCH QUESTIONS

QUESTION 1: What is the expected range of wildfire behavior in the eastern Edwards Plateau during conditions that range from an average September day to an overly hot, dry, and windy September day and what are the influences of weather, climate, topography, and vegetation in the observed variation of wildfire behavior?

Sub-question 1a: What are the expected flame lengths, rates of spread, and crown fire activity levels that result from simulated wildfires in eight weather scenarios ranging from an average September day to an overly hot, dry, and windy September day in the eastern Edwards Plateau?

Sub-question 1b: How much do three fire-inducing conditions, increased wind speed, decreased fuel moisture, and hotter, dryer days, increase the magnitude of flame lengths, rates of spread, and crown fire activity under simulated wildfire events in the eastern Edwards Plateau?

Sub-question 1c: What is the correlation between landscape structure, i.e. topography and vegetation characteristics, and the variation of flame lengths, rates of spread, and crown fire activity observed across eastern Edwards Plateau under simulated fire events?

QUESTION 2: What are the expected spatial distributions of wildfire susceptibility and wildfire behaviors and the in two WUI communities in the eastern Edwards Plateau under September 4, 2011 weather conditions?

Sub-question 2a: What is the spatial distribution of areas susceptible to burning under September 4, 2011 wind speeds, fuel moisture, and temperature and precipitation conditions for the Travis County ESD #3 and Boerne study areas?

Sub-question 2b: What areas are predicted to experience flame heights over eleven feet and active crown fire activity from simulated wildfire events that mimic the September 4, 2011 wind speeds, fuel moisture, and temperature and precipitation conditions for the Travis County ESD #3 and Boerne study areas?

QUESTION 3: What is the current capacity of the Travis County ESD #3 and Boerne City Fire Department to respond to wildfire hazards in order to protect the lives and property of residents and what plans, programs, or strategies have the communities within each fire department jurisdiction adopted for mitigating wildfire hazards now an in the future?

Sub-question 3a: What is the emergency response capacity of the Travis County ESD #3 and the Boerne City Fire Department in terms of notifying and evacuating residents during wildfire emergencies, responding to wildfire events, and coordinating with surrounding fire departments?

Sub-question 3b: What plans, programs, or strategies, such as those promoted by the CWPP or Firewise programs, have the communities within each fire department jurisdiction adopted for the purpose of building resilience to wildfire hazards and what, if any, actions indicate that plans, programs, and strategies may be adopted in the future?

3.3: DATA COLLECTION

Data collection for the thesis falls into three broad categories. Data was either obtained from using wildfire simulation software, compiled from publicly available documents or data warehouses, or collected from personal communication with representatives of state, county, and local agencies. In order to perform the wildfire simulations, input data from multiple sources is also required. The following three subsections describe the FlamMap wildfire simulations, mapping the FlamMap results within the two WUI communities, and the collection of fire department response capacity and local mitigation plans, programs, and strategies.

3.3.1: FLAMMAP WILDFIRE SIMULATIONS

FlamMap is a free fire behavior modeling program developed by the USDA Forest Service, Rocky Mountain Research Station, and Systems for Environmental Management. FlamMap simulates fire events over a digital replication of a real landscape, made up of a grid of cells with values for elevation, slope, canopy height, etc. The user defines weather and climatic conditions to be tested, which remain constant through the duration of the simulation. The program has two functions that are used in the present thesis, the Fire Behavior (FB) function and the Minimum Travel Time (MTT) function.

FlamMap FB measures the expected fire behavior, such as flame lengths, for each grid cell in the landscape under a given set of weather and climate conditions. It assumes that each cell has been ignited and calculates how the cell responds. To collect the necessary simulation data to answer Question 1, I input data files that describe the study extent's landscape and designed eight weather and climate scenarios to be tested. To collect the necessary simulation data to answer Question 2, I input landscape data files corresponding to the smaller extents and designed one weather scenario mimicking September 4, 2011 conditions. The completed simulations produce three output data files for each simulation with measures of flame length, rate of spread, and crown fire activity.

The chances of a real fire behaving exactly how it has been predicted by MTT are slim given the shifts in wind and temperature in a real fire event. However the MTT simulations are capable of highlighting areas that are more susceptible to wildfire events. The benefit of the MTT software is not to track how one fire might move across the landscape, but instead to predict how susceptible the landscape is to burning. This is a subtle but important difference from fire behavior prediction. The predicted fire behavior in given cell assumes that the cell is already ablaze, but it does not predict if the cell would ignite given that its neighbor is ablaze, which is what MTT seeks to address.

3.3.1.1: FlamMap Landscape Inputs

Raster input data files required by FlamMap include: three topographic layers, four canopy structure files, and one fuel model layer. Table 3.1 lists the data files input into FlamMap and their descriptions. Each raster is made up of a grid of thirty meter by thirty meter cells, simply called thirty meter resolution, which each measure approximately one quarter of an acre. Each cell contains the average value for that cell, for example, the average elevation or slope over nine hundred square meters. For an example of the quantity of data contained in each raster, the eastern Edwards Plateau study extent contains 19,071,324 grid cells.

FLAMMAP LANDSCAPE INPUT DATA

File Name	Description	Units	Resolution	Created By	Accessed From
Aspect	Azimuth of sloped surfaces	Azimuth degrees	30 m	USGS	www.landfire.gov
Elevation	Distance above sea level	Meters	30 m	USGS	www.landfire.gov
Slope	Percent change in elevation	Percent	30 m	USGS	www.landfire.gov
Fuel Model	40 Scott and Burgan Fire Behavior Fuel Models	Categorical	30 m	LANDFIRE	www.landfire.gov
Canopy Bulk Density	Density of available canopy fuel	Kg per cubic meter * 100	30 m	LANDFIRE	www.landfire.gov
Canopy Base Height	Average height from ground to bottom of canopy	Meters * 10	30 m	LANDFIRE	www.landfire.gov
Canopy Cover	Percent of cell covered by canopy	Percent	30 m	LANDFIRE	www.landfire.gov
Canopy Height	Average height of top of canopy	Meters * 10	30 m	LANDFIRE	www.landfire.gov

Table 3.1: Input raster data files required for FlamMap modeling.

3.3.1.2: FlamMap Weather and Climate Settings

The following weather and climate conditions need to be set by the user for all FlamMap simulations: wind direction, wind speed, fuel moisture, foliar moisture, and the fuel conditioning period. Determining appropriate settings for simulations is a lengthy process requiring multiple sources of climate and weather data for the area. The weather data were obtained by using Remote Automatic Weather Stations (RAWS) for stations within the extent. This information is available through the website: www.raws.dri.edu. The data obtained from the RAWS stations were then confirmed using local weather station reports on WeatherSpark (weatherspark.com).

Based on historic average wind direction for the extent, all FlamMap FB simulations used the south-southeast wind trajectory. The effect of wind direction was not tested as a variable influencing fire behavior. Wind direction is, however, a critical component to how fire spreads from a cell to its neighboring cells and was varied in the MTT simulations. In order to increase the accuracy of susceptibility for each cell, eight directions were tested in the simulations: north, northeast, east, southeast, south, southwest, west, and northwest. For the set of eight climate scenarios I tested a mild and extreme wind speed. Based on historic average wind speeds across the extent, the scenarios tested five miles per hour as the mild speed and twenty miles per hour as the extreme speed.

FlamMap defines fuel moisture, the moisture content of surface fuels, as a set of five total measurements of percent moisture. Scott and Burgan (2005) derived a set of four states (Table 3.2), from high to very low fuel moisture content to be used in various fire behavior simulators including FlamMap. For the set of eight climate scenarios I tested a mild and extreme fuel moisture state: the moderate state, which represents a ninety percent fuel moisture content of live herbaceous fuels; and the very low state, which represents a thirty percent fuel moisture content of live herbaceous fuels.

SCOTT AND BURGAN FUEL MOISTURE STATES

		Very Low	Low	Moderate	High
Dead fuel	1-hour	3	6	9	12
Dead fuel	10-hour	4	7	10	13
Dead fuel	100-hour	5	8	11	14
Live Fuel	Herbaceous	30	60	90	120
Live Fuel	Woody	60	90	120	150

Table 3.2: Scott and Burgan's (2005) fuel moisture content (percent moisture) recommendations. The very low and moderate states were tested in the scenarios.

Scott and Burgan (2005) also recommend maintaining a foliar moisture setting, the moisture content of tree canopies, of one hundred percent for all simulations, which they claim to be a conservative calculation. However, the

USDA Forest Service's National Fuel Moisture Database (http://www.wfas .net/ index.php/national-fuel-moisture-database-moisture-drought-103) reports that average foliar moisture for Ashe Juniper and Live Oak measured within this extent ranges from fifty-nine percent to ninety-four percent moisture in August and September. Thus, for the FlamMap simulations, when a scenario has moderate fuel moisture content, the foliar moisture was set to one hundred percent, and when the fuel moisture is very low, the foliar moisture is set to sixty percent.

The fuel and foliar moisture settings describe the general state of fuels as a result of long-term temperature and precipitation patterns. If an area is undergoing a period of extended drought, it is presumed to resemble the very low fuel moisture state described by Scott and Burgan (2005). If an area is undergoing a rainy season, then the high fuel moisture state is presumed. Thus fuel and foliar moisture are a reflection of long term trends. In contrast, the fuel conditioning period setting in FlamMap effects fuel moisture in a shorter time scale. By inputting local RAWS data for a given period of time, FlamMap will "condition" fuels with precise daily temperature and precipitation measurements as well as hourly wind speeds. This process recreates more realistic fuel conditions than can be achieved by setting fuel moisture levels alone. Like the fuel moisture, I tested one mild and one extreme state of fuel conditioning.

As mentioned in Chapter 2, the year 2011 was an active fire year for Texas, and specifically September 4, 2011 for this extent. The Balcones RAWS is located within close proximity to the location of the Pedernales fire. Thus I used the Balcones RAWS data for the two weeks leading up to September 4, 2011 (August 22 to September 4, 2011) as the more extreme fuel conditioning period. Average daytime highs recorded at Balcones during this period were 103 degrees Fahrenheit (ninetieth percentile temperature for August) and there was no precipitation. For the less extreme case, I chose the same two week period for 2010. In contrast, the average daytime highs recorded at Balcones for this period were 97 degrees Fahrenheit (approximately the median August temperature) and there was over an inch of rainfall on September 3, 2010 (Table 3.3).

FUEL CONDITIONING PERIODS

RAWS	Year	Dates	Average Temperature	Rain Events
Balcones	2010	August 11 – September 4	97 degrees Fahrenheit	1.2 inches on September 3
Balcones	2011	August 11 – September 4	103 degrees Fahrenheit	None

Table 3.3: Fuel conditioning periods tested in the scenarios.

3.3.1.3: MTT Ignitions and Simulation Duration

In order to determine the correct number of ignitions and appropriate duration to use in the MTT simulations, a set of exploratory runs were conducted. For each simulation, FlamMap MTT calculates the number of times a cell has ignited and divides it by the total number of ignitions to give what they define as the burn probability. This calculation can be easily misinterpreted. Take an example where the user sets four ignitions that each burn for only one minute. Under normal conditions, these fires will be very small in size and are unlikely to spread to neighboring cells even of the neighboring cell is susceptible to burning. Yet, FlamMap will calculate a value of 0.25 for each of the cells that had the initial ignition and zero for all other cells. Thus the burn probability calculation is relative to the number of ignitions and the area burned by each ignition. The greater the number of ignitions and the longer the duration, the more accurate the burn probability calculations will be.

I conducted multiple test simulations to set these parameters. Comparing test simulations with one hundred, two hundred, three hundred, four hundred, and five hundred ignitions running for two hours showed that results converge above three hundred ignitions. Based on this I chose five hundred random ignitions, at two hours, to be run for each of the eight wind speeds. The result was a total of four thousand random ignitions.

3.3.1.4: Simulation Trials

For the FlamMap FB simulations, I designed eight scenarios combining the two wind speeds, two fuel moisture states, and two conditioning periods (Table 3.4). In order to assess the level of stochastic error between identical simulations, each unique scenario was run three times. If FlamMap FB gets a different measurement for a given cell between two identical runs, then that amount of variation needs to be taken into account when measuring differences between non-identical runs.

EIGHT WEATHER AND CLIMATE SCENARIOS

Scenario	Number of Repeats	Wind Speed	Fuel Moisture / Foliar Moisture	Fuel Conditioning Period
1	3	5	Moderate / 100	8/22 to 9/4 2010
2	3	20	Moderate / 100	8/22 to 9/4 2010
3	3	5	Very Low / 60	8/22 to 9/4 2010
4	3	20	Very Low / 60	8/22 to 9/4 2010
5	3	5	Moderate / 100	8/22 to 9/4 2011
6	3	20	Moderate / 100	8/22 to 9/4 2011
7	3	5	Very Low / 60	8/22 to 9/4 2011
8	3	20	Very Low / 60	8/22 to 9/4 2011

Table 3.4: Eight scenarios tested in FlamMap Fire Behavior simulations.

The outputs for each run included: one raster with the predicted flame lengths (in feet); one raster with the predicted rates of spread (in chains per hour, one chain equals sixty-six feet); and one raster with the predicted crown fire activity. Crown fire activity is given an integer score from zero to three, with zero being no fire activity, one being surface fire activity only, two being passive crown fire activity, and three being active crown fire activity. Table 3.5 lists the final set of explanatory variables input into FlamMap FB and response variables derived from FlamMap FB.

EXPLANATORY AND RESPONSE VARIABLES

Explanatory Variables			Response Variables
Topography	Vegetation	Weather/Climate	
Aspect	Fuel Model	Wind Speed	Flame Length (feet)
Elevation	Canopy Bulk Density	Fuel/Foliar Moisture	Rate of Spread (chains per hour)
Slope	Canopy Base Height	Fuel Conditioning Period	Crown Fire Activity 0 = no fire activity 1 = surface fire activity 2 = passive crown fire activity 3 = active crown fire activity
	Canopy Cover		
	Canopy Height		

Table 3.5: FlamMap FB simulation explanatory and response variables.

Table 3.5 describes two main types of variables used in the FlamMap FB modeling. The topography and vegetation, i.e. landscape, variables vary across space but remain constant between runs (spatially dynamic but temporally static). The opposite is true for the weather conditions. Weather remains constant across space for each run but varies between runs (spatially static but temporally dynamic). This distinction is important for Sub-questions 1b and 1c. While Sub-question 1b questions the temporal effect of weather and climate *between* runs, Sub-question 1c questions the spatial effect of landscape structure *within* runs.

The final resulting data collected from the FlamMap FB simulations is over 152,000,000 measurements for each response variable for a total of over 457,000,000 data points.

For the MTT simulations, only one set of weather conditions were applied with the exception of the eight wind directions. The simulation was deigned to mimic the September 4, 2011 weather conditions. To do so, the fuel moisture state was set to very low and the fuel conditioning period spanned from August 22, 2011 to September 4, 2011. The wind speeds on September 4, 2011 did reach seventeen to twenty-four miles per hour according to the Travis County Fire Marshal (Lee 2012). However it is unlikely that these wind speeds were sustained for two hours straight. Balcones RAWS recorded a wind speed or fourteen to sixteen miles per hour for several consecutive hours on September 4, 2011. Thus, for the sake of making conservative predictions, fourteen miles per hour was chosen for the two hour simulations.

Table 3.6 summarizes the parameters of the MTT simulations. The results include burn probability raster data files indicating the number of times each cell burned and vector files of burn perimeters from the four thousand ignitions. FlamMap FB simulations for these two study extents were simultaneously run with the MTT simulations. The results of the FlamMap FB do not change with wind direction. One flame length raster and one crown fire activity raster was stored for each of the two WUI communities.

FLAMMAP MINIMUM TRAVEL TIME SIMULATION PARAMETERS

Fuel / Foliar Moisture	Very Low / 60
Fuel Conditioning Period	August 22 to September 4, 2011
Wind Speed	14 miles per hour
Wind Direction	North, northeast, east, southeast, south, southwest, west, northwest
Number of Simulations	8
Number of Ignitions/Simulation	500
Duration of Each Simulation	6 hours

Table 3.6: Parameters used in the FlamMap MTT simulations.

3.3.2 DATA ON RESPONSE CAPACITY AND HAZARD MITIGATION

Multiple sources were consulted to obtain data on the response capacity and adopted mitigation measures of each focal community. When possible, published data from public records and agency websites were used. For unpublished information, semi-structured interviews were conducted. Table 3.7 lists the published data compiled and Table 3.8 lists the organizations and interviewees that participated in the semi-structured interviews.

PUBLISHED DATA ON RESPONSE CAPACITY AND MITIGATION

Data	Source	Date Accessed	Web Address
Fire Department Budgets, Staff, Ratings and Response Statistics	Travis County ESD #3	July 2013	http://www.oakhillfire.org/
	Boerne Fire Department	July 2013	http://www.ci.boerne.tx.us/index.aspx?nid=85
STARFlight Rescue Service	Travis County STARFlight	July 2013	https://starflight.traviscountytx.gov/
Emergency Notification Systems	Capital Area Council of Governments	July 2013	http://www.capcog.org/
	Alamo Area Council of Governments	July 2013	http://www.aacog.com/
Emergency Management Plans and Assessments	Travis County Emergency Management	July 2013	http://www.co.travis.tx.us/emergency_services/emergency_management.asp
	Kendall County Office of Emergency Management	July 2013	http://www.co.kendall.tx.us/default.aspx?Kendall_County/Emergency%20Management
Participation in Firewise Programs	Firewise Communities	July 2013	http://www.firewise.org/

Table 3.7: Data types and sources on response capacity and hazard mitigation in the two WUI study regions.

PARTICIPANTS OF SEMI-STRUCTURED INTERVIEWS

Level of Organization	Organization	Name, Title	Date(s) of Contact
Fire Department	Travis County ESD #3	Kurstin Bluemel, Office Administrator	July 12, 2013
Fire Department	Boerne Fire Department	April Bueno, Administrative Assistant	July 12, 2013
		Ray Hacker, Assistant Fire Chief	August 2, 2013
County	Travis County Emergency Management	Stacy Moore, Assistant Emergency Management Coordinator	July 15, 2013 July 22, 2013
County	Kendall County Office of Emergency Management	Jeffery Fincke, Kendall County Fire Marshal	July 15, 2013
State	Texas Forest Service	William Boettner, WUI Specialist	July 12, 2013

Table 3.8: Organizations and individuals that participated in the semi-structured interviews.

The questions asked of interviewees depended upon the level of organization they represented. The two fire departments, upon which the study areas were defined, were consulted on three broad categories. First they were asked about the protocol for cooperating with surrounding fire departments. Second they were asked about methods employed to notify and evacuate residents, if necessary. Third they were asked about the existence of any fuel management practices in the jurisdiction.

Interviewees from county organizations were asked questions based on two broad categories: whether they have in the past or plan to in the future develop a CWPP; and the types of fuel management programs that exist at the county level, if any. The final interviewee, a WUI specialist from the Texas Forest Service, the organization that facilitates the Firewise process in Texas, was asked about the participation of Texas communities in the Firewise program, the protocol for doing so, and how communities are informed about it.

3.4: DATA ANALYSIS

The data analyses used in this thesis are explained in the three sections below. Each section specifically addresses one of the three research questions posed at the beginning of the chapter. The first section describes the suite of analytical methods used to predict wildfire behavior in the full eastern Edwards Plateau extent. The second section describes the analysis of predicted fire behavior and susceptibility in the two focal WUI communities. The third section describes how the response capacity and mitigation data were synthesized.

3.4.1: FLAMMAP SIMULATIONS: EASTERN EDWARDS PLATEAU

One of the benefits of studying simulated data that were obtained in a fixed, user-controlled environment is that analytical methods can be straightforward. All variables used by FlamMap FB to measure fire behavior are known to the user and explanatory variables can be easily isolated to test their individual effect.

3.4.1.1: Data Preparation

Before data could be analyzed, the output data files from FlamMap FB were assigned the spatial reference North American Datum 1983 Albers equal-area conic projection, using ArcGIS 10.0. Statistical modeling, which was performed using R statistical software, was not possible on such a large dataset. Thus a subset of one thousand cells was randomly selected using ArcGIS and the data within the one thousand cells were transferred to a spreadsheet in order to perform analysis of covariance (ANCOVA) in R. Of these one thousand data points, 118 represented cells that were defined as non-burnable (roads, water, bare ground, etc.) by the fuel models and were ignored by FlamMap FB. These 118 points were omitted from analysis. The remainder was a subset of 882 data points.

For analysis of changes in crown fire activity, the dataset was reduced again. Crown fire activity is only possible on data points with tree canopies. Of the 882 data point subset, 421 data points had zero percent canopy cover and were omitted from analysis on changes in crown fire activity. The remainder was a 461 data point subset that is used for ANCOVA on crown fire activity only.

3.4.1.2: Measuring Stochastic Error

ArcGIS 10.0 was used to calculate the change between repeated runs. Each original raster was subtracted from its repeat to calculate differences between runs. Any stochastic error detected would alter the interpretation of further simulations. In other words, if there is an increase in flame length for a given cell between Scenario 1 and Scenario 2, is it due to the increase in wind speed or just stochastic error made by the instrument? It is important to state now (to legitimize the methods used below) that there was no stochastic error in any of the repeated runs. Every cell in every repeat had identical measurements. This indicates that any change measured in a cell between scenarios must be attributed to the change in scenario, not due to variation between measurements.

3.4.1.3: Expected Fire Behavior of the Eight Scenarios

To determine the range of expected flame lengths, rates of spread, and crown fire activity resulting from the eight scenarios, the results of each scenario were displayed in a series of maps and charts for each of the three response variables. Flame lengths were symbolized based on the divisions described in the NWCG Incident Response Pocket Guide for tactical interpretations of flame lengths. Rate of spread was symbolized based on divisions that easily translate to miles per hour: eighty chains per hour is one mile per hour, forty is one half, twenty is one quarter, and ten chains per hour is one eighth of one mile per hour. Crown fire activity was symbolized based on no fire activity, surface activity only, passive crown fire activity, and active crown fire activity.

3.4.1.4: Effect of Weather and Climate Variables

To measure the impact of each weather and climate condition, the scenarios were paired in ways that held two variables constant while the variable of interest changed. For example, Scenarios 1 and 2 only differ in wind speed, all other settings are fixed. Thus any differences detected between the two scenarios would be due to the change in wind speed alone. The weather and climate conditions were tested using two combinations each, one combination represents mild fixed conditions and the other combination represents extreme fixed conditions. Table 3.9 lists the comparisons.

SCENARIO COMPARISONS TO TEST THE EFFECT OF WEATHER

To Test the Effect of Wind		
Wind = 5	**Wind = 20**	**Fixed Conditions**
Scenario 1	Scenario 2	Moderate Fuel Moisture 2010 Fuel Conditioning Period
Scenario 7	Scenario 8	Very Low Fuel Moisture 2011 Fuel Conditioning Period

To Test the Effect of Fuel Moisture		
Fuel Moisture = Moderate	**Fuel Moisture = Very Low**	**Fixed Conditions**
Scenario 1	Scenario 3	5 mph Wind Speed 2010 Fuel Conditioning Period
Scenario 6	Scenario 8	20 mph Wind Speed 2011 Fuel Conditioning Period

To Test the Effect of Fuel Conditioning		
Fuel Conditioning Year = 2010	**Fuel Conditioning Year = 2011**	**Fixed Conditions**
Scenario 1	Scenario 5	5 mph Wind Speed Moderate Fuel Moisture
Scenario 4	Scenario 8	20 mph Wind Speed Very Low Fuel Moisture

Table 3.9: Scenario comparisons testing the effect of weather and climate.

Differences between scenarios were calculated using ArcGIS 10.0. As mentioned above, since i) simulations are conducted in a controlled environment, ii) the weather conditions are static across space for each run, and iii) there is no stochastic error made by the instrument, any difference between runs based on a single variable is due to that variable alone. In return, no additional measures are necessary to measure statistical significance of the impact of weather conditions on flame length, rate of spread, or crown fire activity.

3.4.1.5: Effect of Landscape Variables

ANCOVA multiple linear regression modeling was used to evaluate the correlation between landscape structure and flame length, rate of spread, and crown fire activity across the spatial extent. Explanatory variables included the same set of eight landscape variables used in FlamMap FB. The response variables included flame length, rates of spread, and crown fire activity observed in Scenario 8. A separate ANCOVA regression model was built for each response variable. Models including interaction terms between all explanatory variables were built and fitted manually through stepwise model selection using F-tests to measure goodness of fit and compare nested models. The fitted models were then interpreted to identify the landscape variables, or their interactions, that correlate with high flame lengths, high rates of spread, and active crown fire activity.

3.4.2: FLAMMAP SIMULATIONS: TRAVIS COUNTY ESD #3 AND BOERNE

Analysis of the FlamMap FB and MTT simulations within the two WUI community extents was performed entirely in ArcGIS 10.0. Output data files from FlamMap were assigned with the North American Datum 1983 Albers equal-area conic projection. The vector files containing the burn perimeters were combined to show the total area that burned at least once during all of the simulations. The number of times each cell burned for each of the eight simulations were summed and divided by four thousand to derive the total number of times each cell burned per ignition. The resulting data range was then divided into quintiles, giving five categories from lowest to highest number of burns per ignition. New rasters symbolized by quintile were then produced to show the spatial distribution of the ranked data.

Raster data files containing flame lengths were symbolized by showing only flame lengths over eleven feet to show the areas exhibiting the most extreme category of flame lengths. Similarly, raster data files of crown fire activity were symbolized to show only the areas with exhibiting active crown fires.

3.4.3: RESPONSE CAPACITY AND MITGATION: TRAVIS COUNTY ESD #3 AND BOERNE

The data on community wildfire response capacity and measures to reduce wildfire hazards compiled for the two focal WUI study areas were synthesized into two categories and then compared and interpreted. The first category contains indicators of how well-equipped each jurisdiction is to responding to a wildfire hazards that materialize. These indicators include: how residents are informed about the hazard; fire department statistics including the number of paid and volunteer firefighters on staff, annual budgets, Insurance Services Office (ISO) ratings, and average response times; the cooperation of each fire department with outside suppression resources; and the distance of those resources from the jurisdiction.

The second category contains indicators that local governments and residents have adopted, or are considering adopting, plans, programs, or strategies aimed at reducing wildfire hazards before they materialize. These indicators include: participation in the CWPP program; participation in Firewise programs; and the organization of fuel management programs.

3.5: ASSUMPTION AND LIMITATIONS

While there are many benefits to using FlamMap simulation software, there are also many assumptions and limitations that need to be understood before interpreting simulation results. First, the landscape input data acquired from the LANDFIRE database may incorrectly describe some of the data cells. LANDFIRE is an interagency mapping program sponsored by the Department of the Interior to create digital files of fuel and vegetation characteristics for the United States (www.landfire.gov). Data products created by LANDFIRE utilize spatial prediction models along with expert knowledge to create data layers on vegetation and fuels, yet there is no guarantee that the landscape measurements are correct for every cell. Due to the unavailability of superior data sets for this region that are compatible with FlamMap, LANDFIRE data sets are the only option for this study.

Second, the resolution of any raster calculates an average of actual values within one grid cell. The resolution used for this study, thirty meters, means that all the existing spatial variation within a thirty by thirty meter grid cell is deduced to a single value. This leads to potential problems with predicting fire behavior at very small extents, such a one acre.

Fire behavior predictions are specific measurements of how a fire would behave for a static moment in time, when the actual conditions exactly match the simulated settings. A wildfire in real time is constantly fluctuating due to changes in wind speed, wind direction, and temperature, as well as how fire is behaving around it. Furthermore, the burn probabilities calculations are difficult to interpret as discussed above. The process of MTT simulations highlights common pathways that hypothetical fires would take under given conditions. More common pathways receive higher scores. This does not mean that areas with low scores are not going to burn; it means that they are less likely to burn in relation to the surrounding conditions.

Finally, the results of the MTT simulations cannot predict structure ignitability. How close a structure is to the WUI is only a broad indication of how likely it is to burn in the event of a fire. In actuality, the ignitability of a structure is influenced by building materials and combustible material around the structure (Cohen 2000).

CHAPTER 4: RESULTS

4.1: INTRODUCTION TO CHAPTER 4

Chapter 4 provides results from the methods described in Chapter 3. The three succeeding sections directly refer to each of the main research questions. The first section presents the results of the FlamMap simulations under eight scenarios for the eastern Edwards Plateau extent. This includes: simulation outputs, assessments of how weather and climate variables influenced the response variables, and the ANCOVA results highlighting the relationship between response and landscape variables.

The second section presents the results of the FlamMap simulations for the two WUI communities within the eastern Edwards Plateau extent delineated by the Travis County ESD #3 and Boerne City Fire Department jurisdictions. Simulation modeling took place under one set of conditions designed to mimic the September 4, 2011, which is known to have been conducive to wildfire activity. These results include both a spatial evaluation of the susceptibility to burning and extreme fire behavior of each study area.

The third section presents the results of the investigation into the response capacity and mitigation measures of the two WUI communities. Data were gathered from multiple sources, including public records, published information, and personal communication with representatives of local and state organizations. The results were then compiled and synthesized to show the current state of response capacity in each fire department jurisdiction as well as any participation of the communities in programs such as CWPP or Firewise that aim to prevent wildfire hazards.

4.2: FLAMMAP SIMULATIONS: EASTERN EDWARDS PLATEAU

4.2.1: RANGE OF FIRE BEHAVIORS PREDICTED

As anticipated from literature indicating a strong relationship between climate and fire behavior, the results from the FlamMap FB simulations across the eastern Edwards Plateau varied significantly between conditions mimicking an average September day to an overly hot, dry, and windy September day. As a refresher, Table 4.1 lists the specific conditions that were tested in the eight scenarios.

EIGHT WEATHER AND CLIMATE SCENARIOS

Scenario	Wind Speed (mph)	Fuel Moisture / Foliar Moisture	Fuel Conditioning Period
1	5	Moderate / 100	8/22 to 9/4 2010
2	20	Moderate / 100	8/22 to 9/4 2010
3	5	Very Low / 60	8/22 to 9/4 2010
4	20	Very Low / 60	8/22 to 9/4 2010
5	5	Moderate / 100	8/22 to 9/4 2011
6	20	Moderate / 100	8/22 to 9/4 2011
7	5	Very Low / 60	8/22 to 9/4 2011
8	20	Very Low / 60	8/22 to 9/4 2011

Table 4.1: Eight scenarios tested in FlamMap Fire Behavior simulations for the eastern Edwards Plateau extent.

Figures 4.1, 4.2, and 4.3 display the simulation outputs of flame lengths across the extent in the eight scenarios. Ninety-three percent of the extent exhibited flame lengths under one foot in height in Scenario 1. In contrast, forty-four percent of the extent exhibited flame lengths over eleven feet tall and another forty-four percent were between four and eight feet tall in Scenario 8 (Figure 4.1). The maps provided in Figures 4.2 and 4.3 show that as weather and climate conditions became more conducive to extreme fire behavior, the areas along the Balcones Escarpment exhibited the highest concentration of flame lengths over eleven feet.

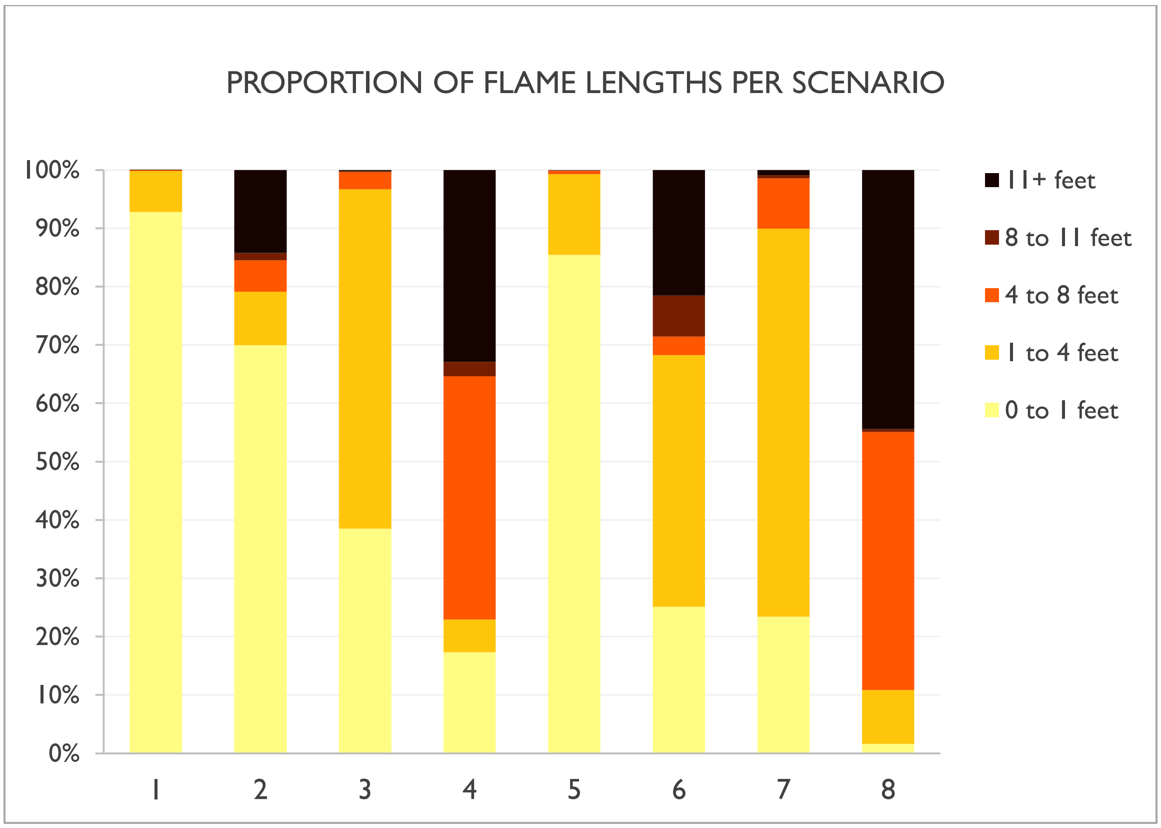

Figure 4.1: Proportion of data in each flame length category per scenario.

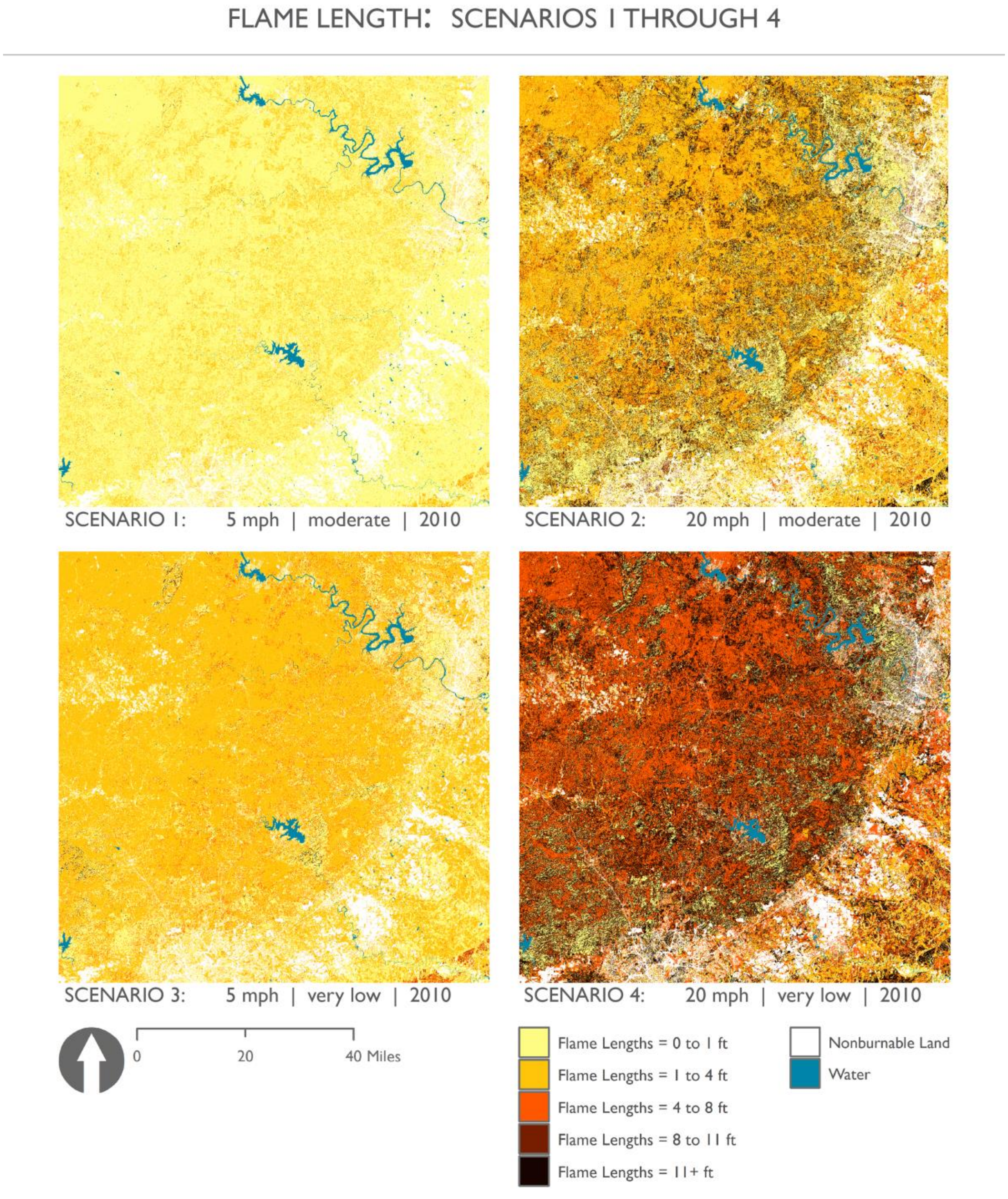

Figure 4.2: FlamMap results for flame length, Scenario 1 through Scenario 4.

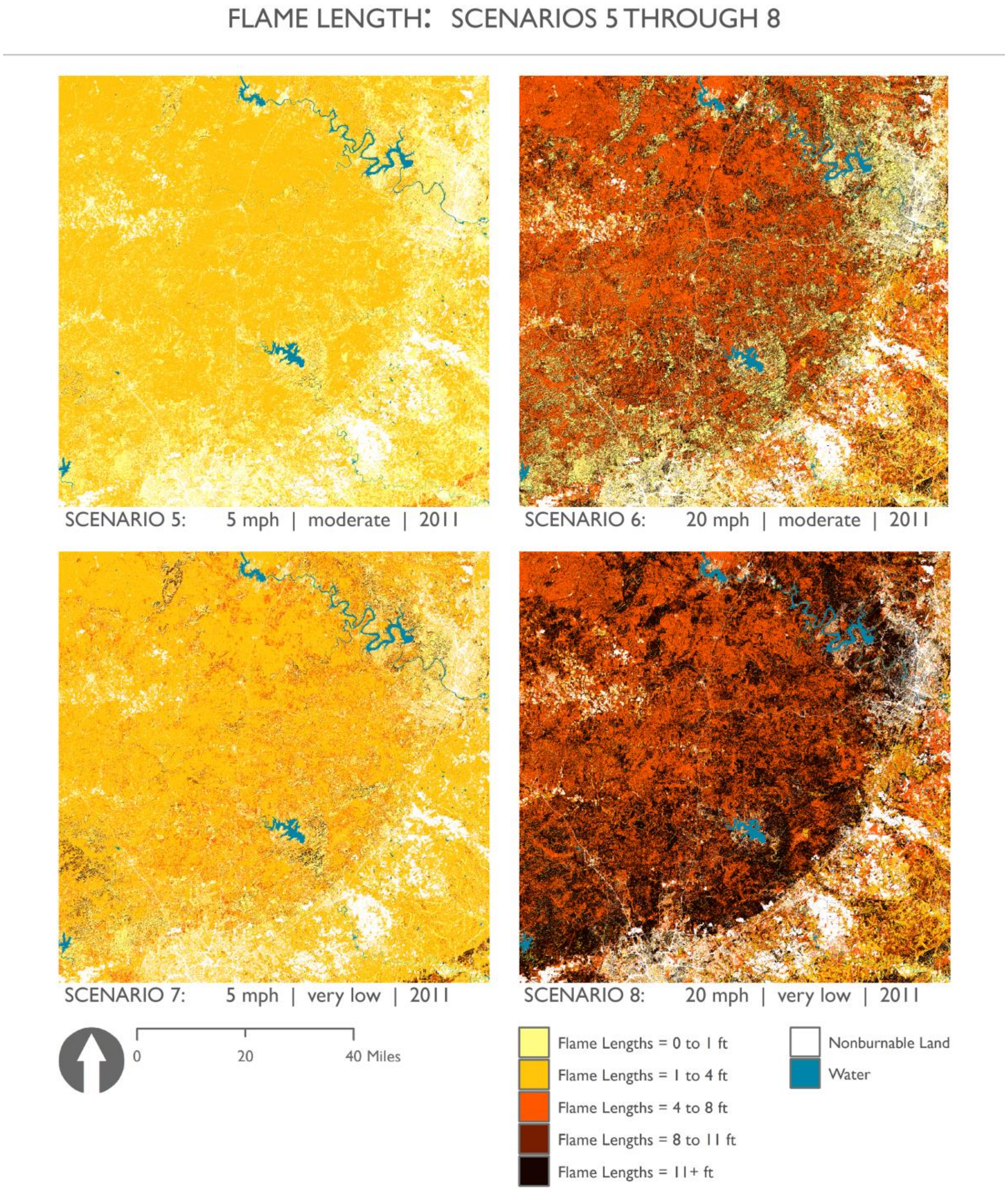

Figure 4.3: FlamMap results for flame length, Scenario 5 through Scenario 8.

Figures 4.4, 4.5, and 4.6 display the simulation outputs of rates of spread across the extent in the eight scenarios. The unit for describing rates of fire spread is chains per hour, which is sixty-six feet per hour. The symbology used in the maps is conveniently translated into miles per hour: ten chains equals one eighth of one mile, twenty chains is one quarter, forty is one half, and eighty chains equals one mile. One hundred percent of the extent in Scenario 1 exhibited rates of spread under ten chains per hour. In contrast thirty-eight percent of the extent exhibited rates of spread over eighty chains per hour and another fifty percent exhibited rates between forty and eighty chain per hour in Scenario 8. As weather and climate conditions became more conducive to increased fire behavior, the northwest portion of the extent, farther from the dense canopies along the escarpment, exhibited the highest rates of spread.

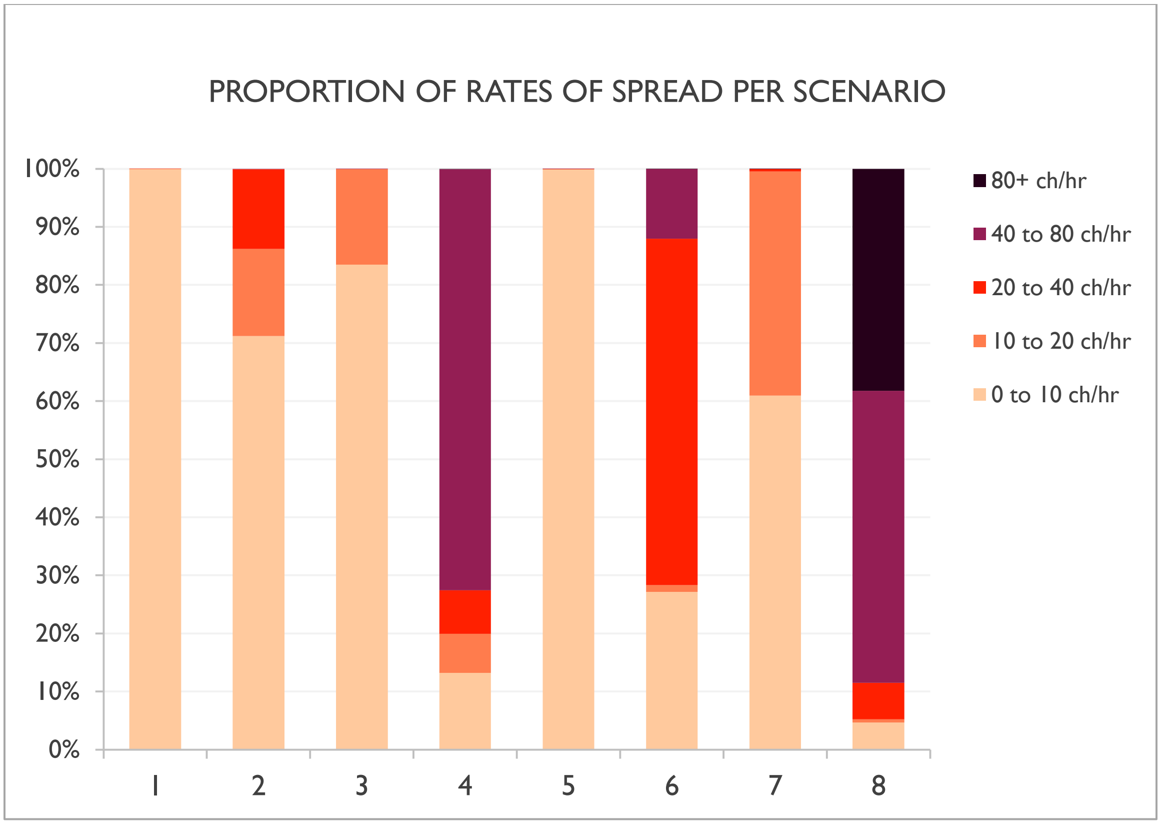

Figure 4.4: Proportion of data in rate of spread category per scenario.

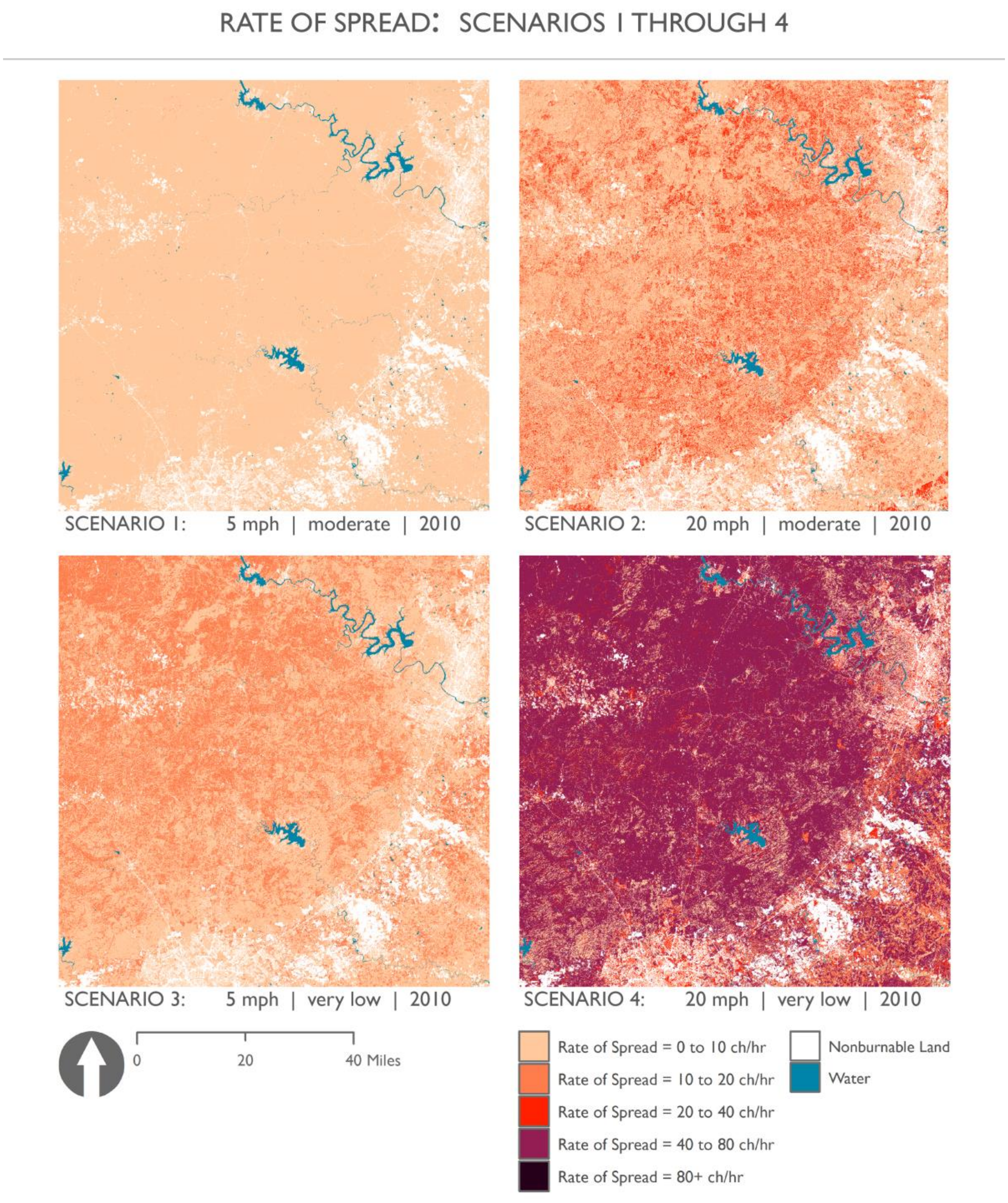

Figure 4.5: FlamMap results for rate of spread, Scenario 1 through Scenario 4.

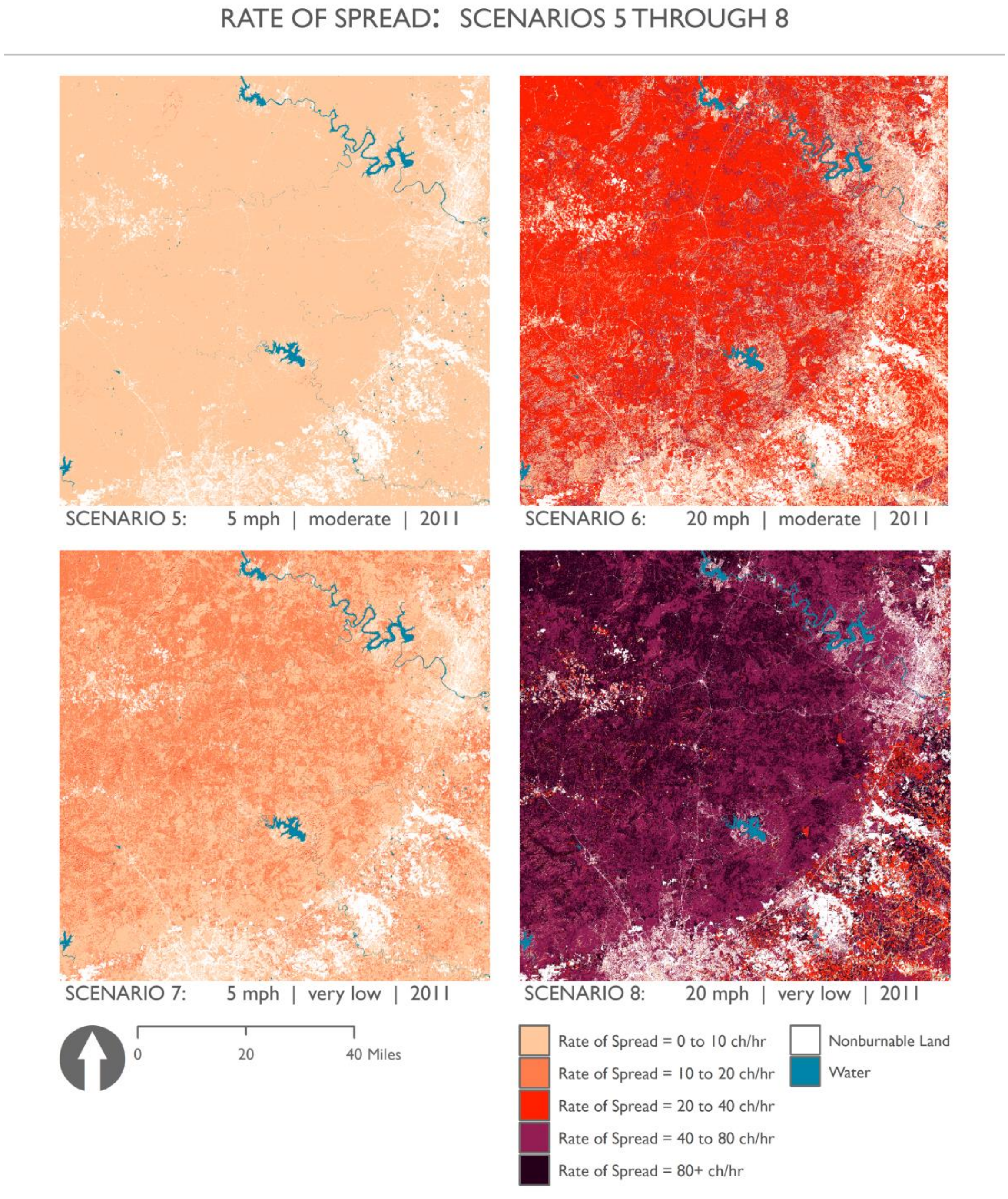

Figure 4.6: FlamMap results for rate of spread, Scenario 5 through Scenario 8.

Figures 4.7, 4.8, and 4.9 display the simulation outputs of crown fire activity across the extent in the eight scenarios. Crown fire activity is categorized in three levels: level one is surface fire only, level two is passive crown fire, and level three is active crown fire. In Scenario 1, sixty-three percent of the extent with canopy cover exhibited surface fires only and the remaining extent with canopy cover exhibited passive crown fires. In contrast, fifty-six percent of the extent with canopy cover exhibited active crown fires and an additional forty percent exhibited passive crown fires, for a total of ninety-six percent of the extent with canopy experiencing some form of crown fire activity in Scenario 8. Similar to the results for flame length, a concentration of active crown fires took place along the Balcones Escarpment as the weather and climate conditions became more conducive to fire.

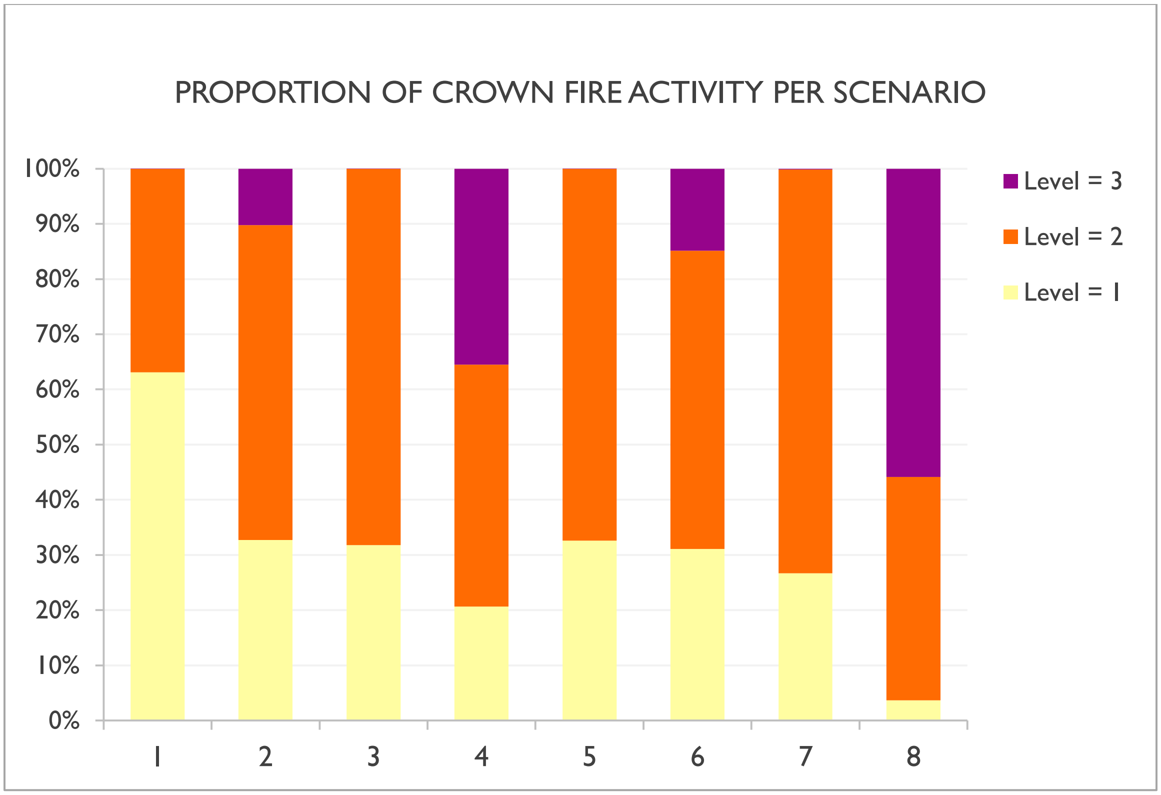

Figure 4.7: Proportion of data in crown fire activity category per scenario.

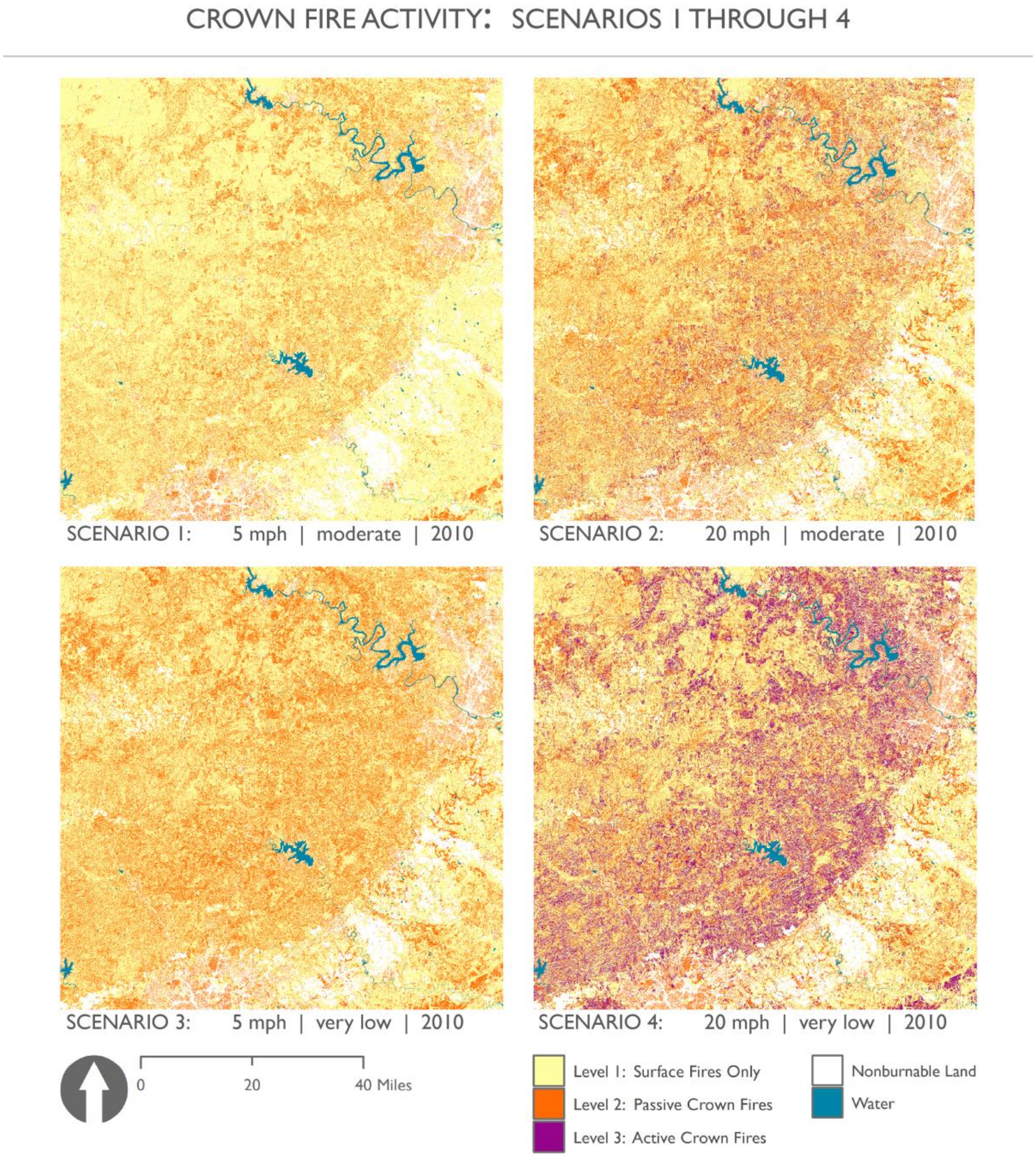

Figure 4.8: FlamMap results for crown fire activity, Scenario 1 through Scenario 4.

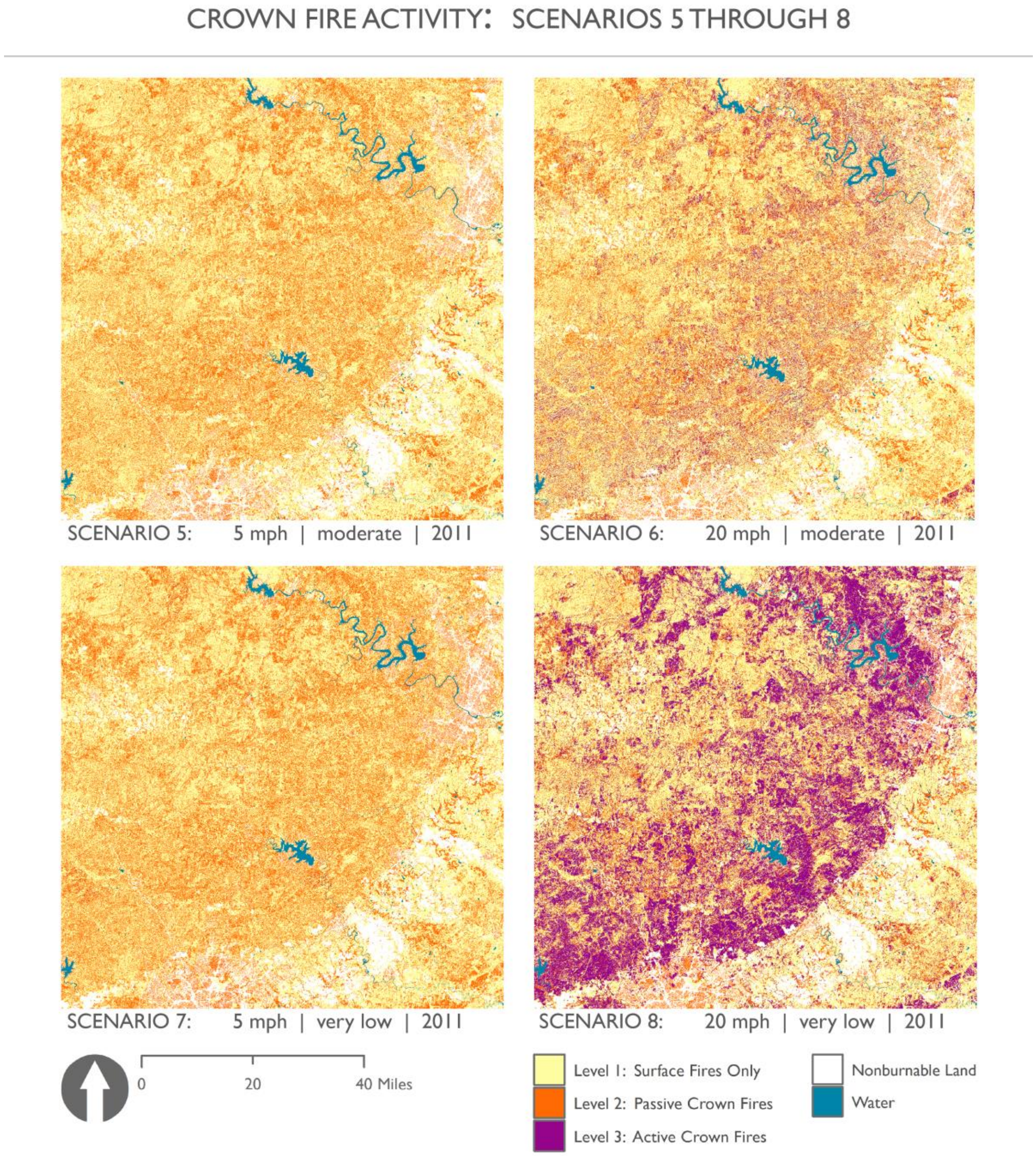

Figure 4.9: FlamMap results for crown fire activity, Scenario 5 through Scenario 8.

4.2.2 EFFECT OF WEATHER AND CLIMATE ON FIRE BEHAVIOR

The three explanatory variables, fuel moisture, wind speed, and fuel conditioning were evaluated for their independent contribution to increasing flame lengths, rates of spread, and crown fire activity. The effect of each explanatory variable was measured by comparing scenarios where the variable of interest changed while all other variables remained constant.

Figure 4.10 displays how a change in each explanatory variable increased flame lengths. When fuel moisture was decreased from the moderate state to the very low state and wind speed and fuel conditioning were held at mild constants (five miles per hour, 2010 fuel conditioning), flame lengths increased 1.2 feet on average. When the fuel moisture decreased and wind speed and fuel conditioning were held at extreme constants the increase in flame height was 14.3 feet on average. When wind speed was increased from five to twenty miles per hour the average increase was 4.1 feet under mild conditions and 19.6 feet under extreme constants. When fuel conditioning was changed from 2010 conditions to 2011 conditions, the average increase was 0.6 feet under mild constants and 10.1 feet under extreme constants.

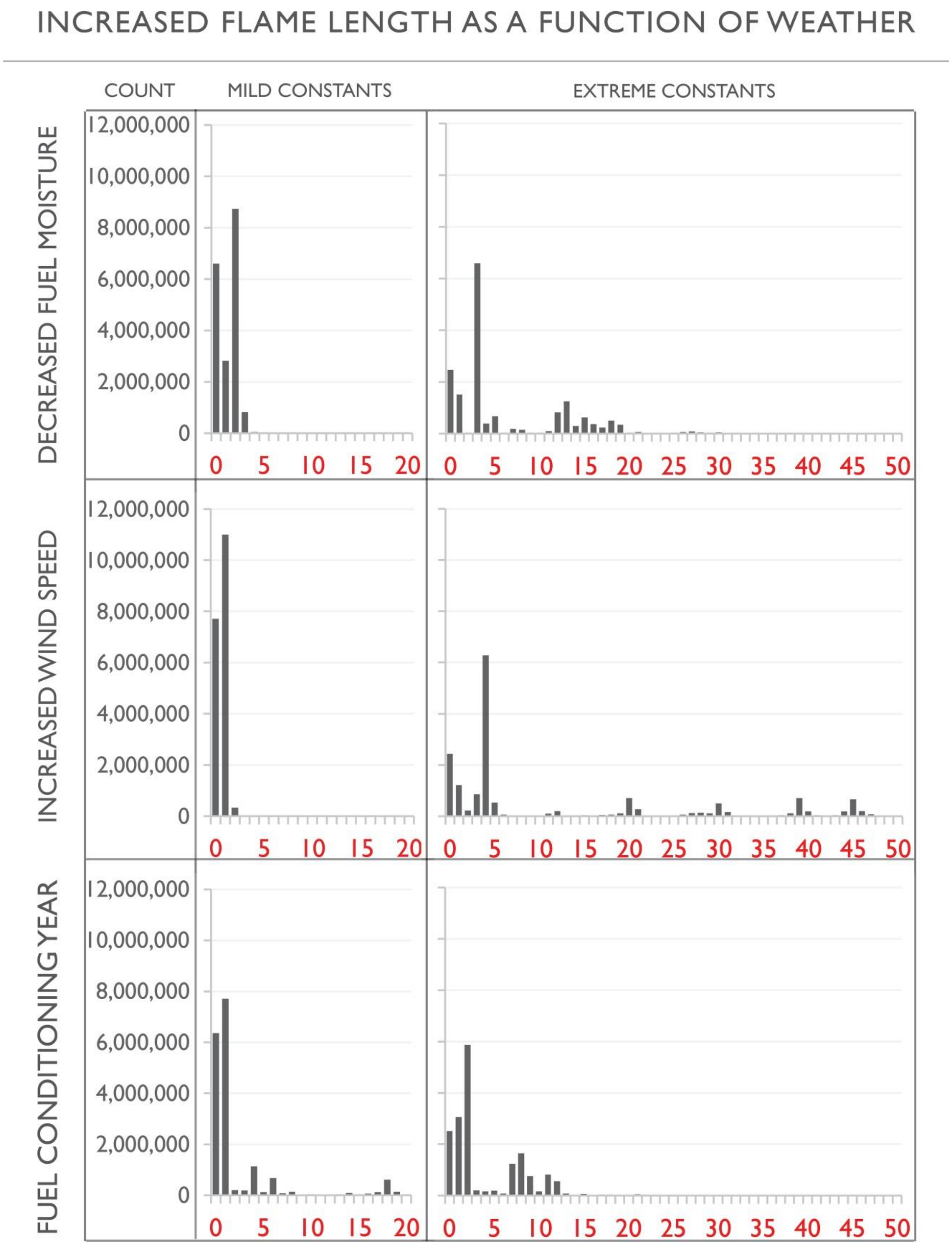

Figure 4.10: Frequency distribution of increased flame lengths in feet.

These six results for the increase in flame lengths as a result of a change in weather conditions shows that while each variable has the ability to increase flame heights alone, it also has an interactive effect with the other two conditions. The same was true for rates of spread. Figure 4.11 displays the frequency distributions of increases in rates of spread that resulted from changing the three explanatory variables. A decrease in fuel moisture when wind speed and fuel conditioning were at mild states resulted in an average increase of 4.4 chains per hour, while an average increase of 42.9 chains per hour occurred under extreme constants. When wind speed was increased, the average rate of spread increased 7.2 chain per hour under mild constants and 56.4 chains per hour under extreme constants. When fuel conditioning period was changed from 2010 to 2011, the average increase in rate of spread was 1.5 chains per hour under mild constants and 21.4 chains per hour under extreme constants.

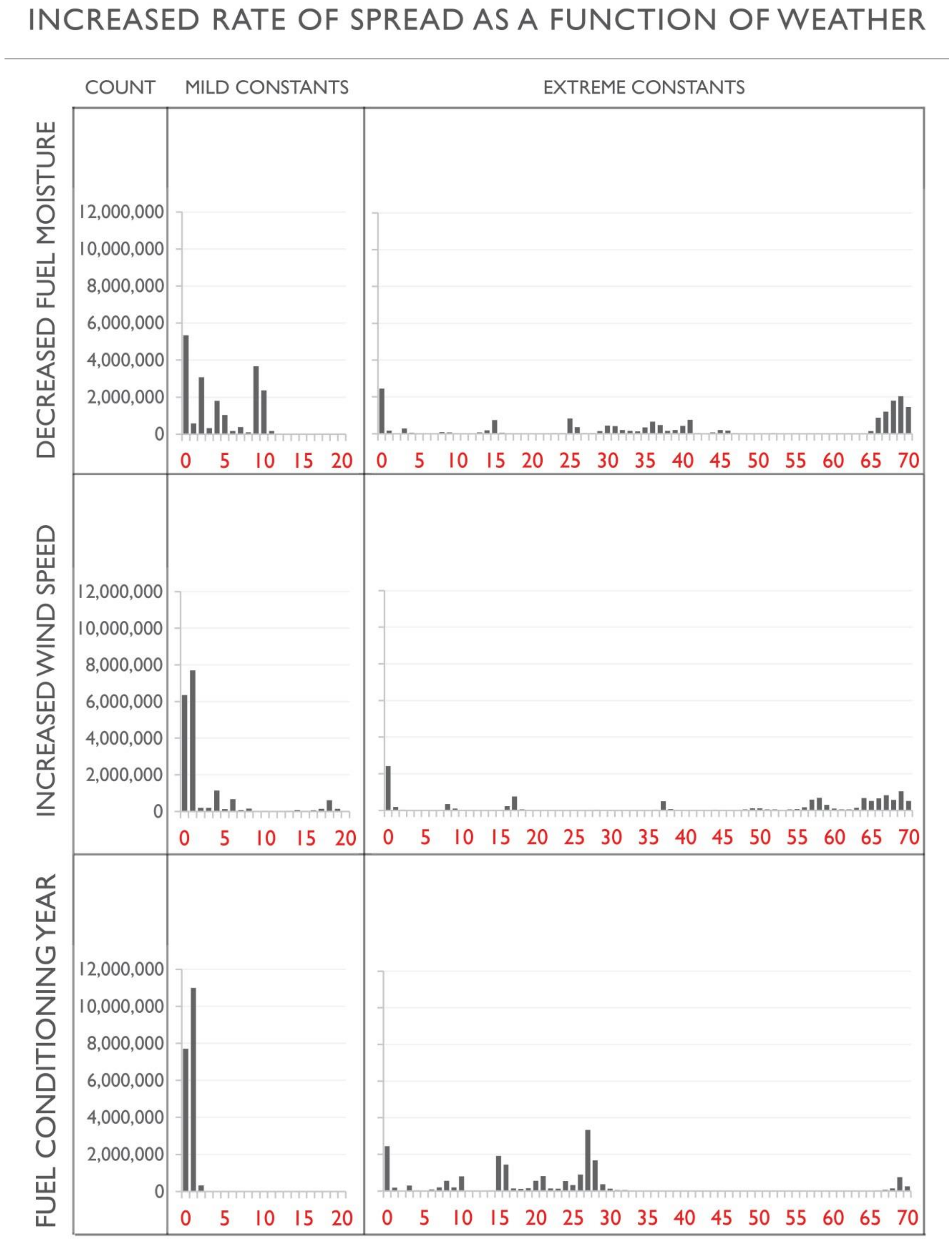

Figure 4.11: Frequency distribution of increased rates of spread in chains/ hour.

Level three crown fire activity showed similar trends as flame lengths and rates of spread when evaluated for the impact of weather. Because crown fire activity is not a continuous variable, the increase in activity can only be expressed in terms of percentage change between scenarios. Table 4.2 shows the change in level two, level three, and total crown fire activity as a result of decreased fuel moisture, increased wind speed and a change in fuel conditioning.

INCREASED CROWN FIRE ACTIVITY AS A FUNCTION OF WEATHER

Explanatory Variable	Constants	Level 2	Level 3	Total Increase in Crown Fire Activity
Fuel Moisture	Mild	31%	0%	31%
	Extreme	-13%	42%	29%
Wind Speed	Mild	20%	10%	30%
	Extreme	-33%	56%	23%
Fuel Conditioning	Mild	31%	0%	31%
	Extreme	-3%	20%	17%

Table 4.2: The change in level two, level three, and total crown fire activity.

Crown fire activity increased in each test with total crown fire activity increasing between seventeen and thirty-one percent. When constants are held at their extreme values, the passive crown fires decrease and active crown fires increase forty-two percent, fifty-six percent, and twenty percent when fuel moisture is decreased, wind speed is increased, and fuel conditioning is changed from 2010 to 2011, respectively.

4.2.3 EFFECT OF VEGETATION AND TOPOGRAPHY ON FIRE BEHAVIOR

In addition to the variation in fire behavior across weather and climate scenarios, the FlamMap FB outputs displayed variation in fire behavior across the landscape within each scenario. Analysis of Covariance was used to identify the landscape variables that correlated with the observed variation in Scenario 8. Explanatory variables in the linear models included four continuous variables measuring canopy characteristics, one categorical variable of fuel models, and three continuous variables measuring topography (Refer to Table 3.1 in the Research Design chapter for more detail). Results of the ANCOVA linear models indicated that fuel model and percent canopy cover explained the most variation in response variables across the eastern Edwards Plateau extent. Table 4.3 lists the nine fuel model categories and their descriptions as defined by Scott and Burgan (2005).

FUEL MODELS PRESENT IN THE EASTERN EDWARDS PLATEAU

Model	Fuel Type	Fuel Description
GR1	Grass	Grass is short, patchy, and possibly heavily grazed. Spread rate moderate; flame length low.
GR2	Grass	Moderately coarse continuous grass, average depth about 1 foot. Spread rate high; flame length moderate.
GS1	Grass-Shrub	Shrubs are about 1 foot high, low grass load. Spread rate moderate; flame length low.
GS2	Grass-Shrub	Shrubs are 1 to 3 feet high, moderate grass load. Spread rate high; flame length moderate.
TU1	Timber-Understory	Fuel bed is low load of grass and/or shrub with litter. Spread rate low; flame length low.
TL2	Timber Litter	Low load, compact. Spread rate very low; flame length very low.
TL3	Timber Litter	Moderate load, less compact. Spread rate moderate; flame length low.
TL5	Timber Litter	Moderate load conifer litter. Spread rate very low; flame length low.
TL6	Timber Litter	High load conifer litter; light slash or mortality fuel. Spread rate low; flame length low.

Table 4.3: Scott and Burgan (2005) fuel model descriptions. Only fuel models present in the eastern Edwards Plateau study extent are listed.

Table 4.4 lists the fitted ANCOVA model results for the effect of landscape variables on flame lengths. The variables that explained the most variation in flame lengths were fuel model, canopy cover, slope, and the interaction between fuel model and canopy cover (adjusted R-squared = 0.97). The coefficients indicate the following: grass and grass-shrub fuel models resulted in higher surface flame lengths, while the timber and timber-understory variables had lower surface flame lengths; increased slopes corresponded to increased fuel lengths; and the impact of canopy cover increased or decreased flame lengths depending on the fuel model with which it was interacting. For instance, the fuel model GS1 had a predicted flame length of approximately six feet minus 0.064 feet for every percentage point of canopy cover present (e.g. subtract 2.24 feet for thirty-five percent canopy cover). In contrast the fuel model TL6 had a predicted flame length of approximately two feet plus 0.0013 feet for every percentage point of canopy cover present (e.g. add 0.1 feet for seventy-five percent canopy cover).

ANCOVA RESULTS: FLAME LENGTH

Variable	Coefficient	Significance
(Intercept)	2.5273	0.01 ***
GR2	5.6041	0.01 ***
GS1	3.5069	0.01 ***
GS2	6.8441	0.01 ***
TL3	-7.9222	0.01 ***
TL5	-9.1346	0.01 ***
TL6	-0.7138	0.10 *
TU1	-1.2520	0.05 **
Canopy Cover	0.1189	0.05 **
Slope	0.1034	0.01 ***
Aspect	0.0008	0.05 **
GS1 * Canopy Cover	-0.1828	0.01 ***
GS2 * Canopy Cover	-0.1009	0.05 **
TL6 * Canopy Cover	-0.1176	0.05 **
TU1 * Canopy Cover	-0.1232	0.05 **
Canopy Cover * Slope	-0.0005	0.05 **
Elevation * Slope	-0.0002	0.01 ***
Slope * Aspect	-0.0001	0.05 **

Table 4.4: ANCOVA results predicting Scenario 8 flame lengths.

Given these results, simple univariate plots of flame lengths as a function of fuel model (Figure 4.12) and flame lengths as a function of canopy cover (Figure 4.13) were produced to better illustrate these relationships. Figure 4.12 shows that the GS2 fuel model resulted in the highest median flame heights (approximately nine feet) but that GR1 had the highest 1.5 interquartile range, reaching over sixteen feet. Of the timber fuel models, TL6 had the highest predicted flame heights of two to three feet.

Figure 4.13 shows that canopy covers of fifteen percent to forty-five percent corresponded with higher flame lengths, up to fourteen feet. Areas with no canopy cover corresponded to higher flame lengths than those with fifty-five to eighty-five percent canopy cover, which did not surpass three feet. Two of the four data points with fifteen percent cover revealed the highest recorded flame lengths for this data set.

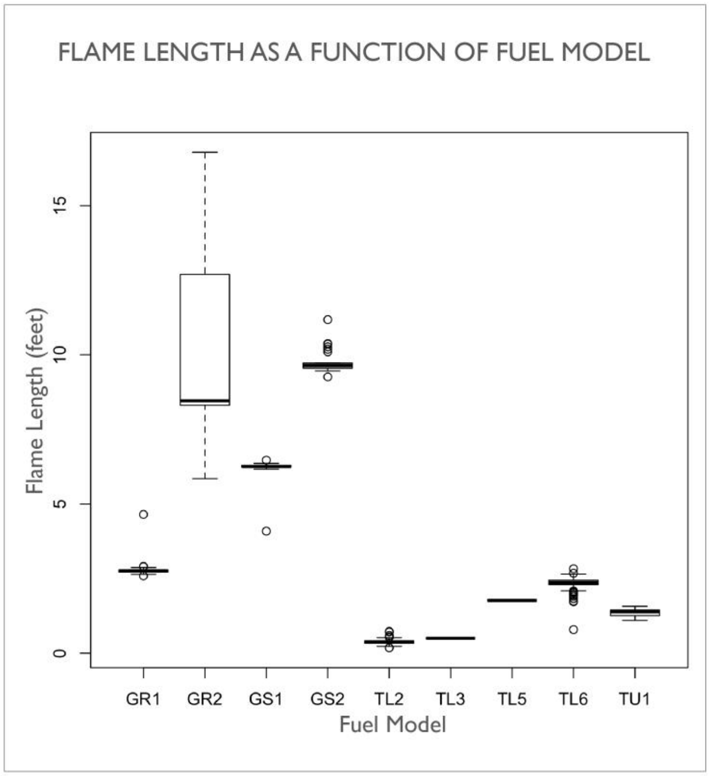

Figure 4.12: ANCOVA results of flame lengths as a function of fuel model for Scenario 8 data.

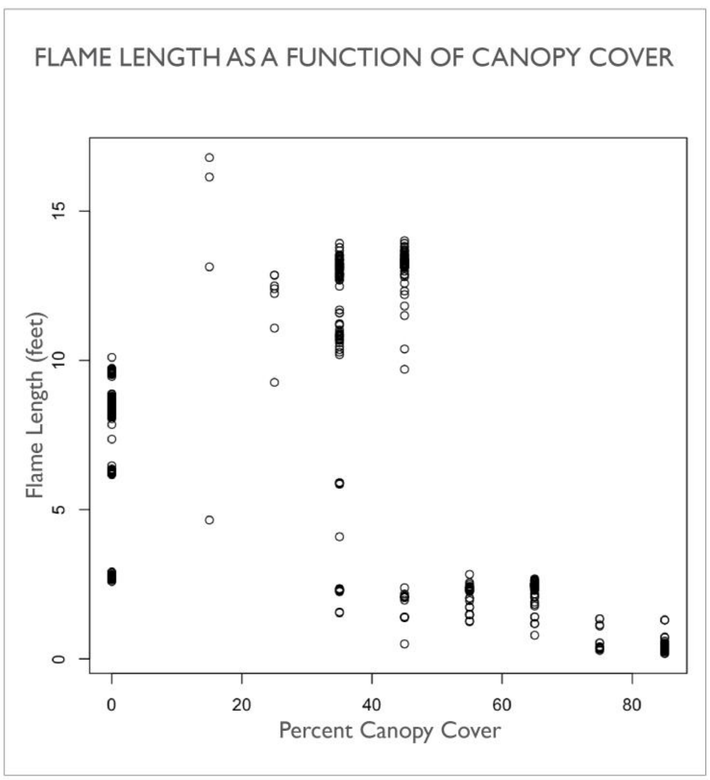

Figure 4.13: ANCOVA results of flame lengths as a function of percent canopy cover for Scenario 8 data.

Similar to the ANCOVA results for flame lengths, the variables that explained the most variation in rates of spread were fuel model, canopy cover, and the interaction between fuel model and canopy cover (adjusted R-squared = 0.99). The grass and grass-shrub fuel models corresponded with higher rates of spread while timber fuel models did not. Slope and canopy cover are both individually influential in the model, and the interaction between fuel models and canopy cover could either increase or decrease the rate of spread depending on the interacting fuel model. Table 4.5 lists the ANCOVA coefficients that resulted from the fitted model.

Figures 4.14 and 4.15 illustrate the univariate relationships between rate of spread and fuel model and rate of spread and canopy cover, respectively. Fuel Model GR2 corresponded to the highest rates of spread (> 120 chains/hour), with all grass and grass-shrub fuel models resulting in higher rates of spread than the timber fuel models, which stayed below ten chains per hour. In contrast to the relationship between canopy cover and flame heights, the highest rates of spread correlate with a zero percent canopy cover. As canopy cover increased, rate of spread decreased. Canopy cover over fifty-five stayed below ten chains per hour.

ANCOVA RESULTS: RATE OF SPREAD

Variable	Coefficient	Significance
(Intercept)	30.0559	0.01 ***
GR2	85.1464	0.01 ***
GS1	17.1471	0.01 ***
GS2	44.3127	0.01 ***
TL2	-29.2534	0.01 ***
TL6	-24.3811	0.01 ***
TU1	-28.3001	0.01 ***
Canopy Cover	-0.4158	
Slope	0.3395	0.05 **
Aspect	0.0129	0.01 ***
GR2 * Canopy Cover	-1.7608	0.01 ***
GS1 * Canopy Cover	-0.5189	0.10 *
GS2 * Canopy Cover	-1.0613	0.01 ***
TL2 * Canopy Cover	0.3823	
TL6 * Canopy Cover	0.3317	
TU1 * Canopy Cover	0.3927	
Canopy Cover * Elevation	0.0001	0.10 *
Canopy Cover * Aspect	-0.0001	0.01 ***
Elevation * Slope	-0.0007	0.05 **
Slope * Aspect	-0.0007	0.10 *

Table 4.5: ANCOVA results predicting Scenario 8 rates of spread.

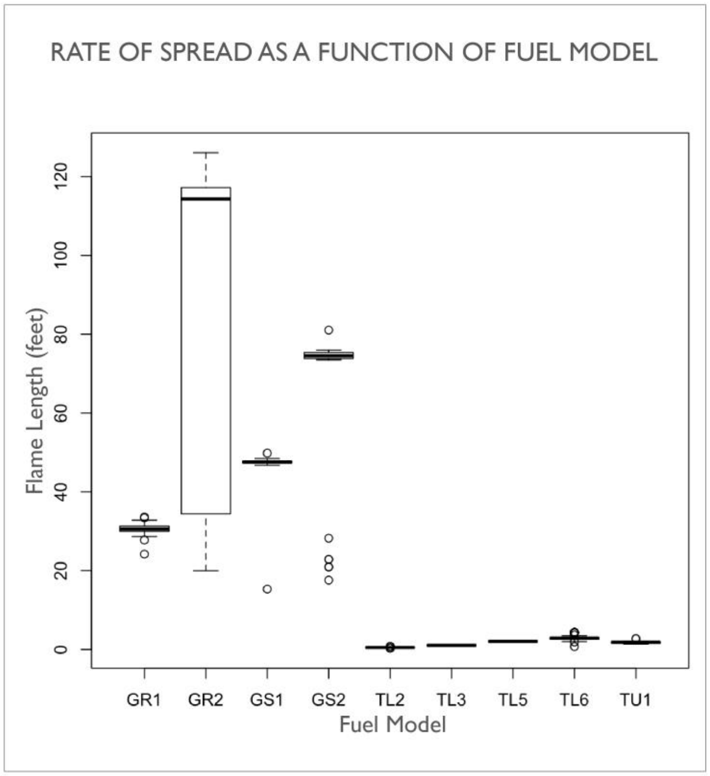

Figure 4.14: ANCOVA results of rates of spread as a function of fuel model for Scenario 8 data.

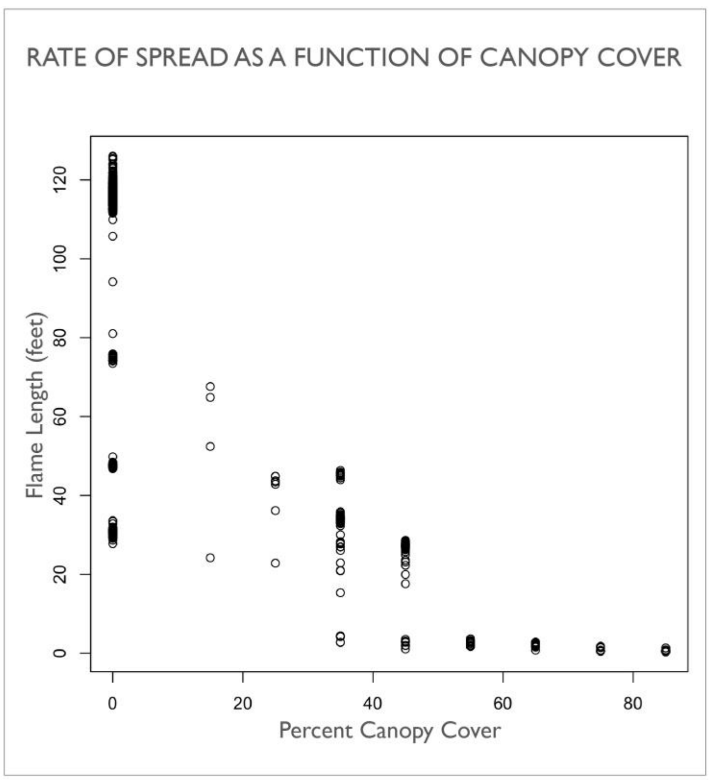

Figure 4.15: ANCOVA results of rates of spread as a function of percent canopy cover for Scenario 8 data.

Table 4.6 displays the results of the ANCOVA model for the effect of landscape variables on crown fire behavior. As stated in Chapter 3, since crown fire activity cannot occur within cells with zero percent canopy cover, cells without canopy cover were omitted from the analysis. The fitted model included multiple explanatory variables with poor significance values. However the model performed significantly better by retaining them.

In Scenario 8, sixty-two percent of the grid cells with canopy cover exhibited active crown fire activity and thirty-five percent exhibited passive crown fire activity. Only three percent of the grid cells with canopy cover resulted in surface fire only. With that in mind, this ANCOVA detected the landscape variables that led to active versus passive crown fires. Fuel model, slope, and canopy cover were influential in crown fire activity. Unlike the previous models, elevation and aspect were also influential in crown fire activity (adjusted R-squared = 0.77). The large number of interactions complicates the model's interpretation. However the coefficients indicate that fuel model, slope, fuel model-canopy cover interactions, and the fuel model-slope interactions had the greatest correlation with active crown fire activity.

ANCOVA RESULTS: CROWN FIRE ACTIVITY

Variable	Coefficient	Significance
(Intercept)	0.5528	
GR2	-0.8653	0.10 *
GS1	0.8082	0.05 **
GS2	-2.8166	
TL2	0.6139	
TL5	1.5324	0.01 ***
TL6	-0.2682	
TU1	0.8003	0.05 **
Canopy Cover	-0.0082	0.05 **
Elevation	0.0028	0.01 ***
Slope	0.2545	0.01 ***
Aspect	-0.0021	0.05 **
GR2 * Canopy Cover	0.0745	0.01 ***
GS2 * Canopy Cover	0.1231	0.01 ***
TL2 * Canopy Cover	0.0279	0.01 ***
TL6 * Canopy Cover	0.0477	0.01 ***
GR2 * Elevation	-0.0023	0.01 ***
GS2 * Elevation	-0.0023	0.10 *
TL2 * Elevation	-0.0025	0.01 ***
TL6 * Elevation	-0.0019	0.01 ***
GR2 * Slope	-0.1662	0.01 ***
GS2 * Slope	-0.1109	0.05 **
TL6 * Slope	-0.0926	0.01 ***
GR2 * Aspect	0.0023	0.01 ***
TL2 * Aspect	0.0026	0.01 ***
TL6 * Aspect	0.0024	0.01 ***
Canopy Cover * Slope	-0.0028	0.01 ***
Slope * Aspect	0.0001	0.05 **

Table 4.6: ANCOVA results predicting Scenario 8 crown fire activity.

Figures 4.16 and 4.17 provide a closer look at the univariate relationship between crown fire activity and fuel model as well as between crown fire activity and canopy cover, respectively. Since crown fire activity is one of only three ordered, categorical variables, the box plots tended to collapse into one value. Nonetheless, the plots illustrate trends. The grass and grass-shrub fuel models in Figure 4.17 predominantly resulted in passive crown fire activity (with the exception of GR2) while the timber fuel models TL2, TL5, and TL6 corresponded with active crown fire activity. Figure 4.18 illustrates a correlation between canopy cover of fifteen percent to thirty-five percent and passive crown fires. Canopy cover of forty-five percent to eighty-five percent correlated with active crown fires.

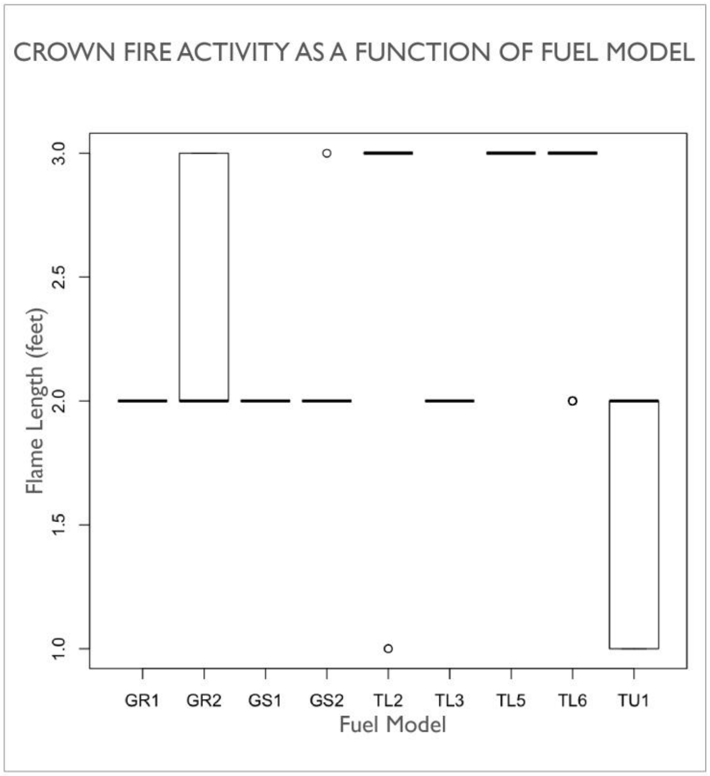

Figure 4.16: ANCOVA results of crown fire activity as a function of fuel model for Scenario 8 data.

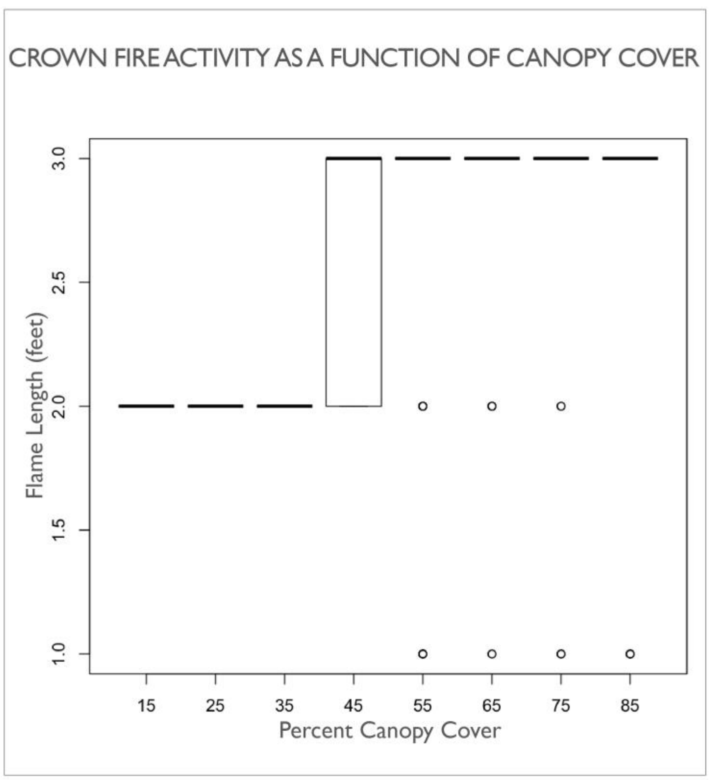

Figure 4.17: ANCOVA results of crown fire activity as a function of percent canopy cover for Scenario 8 data.

4.3: FLAMMAP SIMULATIONS: TRAVIS COUNTY ESD #3 AND BOERNE

4.3.1: BURN SUSCEPTIBILITY

FlamMap MTT simulations mimicking September 4, 2011 weather conditions revealed patterns within the landscape of low to high susceptibility to fire as a result of four thousand ignitions that ran for two hours each. Ninety-nine percent of area within the Travis County ESD #3 study extent burned at least once during the MTT simulations. Twenty-two percent of the study area burned in the highest quintile (the top twenty percent of the data), while seven percent burned in the lowest quintile (the bottom twenty percent of the data). Overall, sixty-nine percent of the Travis County ESD #3 study area burned in the top three quintiles.

Within the Boerne City Fire Department study area, eighty-eight percent burned at least once during the simulations. Seven percent burned in the highest quintile, and forty-nine percent burned in the lowest quintile. In contrast to the Travis County ESD #3 study area, only twenty-eight percent of the Boerne study extent burned in the top three quintiles. Table 4.7 provides a comparison of these data. Figures 4.18 and 4.19 provide maps of the spatial distribution of burn susceptibility in the Travis County ESD #3 extent and the Boerne extent, respectively.

PERCENTAGE OF STUDY AREA SUSCEPTIBLE TO BURNING

	Travis County ESD #3		Boerne	
Percentage of Area that Burned At Least Once	99%		88%	
	Percentage of Study Area	Cumulative Percentage	Percentage of Study Area	Cumulative Percentage
Fifth Quintile	22%	22%	7%	7%
Fourth Quintile	21%	43%	8%	15%
Third Quintile	26%	69%	13%	28%
Second Quintile	24%	93%	23%	51%
First Quintile	7%	100%	49%	100%

Table 4.7: Percentage of area in the two focal WUI communities susceptible to burning in the MTT simulations.

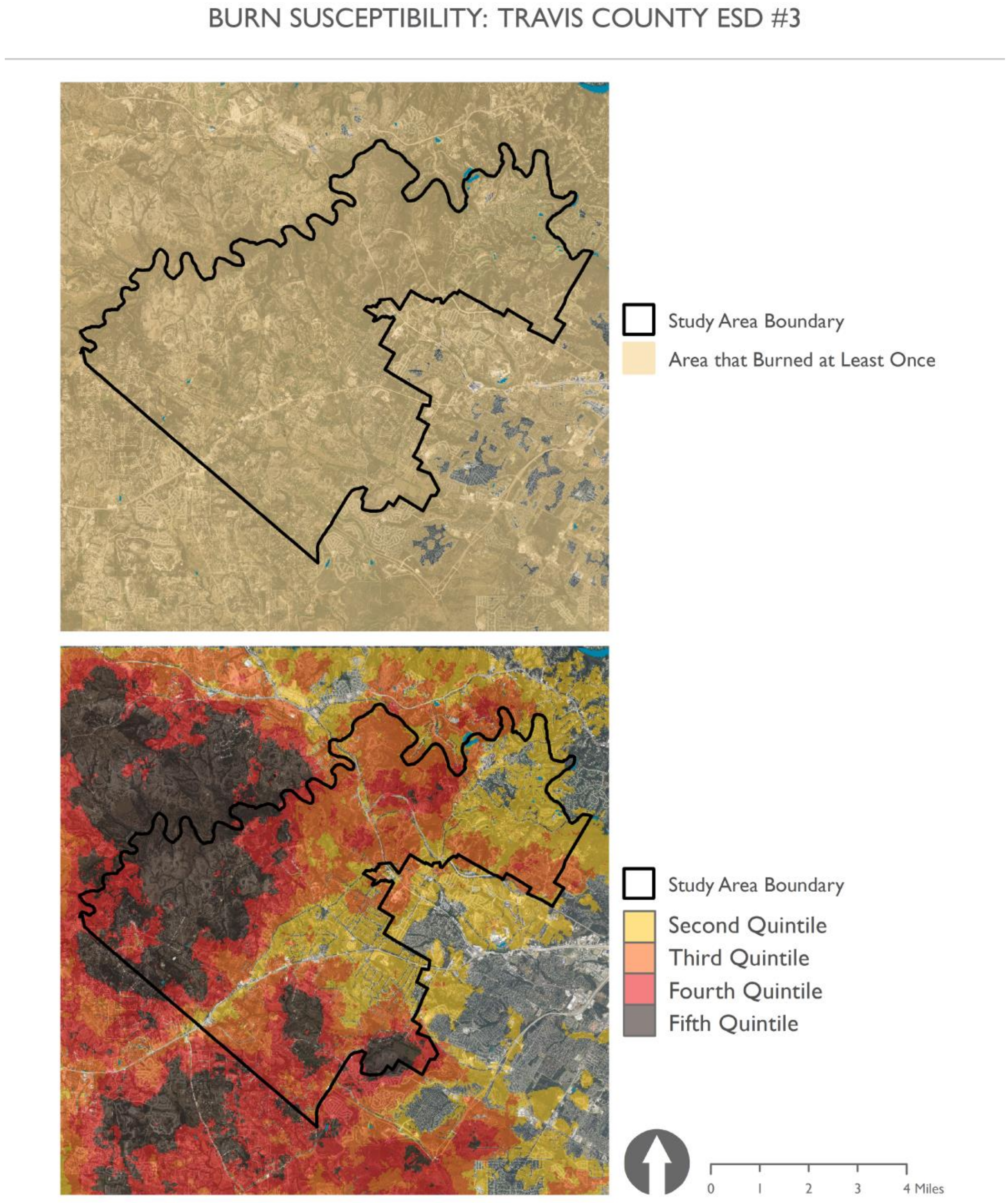

Figure 4.18: Spatial Distribution of Burn Susceptibility in Travis County ESD #3.

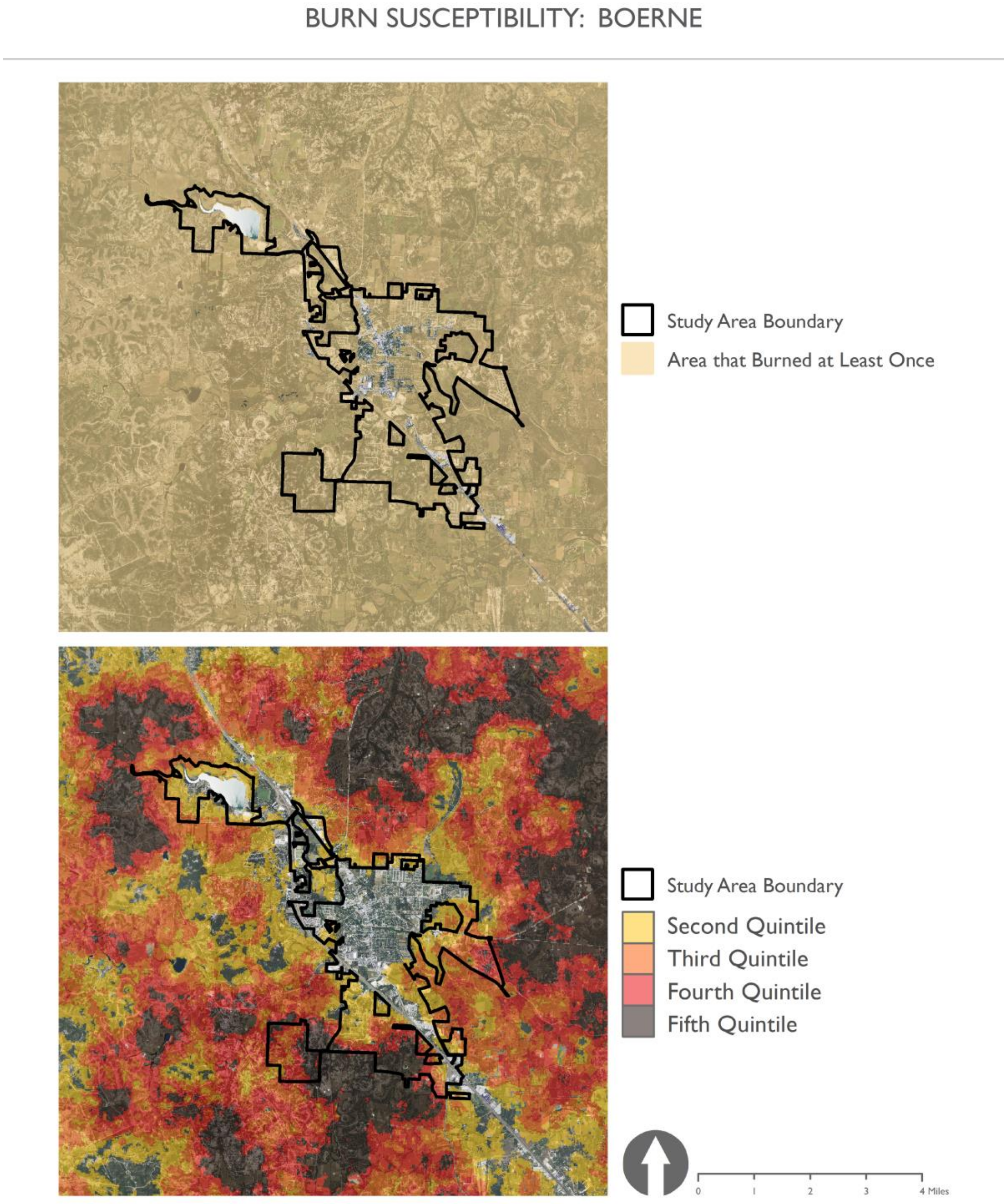

Figure 4.19: Spatial Distribution of Burn Susceptibility in Boerne.

4.3.2: FIRE BEHAVIOR

Flame lengths and crown fire activity were also measured during the FlamMap MTT simulations. Sixty percent of the Travis County ESD #3 study area exhibited the potential for flame lengths surpassing eleven feet in height under weather conditions mimicking September 4, 2011 (Figure 4.20). Forty-one percent of the study area also exhibited the potential for active crown fires. In contrast thirty-four percent of the Boerne study area exhibited the potential for flames lengths over eleven feet, while fifteen percent exhibited the potential for active crown fires (Figure 4.21).

Figure 4.20: Spatial distribution of fire behavior in Travis County ESD #3.

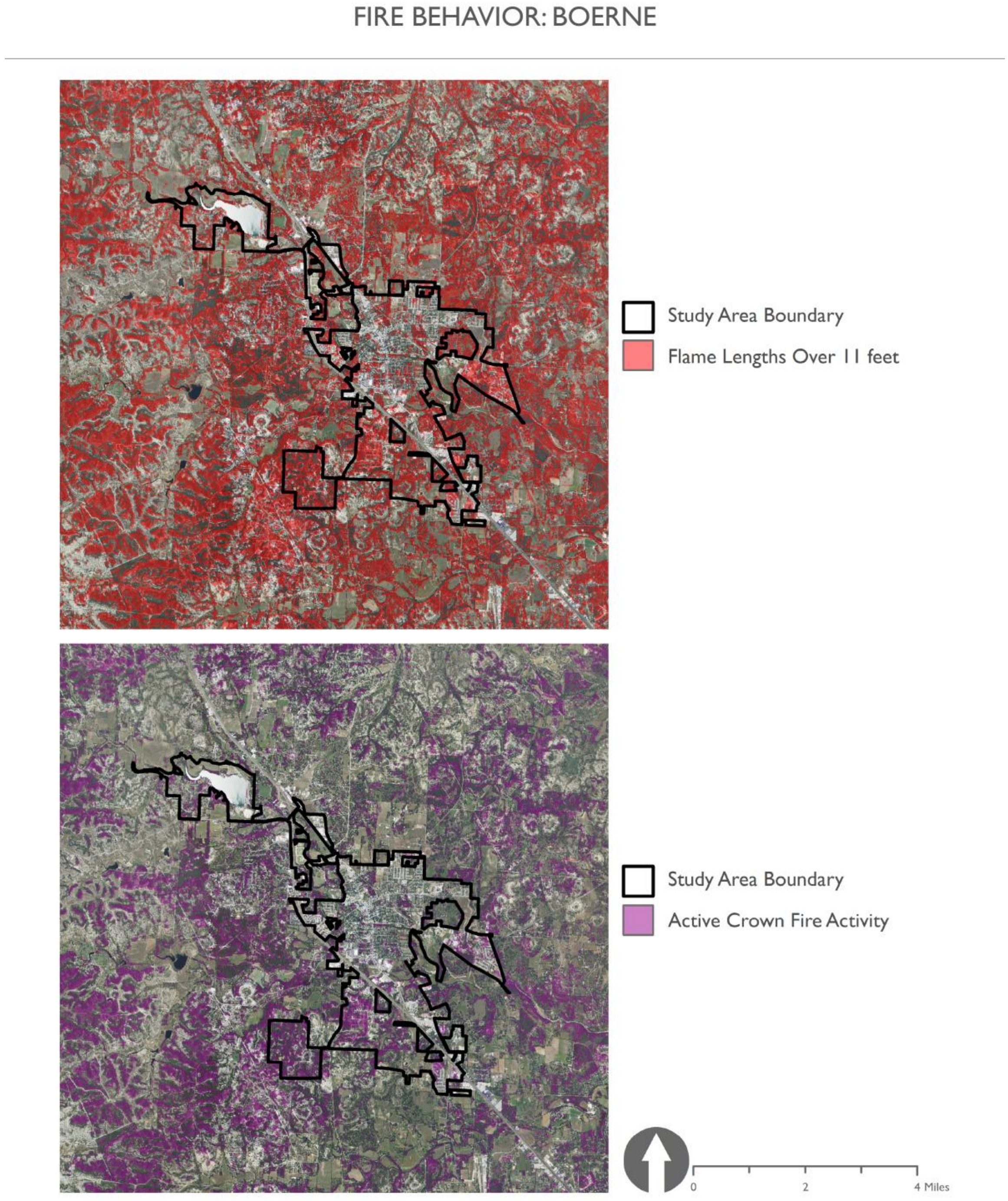

Figure 4.21: Spatial distribution of fire behavior in Boerne.

4.4 RESPONSE CAPACITY AND MITIGATION: TRAVIS COUNTY ESD #3 AND BOERNE

4.4.1: EMERGENCY RESPONSE CAPACITY

A summary of the emergency response capacity indicators obtained for each study area is provided in Table 4.8.

EMERGENCY RESPONSE CAPACITY INDICATORS

	Travis County ESD #3	Boerne Fire Department
Emergency Notification	Reverse 911	Reverse 911
Fire Department Paid Firefighters	27	14
Fire Department Volunteer Firefighters	21	19
Current Fire Department Budget	$3,961,537.00	$1,291,178.00
Average Response Time	5.4 to 6.4 minutes	Less than 6 minutes
ISO Rating	2/8b	4/8b
Distance to Closest Assisting Department	1.4 miles	12 miles
Cooperation with Surrounding Departments	Mutual assistance between all Travis County and City of Austin fire departments	Mutual assistance between all County fire departments
STARFlight Firefighting Helicopter Response Time	Less than 10 minutes	40 minutes or more

Table 4.8: Summary of emergency response capacity indicators.

Based on information gathered from the Capital Area Council of Governments, the Alamo Area Council of Governments, the Travis County Emergency Management Department and the Boerne Fire Department, both study areas participate in reverse 911 systems for notifying the public in case of an emergency. In the case of an emergency, response teams inform the reverse 911 system of the neighborhoods that need to be notified. The reverse 911 system then contacts residents that are registered to live in those neighborhoods by telephone. Residents are not automatically signed up for the service; reverse 911 calling is a voluntary service that requires initiation from households or individuals.

Travis County ESD #3 reported to have twenty-seven paid firefighters and twenty-one volunteer firefighters on staff with an annual budget of 3.96 million dollars. The Boerne Fire Department reported a team of fourteen paid firefighters and nineteen volunteer firefighters with an annual budget of 1.29 million dollars.

The response times are similar between fire departments. Based on monthly averages, the Travis County ESD #3 reported an average of 5.4 to 6.4

minutes in response times. The Boerne Fire Department reported a response time of less than six minutes for calls within city limits.

According to the Texas Department of Insurance, the ISO rating is a widely used public protection classification system derived by the Insurance Services Office for the purposes of rating the capacity of fire departments based on comprehensive attributes of the department (http://www.tdi.texas.gov/fire/fmppcfaq.html). The rates range from ten to one. A score of ten corresponds to the lowest capacity and a score of one corresponds to the highest. The Travis County ESD #3 was upgraded to a split 2/8b classification in 2009. This split classification means that any housing unit that is within one thousand feet of a fire hydrant and within five road miles of a fire department receives services at level two and any housing unit that is more than one thousand feet of a fire hydrant but within five road miles of a fire department receives services at level eight. Any housing unit beyond five road miles of a fire department receives services at level ten. The Boerne Fire Department reported a split 4/8b classification. According to the Texas Department of Insurance, fire departments of large Texas cities typically score three or four and small towns typically score between four and seven. Only a few Texas cities have been rated with an ISO of two.

Figures 4.22 and 4.23 show the location of the fire departments within the Travis County ESD #3 and Boerne study extents, respectively, and buffers to represent portions that lie within the five road mile distance. Figures 4.22 and 4.23 also show the locations of neighboring fire stations. Both the Travis County ESD #3 and the Boerne Fire Department have assistance agreements with other fire departments within their respective counties as well as neighboring county fire departments. The Travis County ESD #3 also has an assistance agreement with the City of Austin. The closest coordinating fire department is 1.4 miles from the Travis County ESD #3 fire department headquarters, while the closest coordinating fire department for the City of Boerne is located twelve miles away.

Central Texas also has a new firefighting helicopter, as of 2013, under the STARFlight system. This helicopter holds 325 gallons of water and refills quickly from open water bodies. STARFlight is operated by Travis County, and is based out of Austin, but it is tailored to serve the five county Austin MSA, of which Kendall County is not a member. However, counties outside of the Austin MSA can also request STARFlight services. The estimated time it takes STARFlight to respond to the Travis County ESD #3 jurisdiction is under 10 minutes and over 40 minutes for Kendall County (https://starflight.traviscountytx.gov/).

FIRE STATIONS: TRAVIS COUNTY ESD #3

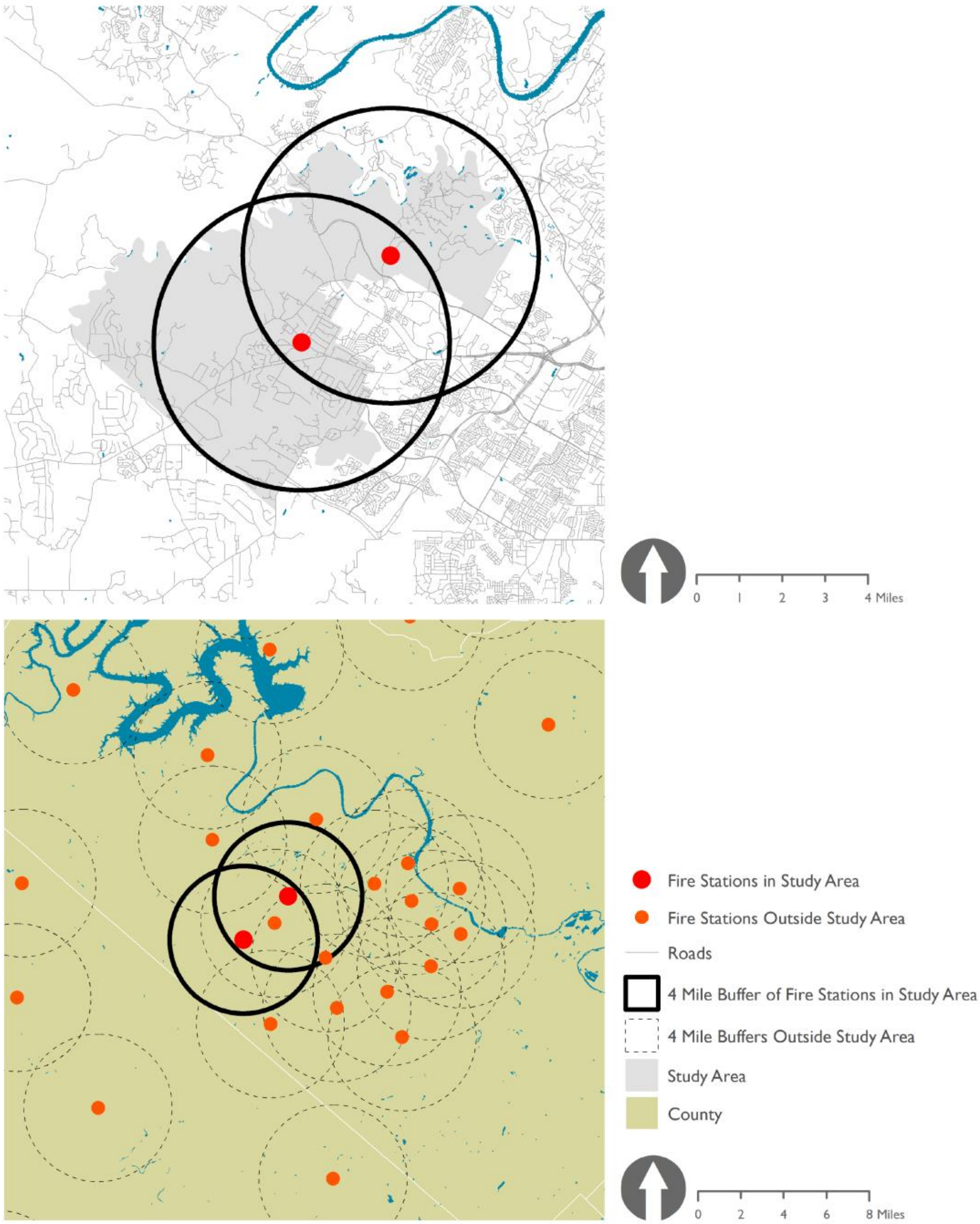

Figure 4.22: Fire Stations and four mile buffers within Travis County ESD #3.

Figure 4.23: Fire Stations and four mile buffers within the Boerne study extent.

4.4.2: PLANS AND PROGRAMS TO MITIGATE WILDFIRE HAZARDS

Each study areas was surveyed for participation in CWPP, Firewise, or any other program aimed at increasing community awareness and encouraging property-level mitigation such as defensible space or fire-resistant building materials. No CWPP process has yet taken place within Travis County, Kendall County, or the city of Boerne. However, according to the Travis County Emergency Management Department, Travis County and the City of Austin, have recently (2013) hired a planning consulting firm to complete a CWPP for the county. A public information session was held in May of 2013 to begin recording public comments.

The Firewise process in Texas can be done at any scale but is commonly performed at the neighborhood or subdivision scale, according to a WUI specialist with the Texas Forest Service. No neighborhoods in either the Travis County ESD #3 jurisdiction or the Boerne Fire Department jurisdiction have been certified as Firewise communities. However, of the communities that have already obtained Firewise certification in Texas, many are neighborhoods in western Travis County. Figure 4.24 shows the location of certified Firewise communities within the eastern Edwards Plateau extent. Eleven of the communities are in Travis County west of Austin. In fact, according to a WUI specialist with the Texas Forest Service, Travis County emergency service districts have been actively promoting the Firewise program to small cities and unincorporated neighborhoods in the county, which has led to their greater participation in the program than other counties in Texas.

Upon searching for other mitigation plans, programs, and strategies outside of the CWPP and Firewise programs that also aim to mitigate wildfire hazards at the property-level, it was determined that neither study area is participating in any such program.

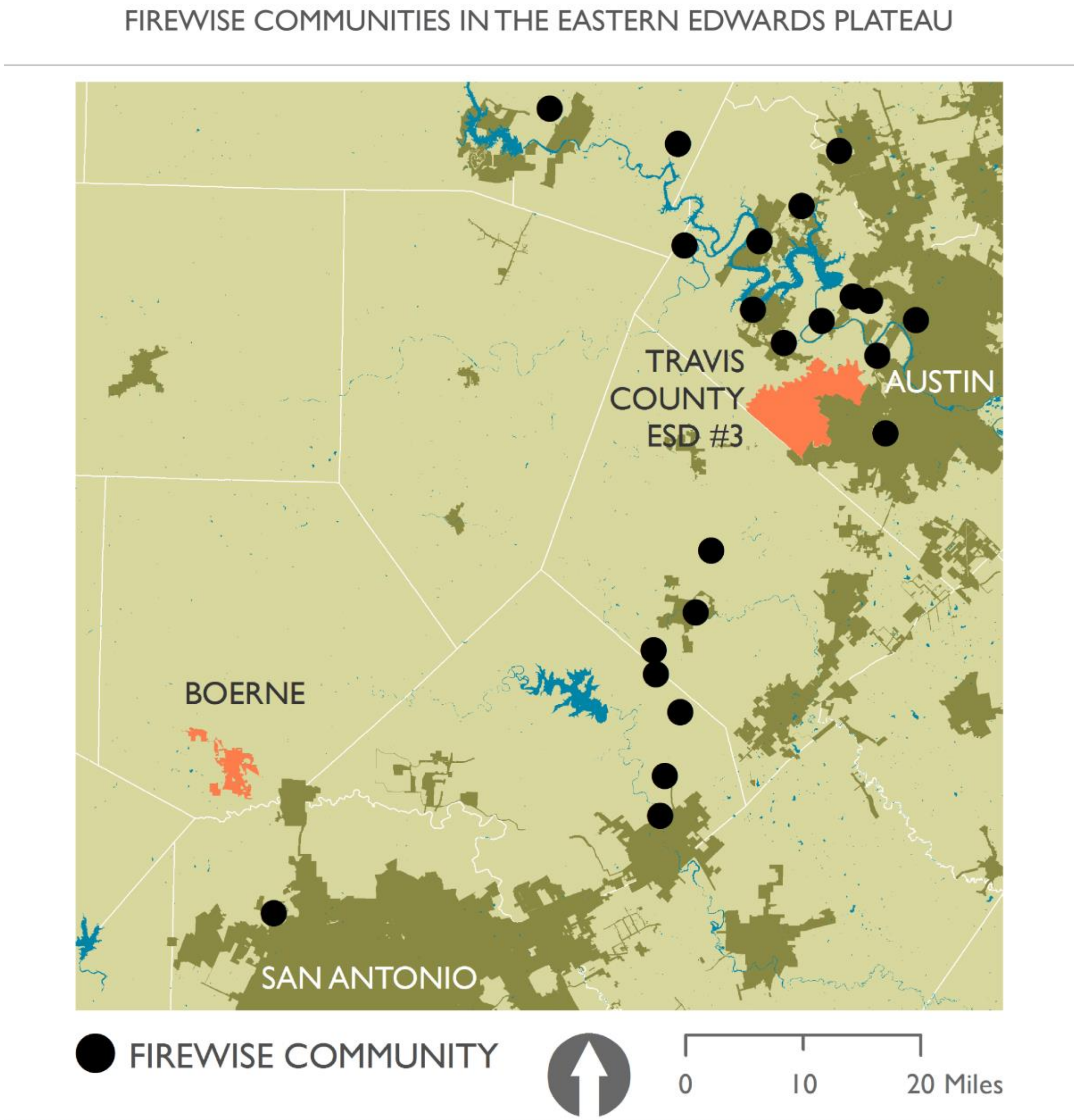

Figure 4.24: FIREWISE communities currently registered in the eastern Edwards Plateau study extent.

CHAPTER 5: DISCUSSION

5.1: INTRODUCTION TO CHAPTER 5

The results provided in Chapter 4 address several questions about wildfire hazards in the eastern Edwards Plateau, first at the regional scale of over six thousand square miles, then down to the community scale of roughly fifteen thousand individuals. Chapter 5 partitions the interpretations of the findings into sections referring directly to the three research questions detailed in Chapter 3. The first section contains a summary of the results from simulation modeling at the regional extent. The second section contains a summary of the simulation modeling performed for the two focal communities within the extent. The third section discusses the findings on response capacity and mitigation for the two focal communities within the extent. Finally the fourth section synthesizes these results and provides a discussion on future work that could improve comprehensive community and regional wildfire hazard assessments.

5.2: WILDFIRE HAZARDS IN THE EASTERN EDWARDS PLATEAU

Dramatic variation in surface and crown fire behavior was witnessed among the eight weather scenarios simulated in FlamMap. Under the mildest scenario only seven percent of the study extent exhibited flame lengths over one foot, one hundred percent of the study extent had rates of spread under ten chains per hour, and no active crown fires occurred. In contrast, the most extreme scenario caused flame lengths in forty-four percent of the study extent to surpass eleven feet in height. Thirty-eight percent of the extent experienced rates of spread over eighty chains per hour. Similarly, fifty-six percent of the study area with canopy cover experienced active crown fires.

The weather and climate parameters that led to these results are all conditions that are known to occur in the region. However, the extreme summer conditions of 2011 are indicative of how climate conditions may change as average daily temperatures increase and long periods of time pass between rain events. In non-drought periods, a burst of wind during a two-week stint of dry, hot days can also cause substantial increases in wildfire behavior. Overall, these results indicate that extreme wildfire behavior is not limited to the summer of 2011. Fire conditions leading to extreme fire behavior are predicted to present themselves more frequently in the future.

The area of greatest concern is the Balcones Escarpment. Not only is this area undergoing the most population growth, it is also the portion of the extent that is the most susceptible to active crown fires. The areas with fifteen to forty-five percent canopy cover that were concentrated within and directly to the west of the Balcones Escarpment were susceptible to the highest surface flame lengths. This should be a concern as woody species encroachment continues in the Edwards Plateau.

5.3: WILDFIRE HAZARDS IN TRAVIS COUNTY ESD #3 AND BOERNE

The wildfire simulations of the two focal communities showed how the extreme fire behavior under September 4, 2011 weather conditions impacted neighborhoods in the WUI. The communities had similar population totals in the year 2010, yet the Travis County ESD #3 spans a much larger area than does the city of Boerne. Likewise, the city of Boerne has a compact urban form when compared to Travis County ESD #3, which is largely made up of properties with greater than one acre of land. The burn susceptibility results showed that more of the Travis County ESD #3 is susceptible to burning while the highest burn susceptibilities of Boerne remained outside its borders. This still puts the edges of Boerne at risk for wildfire activity, yet a smaller proportion of the total population is threatened. The fire behavior results also showed that more of the area within the Travis County ESD #3 jurisdiction has the potential for extreme fire behavior than Boerne. For example, forty-one percent of the Travis County ESD #3 jurisdiction exhibited active crown fires versus only fifteen percent of Boerne under the same test parameters.

The compact urban form of Boerne is also beneficial for providing superior evacuation routes. Boerne contains mostly gridded streets that provide multiple exits from subdivisions (Figure 5.1). According to the Assistant Fire Chief for the Boerne Fire Department, city ordinances require adequate egress for subdivisions developed within the city limits (personal communication). In contrast, the Travis County ESD #3 has many long and winding streets, often with only one distant exit from the subdivision (Figure 5.2).

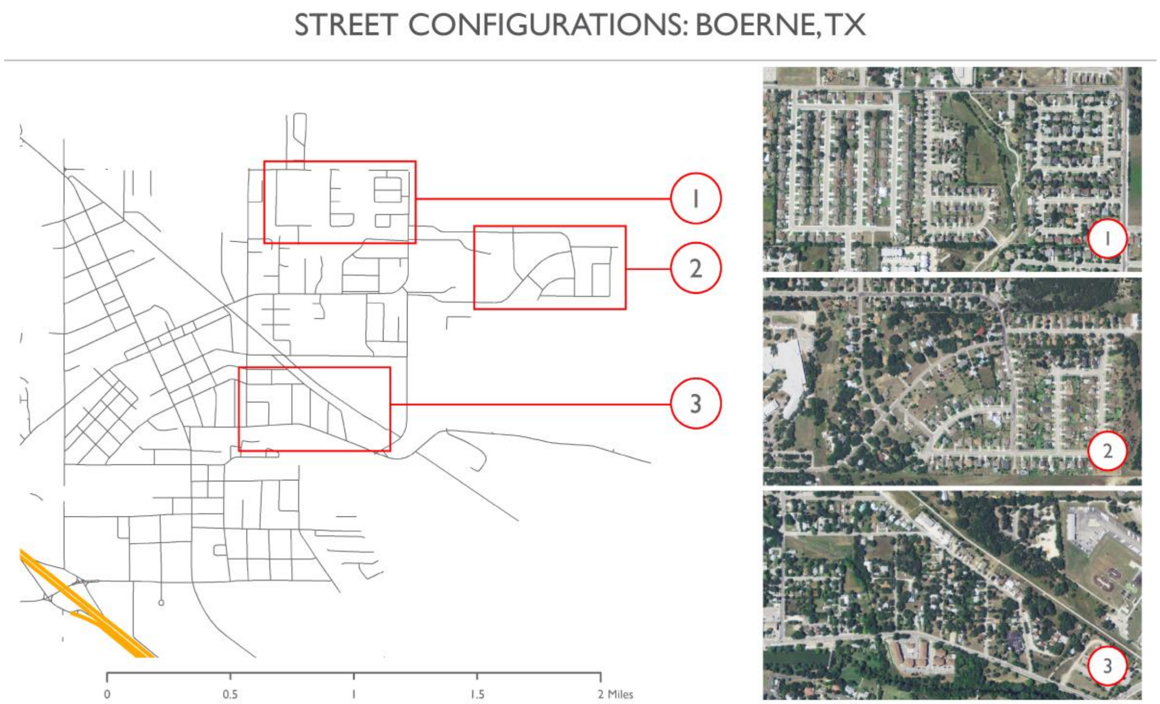

Figure 5.1: Compact street configuration in Boerne, Texas.

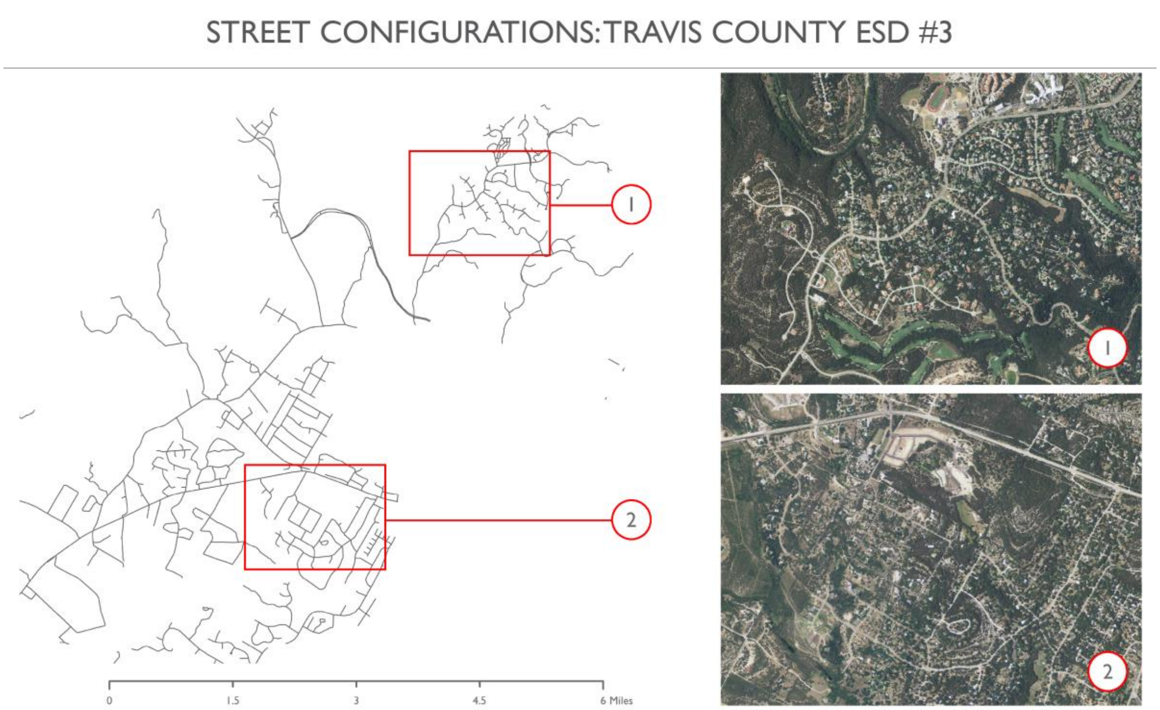

Figure 5.2: Long, winding street configuration on Travis County ESD #3.

5.4: RESILIENCE AND ADAPTATION IN TRAVIS COUNTY ESD #3 AND BOERNE

Based on fire department capacity and coordination with outside agencies, the communities in the Travis County ESD #3 jurisdiction have access to more response capacity. The Travis County ESD #3 not only has over twice the budget (to serve the same number of people), more firefighters, and a higher ISO rating, it also has the benefit of several nearby coordinating fire stations as well as the STARFlight firefighting helicopter only a few miles away. Some research suggests that hazards can impact smaller communities more substantially than larger communities due to their reduced access to infrastructure, emergency services, etc. (Cross 2001). The difference between these two study areas supports this theory.

The Travis County ESD #3 has also shown more potential to adopt strategies that aim to prevent or minimize wildfire hazards. No programs are currently completed for either study area, yet Travis County is making progress toward adopting a CWPP and has inspired eleven neighborhoods in western Travis County to participate in the Firewise program. The difference between these communities' receptiveness to carrying out wildfire mitigation through programs such as CWPP and Firewise is not clear. It could be due to the 2011 fires that occurred within Travis County, which have awakened a sense of urgency in the Travis County population, or it could be based on differences in attitudes or demographics between the populations.

5.5: CONCLUSION

Taken together, these three methods have shown that wildfire hazards exhibiting extreme fire behavior are a real possibility for the eastern Edwards Plateau. The study does not predict how vegetation communities will adapt to shifts in climate, but while the vegetation resembles what we see today, hot, dry summers will pose significant threats to communities. Certain areas are exhibiting signs of adaptation by bolstering response capacity and promoting prevention measures. Yet, other areas are not exhibiting this trend.

Through the process of discovering how the two study areas approached wildfire mitigation, it became evident that even though fuel mitigation is widely understood to be the most effective tool for minimizing wildfire hazards, programs devoted to fuel mitigation around the WUI are not common in the eastern Edwards Plateau. The CWPP and Firewise programs do incorporate some degree of fuel mitigation recommendations, yet it is up to private property owners to coordinate actions that will make meaningful differences at the neighborhood scale. Future analysis into effective fuel management strategies, including cooperation among private property owners would be a valuable contribution to wildfire hazard and mitigation assessments for the region.

Simulation modeling proved to be a beneficial tool for assessing as well as communicating potential wildfire hazards at the regional and community scale. Most of the land area within the eastern Edwards Plateau is susceptible to extreme surface or crown fire behavior under the right conditions, and those conditions are expected to become more frequent. The region is showing some signs of adapting wildfire hazards through the development of a CWPP in Travis County and the voluntary participation of many neighborhoods in the Firewise Program. Yet, mitigating through fuel management was not evident in the study areas. Furthermore, the efficacy of participating in wildfire prevention planning will not be clear until another wildfire incident occurs. More research into the pattern of fuel management that optimize hazard reduction as well as research into structure ignitibility in relation to property-level fuel reductions would greatly enhance this wildfire hazard assessment.

WORKS CITED

Adger, W. Neil. 2006. "Vulnerability." *Global Environmental Change* 16 (3): 268–281.

Adger, W. Neil, Terry P. Hughes, Carl Folke, Stephen R. Carpenter, and Johan Rockström. 2005. "Social-ecological Resilience to Coastal Disasters." *Science* 309 (5737): 1036–1039.

Agee, J. K., and C. N. Skinner. 2005. "Basic Principles of Forest Fuel Reduction Treatments." *Forest Ecology and Management* 211 (1): 83–96.

Ager, Alan A., Nicole M. Vaillant, and Mark A. Finney. 2010. "A Comparison of Landscape Fuel Treatment Strategies to Mitigate Wildland Fire Risk in the Urban Interface and Preserve Old Forest Structure." *Forest Ecology and Management* 259 (8): 1556–1570.

Allen, Craig D., Alison K. Macalady, Haroun Chenchouni, Dominique Bachelet, Nate McDowell, Michel Vennetier, Thomas Kitzberger, Andreas Rigling, David D. Breshears, and E. H. Hogg. 2010. "A Global Overview of Drought and Heat-induced Tree Mortality Reveals Emerging Climate Change Risks for Forests." *Forest Ecology and Management* 259 (4): 660–684.

Benavides-Solorio, J., and L. H. MacDonald. 2001. "Post-fire Runoff and Erosion from Simulated Rainfall on Small Plots, Colorado Front Range." *Hydrological Processes* 15 (15): 2931–2952.

Bowman, David MJS, Jennifer K. Balch, Paulo Artaxo, William J. Bond, Jean M. Carlson, Mark A. Cochrane, Carla M. D'Antonio, Ruth S. DeFries, John C. Doyle, and Sandy P. Harrison. 2009. "Fire in the Earth System." *Science* 324 (5926): 481–484.

Bowman, David MJS, Jennifer Balch, Paulo Artaxo, William J. Bond, Mark A. Cochrane, Carla M. D'Antonio, Ruth DeFries, Fay H. Johnston, Jon E. Keeley, and Meg A. Krawchuk. 2011. "The Human Dimension of Fire Regimes on Earth." *Journal of Biogeography* 38 (12): 2223–2236.

Brooks, Nick. 2003. "Vulnerability, Risk and Adaptation: A Conceptual Framework." *Tyndall Centre for Climate Change Research Working Paper* 38: 1–16.

Brown, Timothy J., Beth L. Hall, and Anthony L. Westerling. 2004. "The Impact of Twenty-first Century Climate Change on Wildland Fire Danger in the Western United States: An Applications Perspective." *Climatic Change* 62 (1-3): 365–388.

Brummel, Rachel F., Kristen C. Nelson, Stephanie Grayzeck Souter, Pamela J. Jakes, and Daniel R. Williams. 2010. "Social Learning in a Policy-mandated Collaboration: Community Wildfire Protection Planning in the Eastern United States." *Journal of Environmental Planning and Management* 53 (6): 681–699.

Capital Area Council of Governments. 2009. "County Land Use Authority in Texas." Accessed June 20, 2013. http://data.capcog.org/Information_Clearinghouse/presentations/2009-11-03%20County%20Land%20Use%20Report%20-%20final%20for%20Publication.pdf.

Cohen, J. D. 2000. "Preventing Disaster: Home Ignitability in the Wildland-urban Interface." *Journal of Forestry* 98 (3): 15–21.

Cohen, J. 2008. "The Wildland-urban Interface Fire Problem." *FOREST*: 21.

Cross, John A. 2001. "Megacities and Small Towns: Different Perspectives on Hazard Vulnerability." *Global Environmental Change Part B: Environmental Hazards* 3 (2): 63–80.

Cutter, S. L. 1996. "Vulnerability to Environmental Hazards." *Progress in Human Geography* 20: 529–539.

Cutter, S. L., B. J. Boruff, and W. L. Shirley. 2003. "Social Vulnerability to Environmental Hazards*." *Social Science Quarterly* 84 (2): 242–261.

Cutter, S. L., J. T. Mitchell, and M. S. Scott. 2000. "Revealing the Vulnerability of People and Places: A Case Study of Georgetown County, South Carolina." *Annals of the Association of American Geographers* 90 (4): 713–737.

Cutter, Susan L., Lindsey Barnes, Melissa Berry, Christopher Burton, Elijah Evans, Eric Tate, and Jennifer Webb. 2008. "A Place-based Model for Understanding Community Resilience to Natural Disasters." *Global Environmental Change* 18 (4): 598–606.

Cutter, Susan L., and Christina Finch. 2008. "Temporal and Spatial Changes in Social Vulnerability to Natural Hazards." *Proceedings of the National Academy of Sciences* 105 (7): 2301–2306.

Eriksen, Christine, and Timothy Prior. 2011. "The Art of Learning: Wildfire, Amenity Migration and Local Environmental Knowledge." *International Journal of Wildland Fire* 20 (4): 612–624.

Fernandes, P. M., and H. S. Botelho. 2003. "A Review of Prescribed Burning Effectiveness in Fire Hazard Reduction." *International Journal of Wildland Fire* 12 (2): 117–128.

Finney, M. A. 2001. "Design of Regular Landscape Fuel Treatment Patterns for Modifying Fire Growth and Behavior." *Forest Science* 47 (2): 219–228.

Finney, Mark A., Rob C. Seli, Charles W. McHugh, Alan A. Ager, Bernhard Bahro, and James K. Agee. 2008. "Simulation of Long-term Landscape-level Fuel Treatment Effects on Large Wildfires." *International Journal of Wildland Fire* 16 (6): 712–727.

Fischer, A. Paige, and Susan Charnley. 2012. "Risk and Cooperation: Managing Hazardous Fuel in Mixed Ownership Landscapes." *Environmental Management* 49 (6): 1192–1207.

Flannigan, Mike D., Meg A. Krawchuk, William J. de Groot, B. Mike Wotton, and Lynn M. Gowman. 2009. "Implications of Changing Climate for Global Wildland Fire." *International Journal of Wildland Fire* 18 (5): 483–507.

Gallopín, Gilberto C. 2006. "Linkages Between Vulnerability, Resilience, and Adaptive Capacity." *Global Environmental Change* 16 (3): 293–303.

Gill, A. M., and S. L. Stephens. 2009. "Scientific and Social Challenges for the Management of Fire-prone Wildland–urban Interfaces." *Environmental Research Letters* 4 (3): 034014.

Headwaters Economics. 2009. *Solutions to the Rising Cost of Fighting Fires in the Wildland-Urban Interface*. Bozeman, Montana. www.headwaterseconomics.org/wildfire.php.

Headwaters Economics. 2013. *The Rising Cost of Wildfire Protection. Bozeman, Montana*. http://headwaterseconomics.org/wildfire/fire-costs-background.

International Panel on Climate Change (IPCC). 2007. *Climate Change 2007: Impacts, Adaptation and Vulnerability: Working Group II Contribution to the Fourth Assessment Report of the IPCC Intergovernmental Panel on Climate Change*. Vol. 4. Cambridge University Press.

Jakes, Pamela, Sam Burns, Antony Cheng, Emily Saeli, Kristen Nelson, Rachel Brummel, Stephanie Grayzeck, Victoria Sturtevant, and Daniel Williams. 2007a. "Critical Elements in the Development and Implementation of Community Wildfire Protection Plans (CWPPs)." In *The Fire Environment—innovations, Management, and Policy, Destin, FL, 2007. Conference Proceedings RMRS-P-46CD. US Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fort Collins*, 26–30.

Jakes, P., L. Kruger, M. Monroe, K. Nelson, and V. Sturtevant. 2007b. "Improving Wildfire Preparedness: Lessons from Communities Across the US." *Human Ecology Review* 14 (2): 188–197.

Jarrett, Adam, Jianbang Gan, Cassandra Johnson, and Ian A. Munn. 2009. "Landowner Awareness and Adoption of Wildfire Programs in the Southern United States." *Journal of Forestry* 107 (3): 113–118.

Jarrett, James E., and J. Jorge Anchondo. 2012. "Texas Emergency Services Districts in High Growth Areas." Bureau of Business Research, the University of Texas at Austin.

Jiang, Xiaoyan, and Zong-Liang Yang. 2012. "Projected Changes of Temperature and Precipitation in Texas from Downscaled Global Climate Models." *Clim Res* 53: 229-244.

Johnson, E. H. "Edwards Plateau," *Handbook of Texas Online.* Accessed June 20, 2013. http://www.tshaonline.org/handbook/online/articles/rxe01.

Keeley, J. E. 2009. "Fire Intensity, Fire Severity and Burn Severity: a Brief Review and Suggested Usage." *International Journal of Wildland Fire* 18 (1): 116–126.

Krawchuk, Meg A., Max A. Moritz, Marc-André Parisien, Jeff Van Dorn, and Katharine Hayhoe. 2009. "Global Pyrogeography: The Current and Future Distribution of Wildfire." Edited by Jerome Chave. *PLoS ONE* 4 (4) (April 8): e5102.

Lee, H. 2011. "Travis County Commissioners Court Declares Local Disaster." Travis County Fire Marshal's Office. Accessed June 20, 2013. http://www.co.travis.tx.us/documents/press_release_disaster_declaration_2011.pdf.

Lee, H. 2012. "Pedernales Wildland Fire Ruled as Accidental." Travis County Fire Marshal's Office. Accessed June 20, 2013. http://www.co.travis.tx.us/fire_marshal/press_release/Pedernales_Spicewood_Fire_investigation_pressrelease.pdf.

Marlon, J. R., P. J. Bartlein, M. K. Walsh, S. P. Harrison, K. J. Brown, M. E. Edwards, P. E. Higuera, et al. 2009. "Wildfire Responses to Abrupt Climate Change in North America." *Proceedings of the National Academy of Sciences* 106 (8) (February 24): 2519–2524.

Mell, W. E., S. L. Manzello, A. Maranghides, D. Butry, and R. G. Rehm. 2010. "The Wildland–urban Interface Fire Problem–current Approaches and Research Needs." *International Journal of Wildland Fire* 19 (2): 238–251.

Miller, J. D., H. D. Safford, M. Crimmins, and A. E. Thode. 2009. "Quantitative Evidence for Increasing Forest Fire Severity in the Sierra Nevada and Southern Cascade Mountains, California and Nevada, USA." *Ecosystems* 12 (1): 16–32.

Moritz, M. A., M. A. Parisien, E. Batllori, M. A. Krawchuk, J. Van Dorn, D. J. Ganz, and K. Hayhoe. 2012. "Climate Change and Disruptions to Global Fire Activity." Ecosphere 3 (6).

National Interagency Fire Center (NIFC). 2009. "Quadrennial Fire Review." Accessed May 20, 2013. Accessed May 20, 2013. http://www.nifc.gov/PUBLICATIONS/QFR/QFR2009Final.pdf.

National Interagency Fire Center (NIFC). 2013a. "Federal Firefighting Costs (Suppression Only)." Accessed May 20, 2013. http://www.nifc.gov/fireInfo/fireInfo_documents/SuppCosts.pdf.

National Interagency Fire Center (NIFC). 2013b. "1997-2012 large fires (100,000+ acres)." Accessed May 20, 2013. http://www.nifc.gov/fireInfo/fireInfo_stats_lgFires.html.

National Oceanic and Atmospheric Administration (NOAA). 2013. "Billion-Dollar Weather/Climate Disasters." Accessed May 20, 2013. http://www.ncdc.noaa.gov/billions.

National Wildfire Coordinting Group. 2010. "Incident Response Pocket Guide." Accessed May20, 2013. http://www.nwcg.gov/var/products/incident-response-pocket-guide.

Olmstead, Sheila, Carolyn Kousky, and Roger Sedjo. 2012. "Wildland Fire Suppression and Land Development in the Wildland/Urban Interface." USDA Forest Service. http://www.firescience.gov/projects/10-3-01-33/project/10-3-01-33_final_report.pdf.

Parisien, M. A., and M. A. Moritz. 2009. "Environmental Controls on the Distribution of Wildfire at Multiple Spatial Scales." *Ecological Monographs* 79 (1): 127–154.

Pausas, Juli G., and Jon E. Keeley. 2009. "A Burning Story: The Role of Fire in the History of Life." *BioScience* 59 (7): 593–601.

Paveglio, Travis B., Pamela J. Jakes, Matthew S. Carroll, and Daniel R. Williams. 2009. "Understanding Social Complexity Within the Wildland–urban

Interface: a New Species of Human Habitation?" *Environmental Management* 43 (6): 1085–1095.

Pearson, Richard G., and Terence P. Dawson. 2003. "Predicting the Impacts of Climate Change on the Distribution of Species: Are Bioclimate Envelope Models Useful?" *Global Ecology and Biogeography* 12 (5): 361–371.

Pettit, N. E., and R. J. Naiman. 2007. "Fire in the Riparian Zone: Characteristics and Ecological Consequences." *Ecosystems* 10 (5): 673–687.

Radeloff, V. C., R. B. Hammer, S. I. Stewart, J. S. Fried, S. S. Holcomb, and J. F. McKeefry. 2005. "The Wildland-urban Interface in the United States." *Ecological Applications* 15 (3): 799–805.

Schoennagel, T., C. R. Nelson, D. M. Theobald, G. C. Carnwath, and T. B. Chapman. 2009. "Implementation of National Fire Plan Treatments Near the Wildland–urban Interface in the Western United States." *Proceedings of the National Academy of Sciences* 106 (26): 10706–10711.

Schröter, Dagmar, Wolfgang Cramer, Rik Leemans, I. Colin Prentice, Miguel B. Araújo, Nigel W. Arnell, Alberte Bondeau, Harald Bugmann, Timothy R. Carter, and Carlos A. Gracia. 2005. "Ecosystem Service Supply and Vulnerability to Global Change in Europe." *Science* 310 (5752): 1333–1337.

Scott, Joe H., and Robert E. Burgan. 2005. "Standard Fire Behavior Fuel Models: a Comprehensive Set for Use with Rothermel's Surface Fire Spread Model." *The Bark Beetles, Fuels, and Fire Bibliography*: 66.

Smit, Barry, and Johanna Wandel. 2006. "Adaptation, Adaptive Capacity and Vulnerability." *Global Environmental Change* 16 (3) (August): 282–292.

Stephens, S. L., J. J. Moghaddas, C. Edminster, C. E. Fiedler, S. Haase, M. Harrington, J. E. Keeley, et al. 2009. "Fire Treatment Effects on Vegetation

Structure, Fuels, and Potential Fire Severity in Western US Forests." *Ecological Applications* 19 (2): 305–320.

Stephens, Scott L., and Lawrence W. Ruth. 2005. "Federal Forest-fire Policy in the United States." *Ecological Applications* 15 (2): 532–542.

Stewart, S.I. and V.C. Radeloff. 2012. "2010 Wildland Urban Interface – Public Land Adjusted." Accessed May 23, 2013. http://silvis.forest.wisc.edu/maps/wui/2010/download.

Texas A&M Forest Service. 2011. "2011 Texas Wildfires: Common Denominators of Home Destruction." Accessed July 23, 2013. http://tfsweb.tamu.edu/uploadedFiles/FRP/New_-_Mitigation/Safety_Tips/2011%20Texas%20Wildfires.pdf.

Theobald, D. M., and W. H. Romme. 2007. "Expansion of the US Wildland-urban Interface." *Landscape and Urban Planning* 83 (4): 340–354.

Travis County Fire Marshal's Office. 2011. "Case #11-22090 Steiner Ranch Wildland Fire 9/4/2011." Accessed June 2, 2013. http://www.co.travis.tx.us/fire_marshal/pdf_files/Steiner_Ranch_Fire_Report.pdf.

Turner, B. L., R. E. Kasperson, P. A. Matson, J. J. McCarthy, R. W. Corell, L. Christensen, N. Eckley, et al. 2003. "A Framework for Vulnerability Analysis in Sustainability Science." *Proceedings of the National Academy of Sciences* 100 (14): 8074.

USDA Forest Service. 2000a. *Wildland Fire in Ecosystems. Effects of Fire on Fauna*. US Department of Agriculture, Forest Service, Rocky Mountain Research Station Ogden, UT.

USDA Forest Service. 2000b. *Wildland Fire in Ecosystems: Effects of Fire on Flora*. US Department of Agriculture, Forest Service, Rocky Mountain Research Station Ogden, UT.

USDA Forest Service. 2005. *Wildland Fire in Ecosystems: Effects of Fire on Soils and Water*. US Department of Agriculture, Forest Service, Rocky Mountain Research Station Ogden, UT.

USDA Forest Service. 2013. *Wildland, Wildlands, and People: Understanding and Preparing for Wildfire in the Wildland-Urban Interface.* US Department of Agriculture, Forest Service, Rocky Mountain Research Station Ogden, UT.

Van Mantgem, Phillip J., Nathan L. Stephenson, John C. Byrne, Lori D. Daniels, Jerry F. Franklin, Peter Z. Fulé, Mark E. Harmon, Andrew J. Larson, Jeremy M. Smith, and Alan H. Taylor. 2009. "Widespread Increase of Tree Mortality Rates in the Western United States." *Science* 323 (5913): 521–524.

Westerling, Anthony L., Hugo G. Hidalgo, Daniel R. Cayan, and Thomas W. Swetnam. 2006. "Warming and Earlier Spring Increase Western US Forest Wildfire Activity." *Science* 313 (5789): 940–943.