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A COST EFFECTIVENESS ANALYSIS OF PREVENTATIVE MITIGATION OPTIONS FOR WILDLAND URBAN INTERFACE HOMES THREATENED BY WILDFIRE

By

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A COST EFFECTIVENESS ANALYSIS OF PREVENTATIVE MITIGATION OPTIONS FOR WILDLAND URBAN INTERFACE HOMES THREATENED BY WILDFIRE

Chair: Dr. James Burchfield

Fire seasons in the western United States (US) during the years 2000-2006 have put issues surrounding structure protection from wildfires squarely in the public land management limelight with large amounts of money and firefighter exposure needed to protect residences from wildfire. No single modeling tool is currently capable of predicting wildfire ignition risk to WUI residences. This dissertation demonstrates the construction of an existing thirty-year wildfire hazard estimate at each house by pioneering a modeling system that combines results from a structure ignition assessment model (SIAM) with wildfire probability results from an ecological disturbance model (SIMPPLLE). Analysis of western Montana study area data reveal that nearly all of the structure ignition probability results modeled with extreme wildfire weather for visited homes are 1.0. This contrasts the low probabilities (0-0.05) that wildfire will reach the vegetation polygons hosting these houses. The result of the modeling system equation is that the average existing thirty-year ignition hazard estimate across the study area is roughly half of one percent.

Two suites of mitigation options are then designed, one concentrating on structural modification and fuels removal / replacement within 100 feet of each home (generally homeowner responsibility), and one using an optimization tool (MAGIS) to schedule thinning and prescribed burning treatments within 1.5 miles of homes (generally land management agency responsibility). The effectiveness of the mitigation options on both the individual model results and the combined average hazard estimates range from zero to 63 percent. While both home ignition zone mitigations and silvicultural treatments can markedly reduce wildfire hazard estimates, the former appear to provide a more linear reduction in hazard as correlated with budgets. Future work should focus on upgrading SIAM, stabilizing SIMPPLLE predictions or substituting a wildfire behavior model, and integrating the modeling system into a user-friendly GIS tool.

Acknowledgments

Only through the amazing support of a cast of dozens was this work possible. My Mother and Father provided so many wonderful opportunities in my life and encouraged the pursuit of a personally rewarding career and lifestyle. I appreciate how they have kept up with my progress at each point and the constant umbrella of support they provide. My wonderful wife Karen has been at my side the entire time. Five years ago I was only able to ask her to prepare for many challenges, not knowing what was to come, and she has been terrific and sustaining all the way. Robert Ahl was a key colleague; he asked difficult questions, offered sage advice and valuable perspective throughout the last 10 years. Friends in Missoula and across the country have also provided tremendous support and curiosity to both motivate my work and provide key points of relaxation on the slopes and rivers of Montana.

My amazing committee of six has worked very hard with me to address the many challenging modeling decisions at various meetings and through excellent conversations. My Chair Dr. Jim Burchfield has carried the torch since the dissertation was redesigned three years ago. Dr. Dave Calkin has been especially helpful at crafting solutions and keeping the dissertation focused. Tyron Venn's extensive reading and editing of very rough drafts of dissertation chapters have been especially valuable.

I owe a great debt to the community of Darby, Montana. They met my research project requests with participation and interest that allowed me to ground the project in the reality of a truly beautiful place. While I will not mention their names to protect their confidentiality, I want to thank each and every participating homeowner for granting access to their homes and property to conduct this research. I hope that my visits were helpful in elevating the safety of your homes from future wildfires.

The Northern Region of the US Forest Service has shown tremendous support for this project. My thanks to Fred Stewart for the help launching my economics career and enrolling me in the SCEP program, to Cynthia Manning for pushing me to redesign my dissertation and to Mike Niccolucci for providing the flexibility that has truly allowed this project to occur. The Region One Student Career Employment Program has also made a significant investment in my professional development, concurrent with the degree. Another thank-you goes to the Rocky Mountain Research Station for hosting me during the duration of this project. The office, access to support staff, and funding from RMRS were another thread of support that held this effort together. Jack Cohen's support and assistance in understanding and developing the Structure Ignition Assessment Model was key. Help from Chris Stalling and Jimmie Chew with SIMPPLLE has been terrific. Janet Sullivan and Kurt Krueger made MAGIS modeling fun, and Kevin Hyde helped in all aspects of modeling. Finally, the College of Forestry and Conservation has provided a great deal of administrative support as well as funding through the McIntire Stennis Grant Program and teaching assistantships.

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CHAPTER I - INTRODUCTION

Fire seasons in the western United States (US) during the years 2000-2006 have put issues surrounding structure protection from wildfires squarely in the public land management limelight. Average acres burned in the years since 1960 have escalated (Agee 1993). The burn severity[1] has also increased for many acres of wildfire across the low elevation forests of the western US (Schmidt et al. 2002). The forestry community generally agrees that human resource development and fire protection activities since settlement have substantially modified fire regimes in high fire frequency landscapes of the western U.S. for roughly a century (Romme et al. 2003, Swetnam et al. 1999, Arno et al. 1997, Covington and Moore 1994). Many authors and even special issues of reputable journals such as Conservation Biology 2004 18(4) describe transitions in forest fire regimes and note how ironically fire management policies preventing low intensity fire in dry ponderosa pine landscapes increased the long-term threat of dangerous crown fire and associated home loss (Brose and Wade 2002, Taylor and Skinner 1998, Quigley et al. 1996, Agee 1994, 1993, Arno 1980).

Extreme fire behavior, following natural and human-caused ignitions and partially attributable to a century of fire-exclusion, has already collided with many human communities nestled in and around flammable forests in the wildland urban interface

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[1] Although severity is not clearly defined in the wildfire literature, for purposes of this project it means the amount of tree mortality from fire, where high (stand replacing) severity equates to nearly complete mortality. Light severity is very little tree mortality and moderate is between the two extremes. Tree mortality (severity) is used as a proxy for fire intensity and will be connected to fire intensity for modeling purposes using numerous assumptions based on recent literature and fire models.

(WUI) [2], resulting in substantial home losses to wildland fires. Despite these losses, increasing numbers of homes are being built to accommodate rapid population growth in low elevation ponderosa pine (Pinus ponderosa) areas that historically burned on a 5 - 25 year cycle (Agee 1993). The recent Quadrennial Fire and Fuels report (NFAEB, 2005) included some new perspectives on the pace of residential growth in WUI areas of the country where growth rates between 1990 and 2000 were estimated at three times that of non-WUI areas.

The intermix[3] areas, often outside of fire district protection boundaries, appear to be experiencing the fastest residential development. Trends show that people are moving to the western US and to unincorporated[4] places in the west. Cordell and Overdevest (2001) estimated that the US population would more than double to 571 million Americans by year 2100. Hedonic pricing model research suggests that homes in close proximity to forested areas are highly desirable (Kim and Johnson 2002), indicating that much development will occur in existing and new WUI areas. The fire hazard is expected to remain stable or grow in these areas, translating into more homes at risk in the west. Homeowner decisions to mitigate fire risk with preventative actions will therefore become increasingly important in the future.

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[2] WUI is defined broadly for this project as the zone where structures or other human developments meet to intermingle with undeveloped wildland or vegetative fuels. The width of the zone is determined on a site-specific basis, but Healthy Forest Restoration Act guidelines suggest an area within 1.5 miles of dense vegetation.

[3] Wildland urban intermix differs technically from wildland urban interface because it has more land covered by vegetation within the area surrounding structures buffered to a distance of 1.5 miles.

[4] Unincorporated towns lack formal governance structure beyond federal, state and county governments and often have limited fire protection resources.

Statistics provided by the National Interagency Fire Center (NIFC 2006), and reproduced in Table 1, indicate annual wildfire suppression costs of roughly $1 billion and numerous structures destroyed by wildfire during the period 2000-2006. During 2003 alone, wildland fires burned 4,090 primary residences in the US, mainly in fires near San Diego, California. In addition, there has been loss of resident and firefighter lives associated with several of the wildfires that destroy WUI homes. Although these numbers represent a small portion of all the structure fires[5] in the US each year, all signs point to a rapidly growing number of WUI residences being threatened frequently by wildfire in the future. Recent research on climate change also suggests the potential for positive reinforcement loops where higher temperatures and longer summers will elevate North America's annual forest fire acreage. With more fire converting stored carbon into carbon dioxide in the atmosphere, this climate change may lead to even more severe fire weather in the future (Westerling et al. 2006). If this happens, then both the number of WUI residences threatened each year by wildfire and the wildfire suppression expenditures devoted to defending these structures will likely continue to rise.

Recognition of the escalation in available fuels combined with the recent rapid (US Census 2001) and expected future residential development of western unincorporated areas (NFAEB 2005, McCool and Haynes 1996), raises a suite of questions for land managers and planners. For example, with regard to social equity, questions are being raised by society as to who should pay to enhance the safety of the growing number of homes built in areas at risk from wildfire. Should all taxpayers pay for prevention and suppression of fires that threaten WUI homes? One must also consider that federal land

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[5] There were approximately 511,000 structural fires during 2001 in the US (US Fire Administration 2002)

management is now based on multiple and competing objectives such as wildlife management, recreation management, watershed protection and timber production. With these notions in mind, how does structure protection fit into this picture and how will this protection rank with other program priorities for land management agencies?

Table 1. Wildfires, suppression costs, structures and acres burned by year, 2000-2006.

Year	Number of Fires	Primary Residences Burned	Acres Burned (millions)	Total Federal Agency Suppression Costs
2006	83,522	721 †	9.0	Not Available Yet
2005	66,552	402	8.7	$0.88 billion
2004	77,534	315	6.8	$0.89 billion
2003	85,943	4,090 ‡	4.9	$1.33 billion
2002	88,458	835	6.9	$1.66 billion
2001	84,079	731 (All Structures)	3.6	$0.92 billion
2000	122,827	861 (All Structures)	8.4	$1.36 billion

Source: National Interagency Fire Center (2006).
† Five firefighters killed protecting WUI structures
‡ 15 People killed in association with Cedar Fire

For the most part, managers now realize they cannot and should not stop all wildfires (Finney and Cohen 2003). Wildfire suppression is a dangerous, expensive activity undertaken for myriad reasons other than only the protection of homes. Many scientists and agency documents list other considerations, including critical infrastructure, sensitive wildlife habitat, soil productivity, aesthetics, and air quality as reasons why residents and visitors value forests and why land management agencies attempt to control wildfires (Graham et al. 2004, Cohen and Stratton 2003, Kalabokidis et al. 2002, Conrad et al.

2001, Tiedemann et al. 2000, Swetnam et al. 1999, Covington et al. 1997, Fulé et al. 1997, Covington and Moore 1994, Reynolds et al. 1992, Weaver 1943). Yet not all fires can or should be suppressed. There are many benefits derived from wildfire. Ecosystems rely on the wildfire process in many areas and burns that occur with sufficient frequency to control fuel loads can reduce the potential for future fires that may cause widespread structure loss.

A better alternative to suppressing all wildfire may be modifying forested areas to protect at-risk values in specific locations. Davis (1990) pointed out that, historically, the Forest Service and other agencies worked with legislation that did not acknowledge responsibility for protecting homes and property from wildfire. More recently, the Federal Wildland Management Policies of 1995 and 2001 recognized the need to base the second protection priority in part on the relative values of community, with the latter stating,

> "The protection of human life is the single overriding priority. Setting priorities among protecting human communities and community infrastructure, other property improvements, and natural and cultural resources will be based on the values to be protected, human health and safety and the costs of protection. Once people have been committed to an incident, these human resources become the highest value to be protected."
>
> (USDI et al. 2001: Chapter 3, page 3)

In addition to articulating protection priorities on the fire line, project-planning priorities have shifted as a result of recent legislation. For example, the Healthy Forest Restoration Act of 2003 (HFRA) prioritizes thinning work around communities (US Congress 2003). As a result of this legislation WUI areas are slated to receive intense forest manipulation in coming decades. Given that the US Congress appears willing to allocate money to manage fire risks in the WUI, one important question remains: How can the public most effectively allocate its resources to protect residential structures in the WUI from wildfire. In other words, what is the cost effectiveness of conducting various preventative mitigations to protect structures from wildfire? This thesis develops a modeling system capable of comparing the cost effectiveness of alternative wildfire structure protection strategies in a low elevation WUI area of western Montana. This is done to test the proposition that there is some difference in the cost effectiveness of the various options to mitigate the hazard of wildfire. By putting together a modeling system that constructs the existing hazard and is capable of looking at the cost and effectiveness of these mitigation options, society can begin to make better selections of preventative wildfire mitigations.

This dissertation compares two suites of mitigation options. One suite is comprised of activities conducted in the home ignition zones[6] (HIZs) across the study area.
Firewise mitigation efforts are actions taken to modify the building itself as well as fuel conversions within the home ignition zone. In general, homeowners are only partially successful at reducing fuel on their properties. These actions are restricted by cost, lack of ownership of the entire HIZ, action or inaction by adjacent landowners, subdivision covenants, and tradeoffs with other values provided by fuels, such as shade, wildlife habitat and privacy. The initiation of these actions is generally considered the responsibility of homeowners. The other suite of activities consists of silvicultural treatments in the forest and grassland area surrounding the community. These actions are

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[6] The home ignition zone is defined by Cohen (2001) as the area that principally determines the home ignition potential. The HIZ includes the home, its exterior materials and design, and the area around the home typically within 100 to 200 feet (Cohen, J. 2001) and is used in this dissertation as the area extending 100 feet from side of each structure.

constructed to represent options generally considered the responsibility of land management agencies funded mainly with tax revenues.

Justification for this Research

Communities across the country are now discussing an appropriate reaction to the wildland fire hazard problem. Land management agencies are implementing new techniques to reduce fuels. Some scientists argue that conditions in the immediate vicinity surrounding the home (such as flammable landscaping and debris) explain most ignitions (Cohen 1999, Foote 1994, Davis 1990, Howard et al. 1973). This idea has been supported with research like that of Wilson and Furgeson (1986) who developed an early regression model to calculate the probabilities that any of 450 exposed residences would survive a bushfire following the famous Australian Ash Wednesday fire in 1983. These authors imply that modifications in the immediate proximity of homes could be a better investment than fuel treatments away from the HIZ. Based on this philosophy, many fire departments and government agencies now suggest application and enforcement of *Firewise*[7] building codes for building design and proximate fuel management as needed steps to reduce the probability of home ignition.

This school of thought, championed lately by Jack Cohen (Research Physical Scientist, USDA, Forest Service, Fire Sciences Laboratory), claims that these steps are more effective at reducing home loss from inevitable fire events in the low elevation dry forests of the inland west than fuel treatments in the surrounding wildlands. As evidence that the

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[7] *Firewise Program* is a term used to describe efforts to reduce the structure ignitability in the home ignition zone. These can be thought of as a combination of one time changes (e.g., replacing a cedar shake roof with a non-flammable roof) and annual maintenance (e.g., keeping a non-flammable lawn, removing litter fall from gutters, etc.).

public often misperceives the nature of the wildland fire threat, Finney and Cohen (2003:359) assert, “Because homes [can] survive high intensity fires and are [often] destroyed in low intensity fires … it is questionable whether wildland fuel reduction activities are necessary and sufficient for mitigating structure loss in wildland urban fires.” This basis of explanation for structure ignitions has organizations like the Australian Commonwealth Scientific and Industrial Research Organization and *Firewise Communities/USA* ramping up efforts to educate WUI homeowners about mitigation opportunities and encouraging them to improve structure resistance to wildfire through mitigations at and close to their homes.

Other authors focus more on the ability of silvicultural treatments to reduce fire probabilities. Omi and Kalabokidis (1998) used fuel treatment experiments in WUI areas to ascertain the impact on surface fire behavior and its contribution to potential suppression control. Pollet and Omi (2002) reported how fire severity and crown scorch are reduced across treatment areas in the western US following combinations of thinning and prescribed burning. Likewise, Strom’s (2005) masters thesis used a sampling methodology two years after the 2002 Arizona Rodeo Chediski fire and revealed that prescribed burning treatments within one decade of a passing fire reduced burn severity and the effect is magnified by the addition of thinning to prescribed burning treatments. Finney (2004a, 1998) has been actively using software he has designed (the FARSITE fire area simulator model, Minimum Travel Time and FlamMap) to investigate the impact of treatment amounts and patterns on wildfire expectations.

Work published by Fried et al. (1999) conceptually combined estimates of wildfire with conditional estimates of ignition, given a wildfire, to estimate the value of risk reduction in WUI areas. Findings from that study concluded that the probability of structure ignition is mainly a function of the clearing of trees, grass and debris from the area immediately around the home. This work provides an important conceptual underpinning for this dissertation, but lacks probability-based estimates needed to include a cost effectiveness analysis of mitigations opportunities. Other authors have applied cost considerations to individual parts of this wildfire caused structure ignition problem and possible mitigation efforts. For example, Berry and Hesseln (2004) found higher costs for preventative silvicultural treatments in WUI areas compared to other public lands. Sanchez-Guisandez (2004) reported the design of a coarse-scale decision support system that prioritizes silvicultural forest fuel treatments based on the cost-effectiveness of fire protection for timber resources and WUI areas. Looking more at structure factors, one author investigated the cost effectiveness of safety and protection design requirements for Australian building codes intended to reduce wildfire-caused structure ignitions (Beck 1987). These works help provide valuable foundations for this thesis. However, the current tools all lack a consolidated methodology combining probability based ignition expectations with the cost effectiveness information for the full range of possible mitigation work.

Large amounts of money are being requested and spent to protect growing residential communities from the threat of wildfire-caused home loss (MT DNRC 2004, NIFC 2006). Given this desire to use preventative measures to protect WUI structures, it is important to develop the means to site-specifically determine the most cost effective course of action: Are schedules of silvicultural manipulations of existing forest fuels[8] better investments than *Firewise* mitigations inside the HIZ? Communities across the country are preparing wildfire protection plans to stimulate landowners and agencies to engage in preventative actions yet there is little information regarding the relative effectiveness of alternative investments. Modeling can be used as an alternative to field-testing typical treatments to address cost effectiveness without endangering structures, firefighters or citizens.

Most economists would acknowledge that in order to find the optimal mix of silvicultural forest fuel treatments surrounding a community and *Firewise* modifications in home ignition zones, one would need information about all the values at risk from wildfires' negative impacts and all the values that would be enhanced by wildfires' positive impacts. For this research however, the focus is protection of structures with a clear recognition that the methodology used for this research ignores other market and non-market values[9]. This simplification is done to make this project manageable, allowing construction of a basic modeling system that can be expanded in the future.

This research is intended to advance the field of forest economics by applying cost effectiveness analysis to results from three modeling tools. It is not the intent of this project to validate any of the modeling tools contributing to the existing hazard estimate

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[8] Here, the term ‘fuels’ refers to live and dead plant material from the boundary of each home ignition zone to a distance limited by firebrand lofting distance, roughly 1.5 miles from structures.
[9] Examples of additional market values are infrastructure and commercial buildings, examples of non-market values impacted include community aesthetics, wildlife habitat, water quality, and nutrient cycles.

or the effectiveness determinations in this research. Once the economic concept is demonstrated, future modeling tools, improved versions of current tools or substitute models could enhance predictive abilities for this form of ex ante analysis. This dissertation will hopefully contribute a new economic perspective to the growing problem of houses threatened by wildfire and move management of these issues toward more cost effective preventative mitigation planning.

Research Goal and Objectives

There is one goal with four objectives for this research project. The goal of this research is to demonstrate a cost effectiveness analysis of mitigation options to reduce home ignition expectations in a low elevation, WUI area of the western United States. The comparison is between a suite of *Firewise* options conducted inside the HIZ versus thinning and prescribed burning silvicultural treatments applied to surrounding wildlands. The research utilizes a study area in the Bitterroot Valley of western Montana with 291 WUI residences. The goal will be accomplished with the following four objectives: 1) Estimation of the existing wildfire structure hazard for a study area by selecting wildfire modeling tools, collecting structure and home ignition zone fuels data, and combining the probability results 2) Development of mitigation options, mitigation costs estimation, and effectiveness evaluation for a suite of HIZ mitigation options 3) Application of a scheduling tool to develop and evaluate the effectiveness for the silvicultural treatment suite in the forests and grasslands surrounding the study area, and 4) Generation of a cost effectiveness analysis that compares the effectiveness levels between the HIZ and silvicultural mitigation suites at several budget levels using cost effectiveness ratios and charts.

Figure 1 is a flowchart that schematically represents the objectives of the dissertation. This figure will be referred to at various times in the dissertation to explain how steps and decisions relate to the overall project.

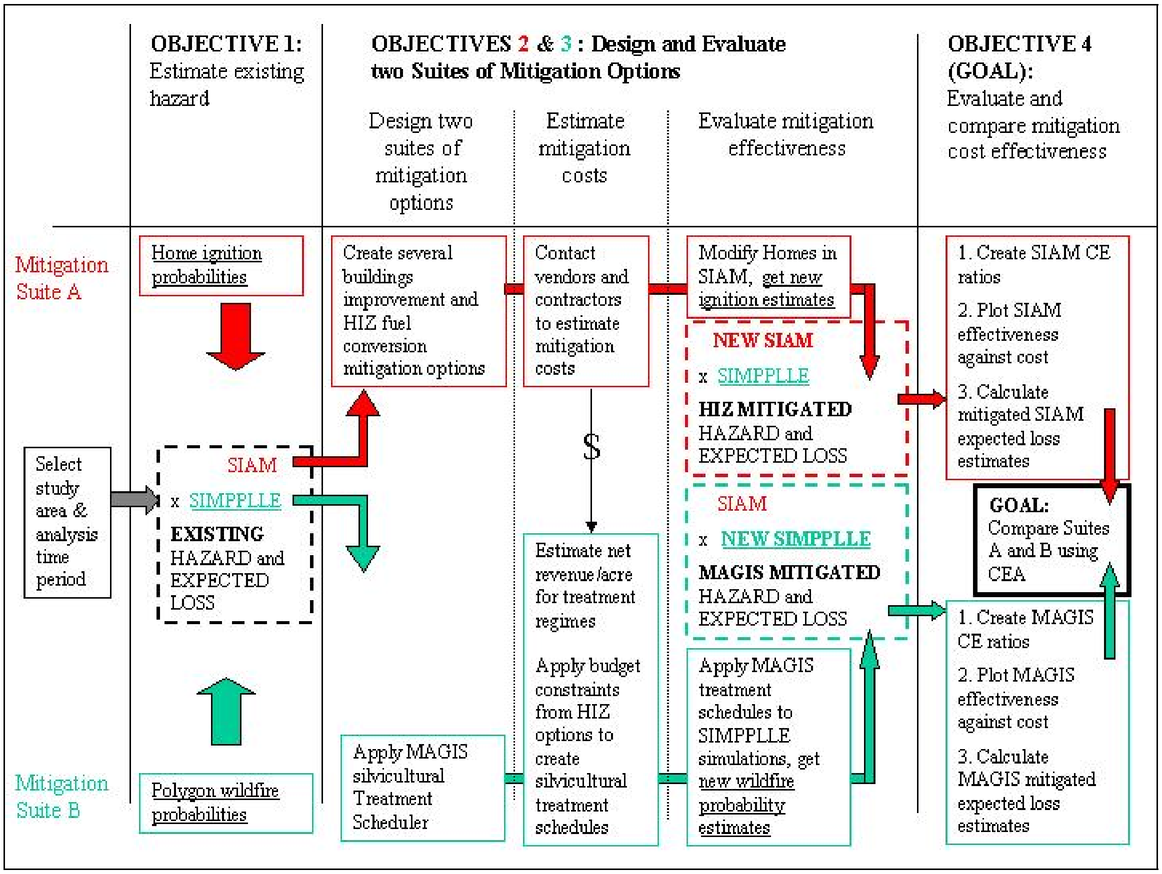

Figure 1. Study design flowchart

Objective 1 is generation of baseline home ignition probability estimates for the study area. The first step is to design a modeling system that links a modeling tool capable of predicting home ignition given a fire, with one capable of predicting the probability of fire encroaching on each house within a study area in the future. The SIAM (Cohen 1995) and SIMPPLLE (Chew et al. 2004) models are chosen for this purpose. The next chapter

(II) describes the model selection process in detail. Once a modeling system is established the data required for the models must be collected. For SIAM this means first learning about the evolving model parameters, designing a data collection protocol to support data entry, and testing the instrument on volunteer houses. Site visits by the author are used to draw elevation and plan views needed for SIAM; using a worksheet to document the building and fuels characteristics within each home ignition zone and to evaluate firebranding potential. Data is entered into the SIAM model for the four sides of each visited home. A siding flammability classification system was developed that allowed extrapolation from 39 visited homes to the full set of 291 study area homes to generate ignition probabilities used with SIMPPLLE results to the calculate of existing hazard estimates.

The second step to accomplish Study Objective 1 is modeling wildfire probabilities. Modeling of fire probabilities for each of 243 polygons hosting 291 houses was conducted after collecting site-specific vegetation and historical disturbance information (ignition probabilities per acre, fire perimeters, harvest and fuel treatments perimeters, insect and disease infestation locations) to initiate the model. This information was all used to improve the accuracy of future fire probability predictions modeled with one hundred 30-year simulations across the study area.

The two probabilities predicted by the two models are then multiplied to generate the existing 30-year ignition hazard at each study area house. Chapter III describes this process in detail. The average existing 30-year ignition hazard of these 291 structures is used as the starting point for the next two objectives.

Study Objective 2 is to derive and evaluate a suite of *Firewise* options for reducing modeled home ignition estimates. Countless combinations of building improvement and fuel conversions inside the visited HIZs are possible. By consulting with local contractors who perform fuel mitigation work and with consideration of the modeling limitations, seven general HIZ treatments are developed. Three of these treatments are building upgrades-replacing single pane windows with double pane windows, upgrading flammable siding to non-ignitable siding, and a combination of these two upgrades. Two are removal and replacement (conversion) of existing fuels near the home-a light fuels conversion to watered lawn, and a full fuels conversion with replacement using non-flammable alternatives. The other two options are combinations of structure upgrades and fuels modification in the HIZ. Chapter III describes the methods used by the author, following consultation with local contractors and businesses, to calculate cost estimates for each of the seven mitigation options. That chapter also details how the effectiveness of each of these seven possible HIZ mitigations is modeled.

Study Objective 3 moves away from the HIZ and focuses on the surrounding wildlands. It applies a suite of silvicultural fuel treatments that potentially reduce modeled home ignition estimates. The Multiple Resource Analysis and GIS (MAGIS; Zuuring et al. 1995) software is used with the same budget constraints needed to accomplish the suite of seven *Firewise* options to generate seven schedules of thinning and prescribed burning in an area extending one and a half miles from the 291 structures. The seven schedules that contain variable areas of five possible treatment regimes[10] are then loaded into SIMPPLLE to generate one hundred new thirty-year simulations. The results of these simulations are used to estimate new wildfire probabilities for each polygon hosting a study area house.

Study Objective 4 is the generation of cost effectiveness ratios and charts that facilitate a cost effectiveness analysis between the two mitigation suites. Because each of the two suites of mitigation options uses the same seven budget levels, effectiveness results from Objectives 2 and 3 permit achievement of the this objective, and the project goal: a direct comparison of the cost effectiveness for all mitigation options. This pioneering work is expected to show that economics should be included as a guide to future mitigation selections.

Once the objectives are designed, the first step in this study is selection of a study area for demonstration. The area selected near Darby, Montana (Figure 2) is typical of many areas in the western US threatened by frequent wildfires. The location includes a mix of national forest, private, and state of Montana land. This study area has several important qualities that make it a suitable case study. The first characteristic is a physical setting where wildfire is likely, and where, if a fire occurred, expected home loss is likely (it is a WUI area with multiple homes at risk from heavily stocked private and public timber lands in the vicinity). The area west /southwest of Darby, Montana is also within a

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[10] Schedules of treatment regimes are generated by MAGIS in an attempt to minimize the expected 30-year fire probability across the roughly 36,000 acres of treatable area by comparing variable levels of net cost and expected effectiveness, given the seven budget levels.

reasonable distance of The University of Montana and is also a location with building, home ignition zone, and forest vegetation conditions that can be improved, a quality necessary to display mitigation effectiveness.

The bulk of the wildfire probability analysis area (Figure 3) of roughly 381,361 acres is on the eastern slope of the Bitterroot Mountains to the west of the Bitterroot River, which flows north to its confluence with the Clark Fork of the Columbia River. The elevation in this area ranges from approximately 3,800 to 10,160 feet above sea level. Average percent slopes for vegetative units range from 0 to 236%.

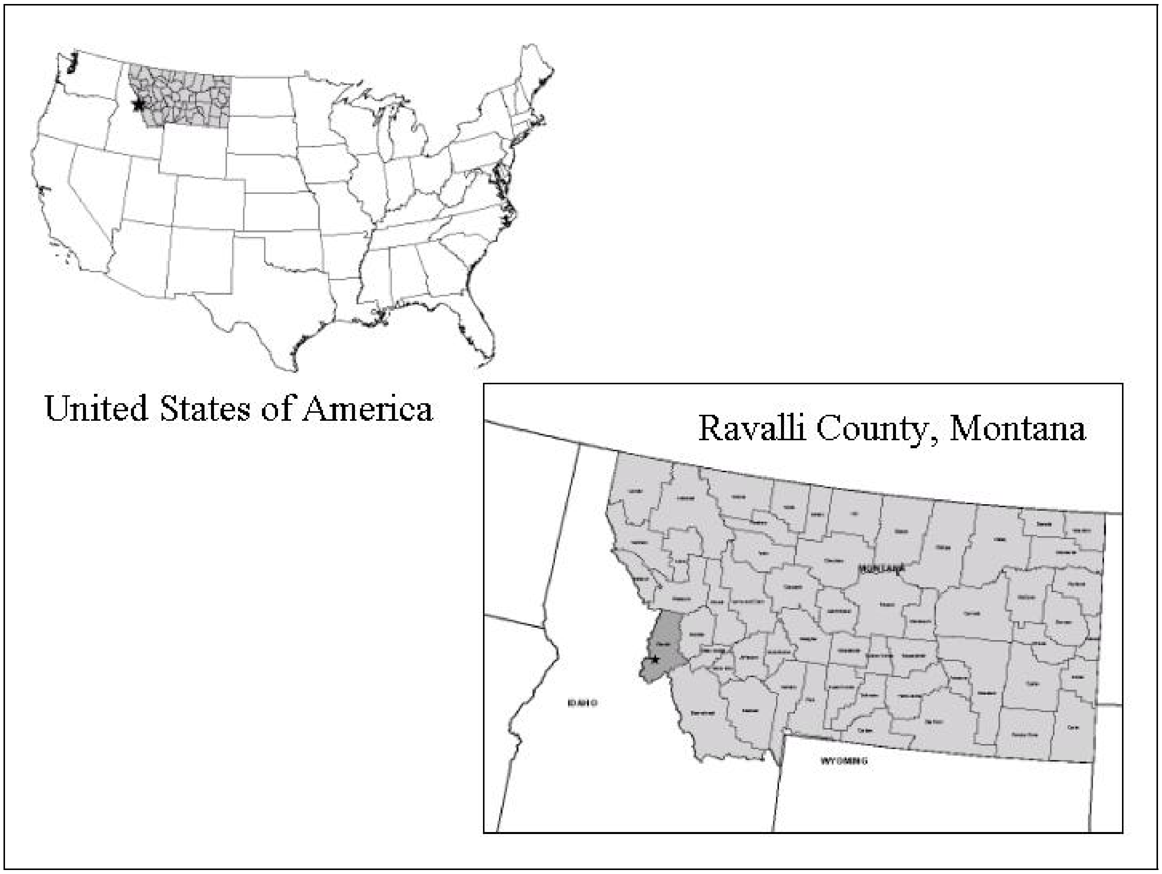

Figure 2. Locator map for study area

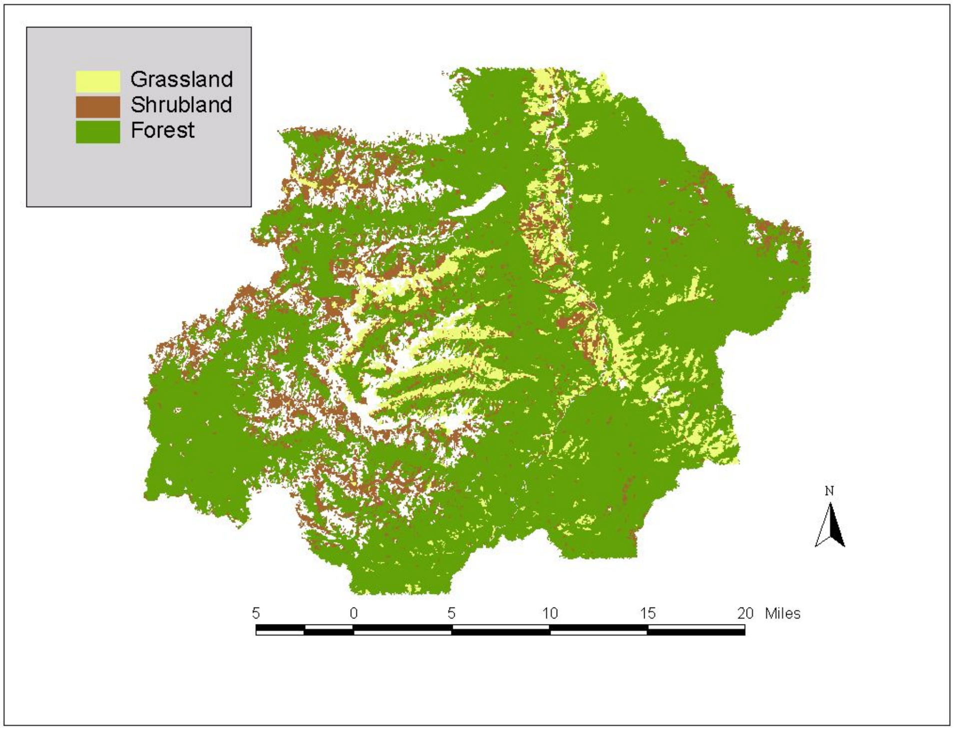

Figure 3. Vegetation types in the 381,361 acre wildfire probability analysis area

A WUI study area is defined within this wildfire probability analysis area. The *Firewise* glossary defines the WUI as any area where wildland fuels threaten to ignite combustible homes and structures. Radeloff et al. (2005) used a more technical definition based on a published Federal Register notice from the USDA and USDI (2001). They describe the interface as an area with more than 1 house per 16 ha, and less than 50 percent vegetation, which is within 2.4km (1.5 miles) of an area of at least 500 ha in size containing more than 75 percent vegetation. Intermix areas are defined similarly, but have more than 50 percent vegetation around homes. These definitions are used to guide the selection of study area WUI homes for this dissertation.

For this project, the WUI in the study area extends from the main stem of Bunkhouse Creek south to the main stem of Trapper Creek along the Bitterroot National Forest boundary, then north along the West Fork Road (473) to Highway 93 and north along this road to the point of intersection with a line 1.5 miles from the USFS boundary, north towards Bunkhouse Creek, skirting the high density area comprising downtown Darby (Figure 4). The CWPP WUI area was modified to accommodate this study. The study area WUI extends to the east of the Community Wildfire Protection Plan (CWPP) WUI toward the Bitterroot River in order to include numerous homes within 1.5 miles of national forests. Also, homes in high-density residential areas just west of Highway 93 in Darby are excluded because this is high-density housing area and the structure ignition model being used currently cannot calculate risk from adjacent structures. The intent is not to focus on this area because it has unique hazard levels compared to other areas in the western US, but rather to provide a case study of a potential analytical aid for addressing a generic problem across much of the western US.

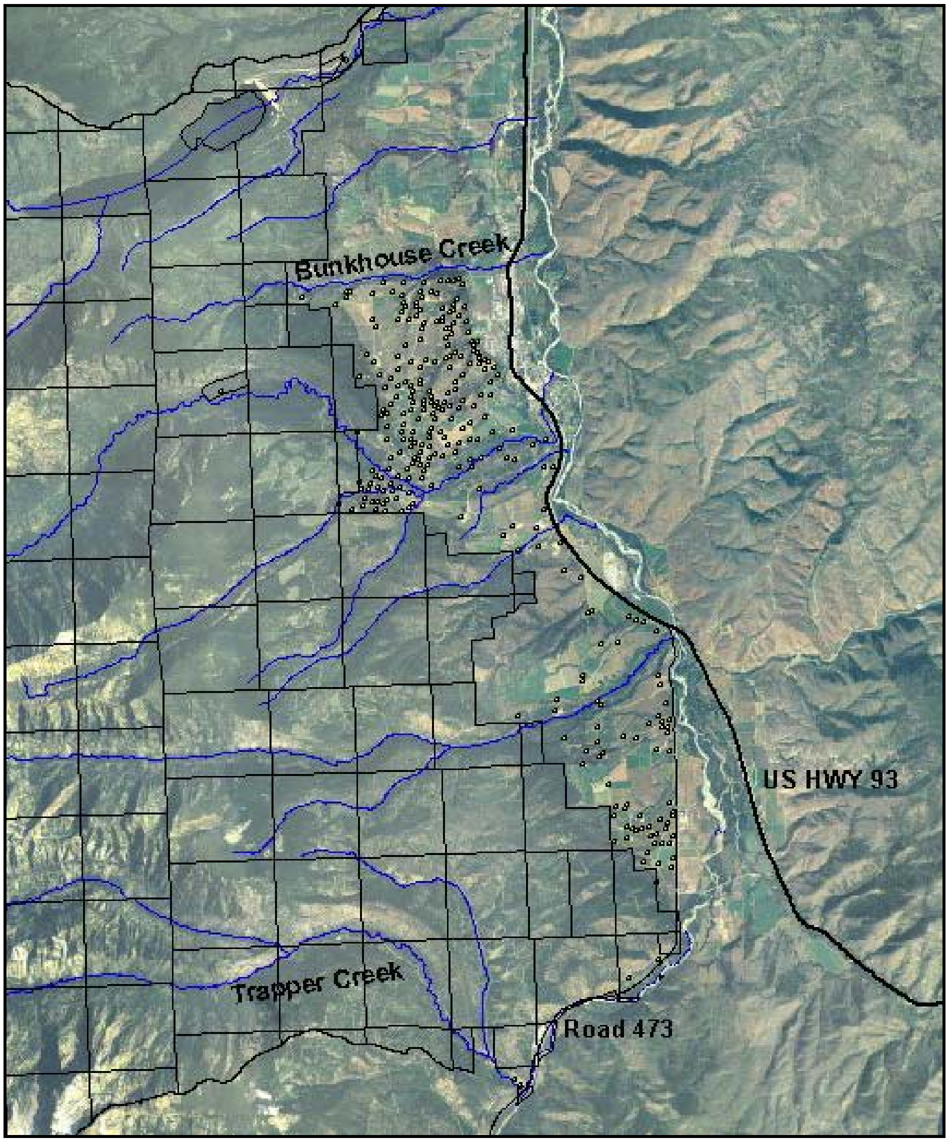

Figure 4. Aerial view of the 291 study area residences atop the 2004 National Agricultural Imagery Program base map. Bitterroot National Forest lands are outlined with black.

Once a study area is selected, a time period for the analysis is needed. For this dissertation a 30-year period is selected. If the time period selected for the project is too short, the mitigated change to the long-term hazard faced by homeowners will not be detectable. If it is too long, then residential development, which is beyond the scope of this study, could alter the relationship between the two modeling tool results, wildfire expectations and ignition expectations. The changes to tree density and size class resulting from thinning and burning treatments are assumed to persist for several decades. There is also a practical constraint on the amount of thinning and burning that can occur each decade due to smoke production and other social acceptance considerations. The 30-year planning horizon modeled for this project therefore reflects a compromise between the uncertainties about human population distribution beyond 30 years and the need to temporally evaluate the impact of various mitigations on wildfire hazard. With a study area and time period selected, objectives can be pursued.

Organization of this Dissertation

Chapter II provides background on wildfire modeling and context for this dissertation by introducing the modeling approach. Chapter III contains methods to accomplish objectives 1, 2, 3, and 4 of this dissertation. The first section of chapter III explains how the modeling tools are used to create an existing hazard estimate. This forms the starting point to address the cost effectiveness of tenable mitigations that can be chosen. The next sections in chapter III introduce mitigation suites and describe the methods to estimate costs and evaluate effectiveness. The results chapter (IV) shares the same objective-based format as the methods chapter. The existing condition results are provided first. Then cost estimates for each mitigation option, as well as the impacts that each mitigation option has on modeled structure ignition expectations, wildfire probabilities, and on the combined 30-year hazard estimate are reported. Finally, the cost effectiveness analysis results are reported at the end of the results chapter. Chapter V adds several important discussions about key modeling system assumptions and the limitations these create for the results. The document ends with chapter VI, which provides conclusions and makes some recommendations for future work.

CHAPTER II – THE MODELING APPROACH

This chapter provides some fire modeling context and explains why modeling is the most viable technique to approach an economic comparison of preventative wildfire hazard mitigation options designed for structure protection. A literature review of various fire modeling and economic efforts helps identify reasons why the modeling tools that comprise the modeling system for this dissertation are selected. The literature suggests that the process of wildfire destroying a home through ignition occurs at multiple spatial and temporal scales. This reality drives the selection of two independent models to estimate a baseline wildfire structure ignition hazard estimate. The selection criteria of an economic analysis tool for this project is then covered, and the selection of an economic analysis tool is described. The existing hazard estimation, mitigation cost estimation, mitigation effectiveness evaluation, and cost effectiveness methods and results are all found in chapters III and IV.

Models as Assessment and Evaluation Tools

Numerous vegetation and structure variables combine in a multitude of arrangements allowing wildfire to ignite and destroy residences. There is prohibitive liability in field-testing the effectiveness of various mitigations with wildfire in real settings. Mitigation effectiveness cannot be tested by either intentionally burning treated areas, or even by allowing natural ignitions to burn treated areas. There are also far too many variables to create useful controlled experiments. As a result, modeling tools emerge as the most pragmatic way to address the question of which mitigation strategies appear to be most cost-effective. This dissertation employs various models that represent what scientists in the field of fire management have applied to understand the wildfire behavior relationships between buildings and fuel conditions.

"Models of natural systems are inevitably designed as simplified representations of reality,"(Annan 2001:297). And models have been an integral part of ecosystem analysis since the earliest days of systems ecology (Odum 1983). Some models address management questions about future ecosystem response to interrelated disturbances. These are generally termed process or mechanistic models (Korzukhin et al. 1996). Due to the desire to accurately portray a small piece of reality, models are often limited in their scope. Although few exist that are comprehensive enough to answer multidisciplinary questions (Machlis and McKendry 1996), people's natural tendency is to stretch models to their limits. Because models become unwieldy when they attempt to address too many issues they must sometimes be linked in a modeling system to address important management questions.

Even armed with an understanding of how an ecological system generally behaves, one still encounters trouble explaining how disturbance processes such as wildfire will affect both forests and human communities. The degree of difficulty associated with this explanation depends on the question the researcher is attempting to address. Is the researcher curious what will be the likely temporal and spatial distribution of future fires, or how many homes a community should expect to lose to these wildland fires? Maybe she wants to know if there are combinations of vegetation and home characteristics that seem most at risk? Finally, she may wonder given the modeled responses to these questions, where is the wisest place to invest money and effort to reduce negative impacts on the human community from a disturbance process that by most accounts has lost its ‘natural’ role in the ecosystem?

These questions are important to this study. The goal for this dissertation is to compare the cost effectiveness between two suites of options for improving modeled home survival when wildfire threatens the WUI. Efforts to evaluate models for this research are grounded in a conceptualization of the system being simulated with the modeling tools. By first asking what is the ideal data, what are the ideal modeling tools and what is the ideal connection between modeling tools, the design of an ideal modeling system begins to emerge. Only after considering the spatial and temporal scales at which wildland fires that destroy homes can the fitness of the modeling system be evaluated.

Scale – An Important Fire Modeling Consideration

Scale includes both spatial and temporal components and is a topic that needs consideration in this research project. Spatial resolution refers to both the extent and scale of a research effort, with the latter meaning the size of the mapping units. Both the extent and scale of fire-related studies can vary from the degree of mortality within a single tree to the impact of smoke emissions on the gaseous composition around the global atmosphere. The main limitation of creating a modeling system is that the wildfire caused structure ignition phenomena being modeled occurs at multiple spatial scales. By summarizing a few of the models used previously in several other fire-related modeling projects scale selection is put into context.

Spatial Scale

Preisler et al. (2004) presented empirical models to estimate the probabilities of wildland fire on each square kilometer (voxel) of federal lands for a given day. Their non-parametric logistic model is used to create a probability for each voxel, each day. Like similar efforts to produce coarse scale data (e.g., Schmidt et al. 2002), Preisler's application is more useful for improving suppression readiness than for prioritizing changes to forest structure or changes in and around home ignition zones. Recent work by Haight et al. (2004) explored the regional fire risk in the WUI areas of northern lower Michigan. They ascertained the risk of stand replacing fire using GIS information describing fire regimes and fuel flammability. However, they were interested in a regional area and thus restricted their consideration of this risk to homes and people by using housing density information from the recent 2000 US Census. At the fine-scale and small extent end of the spectrum, work by Jones et al. (2004) used a flux-time profile in combination with fire behavior models to evaluate stem heating related mortality to inform prescribed burning expectations.

Mark Finney, the designer of FARSITE,[11] notes that modeling expectations for fire can be very misleading (Finney Pers. Comm. 2004b). In a document describing the model development and evaluation he states, "Wind data is typically input at hourly or half-hourly intervals. Fuels and topography are resolved spatially to about 30m. These scales are coarse compared to the real frequency of wind variation over a scale of seconds, and fuels over distances of meters or fractions of meters," (Finney 2004: 31-32). While it is tempting to address this phenomenon at the acre scale, this is not how fires burn. They

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[11] FARSITE is a very popular fire behavior modeling tool. It is used mainly to look at fire growth expectations given an ignition site and numerous facets of fuel information.

burn at the tree level. A tree either burns or it doesn't (Finney Pers. Comm. 2004b). The same could be said for a home. This explains why data describing each building and the fuel in its surrounding home ignition zone needs to be collected and modeled.

Although fires vary in intensity at a small scale, the spatial probability of fires of variable severity is influenced by factors at the landscape scale (Turner and Romme 1994). Because ignition sources occur at this landscape scale modeling fire probabilities should reflect this spatial reality. This explains why a tool must be selected to model the probability that each stand collectively comprising the landscape will experience a wildland fire in the future.

It is acknowledged that the large wildfires that destroy many WUI structures occur at landscape scales and that firebrands can reach a house from more than a mile away (Albini 1983) yet several factors impacting the radiant heat flux, and subsequent ignition vary at the home ignition zones scale (Cohen and Butler 1998). These authors suggest that wildland fires burning homes is the coincidence of events affected by factors occurring at multiple scales. Therefore, modeling should combine elements at the landscape scale with elements at the individual HIZ scale. The most logical modeling system to assess existing hazard therefore appears to be one that can both describe expectations for future fire occurrence at the landscape scale, and one that can predict the probability of home ignition at the scale of a residential lot, given a passing fire. This reality suggests a linkage of tools such as the Structure Ignition Assessment Model (SIAM) that could be used for structure ignition modeling, and the Simulating Patterns and Processes at the Landscape Scale (SIMPPLLE) model, which uses logic to simulate processes operating at the landscape scale, could be used to make wildfire structure ignition predictions.

Temporal Scale

The cost-effectiveness analysis of wildfire-caused structure ignition hazard mitigation options invokes a need to assess the temporal longevity of impacts from any implemented mitigation activities. Most of the fire risk studies described above are based on existing conditions, creating a snapshot in time of wildfire hazard. However, because fire is not expected every year, the ideal modeling system should evaluate cost effectiveness using a temporal component that reflects the durability of efforts to modify home loss expectations. Modeling with this temporal component will enhance mitigation evaluation.

Modeling Wildfire Caused Home Ignition

Countless ways exist for homes to ignite and burn. Here the focus is wildland fire-caused structure ignitions. When considering structure ignitions in the wildlands, most readers likely envision large walls of flames engulfing homes. While this is the story often told by the media during ‘firestorms,’ many types and intensities of wildfire are capable of igniting widland urban interface structures. Although numerous homes are burnt during high intensity events each year the full spectrum of wildfire intensities comprise the threat of structure ignition. In fact, investigations done following WUI fires reveal that many of the ignitions appear to have been caused by short flame length fires and burning embers delivered to ignitable materials by wind as firebrands (Cohen and Stratton 2003, Foote 1994, Howard et al. 1973).

Given that structure ignitions are caused by piloted ignitions[12] (which results from combinations of delivered radiation, convective heating and direct flame contact), and glowing embers (igniting exterior structure components and/or entering through broken windows) in varying combinations, a modeling tool is needed that represents all of these potential sources. Furthermore, a model is needed that reports an overall probability by using the most vulnerable ignition threat at each house. Similar to the idea of the weakest link in a chain, the weakest resistance to ignition will allow wildfire to prevail with structure ignition. This is especially true in the US, where evacuation of residents typically precedes the passage of fire fronts, and seldom are fire fronts weathered in place. As a result, homeowners are rarely on hand to provide an immediate fire suppression response following a wildfire event.

Home Ignition Modeling Options

Numerous attempts are underway to rate wildfire home ignition risk in communities across the US. The National Wildland Urban Interface Fire Program (*Firewise*.org) teamed up with several communities across the US to develop rating systems that generally consist of the same set of input variables, namely variables describing the home, the physical setting, and suppression force access. Most rating schemes are based on variants of National Fire Protection Association Form 1144. The Montana Department of Natural Resources Conservation risk evaluation form, Ecosmart, Firewise, and the Fire Comparative Risk Assessment Framework Tool, are similar examples of hazard rating systems. Although field collected variables are combined to derive a risk rating, the results of these ratings (sometimes based on proprietary algorithms) are

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[12] Piloted ignition: flaming is initiated in a flammable vapor/air mixture by a 'pilot' such as an electrical spark or an independent flame (Drysdale 1998).

usually either suggested improvements or categorical assessments. In order to evaluate the effectiveness of wildfire mitigations a model is needed that can quantify the improvements in fire safety that result from potential mitigation efforts. This means that a probability-based output is desirable, especially when attempting to quantify the cost effectiveness of mitigation efforts in the home ignition zone.

In order to create a diagnostic model of existing risk, a probability-based model considering radiant and convective heating as well as fire branding is necessary. There are not many of these probabilistic home ignition models to choose from at this point. Most homes burned during wildland fires are lost during extreme[13] weather events (Cohen, Pers. Comm. 2004). Putting firefighters in harm's way during extreme fire weather events is very risky for managers. Given these realities, a home-ignition modeling tool such as the Structure Ignition Assessment Model (SIAM) that models the worst-case weather scenario, with no suppression resources available at individual homes seems appropriate.

The Structure Ignition Assessment Model (SIAM), Foundations and Parameters

The Structure Ignition Assessment Model (SIAM) was the first US wildfire home ignition modeling tool produced (Cohen 1995). This modeling software is currently being reprogrammed to be user-friendlier, and has not been officially released yet. The SIAM was designed to develop expectations of home survival during severe weather events. It is selected to address the home ignition probability part of the modeling system.

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[13] Extreme weather events differ based on climate and topography. The term extreme is typically associated with temperatures, winds and relative humidity that only occurs a small percent of the time. For example the 95th and 99th percentile conditions are often cited as extreme fire weather.

There are three main ignition vectors in SIAM: piloted ignition through convective heating or radiation, window breaks that allow firebrands to ignite the structure internally and external firebrand ignitions of receptive nooks and crannies. While this model produces an ignition probability, it is important to realize how this probability is obtained. The probability of burning is not based on empirical probability density functions. It is instead based on thresholds that reflect combinations of heat transfer and burning times. There is one set of these flux time product thresholds for (radiant and convective) heating and one for window breaks that would allow ignition from firebrands (representing structure vulnerability to burning embers) (Cohen 1995). The probability of a structure burning is a reflection of the easiest way a structure could ignite (Cohen Pers. Comm. 2005).

The SIAM calculates the radiant heat generated from each ignition source based on flame characteristics derived from Rothermel, Albini, Byram and rule of thumb relationships (Cohen Pers. Comm. 2006). Fire behavior parameters are similar to that used by BEHAVE (Andrews 1986, Andrew and Chase 1989). The influence of user-selected ignition sources (each with a defined height, depth and width) is modeled for each side of each house in SIAM. The physics equations that represent thermal heating are based on five default thermal properties for each fuel type (Rothermel's (1983) intensity, fuel moisture, spread rate, burning time, a flame height factor), distance from structure, several climatic constants (e.g., 90º F degree structure temperature and a 20 mph wind from a selected azimuth), and the building height. These are used to calculate the flux time product (a combination of radiant heat flux and convective heat flux calculated into thermal energy) that confronts each third of each structure's four ignitable walls. The probability of piloted ignition is taken from the highest heat transfer possible for each side of each structure. For the window break ignition threshold the total surface area of windows is calculated for each third of each wall to calculate the house's probability of ignition by way of window break and firebrand ignition. These probabilities are then combined with a fire branding ignition probability to assign a final probability. All of these model aspects make SIAM a suitable choice for this project.

Modeling Wildfire Probabilities Through Time at the Landscape Scale

Prediction of wildfire probabilities for the next three decades is also needed to accomplish the first objective of this dissertation, calculation of the existing ignition hazard to WUI structures. Wildfire ignitions in many parts of the western US are dominated by dry lighting events with human-caused ignitions contributing varying proportions (Agee 1993). Topography and weather combine to generate abundant air to ground lightning strikes each year. Long and short-term weather patterns and vegetation, some of which has been modified through forest management, interact to determine wildfire intensity and severity. Numerous articles, synthesized by Graham et al. (2004), now describe how logging, grazing and successful wildfire suppression efforts during the 20th century changed the structure and composition of western North American forests. Increases in stand density are believed to predispose standing trees to more intense fire behavior, resulting in more severe wildfires than were typical before European settlement (Arno and Fiedler 2005).

Authors have also noted that a general increase in temperatures in recent years has lengthened the number of days each year that can support active insect life cycles (Westerling et al. 2006, Running 2006). Numerous bark beetles in particular have increased their population growth rate (Logan et al. 2003) through a combination of decreased cold-related mortality (Bentz and Mullins 1999) and shorter generation times in North America (Ungerer et al. 1999). Recent detection surveys have simultaneously focused attention on a trend of increasing infestations with resultant increases in the numbers of dead and dying trees.

Collectively, these factors contribute to expectations of strong interactions between insect and disease infestations and wildfire during upcoming decades. In order to model wildfire in the future, a tool is needed that uses local disturbance history to represent the best expectations for interactions of future vegetation disturbance processes (including wildfire, insects and disease, and forest management practices). Also, recall the discussion regarding the importance of temporal scale and the decision to model a 30-year wildfire probability.

Wildfire Probability Modeling Options

Numerous models, besides SIMPPLLE, can be used to model landscape fire probabilities including: VDDT (Beukema and Kurz 1998), FlamMap (USDA, 2006), and LANDSUM (Keane et al. 1996). A model is needed that can achieve the first and third objectives of this study: estimation of existing wildfire ignition hazard and evaluation of silvicultural forest treatment effectiveness. It is clear that the ability to model the spatial and temporal variability of wildfires across an area is extremely important for this project.

Barrett (2001) describes the four prominent models of vegetative change for landscape planning (FETM (CH$_2$M Hill 1998), LANDSUM, SIMPPLLE, and VDDT). She notes that only SIMPPLLE and LANDSUM are spatial models. Furthermore, only SIMPPLLE uses spatial context, a quality considered quintessential for this analysis. Keane et al. (2004:4) reviewed 40 fire modeling tools and stated “it is now recognized that to function as a comprehensive exploratory tool, vegetation models should simulate transient changes in vegetation in response to climate, disturbance, and environmental change in a spatial domain.” For example, the incorporation of spatially explicit insect and disease infestations and the interaction of this ecological disturbance with future wildfire appear to be important. Table 2 is a comparison of important attributes for available modeling tools that shows that the SIMPPLLE model has many of the desired model characteristics.

The Simulating Patterns and Processes at Landscape Scales (SIMPPLLE) Model

In order to meet the requirements of wildfire probability prediction for the first objective of this research, baseline decadal landscape fire severity probabilities for each polygon hosting a WUI residential structure must be obtained. The Simulating Patterns and Processes at Landscape Scales (SIMPPLLE) modeling tool is employed to derive expected wildfire disturbance probabilities across all (both the private and public) lands in the study area, given existing conditions.

The SIMPPLLE data is based on a three-way classification (dominant species, size class, and density) of remotely sensed data, converting the landscape into irregular shaped vector-based vegetative polygons. The SIMPPLLE modeling tool projects future vegetative states for polygons based on pathways that reflect expert opinion and site-specific recent disturbance history regarding the likelihood of succession and future disturbance (Chew et al. 2004). Note that SIMPPLLE is an ecological process prediction-modeling tool, not a fire behavior-modeling tool.

Table 2. Comparison of available fire modeling tools

Modeling Tool	Spatially Explicit	Spatial Context	Temporal Component	Interaction with Insect and Disease Disturbance Processes
FETM	No	No	Yes	No
FLAMMAP	Yes	Yes	No	No
LANDFIRE	Yes	No	No	Yes
LANDSUM	Yes	No	Yes	No
VDDT	No	No	Yes	Yes
SIMPPLLE	Yes	Yes	Yes	Yes

The SIMPPLLE modeling tool meets many of the criteria for the ideal conceptual modeling system and is well suited to this project for several reasons. First, SIMPPLLE can stochastically simulate landscapes into the future as many times as desired. Description of the data to this point has focused on the spatial scale. One of the advantages of SIMPPLLE compared to fire behavior models is its ability to simulate disturbances into the future. The SIMPPLLE model can be run for any length time period. The SIMPPLLE modeling tool uses decadal time steps, limiting the selection to 10-year increments. Typically, simulations are run for 30 to 50 years with decadal time steps.

The model uses disturbance probabilities to simulate stochastic disturbances spreading across the modeled landscape by interactions with adjacent vegetative communities (neighboring polygons). In the case of wildfire, the model uses records of past fire events in a given area which are then converted into probabilities per acre per decade to form the basis of future fire expectations. Normal wildfire spread is possible to either uphill or downwind stands. A 30-meter digital elevation model is used to build the elevation relationships and a southwest prevailing wind is selected to build the fire contagion relationships between polygons center points in the model's area file. It is important to note that when fire is spreading in SIMPPLLE the logic dictates whether the disturbance spreads as a light, mixed or stand replacing fire to adjacent vegetative communities. The fire will have one and only one impact on each neighbor, that is to say the neighbor either burns completely (in LSF, MSF or SRF) or not at all. All acres inside vegetation community polygons have the same probabilities.

Finally, the SIMPPLLE model also has a demonstrated working relationship with a compatible software program, the Multi-Resource Analysis and GIS (MAGIS), which can be used to schedule fuel treatments across a selected time period, with the potential to affect fire probabilities in SIMPPLLE. Existing MAGIS software is extremely useful to accomplish Study Objective 3, scheduling thinning and prescribed burning regimes across the treatable area based on variable budget levels, facilitating Objective 4 a cost effectiveness analysis with set costs.

In summary, household scale data is needed to model existing ignition probability and potential reductions in this probability through various mitigations. This antecedent household level data is also needed to estimate the costs of HIZ mitigation activities. A sufficient sample of study area houses is collected to represent the spectrum of building types and home ignition fuels configurations that exist across the study area. Collecting this data constitutes a great deal of work and includes many important modeling decisions.

Existing vegetation and historical fire, insect and disease, and forest management disturbance information is also needed to accurately estimate fire probability estimates into the future. Once a time period for the analysis (30 years) and the historical reference period (1995-2004) are selected, data covering a landscape sized adequately to portray the impacts of wildfire and insect and disease disturbance processes on polygons hosting study area WUI houses must be amassed.

By combining results from two separate modeling tools for each study area house an average existing wildfire-caused structure ignition hazard estimate can be generated for the 291 study area houses. From this baseline estimate independent analyses for each of the two mitigation suites as well as a combined effectiveness analysis is possible.

Selecting an Economic Analysis Tool

Now that the discussion of wildfire modeling tools used to estimate the existing hazard and mitigation effectiveness is complete, the focus turns to the selection of a tool for economic analysis. Decisions regarding how best to spend money to achieve a societal goal are often analyzed ex ante with cost-benefit analysis (CBA). A CBA combines the discounted costs with the discounted benefits of an alternative to derive a present net value. If appraised home value with a standard adjustment for contents and belongings (from insurance company records) was used, all reductions in average hazard could be quantified as monetary benefits, and the results could be displayed with a CBA. However, a cost effectiveness analysis (CEA) will be used instead for this research.

Economists have proposed CEA as an alternative to CBA, when benefits cannot easily be quantified with dollars (Boardman et al. 1996, Levin and McEwan 2001, Rideout and Hesseln 2001). As a result, the CEA tool is often used in medical, healthcare, education, and national defense studies. There are several reasons why CEA will be used instead of CBA for this research. First, current preventative fire protection planning is blind to house value[14]. For example, goal one (part d) of the 10-year comprehensive strategy implementation plan lists, "number of homes and significant structures lost as a result of wildland fire," as a performance measure (US Congress 2002:10). Note that neither this nor any other community wildfire protection planning (CWPP) documents refer to house values as a guide to preventative mitigations. County planners and fire hazard assessors treat each home in an area covered by a CWPP equally. To target wildfire hazard mitigation resources at homes based on assessed values would require an assumption that market values accurately capture all the value of a home and its contents and it would suggest a policy that is difficult to defend based on social equity grounds because it would amount to a policy that prioritizes protection based on differences in personal assets.

Generally, the cost effectiveness analysis tool can be used in two ways. You can select a target effectiveness level and let expected costs float, or you can select a budget

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[14] While fire prevention resource allocation may not depend on house value, fire suppression efforts may in reality be allocated based on house values.

constraint and let expected effectiveness float. Due to the complexities of combining several wildfire modeling tools to obtain an effectiveness measure for this project, and the sub-optimal[15] prioritization processes used to select treatment regimes and HIZ mitigation activities, the prospect of setting a specific effectiveness level for reduced average 30-year structure ignition hazard and letting expected budgets (cost) float seems untenable. This is why the same seven budget levels are used to compare the effectiveness of two suites of mitigation options. Effectiveness could be expanded in the future to include additional measures, such as expected acres of high severity fire.

Summary

This concludes the chapter describing modeling tool selection. The selection of the modeling tools strongly impacts the results of the economic analysis for this study. The SIAM model represents the best option to model the likelihood that wildfire will ignite a structure. Although other ecological disturbance and fire behavior models exist, the SIMPPLLE model has many features that make it a good selection to model wildfire probability for this dissertation. Substituting these other models to estimate the probability of wildfire encountering each study area home could alter the results of the mitigation CEA. There are also many modeling decisions represented in the methods chapter that impact the economic analyses. However, in order to maintain the focus of this document, the impact that these modeling decisions and assumptions have on the results is not presented until the discussion chapter (V), which follows both the methods (III) and results (IV) chapters.

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[15] Mitigations are considered sub-optimal for various reasons. The HIZ mitigations are generalized to the application of seven options to all houses in the study area. The MAGIS treatment schedules are sub-optimal because the reduction factors used in the scheduling process are not based on SIMPPLLE outputs following treatments.

CHAPTER III – METHODS

The methods covered in this chapter explain the tasks required to achieve the four study objectives seen if Figure 1. This first section explains Study Objective 1, by describing how the analysis methods are applied with the wildfire modeling tools and data to generate existing hazard results. The next section describes how two suites of mitigation options are developed, assigned costs, and evaluated for effectiveness to achieve Study Objectives 2 and 3. These first three objectives are steps needed to achieve Objective 4, generation of cost effectiveness analysis products. Collectively, these methods permit demonstration of a wildland urban interface (WUI) wildfire structure-ignition mitigation cost effectiveness analysis.

Objective 1: Existing Hazard Estimation

The Structure Ignition Assessment Model

SIAM Data

Separating the home ignition zone (HIZ) and the remainder of the WUI area is essential to this cost effectiveness comparison between two suites of mitigation options. A home ignition zone is defined for this project, prior to data collection, as all fuels within a perpendicular distance of 100 feet from each side of each WUI study area structure and the rectangle that creates.[16] This is the area included in the structure ignition analysis (Figure 5).

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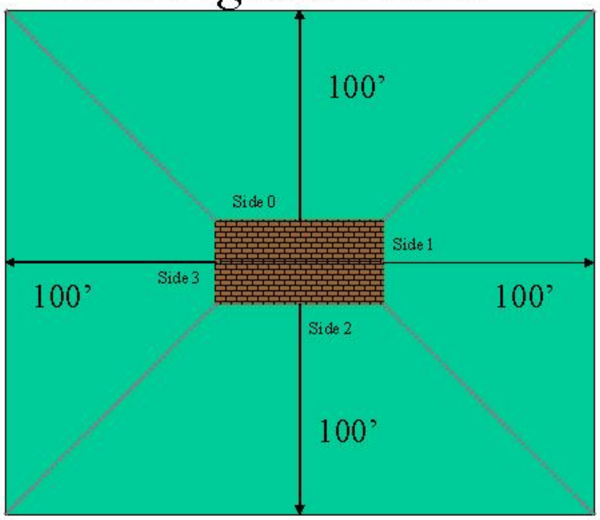
[16] The average size of the HIZ for the 39 visited homes is 1. 38 acres. The range is from 1.05 acres to 1.84 acres, depending on house size.

Home Ignition Zone



Note: The Home Ignition Zone was defined as an area extending 100’ feet from each side of each structure

Figure 5. The home ignition zone.

Data Collection

Data collection occurred during the fall of 2005. With a data collection protocol prepared and a study site selected, the process of contacting potential participants commenced. Thirty-nine participants are included in the representative sample of visited homes (as a result of mailings, phone calls, and neighborhood networking in the study area community). Although the sample of homes visited is not random, it is representative of several gradients of fuel types, building types and the proximity of the structure to closed canopy forests. Attempts were made to contact all 291 homeowners with phone calls and letters. Ocular and stride estimation was used to draw four elevation views (Figure 6) and four plan views (Figure 7) on graph paper, and record information with a worksheet. Worksheets (Appendix A) are used to record measurements and annotate the drawings to ensure data entry needs are met. Visits last roughly two hours and include a verbal report to the homeowner regarding opportunities to improve structure safety from wildfire

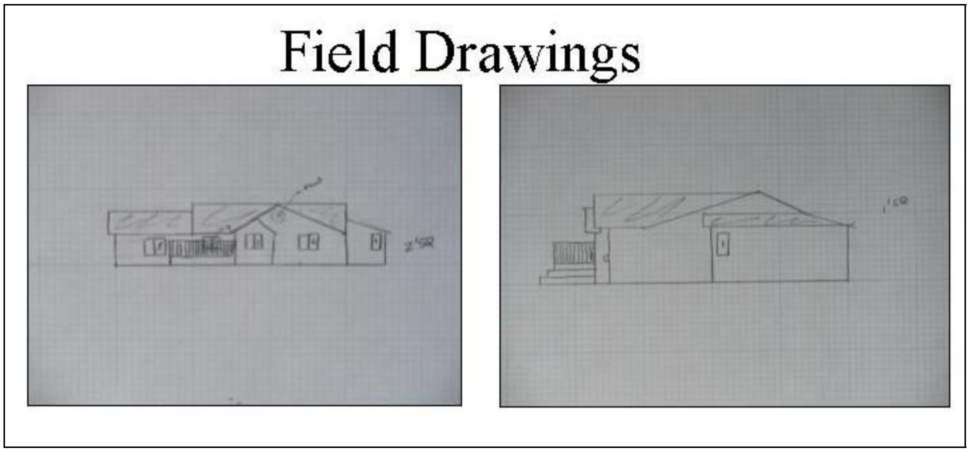

Field Drawings

Figure 6. Example elevation drawings

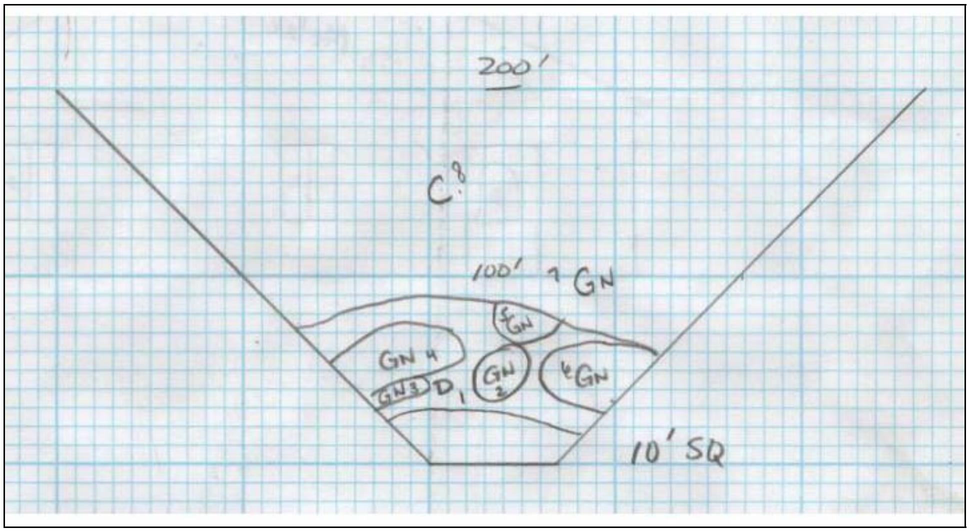


Figure 7. Example plan view drawing

Fire branding[17] potential for SIAM is rated subjectively from 1-3 in the area extending a quarter of a mile from each side, with one representing grasslands, two representing shrubs and open canopy forest, and three representing closed canopy conifer forest. This rating is assigned based on the vegetation between the structure and the visible distance for highly effective burning ember transport. This firebranding rating is the only input into SIAM that is not evaluated inside the HIZ. The firebranding potential interacts with

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[17] Firebrands are lofted embers with sufficient heat energy to ignite structures either by coming into contact with the house, entering through windows or coming into contact with flammable materials near the house.

both window surface area and the subjective nook and cranny rating to contribute to the overall SAIM ignition probability. Numerous factors contribute to the nook and cranny[18] scores (1-5). This subjective score is assigned based on decks, porches, ignitable roofing ends, railings, vent screening, and ignitable windowsills (Cohen, Pers. Comm. 2004).

Data Entry

The SIAM tool requires inputs for many building and fuel variables. It has a user interface whereby building and site-specific fuel information is entered in four elevation views and one plan view. When entering new fuel sources the user selects from ten options (Figure 8) including seven vegetation types, wood piles, debris piles and adjacent structure). The fuel polygon is digitized as it was drawn in the field and assigned a height.

Analysis

The first factor calculated in the modeling system is the structure's ignition expectation if a wildfire occurs in the vegetative polygon hosting the structure. The analysis of ignition expectation for each home is conducted independently for the four sides of each visited structure. Siding flammability, roof flammability and all window information is set prior to each analysis. Then all fuel sources in each side of each HIZ are selected using the computer mouse and the shift key. Overall ignition likelihood is estimated with the click of computer mouse and recorded in a master spreadsheet, where the highest ignition probability is selected and used.

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[18] Nook and cranny is the terminology used by SIAM to represent the degree of receptiveness a home has to lofted firebrands.

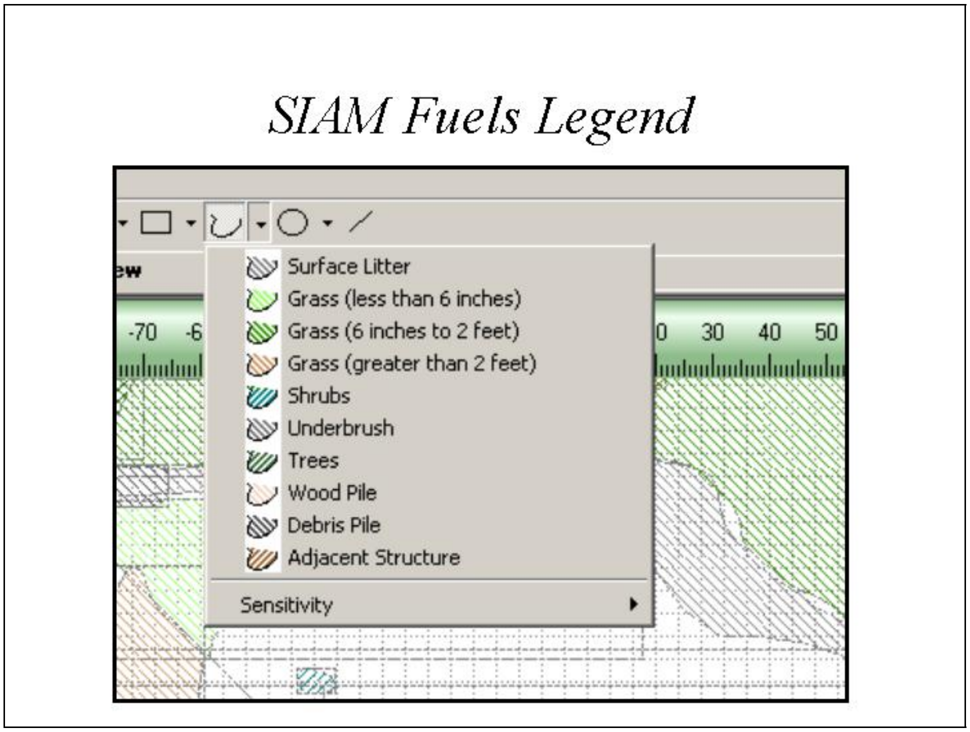

Figure 8. HIZ fuels options in SIAM.

Classification of unvisited homes

Limited willingness of study area residents to participate meant that not all houses in the study area were visited. Extrapolation from the SIAM results of 39 visited houses to the remaining 252 houses is done using the averages of three classes based on information from the MT State Library's Cadastral Mapping Project database. Both the visited homes and the 252 unvisited houses are broken into groups based on the flammability of their exterior walls (siding). The visited homes are put in either a flammable or non-ignitable class whereas the siding for the unvisited homes is classified as flammable, non-ignitiable or unknown based on siding characteristics obtained from the cadastral database. A class average[19] is determined for the visited flammable and non-flammable houses. The

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[19] A random approach was also tested. In this case random numbers within the range for each class were applied to all unvisited homes. This made very little difference in the overall results and was dropped from the analysis.

average for the unknown class is derived from the full set of 39 structures. The average existing SIAM expectation for each of the three classes is applied to all unvisited houses in the respective classes.

Simulating Patterns and Processes at Landscape Scales

SIMPPLLE Data

The second factor needed to derive existing hazard estimates is wildfire probability. Several pieces of fine-scale, spatially explicit vegetative data are needed in order to initiate the fire probability modeling. Vegetative communities are modeled using recent (2005) GIS data from the USFS Northern Region GIS Library. The data is generated by applying a classification scheme to Landsat remotely-sensed (satellite) digital imagery. The remotely sensed imagery describing the area is classified into irregular polygons with an average size of 6.6 acres and a range of 0.9 to 99.2 acres. This "mid-scale" vegetation data, known as R1-VMP, is touted as being between 50 and 93 percent correct at the landscape scale[20] (Brewer et al. 2004). The area analyzed with landscape disturbance software includes roughly 266,400-forested acres (69.8%), 41,400 mixed shrub land acres (10.9%), and 30,600 grassland acres (8.0%). Data indicate that twenty-one forested dominant species types, three shrubs types and five grassland types exist in the area. The remaining analysis area polygons consist of water, non-forested areas, and herbs. There are ten tree size classes and four density classes used to differentiate the forested stands. Across the analysis area there are 240 unique combinations of habitat group, cover type, density, and size class, and 45 unique combinations of size class and density alone. Crosswalks established by the Rocky Mountain Research Station, Ecology and

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[20] However, this error rate itself can only be applied at the level the data is intended to be used, at least a 5th code hydrologic unit code (HUC).

Management of the Rocky Mountains Research Unit are used to transform attributes in the vegetation layer into attributes needed for SIMPPLLE.

In the roughly 1,360-acre area including just the polygons (n = 243) that host study area WUI structures (n = 291) the composition of the vegetative communities is different. There are roughly 520 forested acres (38.2%), 329 shrub land acres (24.2%) and 500 grassland acres (36.8%) plus just more than 10 acres of non-forested area.

Historical Process and Treatment Data

The need to capture the temporal component of wildfire ignition hazard in this modeling system is reflected by the inclusion of several pieces of recent disturbance history, which are appended as stand attributes to initiate the SIMPPLLE analysis. Unless noted, data entered includes events that affected the stands between 1995 and 2004, the most recent decade. A standard GIS operation is used to intersect the R1-VMP polygons with the Timber Stand Management Reporting System polygons where activities or disturbances were recorded, using the 'center in' option of the 'select by theme' procedure in ESRI ArcView 3.2 software. Table 3 reports the last decade’s acres for analysis area polygons of each activity or disturbance type in the SIMPPLLE analysis area modeled in this dissertation.

The first piece of information is the spatial history of fire across the modeled landscape. This polygon information is obtained from the Northern Region’s GIS library as attributed fire perimeters. Fires within the time period 1995-2004 are selected from the longer record of fires in the area. These fire perimeters (Figure 9) encompassing roughly

28,560 acres are then used to select R1-VMP polygons for assignment of a mixed severity fire in the last decade. A mixed severity fire is applied to each of the stands that intersected the fire perimeters, mainly because the severity of the fires is not documented and anecdotal evidence suggested this is a reasonable assumption. This fire severity information is recorded in the initial process field for each vegetative polygon in the area file with this history. These recent fires affect future processes through SIMPPLLE fire spread logic. Stands with recent fires will react differently to wildfire than those with similar stand composition and structure that have not had fire during the past decade. This fire logic is based on information found in publications by Fischer and Bradley (1987) and Smith and Fischer (1997).

Table 3. Silvicultural activities that are entered for the analysis area polygons.

Disturbance	Acres
Mixed-Severity Fire	28,560
Ecosystem management broadcast burn	1,647
Ecosystem management underburn	1,294
Commercial thinning	972
Clearcut with reserves	2,824
Group selection cut	367
Shelterwood final with reserves	346
Seedtree seedcut	73
Sanitation Salvage	2,394
Improvement Cut	19
Insect Infestations	5,875

For SIMPPLLE, a probability of fire ignition per decade per acre (0.00071) is determined by dividing the number of ignitions inside the analysis area during the last decade (271) by the total analysis area (381,400 acres). Figure 10 illustrates the spatial arrangement of ignitions during the previous decade. Red ignitions (1995-2004) are used to create the general probability of ignition per acre per decade and the blue ignitions are additional starts in the area during the period 1970-1994.

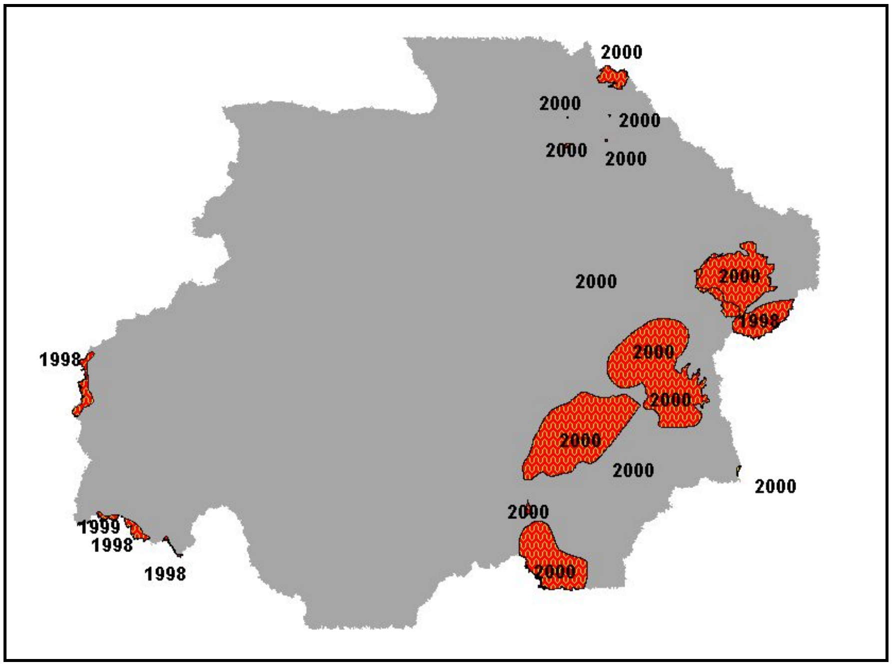

Figure 9 – Recent (1995-2004) fire perimeters, red areas are large fires, dates represent the year of burn, (USDA, Forest Service, Northern Region 2006).

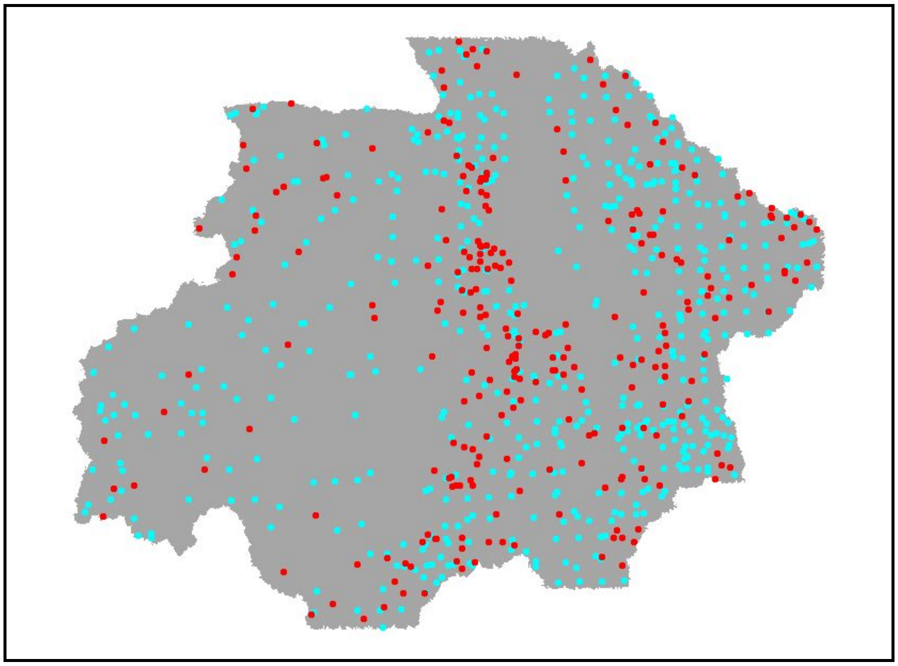

Figure 10. SIMPPLLE study area ignitions, blue = 1970-1994, red = 1995-2004 (USDA, Forest Service, Bitterroot National Forest 2006a).

Insect infestations are also included in the model initialization. Aerial detection surveys (ADS) are conducted annually for all National Forest System lands using fixed wing aircraft. Each fire simulation in SIMPPLLE adopts the 2004 lodgepole mountain pine beetle (1,053 ac.), Douglas-fir beetle (4,747 ac.) and spruce beetle (75 ac.) infestations as the existing locations of infestation. A local western root-rot disease spread logic file is also included for all simulations.

Silvicultural treatments[21] representing a mix of improvement cuttings, regeneration harvest activities, and fuel treatments are also entered as treatments in the last decade for each affected vegetative polygon using the same intersection process described above.

Calculating fire probabilities

One base case is selected to generate results that are combined with SIAM results to accomplish the first objective, estimating the existing 30-year hazard to 291 study area WUI residences. After careful consideration of the sensitivity (SA) results, all of the default settings in SIMPPLLE are selected for base case fire simulation, with the exception of extreme[22] fire spread. This is the most influential continuous SIMPPLLE fire logic parameter tested. The extreme fire spread probability, the probability of each fire greater than 0.25 acres spreading with extreme fire spread logic, is set at five percent to represent conditions in the study area and to match the assumptions of extreme fire

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[21] These recent forest management treatments are described in greater detail in appendix B.

[22] Extreme fire spread in SIMPPLLE means that fires can spread in a downwind direction from the polygon hosting an ignition uphill as well as downhill, to neighboring polygons. An average elevation is calculated using a 30-meter digital elevation model during SIMPPLLE data preparation to allow application of this logic.

weather in SIAM. This parameter setting implies that roughly five of every 100 fires in the SIMPPLLE analysis area will face extreme weather conditions. In addition, all SIMPPLLE modeling for the project is conducted with active suppression. This represents the reality that nearly all wildfires are suppressed by land management agencies before they grow to a large size.

Given the time period selection, a probability across the three decades is needed from SIMPPLLE simulations. Simulation results for each vegetative polygon hosting one or more residential WUI structure(s) are collated in the three different process.txt files generated by 100 simulations. Based on a set of 100 simulations, the number of times fire of three vegetative severity classes[23] occurs is summed to generate a total fire probability for each decade. As Equation 1 demonstrates, the probability of a fire in decade 1 for each polygon equals the number of light severity fires during 100 decade 1 simulations (LSFd1) plus the number of mixed severity fires during 100 decade 1 simulations (MSFd1) plus the number of stand replacement severity fires during 100 decade 1 simulations (SRFd1). Note that simulations are all independent of one another so that while wildfires that burn each decade affect the future succession pathway of a given polygon in a single simulation, they do not affect the other simulations. Equation 1 shows the summation used to derive a decade fire probability for each polygon.

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[23] Each polygon can only have one ecological disturbance process (including any of the three fire severity classes listed) or succession occur in a single decade.

Equation 1:

$\text{Probability}\ (D1) = (LSFd1) + (MSFd1) + (SRFd1)$

For example, $p(D1) = 0.01\ (LSFd1) + 0.02\ (MSFd1) + 0.00\ (SRFd1) = 0.03$

Because the research question addresses the probability of fire reaching a polygon hosting a structure, the probability across three decades is needed, versus the average probability across the time period. In other words the three-decade probability cannot exceed one, and it also should not fall below the highest probability for any given decade. This explains why these numbers are combined with Equation 2, and then used for multiplication purposes in the modeling system. Equation 2 takes the probability for the first decade and adds it to 1.0 minus the probability of the first period multiplied by the probability for the second decade. This creates a conditional probability for two decades. In order to extend this to another decade, the two-decade probability is added to 1.0 minus the two-decade probability multiplied with the wildfire probability of the third decade. In this way probability of events occurring can be extended through time with the wildfire probabilities never exceeding 1.0.

Equation 2:

$P(D1\text{-}3) = p(D1) + ((1 - p(D1) * p(D2)) + (1 - (p(D1) + ((1 - p(D1) * p(D2))) * p(D3))$

For example, $p(D1\text{-}3) = 0.01 + ((1 - .01) * 0.02) + (1 - 0.022) * (0.00) = 0.0298$

The final wildfire probability represents the chance that each polygon will experience a wildfire during the simulated period, 2005-2034. This calculated SIMPPLLE result is the fire probability factor used to derive the exiting hazard for each individual structure using the modeling system equation.

Combining the Modeling Tools to Estimate Hazard

The introduction and modeling approach chapters describe the conceptualization of the modeling system needed to estimate existing ignition hazard to residential structures in the wildland urban interface for the next thirty years. To summarize, obtaining the product of two independent probabilities (one that wildfire will confront a residence, and one to estimate the probability that wildfire will ignite a structure if it passes and sends firebrands) allows a modeler to understand the existing hazard given assumptions embedded in each modeling tool.

Digital aerial photography is used to locate all study area homes. The R1-VMP polygons that host residential structures are determined by locating structures manually in ESRI, ArcView 3.2 using 2-meter digital orthoquad imagery. Based on location assignments, each structure is assigned to a R1-VMP polygon, which allows a connection between SIMPPLLE and SIAM. Although they operate at different geographic scales, the ignition probability results from SIAM for each house and the 30-year wildfire probability for its host polygon from SIMPPLLE are multiplied to generate the existing hazard estimate. The average is then taken from all 291 study area homes. This average is also multiplied with the number of homes to create a 30-year expected loss figure.

Wildfire Modeling Tool Sensitivity Analysis

There are two sensitivity analyses used to detect the parameter sensitivity of the two models used to estimate the existing hazard. Several key SIAM parameters are tested for this dissertation using real field data to provide a better understanding of the model's sensitivity. Five of the 39 structures are randomly selected. Local (changing one variable at a time) sensitivity analyses (SA) are conducted by varying ambient temperature and wind speeds. Ranges are selected to represent realistic summer weather possibilities in the study area during the fire season. Both 80F and 100F temperatures are tested and wind speeds ranging from 0 to 40 miles per hour are tested at five mile per hour (mph) intervals. Combinations of these temperature and wind speed changes from default settings[24] are then used to detect synergistic impacts on the model. The ignition expectations are recorded for all changes, as is the impact on the nook and cranny and fire branding probability, a component of the calculations that represents the interaction of HIZ fuels and the two subjective ratings (firebranding potential (1-3) within ¼ mile of each side, and nook and cranny ratings (1-5) for each side).

The limited SIMPPLLE SA employs local parameter changes in the SA. With recognition that SIMPPLLE is typically used at the landscape scale and that it is being used here at the polygon scale, the sum acreage of fire across three decades is tracked in multiple nested areas for the SA. Suppression is the one discrete parameter tested. All other parameter changes are tested with suppression turned off. For continuous variables a reasonable range for each parameter to be tested is first determined. The probability of extreme fire spread in the simulations is tested from 0 to 100 percent. Both the range for

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[24] SIAM default settings: 90F and 20 mph.

each input parameter and the range of average output of total fire are provided in Appendix C. The assumptions and parameters implicit in these models have a large impact on the results of simulation modeling and these are addressed in the discussion chapter (V).

Mitigation Suites

The purpose of this research is a comparison of cost effectiveness for two suites preventative wildfire hazard structure ignition mitigation opportunities. There is evidence suggesting that structure characteristics and fuels within the home ignition zone are important factors contributing to any structure's ignition potential (Graham 2003, Cohen 1999, Foote and Gilles 1996, Howard et al. 1973). Other evidence suggests that thinning and prescribed burning treatments can reduce fire intensity and promote more successful suppression efforts (e.g., Strom 2005, Graham et al. 2004) The next section of this chapter reveals how Suite A, potential building improvements and HIZ fuel conversion mitigation options at 39 visited structures are modeled to explore the effectiveness of the home ignition zone (HIZ) mitigation options. This represents the upper mitigation path in Figure 1. The subsequent section describes how Suite B options, schedules of silvicultural thinning and prescribed burning treatment regimes, are modeled based on budgets comparable to those needed to support each HIZ mitigation option. Suite B represents the lower mitigation path in Figure 1.

Objective 2: Suite A- Home Ignition Zone Mitigation Options

The HIZ mitigations are broken into three categories: building upgrades, HIZ fuel conversion mitigations, and combinations of building and fuel conversion mitigations.

Building Improvements

Several of the HIZ mitigations involve solely structure modifications to existing residences. The first option is the improvement of windows. The replacement of all single pane windows with double pane windows is modeled. This option is designed to reduce the overall ignition probability for each side by reducing the chance of windows breaking from firestorm winds that allow firebrand ignitions inside the home. The window attribute describing every single pane window is reset to double pane and all ignition calculations are rerun, with results recorded in the master spreadsheet.

The next mitigation option is to replace all flammable siding with a non-flammable alternative, (e.g. Hardiplank®). Siding replacement is intended to reduce the probability of piloted ignitions, which represent a mix of convective and radiation heating from nearby burning HIZ fuel sources. All sides of houses are reanalyzed following the adjustment of the siding type attribute in the component data window of SIAM. The new ignition probabilities are then recorded in the master spreadsheet.

A third purely structure mitigation approach is the concurrent replacement of siding and upgrade of single pane windows to double pane windows. This is simply achieved by changing all single pane windows to double pane windows and simultaneously changing siding from flammable to non-flammable siding and then reanalyzing the ignition probabilities in SIAM.

Note that regarding building improvement, replacing the roof may be the most important mitigation effort for residential structures in WUI areas threatened by wildfire. Consider that the SIAM model automatically sets a side's expected ignition probability to 1.0 when the flammable roof type is selected. While roof replacement analyses would be extremely important in an analysis in many WUI geographic areas, no flammable roofs are modeled for this study, specifically because none were found during visits and none were found in the study area according to the Montana Cadastral Mapping Project Database.

HIZ Fuel Conversion Mitigations

A procedure is needed to simplify fuel mitigation approaches for modeling the 39 visited structures. Given that unlimited combinations of fuel manipulation are possible a reduced set of two (light and full fuels removal/replacement) HIZ fuel conversion options is created to make the analysis tractable. The idea is that homeowners in the area interested in reducing their wildfire ignition hazard would likely undertake various levels of fuel conversion. For the light fuels conversion specific fuel sources within the HIZ are selected for replacement in each side of each structure's HIZ. The light conversion option includes removal of proximate grasses, surface litter, and very few if any additional shrub, tree, or firewood fuel sources and replacement with a watered lawn. Screen captures of the SIAM plan views for each side's mitigation analysis are used to capture the modifications made to each side's set of fuel sources for the light fuels option. The full fuels conversion option selects all fuels for removal and replacement with non-fuel source alternatives (e.g., dry grass is mowed and watered with installed sprinklers, hardwood trees are planted to replace conifers with low branches). In both cases, fuel sources picked for conversion are unselected from the original analysis and new SIAM ignition probabilities are estimated for all four sides of each structure and recorded in the master spreadsheet.

Combinations of building and fuel mitigations

Two HIZ mitigation options are combinations of structure modifications and fuel conversions. One option combines siding replacement with the light fuels conversion. Another option is the combination of siding replacement, window upgrades to double pane, and the full fuels conversion. The changes to the analysis are made as described above, and the ignition probabilities are recorded in the master spreadsheet. These combinations are intended to represent the multifaceted approach often encouraged by wildfire hazard reduction education and grant campaigns.

HIZ Cost Estimation Procedures

The suite of HIZ mitigation options are ascribed budget levels based on two different methods. Costs for the building upgrades are calculated by obtaining local cost estimates for the installation of upgraded windows (double pane) as well as installation of a locally available non-ignitable siding alternative for the estimated number of average houses in the study area with this option available.

Cost estimation for two levels of fuels conversion in the HIZ suite are accomplished by quantifying the surface area of various fuel types[25] in the HIZ that would need to be removed and replaced and multiplying this by area-based cost estimates. Each SIAM

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[25] The data collection/entry protocol balanced time requirements with fuel source mapping detail. As a result, groups of trees and shrubs drawn as single polygons, and annotated with the tallest vegetation in the polygon. The height differences represented by the five height classes (>20’, 21-40’, 41-60’, 61-80, and 80’+) and the single tree versus groups of trees classes are assumed to require different amounts of work and costs for removal, disposal and in some cases replacement with non-flammable hardwood alternatives.

plan view is overlaid with a four-by-four foot grid (Figure 11). A point estimate of the cost to convert a sixteen-square-foot cell for each fuel type is estimated by the author in consultation with fire hazard reduction professionals local to the study area. The author's cost estimates per 16 square foot cell in all twenty-two fuel categories are then multiplied by the number of cells to develop a cost estimate for light and full fuels conversion for each of the 39 visited homes. In all cases, cost estimation for the HIZ mitigation options for all 291 home ignition zones are done through extrapolation; proportions of visited homes in the area are used in combination with information from a state database to determine the number of study area homes with mitigation potential.

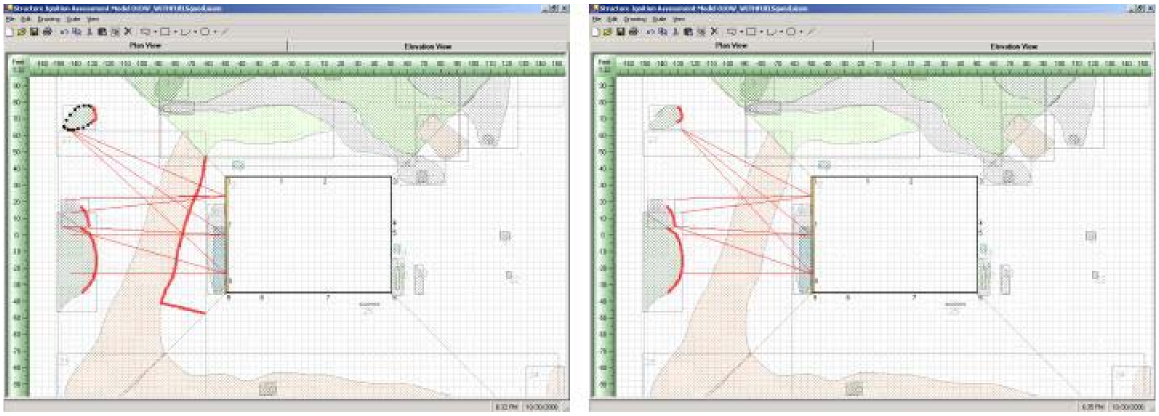

Figure 11. Cell grids overlain plan views for an example of a house modeled first (a) with all fuels in SIAM, and (b) with a light fuels conversion that removes the tall grass, shrubs and surface litter from the HIZ analysis.

Effectiveness Methods

Modeling mitigation effectiveness in SIAM to estimate the reduced ignition probabilities is done with the processes described above. The new overall ignition probabilities at each side of each house following all HIZ mitigations are recorded in the master SIAM spreadsheet. The same technique of using the maximum side probability for each house is also used to evaluate the effectiveness of all the HIZ mitigations.

Objective 3: Suite B – Silvicultural Forest Treatment Regimes

This section describes how the third objective of the dissertation is accomplished. The objective is to design silvicultural treatment regime schedules that minimize the 30-year conditional fire probability for vegetative polygons hosting residential structures. This suite of mitigations is an alternative to the suite of mitigation efforts within the area immediately surrounding each residential structure and represents the lower mitigation analysis path on Figure 1. Thinning and prescribed burning are applied to as many forested and grassland polygons as possible in the area surrounding the polygons hosting houses given a range of budget levels. The budgets are capped at levels that correspond to the HIZ options. This permits a comparison of the effectiveness, simplifying the cost effectiveness analysis. The treatable area is described prior to an explanation of the scheduling process. This is followed by a description of the interaction between MAGIS and SIMPPLLE.

Defining the Area of Acceptable Forest Fuel Treatments

Silvicultural forest treatments (thinning and prescribed burning) are evaluated within the wildland urban interface. Unless specified in a community wildfire protection plan, the maximum distance away from structures called the WUI is one and one half miles[26] in the Healthy Forest Restoration Act (HFRA). Residential structures in the study area are first selected and assigned point locations in a GIS, then these point locations are buffered by one and one half miles. This is done to constrain the area where forest fuel treatments are allowed. Figure 12 shows the 35,134-acre treatable area within the larger

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[26] According the HFRA, this 1.5 mile distance is used instead of 0.5 miles when extenuating circumstances exist. Adjacent steep slopes that represent a hazard to the community are included in this justification list. This is the scenario in the study area.

SIMPPLLE analysis area. This delineation of a treatment area is done to match the suggestions of the HFRA and also to reflect the socio-political realities of conducting fuel treatments with the intent of residential structure protection. In order to make the cost effectiveness in this dissertation an ‘either or’ comparison, the 243 polygons that host the 291 homes are not candidates for treatment regimes.

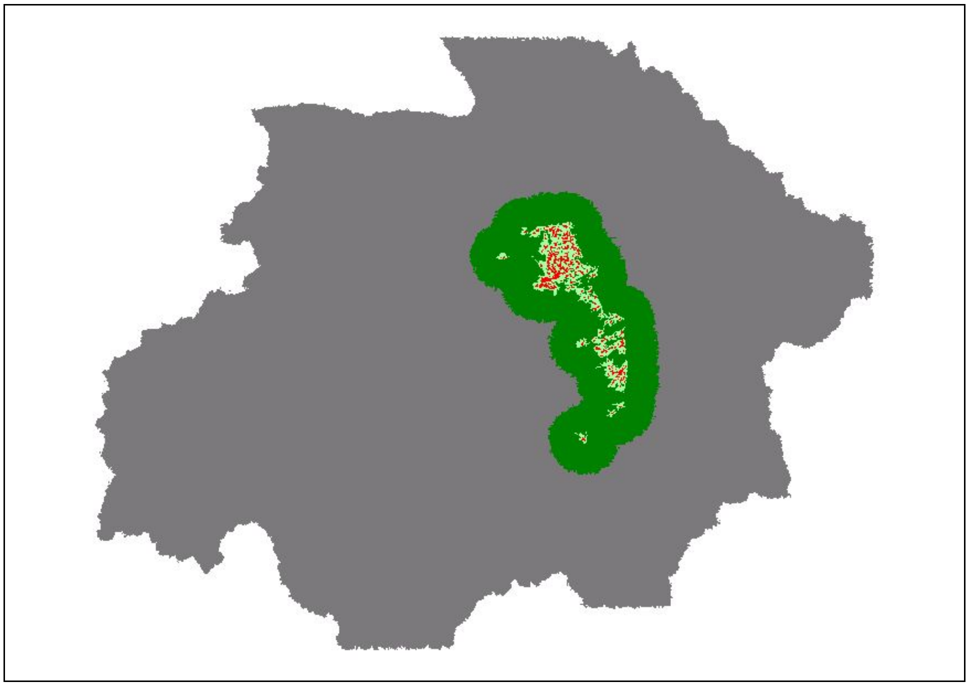

Figure 12. The portion of the analysis area, in shades of green where thinning and prescribed burning treatments are allowed. Light green represent high priority areas, dark green represents low priority treatable areas and red is the set of 243 polygons that host the houses and cannot be treated.

<u>MAGIS treatment scheduling software</u>

The Multi-resource Analysis GIS (MAGIS) software version 1.2.3 is the treatment scheduler used for this dissertation. The software was developed by the Rocky Mountain Research Station’s, Economics of Forest Management Unit in cooperation with the University of Montana, College of Forestry ands Conservation in Missoula, Montana

(Zuuring et al 1995). More information describing this tool is available at the website: (http://www.fs.fed.us/rm/econ/magis/).

The MAGIS software is used in this project to optimize silvicultural treatment regime schedules by multiplying the existing 30-year fire probability by the hazard reduction factors that characterize each treatment regime, with consideration of area and discounted[27] net revenue at each possible polygon. The treatment schedule selected by the MAGIS software for each chosen budget level includes options to homogenously treat any of the 5,310 stands within the 35,134 acres inside the one and one half mile buffer area[28] of residential structures. Stands in this area, other than those hosting houses and their HIZs, can be treated with only one management regime at the start of the first, second, or third decade. Treatments schedules are not extended beyond this decade because the probability of fire occurrence is not modeled beyond that point, negating any detectable difference.

Silvicultural management regimes in MAGIS

Management regimes in MAGIS are suites of silvicultural treatments and accompanying administrative activities that can be applied given antecedent vegetative conditions. Each regime has a cost structure and two regimes also have a revenue stream associated with product harvest. Management regimes modeled for this research include five thinning and/or prescribed burning options, described in increasing order of tree removal. The first

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[27] A standard US Forest Service four percent discount rate is applied to all costs and revenues occurring in the future (treatments scheduled for decades 2, 3, 4, and 5, where decades 4 and 5 include only follow-up burn costs for any restoration treatment regime scheduled to start in decades 2 and 3).

[28] This does not include the 243 polygons hosting houses that comprise 1,361 acres.

regime is an ecosystem management underburn only. The second regime is a thinning from below of only trees below 7” diameter at breast height (dbh). The third regime is this small tree thinning in combination with an ecosystem management underburn. The fourth is a ‘moderate density thinning’, with a 100 square foot per acre residual basal area target. The fifth regime is a ‘comprehensive restoration thinning,’ based on work by Fiedler et al. (1999) with a 50 square foot per acre residual basal area target. Both of these last two treatments also remove all trees under 7”dbh, then harvest a mix of tree species and sizes to reach the residual target. The restoration treatment also includes two follow-up maintenance burns, one in the same time period as the tree removal and one two time periods after the period of the initial treatment.

The last two treatments have revenue associated with predicted product removal estimates. The MAGIS model uses site and stand information with the Transaction Evidence Appraisal model to predict discounted revenues that are combined with discounted costs to derive net revenue per acre for optimization processing. All these treatments will be described in more detail in a pending General Technical Report describing the modeling effort supporting the Trapper Bunkhouse Ecosystem Restoration stewardship contract project.

MAGIS Objective Function

The MAGIS software’s optimization works to select the greatest marginal benefit (reduction in conditional three-decade fire probability for all treatable stands) for treatable polygon in each decade compared to the discounted marginal cost/net revenue.

A solver in the MAGIS software uses a linear programming minimization objective function to schedule scenario solutions. The minimization function is: minimize the average three-decade fire probability for all stands adjacent to polygons with residential structures or within a one and one half mile radius of structures given the same seven budget levels that estimate the costs of each HIZ option.

In order for the optimization to work, post treatment fire probability expectations are needed for each treatments regime. The expected longevity of reduced wildfire probability benefits from the treatment regimes vary and is modeled with a lookup table of reduction factors multiplied with the base case 30-year conditional fire probabilities for scheduling purposes. These reduction factors are best guess generalizations for application of the management regimes to the variety of candidate stands. There is no existing documentation describing how the treatments actually impact SIMPPLLE fire probabilities. All management regimes are modeled with some reduction factors[29]. These reduction factors represent the expected modifications to wildfire probabilities following treatment application. For example, a reduction factor of 0.80 indicates that following application of a treatment regime; a reduction in the wildfire probability from 0.0010 to 0.0008 is expected. Based on work with crowning and torching indices (Fiedler et al. 2004, 1999), the comprehensive restoration treatment is expected to have

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[29] There was an additional attempt made to calculate reduction factors using information from the SIMPPLLE base case. Stands were first grouped by type. Then summary statistics describing the conditional three-decade fire probability were obtained for each stand type. Existing treatment pathways were then used to determine the post treatment stand types for each existing stand type in the treatment area. The median conditional three-decade fire probability from the group that a given stand transitioned into following treatment was then applied to the stands if treatment was scheduled, with durations described above. This provided MAGIS with the effectiveness information it needed to execute optimization of the objective function. However this produced spurious results and was dropped from the analysis.

the strongest reduction factor (0.60) in the first period with slightly waning reduction in the following period (0.70) and resurging reduction in the period following the second maintenance prescribed burn (0.64). Because none of the remaining management regimes retreat the area with a follow-up prescribed burn, none of them have reduction factors extending all 30 years. Table 4 shows the reduction factors applied for all treatment regimes.

Table 4. Fire probability reduction factors for MAGIS treatment regimes.

Treatment Regime	**Decade 1**	**Decade 2**	**Decade 3**
Restoration plus two Underburn[30]s	0.60	0.70	0.64
Cleanup Thinning and Underburn	0.62	0.72	1.00
Ecosystem Management Underburn	0.64	0.70	1.00
Moderate Density Thinning	0.75	0.80	1.00
Thinning with a 7" DBH limit	0.77	0.85	1.00

Scheduling Constraints

Numerous constraints in addition to budget are used to model realistic treatment scenarios in MAGIS. Both public and private lands in the treatable area are eligible for treatment. Private land is not used as a constraint because many of the treatments occurring in the vicinity of the study area occur on both public and private lands and grants are increasingly being used to create multi-jurisdictional fuel hazard reduction partnerships. However, there are several constraints placed on these public and private lands. First, no harvesting can occur within the Selway-Bitterroot Wilderness Area to the

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[30] The restoration treatment regime has two follow up burns. One occurs immediately following treatment at the start of the scheduled time period, the second burn occurs 20 years later.

west of the study area WUI. This is a small issue eliminating only 50 polygons and roughly 400 acres from the treatable area. The second constraint is the type of logging that can be applied in areas outside designated wilderness. For example, only helicopter logging (at a much greater cost than either tractor skidding or cable yarding) can be used in areas beyond 1,500 feet from existing roads. Cable logging is also the only logging method available for areas within 1,500 feet of an existing road with a slope greater than 35 percent (Figure 13). The average percent slope for each polygon (Figure 14) is also used to determine the cost structure for the prescribed burning treatments. In these calculations the steeper slopes (>35%) allow cheaper aerial ignition than prescribed fire on more subdued terrain which requires lighting by ground crews.

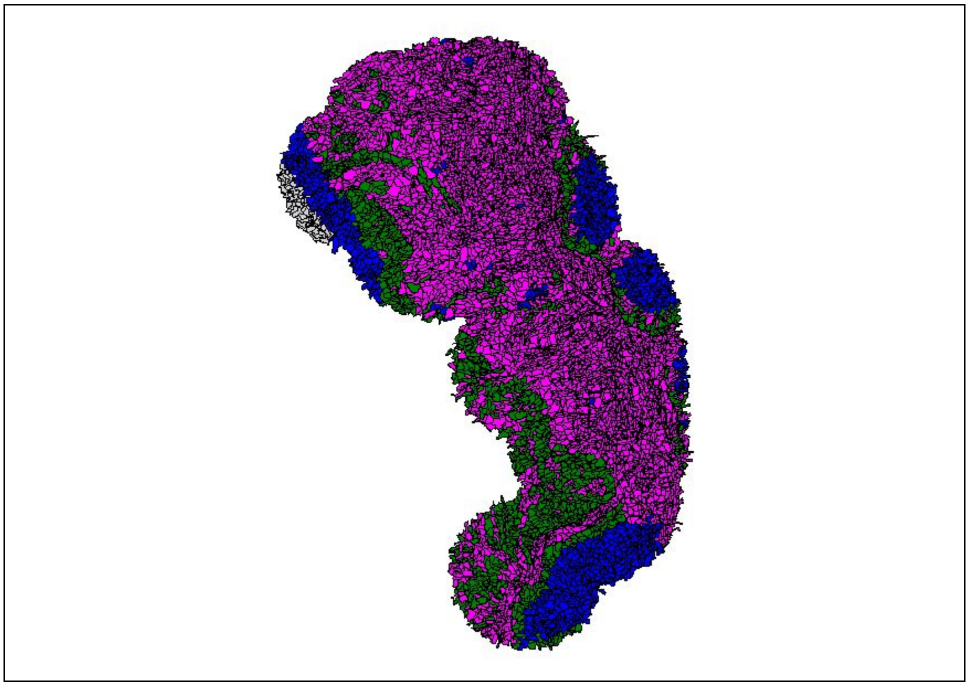

Figure 13. The logging methods that can be applied to each vegetative community in the treatment areas. Helicopter = blue, cable = green and tractor = purple, gray = wilderness (off limits).

In addition to these logging method constraints, several area-based constraints are imposed on the scheduler to create realistic solutions at each budget level. Planning documents for the proposed Trapper Bunkhouse Ecosystem Restoration Stewardship Contact Project (USDA Forest Service, Bitterroot National Forest 2006b) are used as a guide to limit the acreage of several management regimes. The percentages of the proposed study area activity acreages in this project are applied by multiplication with the treatable area in the dissertation to create area limits that reflect limitations to thinning and prescribed burning based on visual and overall activity magnitude acceptability. Table 5 provides these percentage guidelines and conversion to solution area limits for the various management regimes.

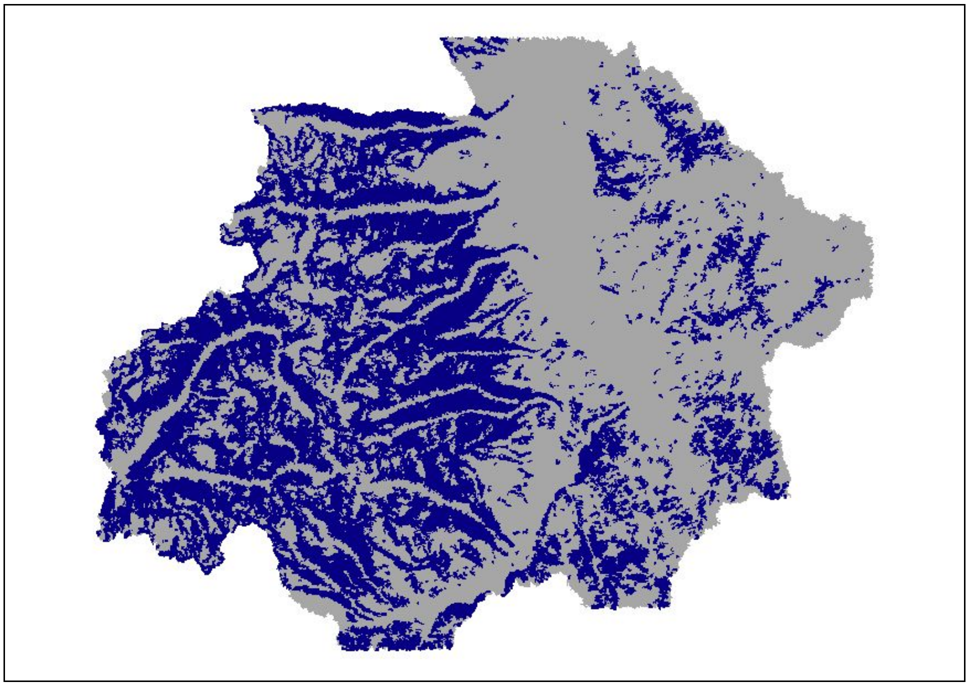

Figure 14. A map of average slope percentage conveys information used to determine both logging method and whether aerial ignitions can be used (only if average percent slope for a vegetative community is less than 45 degrees). Gray areas have average slopes less than 45 percent and blue area have slopes greater than 45 percent.

Milling capacity for the area is not assumed to be a constraint on the harvest because the local timber production area has more capacity than it currently uses (Keegan et al. 2004), and the amount that could be harvested in the 35,134-acre treatable area could not overload this capacity.

Table 5. Percentage of treatable area guidelines from the 34,300-acre Trapper Bunkhouse Project area

Constraint	**Trapper Bunkhouse Acreage**	**Area, applied as constraint to the 36,493 acre treatment area in the dissertation**
Moderate density thinning	1,001 (2.9%)	1,065 acres / decade
Restoration treatment	1,533 (4.5%)	1,640 acres / decade
Total Activity	5,479 (16%)	5,840 acres/ decade

The Interaction of MAGIS and SIMPPLLE

The treatment regimes scheduled by MAGIS affect the wildfire probabilities in polygons hosting houses in SIMPPLLE in three ways. First, the scheduled treatment regimes change the stand conditions (dominant species, density and size class) in neighboring polygons. These changes lead each stand down a different succession/disturbance trajectory than it was on prior to treatment. Table 6 illustrates these transitions by three main stand conditions (dominant species, density, and size class) for the comprehensive restoration treatment regime, considered by MAGIS during scheduling.

Secondly, applied treatment regimes reduce the fire probability by changing how fire spreads across the landscape. The 'type of fire[31]' that occurs given an ignition or encroaching fire from a neighbor changes[32] during the decade immediately after a treatment. In other words, if a fire does occur, the severity is reduced for the next decade.

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[31] This refers to the vegetative severity of the fire (light severity fire, mixed severity fire, and stand replacement fire).

[32] The author expanded this default logic in all SIMPPLLE simulations to include all of the treatments scheduled by MAGIS in this dissertation. For example, for pre-commercial thinning, fire afterwards will be reduced from MSF to LSF in all density classes.

Tables 6. An example of changes in stand attributes following application of the restoration thinning with two underburns treatment regime.

Dominant Species	Size Class	Density	New Dominant Species	New Size Class	New Density
DOUGLAS FIR_ALPINE FIR			DOUGLAS FIR		
DOUGLAS FIR_ENGELMANN SPRUCE			DOUGLAS FIR		
DOUGLAS FIR_GRAND FIR			DOUGLAS FIR		
DOUGLAS FIR_LODGEPOLE PINE			DOUGLAS FIR		
LARCH_ENGELMANN SPRUCE			LARCH		
LARCH_GRAND FIR			LARCH		
LARCH_LODGEPOLE PINE			LARCH		
PONDEROSA PINE_DOUGLAS FIR			PONDEROSA PINE		
LARCH_DOUGLAS FIR_PONDEROSA PINE			LARCH_PONDEROSA PINE		
LARCH_DOUGLAS FIR_LODGEPOLE PINE			LARCH_PONDEROSA PINE		
DOUGLAS FIR_LODGEPOLE PINE_ALPINE FIR			DOUGLAS FIR_LODGEPOLE PINE		
DOUGLAS FIR_PONDEROSA PINE_LODGEPOLE PINE			PONDEROSA PINE_DOUGLAS FIR		
DOUGLAS FIR_PONDEROSA PINE_GRAND FIR			PONDEROSA PINE_DOUGLAS FIR		
LARCH_DOUGLAS FIR_LODGEPOLE PINE			LARCH_DOUGLAS FIR		
LARCH_DOUGLAS FIR_GRAND FIR			LARCH_DOUGLAS FIR		
LARCH_DOUGLAS FIR_ALPINE FIR			LARCH_DOUGLAS FIR		
LARCH_LODGEPOLE PINE_GRAND FIR			LARCH_LODGEPOLE PINE		
LARCH_ENGELMANN SPRUCE_ALPINE FIR			LARCH_ENGELMANN SPRUCE		
ALPINE FIR_ENGELMANN SPRUCE_MOUNTAIN HEMLOCK			ENGELMANN SPRUCE_ALPINE FIR		
	VLMU			VERY_LARGE	
	VLTS			VERY_LARGE	
	LMU			LARGE	
	LTS			LARGE	
	MMU			MEDIUM	
	MTS			MEDIUM	
		2			2
		3			2
		4			2

LEGEND:

Size-Class/Structure Attributes:
SS – seedling and sapling, less than 5 inches dbh
Pole – single vertical story, 5 to 8.9 inches
PTS – two vertically distinct stories with the largest being pole size
PMU – three or more vertical distinct stories with the largest being pole size
MEDIUM – single vertical story, 9 to 14.9 inches
MTS – two vertical stories with the largest being medium size
MMU – three or more vertical stories with the largest being medium
LARGE – single vertical story, 15 to 20.9 inches
LTS – two vertical stories with the largest being large
LMU – three or more vertical stories with the largest being large
VERY-LARGE – single vertical story 21 inches or greater dbh
VLTS – two vertical stories with the largest being very-large
VLMU – three or more vertical stories with the largest being very-large

Density Class: Canopy Cover
1: 0-14%
2: 15-39%
3: 40-69%
4: 70-100%

Finally, the suppression potential of a fire in a given polygon is enhanced for one decade following treatment application. Both of the last two impacts of treatment regimes on the SIMPPLLE simulations work through logic screens that reference treatment names. Once the three-time period treatment schedule is designed it is bridged back to a more simplified version that can be loaded by the SIMPPLLE software. The crosswalk used (Table 7) converts the MAGIS treatment regimes into a schedule of treatments that are automatically inserted into SIMPPLLE simulations. Although all four treatments are only differentiated with three treatment names in SIMPPLLE, the simultaneous changes in stand condition in SIMMPPLE help reflect the magnitude of impact from each treatment regime that is used by MAGIS to create the schedule.

Table 7. A crosswalk used to digest MAGIS treatment regimes into management activities in SIMPPLLE.

MAGIS to SIMPPLLE Crosswalk	
Treatment Regime	**SIMPPLLE Treatment**
Prescribed fire	Ecosystem management underburn
Thin from below to 7" limit	Pre-commercial thinning
Thin from below to 7" limit and underburn	Thin and ecosystem management underburn
Moderate density thinning	Pre-commercial thinning
Restoration thinning plus two underburns	Ecosystem management underburn

Silvicultural wildland treatment cost estimation

The section above describes how the costs for each of the seven HIZ mitigation options is calculated into a total cost for the 291 homes. These seven budget levels needed to accomplish each of the HIZ mitigation options are then applied as constraints to the MAGIS version 1.2.3 scheduling optimization software program to schedule treatment regimes for the next three decades in the silvicultural options suite.

Effectiveness Methods

Once treatment schedules are designed for each budget level the treatments are loaded in SIMPPLLE and 100 new simulations are run. This results in three new decade fire probabilities for each stand. The new SIMPPLLE decade fire probabilities are then used to calculate a mitigated three-decade wildfire probability for each of the 243 polygons hosting the 291 residences in the study area. This information for each of the polygons is then multiplied by the existing condition SIAM ignition estimates for each house to create a set of 291 mitigated hazard probabilities. The average of these probabilities is used to compare the cost-effectiveness of silvicultural mitigations with the HIZ mitigations.

Objective 4: Cost Effectiveness Analysis for this Dissertation

Considering the fact that preventative mitigation planning is blind to house value and that the threat of wildfire to WUI structures includes a threat to human life, CEA is a good alternative to CBA for this dissertation. It removes the valuation debate that can be used to refute a standard CBA. The following section describes how the CEA will be presented.

Cost Effectiveness Reporting

The CEA reporting options include cost/effectiveness ratios, effectiveness/cost ratios, total effectiveness, and cost effectiveness beyond a minimum threshold. Ratios and cost-effectiveness (CE) frontiers are common reporting techniques for the CE tool (Levin and McEwan 2001). Researchers reporting CE ratios have the benefit of removing scale from the comparison; once the highest cost to effectiveness ratio is selected the most cost effective scale for an option(s) can be identified. On the other hand, a CE chart shows effectiveness levels across the spectrum of mitigation costs. Both CE ratios and charts representing the various CE points are reported in this dissertation for the CEA comparison between the HIZ and the silvicultural suites. However, curves are not generated to connect these points because this is not a marginal analysis. In other words, the sub-optimal solutions represented by each point on the charts are not part of a linear set of possible options. In order to show these curves the analyst would need the ability to scale options up or down by marginally adjusting the budgets. This would require an expanded optimization analysis, which is beyond the scope of this demonstration.

The cost effectiveness of each of the budgets is first reported by revealing the independent impacts to the SIAM and SIMPPLLE results. Next, the impacts on the modeling system estimated 30-year hazard results for each mitigation option are analyzed. Figure 1 shows how each of the two mitigation suites are analyzed at the seven investment levels by holding the other factor constant at the level used to calculate the existing hazard (*ceteris paribus)*. This assignment of HIZ mitigation budgets to MAGIS for treatment regime scheduling facilitates an effectiveness comparison with the simplified goal of WUI structure protection from wildfire. While other protection goals may also be considered desirable information useful in the selection of mitigation options (e.g., timber values, infrastructure, recreational developments, and specialized wildlife habitat may all warrant protection), they are not considered in this pioneering effort.

Methodological Summary

Now that the modeling tools and the data used have been introduced, a methodological summary should help the reader evaluate how well the modeling system reflects the wildfire caused structure ignition phenomenon and economic analysis of the two suites of mitigation options. This dissertation first explains how an average 30-year existing ignition hazard is estimated for the 291 study area homes by combining results from a deterministic structure ignition assessment model (SIAM) with a stochastic ecological disturbance process prediction model (SIMPPLLE), which calculates wildfire probabilities across the landscape. It then explains how a cost effectiveness analysis is conducted comparing options to reduce the average probability of structure ignition when wildfire threatens WUI homes. It follows advice from Finney (2005:98), who suggested using a quantitative definition of fire risk to evaluate the net value change from uncontrolled wildfires. He listed two main factors: fire behavior probabilities and fire effects applying to a specific geographic area and time period with the following equation:

Expected [net value change] = $\Sigma^{N}_{i=1}\Sigma^{N}_{j=1}$ $p(F_i)[B_{ij}-L_{ij}]$,

where $p(F_i)$ is defined as the probability of the ith fire behavior and B_{ij} and L_{ij} are the benefits and losses afforded the jth value received from the ith fire behavior.

The effectiveness of two suites of mitigation options, given the objective function of minimizing the 30-year average structure ignition hazard across the study area is then evaluated. The modeling tools are rerun independently to evaluate treatment effectiveness, where treatment effectiveness is defined as the predicted reduction in the average 30-year wildfire-caused structure ignition hazard across the 291 structures in the study area. Changes to anticipated home ignition hazard expectations are evaluated under the two following suites of options.

In the first suite, *Firewise* treatment options within the home ignition zone are building upgrades and the removal of fuels and subsequent replacement with non-flammable alternatives. For example, one treatment combines upgrading to nonflammable siding with the removal of grasses and replacement with a watered lawn. The costs of these treatments, as estimated by the author through consultation with local contractors who operate in the study area, serve as the baseline budgets for cost effectiveness comparisons.

In the second suite, silvicultural forest treatments include a mix of various prescriptions actually being proposed by the local management unit in the area. These silvicultural treatments are scheduled during three decades with the Multiple Resource Analysis GIS (MAGIS) software based on the ratios of expected hazard reduction and discounted net cost/revenue per acre. For example, a restoration treatment thins the existing stand to a 50 ft^2/acre residual basal area and follows this thinning with two broadcast burns. There is also a thinning-from-below to moderate density (100 ft^2/acre residual basal area), an ecosystem thinning with a seven-inch diameter limit, and an ecosystem management prescribed burning only.

By taking budgets ascribed to each of seven *Firewise* mitigation options inside the HIZs across the study area (modeled using SIAM) and applying them through MAGIS silvicultural scheduling software to the SIMPPLLE model (similar to past work by Jones and Chew (1999)), a direct cost effectiveness comparison is possible. The effectiveness of reducing average structure ignition potential for the next 30 years is charted against cost for all options to generate a cost effectiveness chart consisting of points that indicate achievable effectiveness at seven budget levels. Cost effectiveness ratios and this chart are the basis for a cost-effectiveness comparison using a simplified definition of effectiveness[33]. This research differs slightly from Finney's conceptual approach (2005)

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[33] Note each house is assumed to have equal value due to uncertainty about contents and social equity considerations.

because economic effects are restricted to structure losses from probable wildfires. In addition, it differs from his approach because the current hazard and potentially attainable improved conditions are assessments of the hazard of any type of wildfire encountering homes valued equally. With future work the analysis can eventually be populated with additional economic values that describe a more complete set of land management objectives and protection priorities. The next two chapters present the results and discuss modeling system limitations.

CHAPTER IV - RESULTS

This chapter provides the results obtained using the models and methods detailed in the previous chapters. The chapter is organized using the four study objectives in Figure 1. Key findings are highlighted briefly throughout the chapter to facilitate interpretation. The assumptions embedded in the results and their significance to the objectives and research goal are discussed in the next chapter.

Objective 1:

Individual modeling tool results are presented first. Next, the combined modeling system results are shown. A short summary of the sensitivity analyses (SA) useful to understand the influence of various parameters (and used to guide the selection of base case simulation parameters) is also provided at the conclusion of this section. Results are reported for wind and temperatures changes in SIAM and suppression and extreme fire spread parameter testing in SIMPPLLE.

SIAM Ignition Expectation Results

Very few areas with houses will likely face a wildfire between 2004 and 2034, but if there is a fire, under extreme conditions (which seems more and more common) the house will likely burn. The SIAM modeling for the 39 homes visited during the field season reveals that very few residential structures are expected to survive an extreme weather wildfire in their current condition. Table 8 shows that according to SIAM modeling of existing conditions only three of the 39 structures modeled has any chance of survival. These results in Table 8 are broken down using a siding flammability classification, and are based on the assumption that the maximum ignition probability of any of four sides is assigned to each home. Note that all homes with flammable siding have a 1.0 probability of ignition and only three of the six houses with fire-resistant siding have an estimated ignition probability less than 1.0. It is noteworthy that although flammable siding does not automatically lead to a 1.0 probability of ignition, all of the homes with an aggregate ignition probability less than 1.0 have non-flammable siding. The average for these homes is 0.966, illustrating that non-flammable siding alone will not suffice to keep all model results below a 1.0 ignition probability in SIAM. The fuels present in the HIZ as well as the firebranding and nook and cranny scores all influence the ignition probability estimates.

Extrapolated SIAM results

When visited homes are classified based on cadastral information describing roof and siding ignitability, the database is found to be 100 percent correct for roofs and 97%[34] correct for siding. The very close correlation between the proportion of the 39 visited homes found to have flammable siding (85%) during visits and proportion of the 252 remaining homes in the siding ignitability classes indicates that although the sample is not random it is representative of the population of WUI structures in the study area. When the average for each siding class (Flammable = 1.0, Non-flammable = 0.966, and unknown = 0.994) is applied, the average ignition expectation for the 291 homes is 0.994. Now that the results from SIAM have been reported, the fire probabilities from SIMPPLLE complete the ignition hazard estimation picture.

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[34] The percentage correct is determined by dividing the number of correct assignments of visited homes by the number of total assignments of visited home to either the flammable or non-ignitable class. There were 37 of 38 classifications made correctly, there was one visited house classified as unknown.

Table 8. Existing ignition probabilities for 39 modeled houses, divided into flammable and non-ignitable siding.

Siding Type	Structure	Existing Ignition Probability
Flammable	DW02	1.0
Flammable	DW03	1.0
Flammable	DW04	1.0
Flammable	DW05	1.0
Flammable	DW06	1.0
Flammable	DW07	1.0
Flammable	DW08	1.0
Flammable	DW09	1.0
Flammable	DW10	1.0
Flammable	DW11	1.0
Flammable	DW12	1.0
Flammable	DW14	1.0
Flammable	DW15	1.0
Flammable	DW17	1.0
Flammable	DW18	1.0
Flammable	DW20	1.0
Flammable	DW21	1.0
Flammable	DW22	1.0
Flammable	DW25	1.0
Flammable	DW26	1.0
Flammable	DW27	1.0
Flammable	DW28	1.0
Flammable	DW29	1.0
Flammable	DW30	1.0
Flammable	DW31	1.0
Flammable	DW32	1.0
Flammable	DW33	1.0
Flammable	DW34	1.0
Flammable	DW35	1.0
Flammable	DW37	1.0
Flammable	DW38	1.0
Flammable	DW40	1.0
minimum		1.0
maximum		1.0
median		1.0
mean		1.0
Siding Type	**Structure**	**Existing Ignition Probability**
Non ignitable	DW23	0.814
Non ignitable	DW16	0.95
Non ignitable	DW01	0.996
Non ignitable	DW13	1.0
Non ignitable	DW24	1.0
Non ignitable	DW36	1.0
Non ignitable	DW39	1.0
minimum		0.814
maximum		1.000
median		1.000
mean		0.966

SIMPPLLE Wildfire Probability Results

The probability that polygons hosting study area houses will experience wildfire during the period 2005-2034 is extremely low according to SIMPPLLE simulation modeling. Table 9 shows summary statistics for total wildfire probabilities for each of the 243 vegetative communities hosting 291 WUI residential structures in the study area. Total 30-year fire probability ranges from 0.0 to 0.0496 for these stands. The average three-decade conditional fire probability for these stands is 0.00486.

Table 9. Wildfire probability summary statistics for the polygons hosting the 291 study area homes.

Statistic	30-Year Wildfire Probability
Minimum	0.00
Maximum	0.0496
Median	0.00
Mean	0.00486
p = 0.0	201 residences

There are clearly many areas that have very little existing 30-year fire hazard in the SIMPPLLE analysis area. There are 254 houses in zero probability polygons for the first decade, 256 for the second decade, and 255 for the third decade. Based on the fire events in each of the 100 simulations, a zero probability occurs for 201 of the 291 houses for the full 30-year period. Some of these areas are water and rock. We know that the probability of an ignition happening in any given polygon can be very low. Most of the fire that occurs will come from the few large fires that escape suppression and spread across the landscape. While a zero probability of wildfire in the next 30 years may not be realistic for polygons with vegetation, some polygons have combinations of vegetative attributes, and geographic and elevation positions relative to their neighbors that resist fire spreading from upwind and which allow effective suppression. The fire probability is essentially zero in many of these polygons.

Table 10 reports the distribution of fires by severity class and decade from the existing hazard SIMPPLLE results using the number of fires[35]. The numbers in the table represent the average number of the total fires in the 1,361 acre area of polygons hosting the 291 WUI homes. It is clear that the number of fires is rather evenly distributed across the three decades and comprised mainly (70.2%) of mixed severity fire (MSF) with smaller amounts of light severity fire (LSF) and stand replacement fire (SRF).

The average number of acres that burn for the 100 simulations in the host polygon (1,361 acres) is 2.7 acres during the first decade, 3.0 acres during the second and 2.5 acres during the third decade for a total average of 8.2 acres for the 30-year period. For any of the 100 simulations a minimum of 0 acres and a maximum 74 acres (5.4% of this area) burn during the 30-year period in the polygons hosting structures.

Table 10. Fire distribution by severity class and decade for the residential host polygons 2004-2034.

Timing	Decade 1	Decade 2	Decade 3
	34.9%	30.1%	35.0%
Severity	Light	Mixed	Stand Replacing
	14.0%	70.2%	15.9%

The wildfire probabilities for host polygons are also on the low end of the results for all the polygons in the SIMPPLLE analysis area. Across the entire 381,361-acre SIMPPLLE analysis area, the range of three-decade wildfire probability (0.0 to 0.287) is greater than

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[35] The amount of fire probability is calculated by using the number of times fires of each severity class occurs in each of three decades of the simulation. This differs from the average acres burned across the 100 simulations which is area based.

that of only those polygons hosting study area homes. This may be explained by the larger number of polygons in the entire analysis area, the increased combinations of vegetative, topographic and geographic configurations of polygons, the polygons with steep slopes not hosting houses, or the lack of silvicultural treatments in wilderness area polygons during the last ten years. The average number of fire events and acres that burn in the total SIMPPLLE analysis area during the 100 simulations are also displayed below in Table 11. The balance across the decades in both the number of events and the acreage burned is likely as much an artifact of the averaging across 100 simulations as an important finding in itself. Figure 15 uses shades of orange to shows the range of conditional fire probability across the SIMPPLLE study area. The darker the orange color, the higher the probability of fire is during the next 30 years according to 100 SIMPPLLE simulations. Blue polygons represent zero probability. Study area homes are intentionally not shown to protect participant confidentiality.

Table 11. The average number of fire events and acres that burn in the total SIMPPLLE analysis area (381,361 acres) during the 100 simulations

Decade	Events	Acres of Fire (%)
1	243	1,628 (0.004%)
2	240	1,574 (0.004%)
3	202	1,547 (0.004%)
Total	685	4,749 (0.012%)

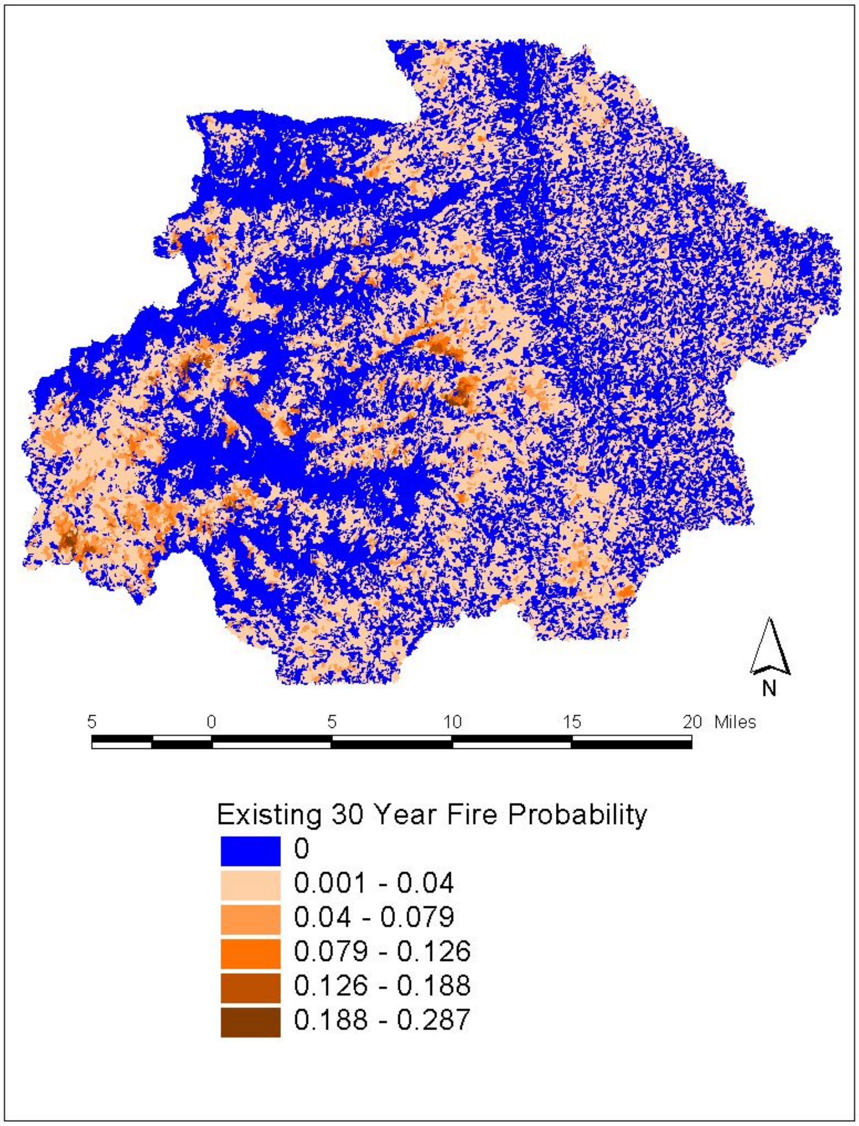

Figure 15. The fire probability across the SIMPPLLE analysis area, 2004-2034.

<u>Combined Modeling System Results</u>

Both the average and the maximum combined 30-year structure ignition hazard estimates for the 291 WUI structures are low. The key finding in this part of the chapter is that the combined modeling system suggests that the 291 study area WUI structures have an average probability of 0.00484 that fire will encounter and ignite them between 2005 and 2034. These results represent the existing hazard estimate box below the Objective 1 column in Figure 1. Table 12 provides modeling system summary statistics to convey the existing wildfire structure ignition expectations for the 291 structures in the study area.

Due to the need to protect the participant confidentiality maps of the results are intentionally not provided.

Table 12. Existing ignition expectations for the 291 study area residences, 2004-2034

Statistic	Existing Hazard Estimate
Minimum	0.00
Maximum	0.0486
Median	0.00
Mean	0.00484
Expected Home Loss (2005-2034)	1.408
p = 0.0	201 residences

Multiplying the number of study area homes with the average 30-year ignition hazard estimate (found in Table 12) generates an expected loss to wildfire result of 1.41 homes between 2005 and 2034. This indicates that the existing hazard estimation system predicts that very few study area homes will be destroyed by wildfire.

Because the SIAM results are so close to a probability of 1.0 the combined existing hazard is nearly a mirror image of the SIMPPLLE results. The number of structures with a zero probability of ignition (the minimum) comprises roughly 69 percent of the residences. Both the number of houses with a zero probability and the difference between the average and median results indicate that the distribution is extremely right skewed (Figure 16). The maximum probability for any home in this area for the period 2004-2034 is 0.0476. These results all indicate that the probability of any house being destroyed by a stochastic event like wildfire is rare.

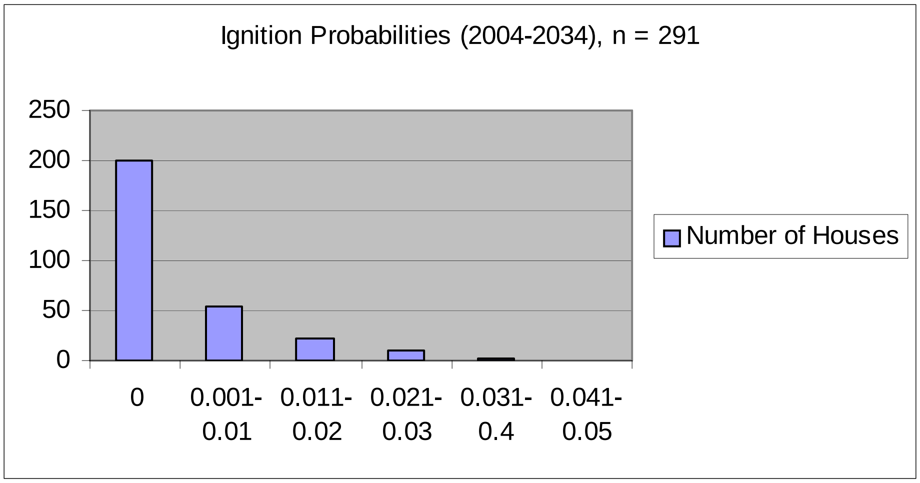

Figure 16. The number of houses in each existing hazard probability class.

These existing hazard results provide the starting point for part II of the dissertation, the modeling of mitigation options and their relative cost effectiveness. However, before describing the mitigation modeling methods it is important to describe several key results from parameter sensitivity for each modeling tool. The remainder of the sensitivity analysis documentation can be found in Appendix C.

SIAM sensitivity analysis results

Changing temperature alone has no impact at all on overall structure ignition probabilities. Wind speed selection influences both the nook and cranny impacts and overall ignition probabilities, with probability changing thresholds varying between sides of each structure, but all occurring below the 20 mph SIAM default wind speed. Figure 17 shows probability changing thresholds for the five randomly selected homes, with wind speeds affecting overall SIAM ignition estimates (SO) in green triangles and those affecting the nook and cranny ignition probabilities (NC) below with blue diamonds. All of these wind speed thresholds are below the 20MPH default setting for SIAM.

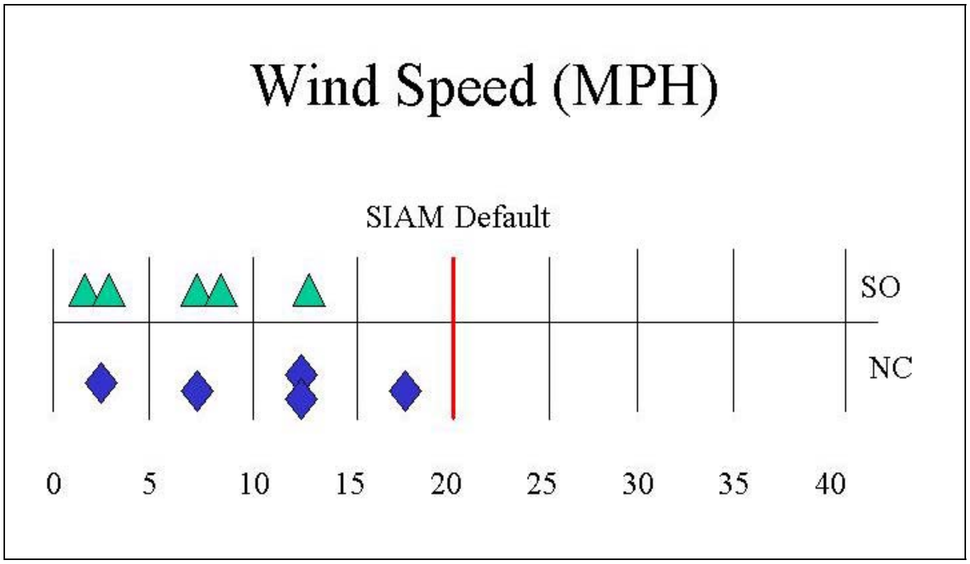

Figure 17. Nook and Cranny (NC) and SIAM (SO) wind speed probability thresholds.

Results from the SA show that the default settings are indeed on the extreme end of the analysis spectrum. When combinations are tested against the default conditions, lower temperature (80F) combined with lower wind speeds reduce the ignition expectations, whereas higher temperature (100F) combined with higher wind speeds do not increase ignition expectations beyond those at default levels. In summary, the default SIAM weather conditions appear to provide the upper limit of home ignition probabilities.

<u>SIMPPLLE Sensitivity Analysis Results</u>

The most important SIMPPLLE parameter for the modeling system is the selection of suppression. Table 13 shows summary statistics of the modeling system results when suppression is turned off. The distribution of existing hazard estimates are clearly much higher than results obtained when modeling with suppression. The maximum and average probabilities are roughly seven and sixteen times, respectively, as high as those estimated when modeling with active suppression. The expected house loss figure increases from 1.41 to 22.4. The median probability is also much higher at 0.03, and the number of houses with zero probability is much lower than the non-suppression modeling results for the 30-year period. This demonstrates how important suppression is in SIMPPLLE for modeling system estimates of existing hazard.

Table 13. Existing ignition expectations for the 291 study area residences, 2004-2034, modeled without suppression.

Statistic	Existing Hazard Estimate
Minimum	0.00
Maximum	0.37
Median	0.03
Mean	0.077
Expected Home Loss (2005-2034)	22.4
p = 0.0	63 residences

The second most potent parameter in SIMPPLLE's fire logic is the probability that any given fire[36] spreads with extreme wind conditions (conceptualized by model designers as spreading with increased downhill contagion ability). The full range of this parameter is tested, with 1-percentile changes between 0.01 and 0.1 and ten percentile changes between 0.1 and 1.0. The three-decade range of mean total fire area for this parameter is 119,051 – 339,922 ac. (Figure 18) and 102 – 1361 ac. (Figure 19) for the total area and residential host polygon areas, respectively. These ranges correspond to ranges of 31 - 89% and 7 – 100% for these two areas. It is clear that the two modeling tools used to estimate existing fire hazard are very sensitive to several key parameters.

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[36] Note that all fires, which grow to 1,000 acres, are also assumed in SIMPPLLE simulations to spread across the landscape with extreme wind conditions.

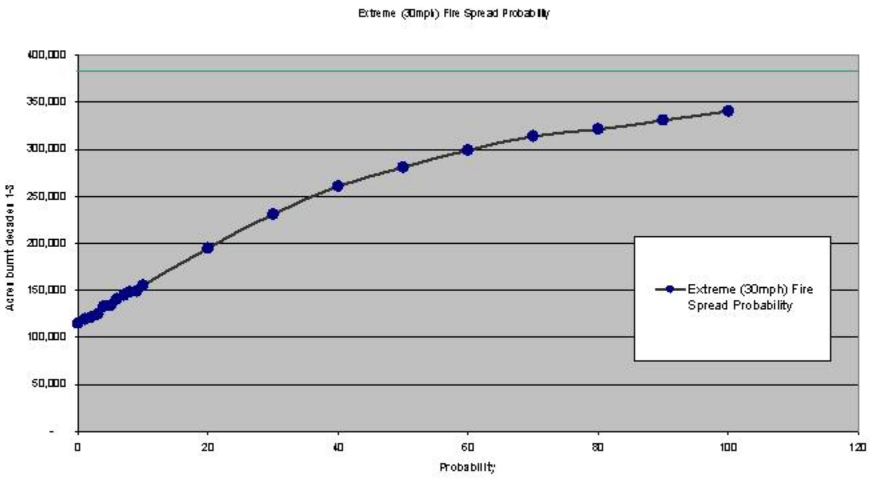


Figure 18. Extreme fire spread parameter sensitivity in total modeling area.

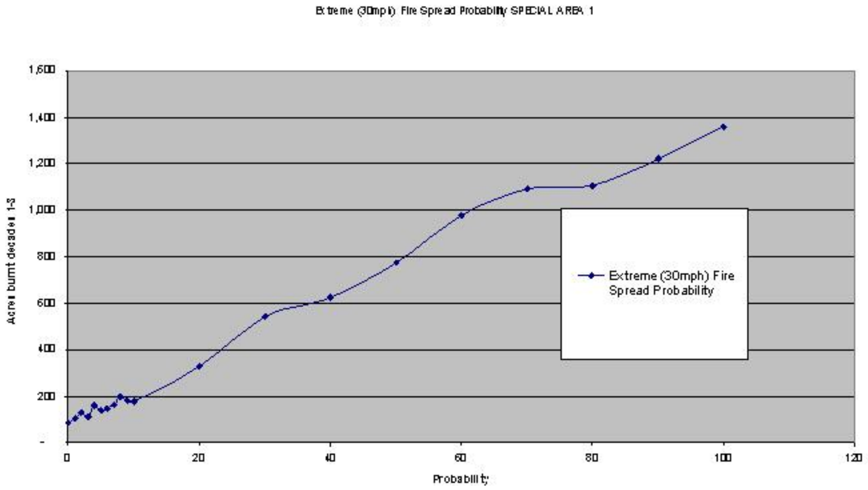


Figure 19. Extreme fire spread parameter sensitivity in polygons hosting residences. Collectively these two sensitivity analyses point to the need to consider and discuss the implications of modeling assumptions and this is done in the next chapter.

Objective 2: HIZ Mitigations

The following two groups of HIZ mitigations results comprise the cost estimate and effectiveness estimation boxes in the upper path (Mitigation Suite A) of the Figure 1 flowchart. Cost estimation results for each HIZ mitigation option are detailed first. Next, structure ignition reduction results are shown for just the houses modeled. Then the impacts on the average probability for the 39 visited houses, and on the average hazard across the 291 structures are provided (when these mitigations are extrapolated to the remaining 252 study area WUI structures and multiplied with the probability that fire will reach the polygon hosting each house in the next 30 years). Together they form one of the two sets of results needed as the basis of comparison for study objective 4, cost effectiveness analysis, which is found later in this chapter.

Cost Estimation Results

The cost estimates for mitigation efforts modeled for the 291 structures in this research ranged from $184,080 to $5,604,048. Table 14 shows the number of houses in the study area estimated to have each option as well as total and average costs for the various HIZ options at these houses.

Building Improvements

The first mitigation option is upgrading windows at a cost estimate of $184,080. This averages $3,609 for each of the 51 houses estimated to have this option. The estimated costs to replace siding with a nonflammable alternative are much higher for these 246 houses. When the average of $8,670 per house is aggregated, a mitigation cost of $2,135,048 is estimated. Option C, which is upgrade of windows at seven houses and siding replacement at 33 houses has an estimated cost of $2,319,128, averaging $9,427 per house).

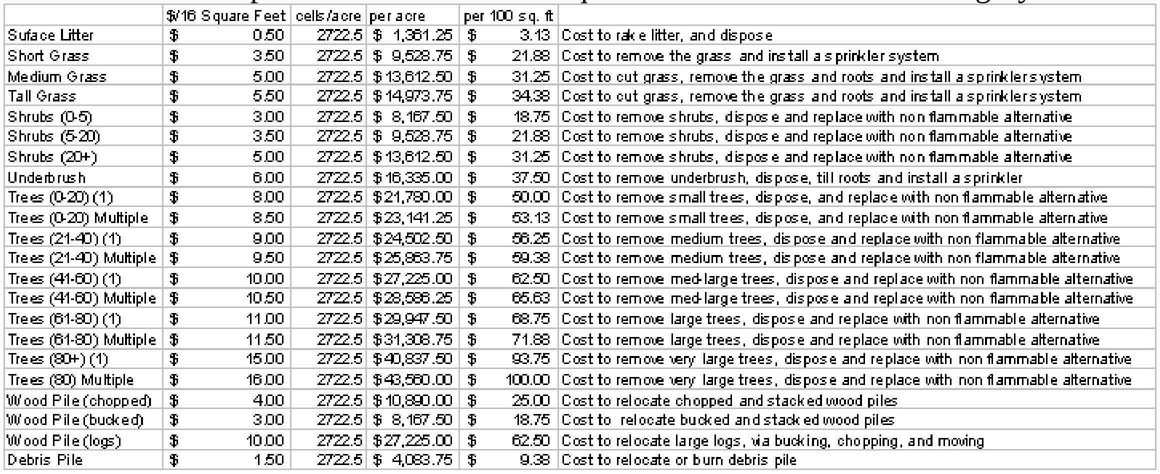
Table 14. HIZ mitigation option costs

	Number of house with option of 291	Cost per Option ($Million) 2006 Dollars
A. Window Upgrades	51	0.184080 (average is $3,609/house)
B. Siding Replacement	246	2.135048 (average is $8,670/house)
C. Windows and Siding	246	2.319128 (average is $9,427/house)
D. Light Fuels Conversion	269	1.235075 (average is $4,591/house)
E. Light Fuels and Siding	224	3.370123 (average is $15,045/house)
F. Full Fuels Conversion	291	3.284920 (average is $11,288/house)
G. Full Fuels plus Siding and/or Windows	291	5.604048 (average is $19,258/house)

HIZ Fuel Conversions

Table 15 provides the cost estimates to covert each cell, 100 square feet, and one acre of the 22 HIZ fuel types with either a light fuels or full fuels conversion. Next, Table 16 displays the estimated costs by fuel type removed and replaced for the two conversion options at each side and as a total for each of the 39 visited houses by multiplying the number of cells in each fuel category with the estimated costs for each structure's four sides. Overall study area cost estimates appear in the bottom of the table for light and full conversion options. The light fuels removal is estimated to cost $1,235,075 with an average of $4,591 for each house. The full fuels conversion option is estimated to cost $3,284, 920, with an average cost of $11,288 per house.

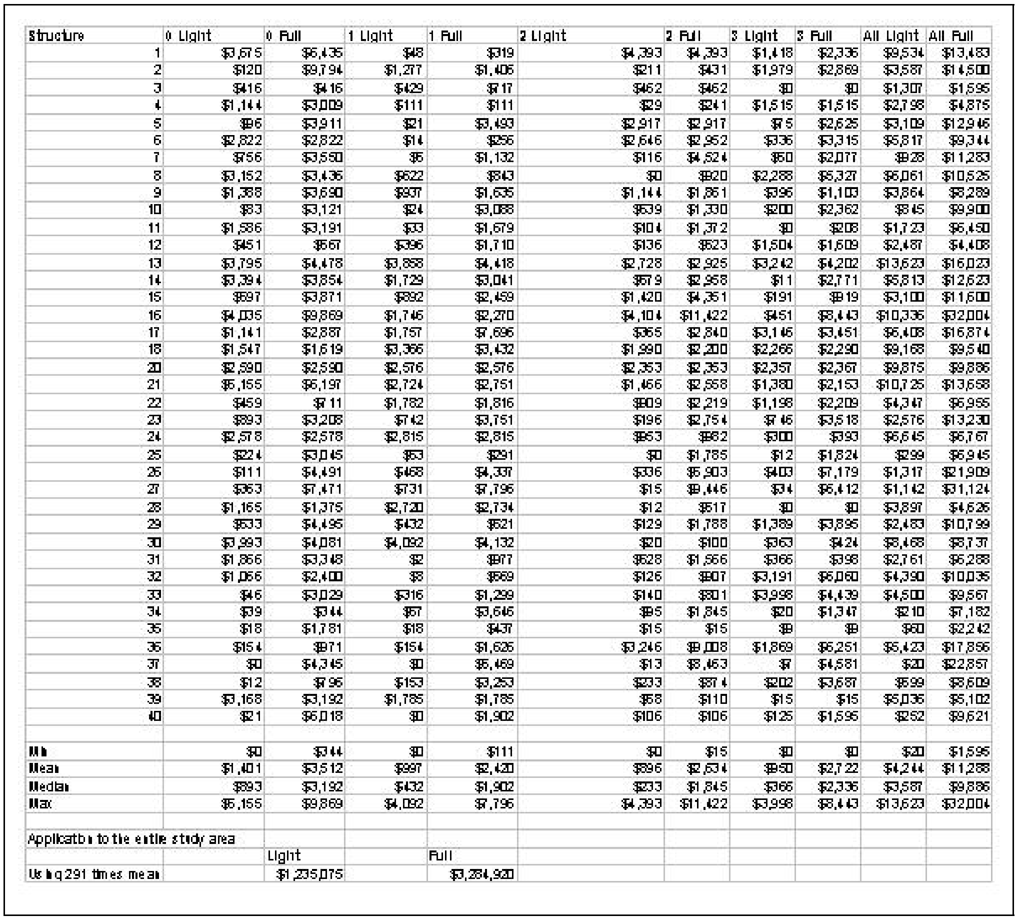
Table 15. The cost per acre to convert a 16 square foot cell of each fuel category.



	$/16 Square Feet	cells/acre	per acre	per 100 sq. ft	
Suface Litter	$ 0.50	2722.5	$ 1,361.25	$ 3.13	Cost to rake litter, and dispose
Short Grass	$ 3.50	2722.5	$ 9,528.75	$ 21.88	Cost to remove the grass and install a sprinkler system
Medium Grass	$ 5.00	2722.5	$ 13,612.50	$ 31.25	Cost to cut grass, remove the grass and roots and install a sprinklers system
Tall Grass	$ 5.50	2722.5	$ 14,973.75	$ 34.38	Cost to cut grass, remove the grass and roots and install a sprinklers system
Shrubs (0-5)	$ 3.00	2722.5	$ 8,167.50	$ 18.75	Cost to remove shrubs, dispose and replace with non flammable alternative
Shrubs (5-20)	$ 3.50	2722.5	$ 9,528.75	$ 21.88	Cost to remove shrubs, dispose and replace with non flammable alternative
Shrubs (20+)	$ 5.00	2722.5	$ 13,612.50	$ 31.25	Cost to remove shrubs, dispose and replace with non flammable alternative
Underbrush	$ 6.00	2722.5	$ 16,335.00	$ 37.50	Cost to remove underbrush, dispose, till roots and install a sprinkler
Trees (0-20) (1)	$ 8.00	2722.5	$ 21,780.00	$ 50.00	Cost to remove small trees, dispose, and replace with non flammable alternative
Trees (0-20) Multiple	$ 8.50	2722.5	$ 23,141.25	$ 53.13	Cost to remove small trees, dispose, and replace with non flammable alternative
Trees (21-40) (1)	$ 9.00	2722.5	$ 24,502.50	$ 56.25	Cost to remove medium trees, dispose and replace with non flammable alternative
Trees (21-40) Multiple	$ 9.50	2722.5	$ 25,863.75	$ 59.38	Cost to remove medium trees, dispose and replace with non flammable alternative
Trees (41-60) (1)	$ 10.00	2722.5	$ 27,225.00	$ 62.50	Cost to remove med-large trees, dispose and replace with non flammable alternative
Trees (41-60) Multiple	$ 10.50	2722.5	$ 28,586.25	$ 65.63	Cost to remove med-large trees, dispose and replace with non flammable alternative
Trees (61-80) (1)	$ 11.00	2722.5	$ 29,947.50	$ 68.75	Cost to remove large trees, dispose and replace with non flammable alternative
Trees (61-80) Multiple	$ 11.50	2722.5	$ 31,308.75	$ 71.88	Cost to remove large trees, dispose and replace with non flammable alternative
Trees (80+) (1)	$ 15.00	2722.5	$ 40,837.50	$ 93.75	Cost to remove very large trees, dispose and replace with non flammable alternative
Trees (80) Multiple	$ 16.00	2722.5	$ 43,560.00	$ 100.00	Cost to remove very large trees, dispose and replace with non flammable alternative
Wood Pile (chopped)	$ 4.00	2722.5	$ 10,890.00	$ 25.00	Cost to relocate chopped and stacked wood piles
Wood Pile (bucked)	$ 3.00	2722.5	$ 8,167.50	$ 18.75	Cost to relocate bucked and stacked wood piles
Wood Pile (logs)	$ 10.00	2722.5	$ 27,225.00	$ 62.50	Cost to relocate large logs, via bucking, chopping, and moving
Debris Pile	$ 1.50	2722.5	$ 4,083.75	$ 9.38	Cost to relocate or burn debris pile

There are also two combinations of building improvements and HIZ fuel conversion mitigations, options E and G. The light fuels conversion and siding replacement option (E) cost estimate of $3,370,123 is the sum of the siding replacement estimate ($2,135,048) and the light fuels conversion cost estimate ($1,235,075). This mitigation option averages $15,045 per house. The full fuels conversion and full building upgrade estimate of $5,604,048 is the sum of the window upgrades at seven houses ($184,080), the siding replacement at 33 houses ($2,135,048) and the full fuels conversion at 39 houses ($3,284,920). This mitigation cost computes to an average cost of $19,258 per house.

Table 16. HIZ Fuel Conversion Cost estimation spreadsheet



Structure	0 Light	0 Full	1 Light	1 Full	2 Light	2 Full	3 Light	3 Full	All Light	All Full
1	$3,675	$6,435	$48	$319	$4,393	$4,393	$1,418	$2,336	$9,534	$13,483
2	$120	$9,794	$1,277	$1,406	$211	$431	$1,979	$2,869	$3,587	$14,500
3	$416	$416	$429	$717	$462	$462	$0	$0	$1,307	$1,595
4	$1,144	$3,009	$111	$111	$29	$241	$1,515	$1,515	$2,798	$4,875
5	$96	$3,911	$21	$3,493	$2,917	$2,917	$75	$2,625	$3,109	$12,946
6	$2,822	$2,822	$14	$256	$2,646	$2,952	$336	$3,315	$5,817	$9,344
7	$756	$3,550	$5	$1,132	$116	$4,524	$50	$2,077	$928	$11,283
8	$3,152	$3,436	$622	$843	$0	$920	$2,288	$5,327	$6,061	$10,525
9	$1,388	$3,690	$937	$1,635	$1,144	$1,861	$396	$1,103	$3,864	$8,289
10	$83	$3,121	$24	$3,088	$639	$1,330	$200	$2,362	$845	$9,900
11	$1,586	$3,191	$33	$1,679	$104	$1,372	$0	$208	$1,723	$6,450
12	$451	$567	$396	$1,710	$136	$523	$1,504	$1,609	$2,487	$4,408
13	$3,795	$4,478	$3,858	$4,418	$2,728	$2,925	$3,242	$4,202	$13,623	$16,023
14	$3,394	$3,854	$1,729	$3,041	$679	$2,958	$11	$2,771	$5,813	$12,623
15	$597	$3,871	$892	$2,459	$1,420	$4,351	$191	$919	$3,100	$11,600
16	$4,035	$9,869	$1,746	$2,270	$4,104	$11,422	$451	$8,443	$10,336	$32,004
17	$1,141	$2,887	$1,757	$7,696	$365	$2,840	$3,146	$3,451	$6,408	$16,874
18	$1,547	$1,619	$3,366	$3,432	$1,990	$2,200	$2,266	$2,290	$9,168	$9,540
20	$2,590	$2,590	$2,576	$2,576	$2,353	$2,353	$2,357	$2,367	$9,875	$9,886
21	$5,155	$6,197	$2,724	$2,751	$1,466	$2,558	$1,380	$2,153	$10,725	$13,658
22	$459	$711	$1,782	$1,816	$809	$2,219	$1,198	$2,209	$4,347	$6,955
23	$893	$3,208	$742	$3,751	$196	$2,754	$746	$3,518	$2,576	$13,230
24	$2,578	$2,578	$2,815	$2,815	$853	$882	$300	$393	$6,645	$6,767
25	$224	$3,045	$53	$291	$0	$1,785	$12	$1,824	$299	$6,945
26	$111	$4,491	$468	$4,337	$336	$5,903	$403	$7,179	$1,317	$21,909
27	$363	$7,471	$731	$7,796	$15	$9,446	$34	$6,412	$1,142	$31,124
28	$1,165	$1,375	$2,720	$2,734	$12	$517	$0	$0	$3,897	$4,626
29	$533	$4,495	$432	$521	$129	$1,788	$1,389	$3,895	$2,483	$10,799
30	$3,993	$4,081	$4,092	$4,132	$20	$100	$363	$424	$8,468	$8,737
31	$1,866	$3,348	$2	$977	$528	$1,566	$366	$398	$2,761	$6,288
32	$1,066	$2,400	$8	$569	$126	$907	$3,191	$6,060	$4,390	$10,035
33	$46	$3,029	$316	$1,299	$140	$801	$3,998	$4,439	$4,500	$9,567
34	$39	$344	$57	$3,646	$95	$1,845	$20	$1,347	$210	$7,182
35	$18	$1,781	$18	$437	$15	$15	$9	$9	$60	$2,242
36	$154	$971	$154	$1,626	$3,246	$9,008	$1,869	$6,251	$5,423	$17,856
37	$0	$4,345	$0	$5,469	$13	$8,463	$7	$4,581	$20	$22,857
38	$12	$796	$153	$3,253	$233	$874	$202	$3,687	$599	$8,609
39	$3,168	$3,192	$1,785	$1,785	$58	$110	$15	$15	$5,036	$5,102
40	$21	$6,018	$0	$1,902	$106	$106	$125	$1,595	$252	$9,621
Min	$0	$344	$0	$111	$0	$15	$0	$0	$20	$1,595
Mean	$1,401	$3,512	$997	$2,420	$896	$2,634	$950	$2,722	$4,244	$11,288
Median	$893	$3,192	$432	$1,902	$233	$1,845	$366	$2,336	$3,587	$9,886
Max	$5,155	$9,869	$4,092	$7,796	$4,393	$11,422	$3,998	$8,443	$13,623	$32,004
Application to the entire study area										
		Light		Full						
Using 291 times mean		$1,235,075		$3,284,920						

HIZ Mitigation Effectiveness Results

Home ignition zone mitigations are both effective at reducing the existing structure ignition probabilities and somewhat linearly correlated with investment levels. The full HIZ fuel conversion option is much more effective than either the light conversion or any of the building improvements. The SIAM mitigation effectiveness results are presented in Table 17, which shows the results for all seven HIZ mitigation options. The first column shows how many of the visited houses have this mitigation option. The next column shows the average SIAM ignition probability only for the houses that are modeled with a given mitigation both before and after the mitigation. Then the reduced average for the 39 visited houses following application of each HIZ mitigation option is shown in the next column. Finally, the impact that this type of mitigation has on the combined modeling system average 30-year ignition hazard is shown for the entire set of 291 study area homes. Note how the mitigated average existing 30-year ignition hazard decreases from 0.00484 all the way down to 0.0018 with various HIZ mitigation options.

Building improvement results

Few of the houses visited are old enough to have single pane windows. There are a total of seven of the 39 visited structures with an opportunity to replace single pane windows, and of these two actually had fiberglass windows. This is roughly eighteen percent of visited homes. When the percentage observed in fieldwork is applied to the 291 study area homes, roughly 51 of the 291 homes have this option. When these windows are upgraded in modeling runs no change in home ignitability is observed at any of the seven houses. As a result, there is no change in the average SIAM ignition probability for the 39 visited homes; it remains at 0.994. This may be a problem with the software or simply a reflection that these structures are modeled as having easier ignition vectors. There is no estimated effectiveness (not changing from 0.00484), which is defined as the reduction in the average existing ignition probability for the 291 homes.

Table 17. Average ignition probabilities and mitigated hazard estimates by mitigation options.

	Number of Houses with option	Average for houses with option (following mitigation)	Average for all 39 visited structures following mitigation	Mitigated average for 291 homes (effectiveness)
Existing Average	NA	0.994	NA	0.00484
A. Window Upgrade	7	1.000 (1.000)	0.994	0.00484 (0.0%)
B. Siding replacement	33	0.962 (0.921)	0.928	0.0045 (-6.3%)
C. Windows and Siding	33	0.962 (0.921)	0.928	0.0045 (-6.3%)
D. Light Fuels	36	0.993 (0.890)	.0883	0.0044 (-8.3%)
E. Light Fuels and Siding	30	1.000 (0.773)	.0786	0.0038 (-20.8%)
F. Full Fuels Conversion	39	0.994 (0.360)	.0361	0.0018 (-62.5%)
G. Full Fuels Plus Siding and/or windows	33	1.000 (0.375)	0.361	0.0018 (-62.5%)

Siding replacement provides much more abundant opportunities across the study area, yet there is little reduction in ignition probabilities observed following these building improvements. There are 33 of 39 visited homes in the study area that have at least some flammable siding (85%). When this proportion is applied to the study area the result is that roughly 246 homes could have flammable siding replaced with non-ignitable siding. This number compares very closely to the number of structures found to have ignitable siding based on the Montana Cadastral Mapping Project database. Results from a classification of homes based on siding found that only 17 percent of the 291 study area structures have non-ignitable siding. The remaining 83 percent are either flammable or unknown. The average ignition probability for the 33 homes that can have siding replaced falls from 0.962 to 0.921. When existing flammable siding is replaced in the modeling for all visited structures the average ignition probability for all 39 visited structures decreases from 0.994 to 0.928. Part of the reason is that probabilities fall below 1.0 for nineteen, roughly half, of the 36 houses. The most substantial reduction is from

1.0 down to 0.416. When these results are extrapolated to the larger set of 291 houses the average mitigated hazard is 0.0045, a 7.0 percent reduction in hazard.

The combination of siding replacement and windows is possible at only the same 33 structures that have siding as an option. Seven of these 33 also have a window upgrade option. The average ignition probability for these 33 houses falls from 1.0 to 0.921. There is no reduction in ignition probabilities beyond that achievable by replacing siding alone for these 33 houses. When these changes are made to the 33 houses with this option the average probability for all 39 visited structures remains at 0.928. The SIAM modeling results reveal that no added effectiveness results from adding window upgrades to siding replacement and the resulting average mitigated hazard is the same as siding replacement alone, 0.0045, or a 7.0 percent reduction from the average existing hazard of 291 homes. This may suggest that windows are not being modeled properly with the current version of the software. Because it is not clear whether windows are being modeled properly or if other ignition vectors are dominant, this option is retained and included in the cost effectiveness analysis.

HIZ light and full fuel conversion mitigations

The HIZ fuel conversion options have stronger impacts on the SIAM modeling results than structure mitigations. There are 36 of 39 visited structures that could have a light fuels conversion applied inside the HIZ. The remaining three houses do not have any dry grasses or shrubs that could be removed and replaced. This proportion (36 of 39) represents about 92 percent of the visited homes and converts to roughly 269 of the 291 study area structures having this option. When the light fuels conversion is applied to the

HIZ at 36 structures, the average ignition probability for these structures decreases from 0.993 to 0.890; this is roughly a ten percent reduction in the average ignition potential estimate for these homes. The average for the 39 visited structures falls from 0.994 to 0.898, also decreasing roughly ten percent. When this type of mitigation is applied to all 291 homes the reduction is from an average of 0.0048 to 0.0044, or an 8.3% reduction. These results indicate that a light HIZ fuels conversion does not remove the bulk of the ignition potential at most houses.

The full fuels conversion option is extremely effective at reducing ignition probabilities across the study area. Removing or replacing all fuels in a structure's HIZ, is an option for all 39 visited houses and would likely be an option at nearly all of the 291 study area structures. The exception would be any of the 252 unvisited structures that are surrounded by 100 feet in all directions with non-flammable materials such as gravel, asphalt, dirt, or completely green (nonflammable) vegetation. As a stand alone HIZ mitigation option full fuels conversion is the most effective. When the full fuels conversion is applied to the HIZ at 39 structures, the average ignition probability decreases from 0.994 to 0.360; this is more than a sixty-three percent reduction in ignition potential estimate. When this type of mitigation is applied to all 291 homes the hazard reduction is from 0.00484 to 0.00179, or a 63.0 % reduction.

Combinations of structure and fuel mitigations

The HIZ combination treatments vary in their effectiveness. While the combination of siding upgrades and light fuels conversions is more effective than either of its components alone, the addition of building upgrades to the full fuels conversion generates no added effectiveness. The light fuels conversion and siding replacement is an option at 30 of the 39 structures (76.9%). This computes to approximately 224 of the 291 structures. The average ignition probability for the 30 houses where this mitigation combination is applied decreases from 1.0 to 0.773, a 23 percent reduction. The reduction across all 39 visited homes is from 0.994 to 0.786, a 21 percent reduction. When this mitigation combination is applied, ignition probability estimates are lower than light fuels conversion alone for 18 of the 30 modeled structures and lower than the siding option alone for 14 of the 30 structures modeled. The mitigated average ignition hazard across the 291 structures decreases from 0.00484 to 0.00388; this is a 20.9 percent reduction. The reduction in average ignition probability achieved by this combination is greater than that achieved by either the siding replacement or light fuels options alone.

The full fuels conversion, with siding replacement (and widow replacement when available) is an option at 33 of the 39 structures (85%). This computes to approximately 246 of the 291 structures. When this mitigation is applied the average ignition probability at these 33 houses decreases from 1.0 to 0.375, a 62.5 percent reduction. The average of all 39 visited homes decreases from 0.994 to 0.360, so when this mitigation combination is applied, probability estimates are no lower than for full fuels removal/replacement alone. However, the combination estimates are lower than the siding option alone for all 33 modeled structures. The average ignition probability across all 291 structures decreases from 0.00484 to 0.00179, and while this is a 63 percent reduction in ignition probability estimates, it is no lower than the full fuels replacement alone. One might expect that removing all fuels would achieve the lowest possible ignition probability for a structure, but there is also the impact of firebranding on ignition potential estimates to consider for each structure. With that said, changing the siding and or windows when possible does not lower the ignition estimates farther that what is achievable by converting all fuels in the HIZ. These findings suggest that in this study area, getting rid of all brush and fuels and converting this to watered lawn and non-flammable substitutes is just as effective as performing this conversion and replacing siding with a non-flammable alternative.

Objective 3: Silvicultural Wildland Treatments (MAGIS) Results

Cost estimates for the five treatment regimes and the effectiveness results from application of MAGIS treatment schedules to SIMPPLLE simulations are presented next. These silvicultural mitigation results represent two boxes in the lower path (Mitigation Suite B) of the Figure 1 flowchart. The details of each schedule are shown in a series of tables and then the results from each mitigation schedule are reported based on how the average fire probabilities from 100 new SIMPPLLE simulations, applying each schedule, affect the SIMPPLLE and combined modeling system results. Like the results above for Suite A, together they form one of the two sets of results needed as the basis of comparison study objective 4, cost effectiveness analysis, which is located below.

Silvicultural Wildland Treatment Cost Estimates

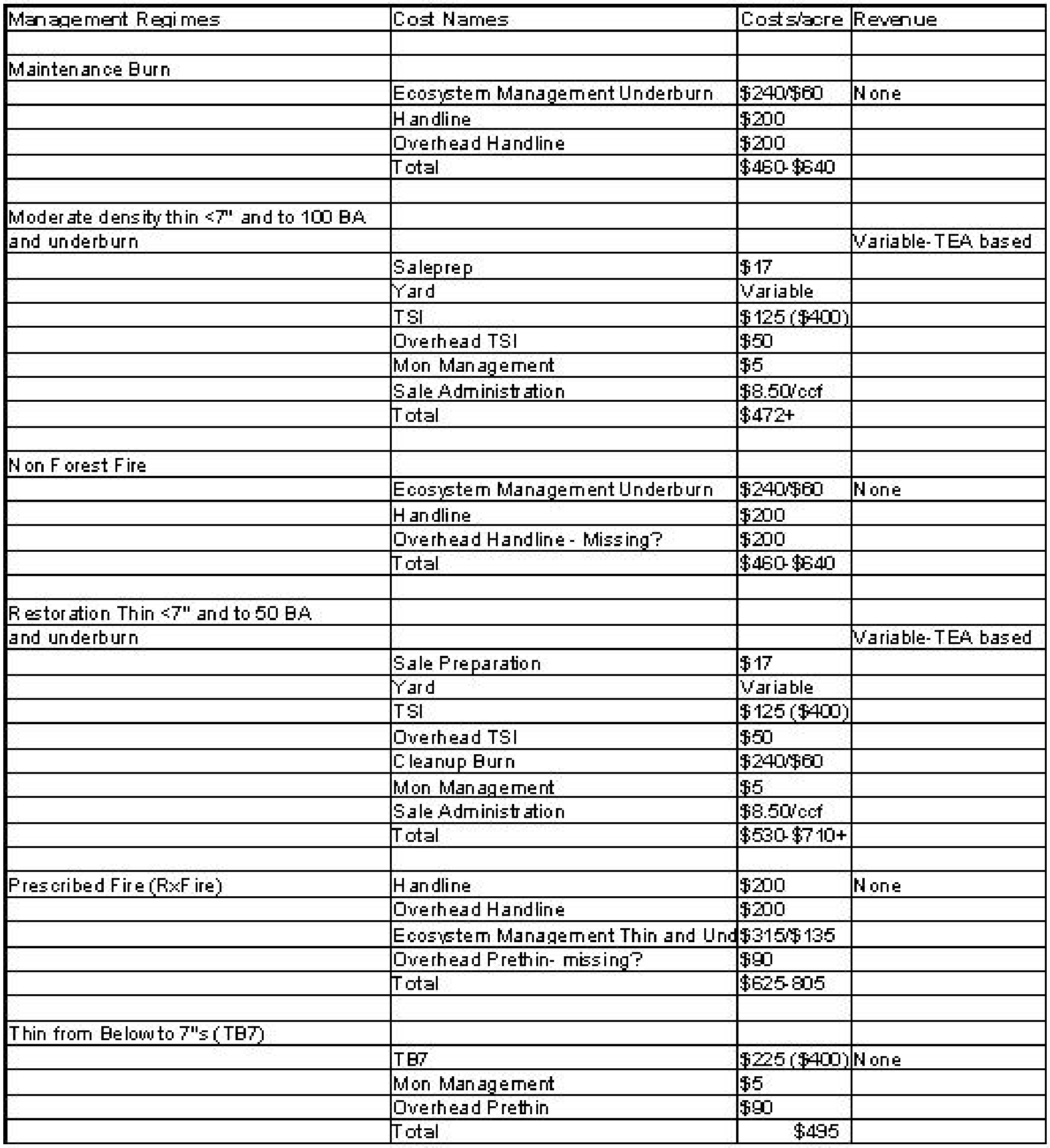
The costs per acre to apply each of the treatment regimes vary based on several stand characteristics including: steepness, logging method, and expected product revenue. The budgets for the seven HIZ mitigation options are used as the cost constraints for seven silvicultural wildland treatment schedules. Table 18 lists the costs and revenues per acre associated with each of the five treatment regimes. Note that the revenues are not listed because they are calculated internally by MAGIS with the transactions evidence appraisal model. The most expensive treatment per acre is prescribed fire alone, costing up to $805/acre.

Silvicultural Wildland Treatment Regime Schedules

The schedules generated by MAGIS are loaded into SIMPPLLE to simulate the implementation of treatment regimes in the next three decades. Tables 19:A-G summarize the schedules generated with MAGIS that correspond to the seven budgets supporting HIZ mitigation options A through G. There are several subtle differences in the schedules that reflect the optimization at different budgets. Note that the total number of acres treated by all regimes does not simply increase linearly with the budgets.

However, the total number of acres treated with the restoration treatment does appear to decline with increasing budgets. Nearly all schedules maximize the acreage of restoration treatment in the first and second period and only as the budget increases does the acreage scheduled for this treatment regime in the third decade decline. This reflects the fact that this restoration treatment regime has the greatest potential to generate net revenue, and although there is a cost associated with the two follow-up burns, costs for the second burn are discounted often leading to net revenue per acre for this treatment regime. Note that in order for the final schedule to reach the budget level comparable to the most costly HIZ mitigation option the total acreage constraint per decade is removed.

Table 18. Cost and revenues associated with the five treatment regimes scheduled by MAGIS.



Management Regimes	Cost Names	Costs/acre	Revenue
Maintenance Burn			
	Ecosystem Management Underburn	$240/$60	None
	Handline	$200	
	Overhead Handline	$200	
	Total	$460-$640	
Moderate density thin <7" and to 100 BA			
and underburn			Variable-TEA based
	Saleprep	$17	
	Yard	Variable	
	TSI	$125 ($400)	
	Overhead TSI	$50	
	Mon Management	$5	
	Sale Administration	$8.50/ccf	
	Total	$472+	
Non Forest Fire			
	Ecosystem Management Underburn	$240/$60	None
	Handline	$200	
	Overhead Handline - Missing?	$200	
	Total	$460-$640	
Restoration Thin <7" and to 50 BA			
and underburn			Variable-TEA based
	Sale Preparation	$17	
	Yard	Variable	
	TSI	$125 ($400)	
	Overhead TSI	$50	
	Cleanup Burn	$240/$60	
	Mon Management	$5	
	Sale Administration	$8.50/ccf	
	Total	$530-$710+	
Prescribed Fire (RxFire)	Handline	$200	None
	Overhead Handline	$200	
	Ecosystem Management Thin and Und	$315/$135	
	Overhead Prethin- missing?	$90	
	Total	$625-805	
Thin from Below to 7"s (TB7)			
	TB7	$225 ($400)	None
	Mon Management	$5	
	Overhead Prethin	$90	
	Total	$495	

Table 19:A-G MAGIS treatment regime schedule acres.

Schedule A. $184,080, Treatment acres by decade (e.g., D1 = Decade 1)

	D1	D 2	D 3	Total
Ecosystem Underburn*[37]	5,234	5,648	3,711	14,594
Moderate Density Thinning	570	192	1,065	1,827
Restoration thinning /burns	1,640	1,640	1,640	4,920
All treatment regimes	5,840	5,840	5,840	16,474

Schedule B. $2,135,048, Treatment acres by decade

	D1	D 2	D 3	Total
Ecosystem Underburn*	5,460	5,573	4,588	15,622
Moderate Density Thinning	358	251	648	1,259
Restoration thinning /burns	1,640	1,640	1,330	4,610
All treatment regimes	5,840	5,840	5,255	16,935

Schedule C. $2,319,128, Treatment acres by decade

	D1	D 2	D 3	Total
Ecosystem Underburn*	5,443	5,590	4,242	15,275
Moderate Density Thinning	372	239	637	1,248
Restoration thinning /burns	1,640	1,640	984	4,264
All treatment regimes	5,840	5,840	4897	16,577

Schedule D. $1,235,075, Treatment acres by decade

	D1	D 2	D 3	Total
Ecosystem Underburn*	5,385	5,648	4,538	15,571
Moderate Density Thinning	419	192	1,065	1,676
Restoration thinning /burns	1,640	1,640	1,640	4,920
All treatment regimes	5,840	5,840	5,621	17,301

Schedule E. $3,370,123, Treatment acres by decade

	D1	D 2	D 3	Total
Ecosystem Underburn*	5,548	5,486	3,569	14,602
Moderate Density Thinning	283	328	896	1,506
Restoration thinning /burns	1,640	1,640	268	3,548
All treatment regimes	5,840	5,840	4,482	16,162

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[37] *This acreage includes burning from the prescribed fire, the thin and underburn and the restoration treatment regimes.

Schedule F. $3,284,920, Treatment acres by decade

	D1	D 2	D 3	Total
Ecosystem Underburn*	5,563	5,470	3,554	14,588
Moderate Density Thinning	268	343	518	1,129
Restoration thinning /burns	1,640	1,640	267	3,547
All treatment regimes	5,840	5,840	4,091	15,771

Schedule G38. $5,604,048 Treatment acres by decade

	D1	D 2	D 3	Total
Ecosystem Underburn*	10,866	1,646	1,925	14,437
Moderate Density Thinning	1,065	156	134	1,355
Restoration thinning /burns	1,640	892	40	2,572
All treatment regimes	11,973	1,801	2,072	15,845

MAGIS / SIMPPLLE Mitigation Effectiveness Results

The effectiveness of silvicultural mitigations varies considerably, and is not linearly associated with the level of investment according to MAGIS and SIMPPLLE modeling. Four schedules reduce wildfire probability estimates, while three increased the hazard. The most effective treatment reduces the average 30-year ignition hazard by 22.1 percent. Table 20 compares summary statistics of the mitigated wildfire probabilities between the base case simulation and the simulations with MAGIS treatment schedules for the 243 polygons hosting 291 study area WUI residences at the seven budget levels. Note that the schedules here are shown in order of HIZ budget levels (versus by increasing budget). Also note that the 243 polygon fire probability results are expanded to include a record for each of the 291 houses before these statistics are calculated. Table 20 also shows the overall effectiveness at reducing the average 30-year ignition hazard estimates for the 291 homes. The new average hazard is obtained by multiplying the SIAM modeling results

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[38] The total acreage limit of 5,840 per decade was removed for this schedule to allow the budget to reach a level comparable to HIZ mitigation G.

for each home[39] with the new mitigated 30-year fire probabilities. These altered SIMPPLLE probabilities are generated using new averages from 100 new simulations for each polygon hosting a study area house, and dividing by 291.

Table 20. Mitigation effectiveness for the 291 structures in 243 polygons, by schedule.

	SIMPPLLE Average	SIMPPLLE Median	SIMPPLLE Maximum	Host Polygons P= 0.00	Modeling System Average	Modeling System Maximum
Existing	0.00486	0.000	0.0496	201	0.00484	0.0476
Schedule A $184,080	0.00507	0.000	0.0592	189	0.00505 (+4.3%)	0.0592
Schedule B $2,135,048	0.00480	0.000	0.0493	199	0.00477 (-1.4%)	0.0473
Schedule C $2,319,128	0.00377	0.000	0.0492	211	0.00376 (-22.3%)	0.0492
Schedule D $1,235,075	0.00507	0.000	0.0397	196	0.00505 (+4.3%)	0.0397
Schedule E $3,370,123	0.00377	0.000	0.0492	209	0.00374 (-22.7%)	0.0472
Schedule F $3,284,920	0.00582	0.000	0.0496	178	0.00579 (+19.6%)	0.0496
Schedule G $5,604,048	0.00466	0.000	0.0494	197	0.00463 (-4.3%)	0.0474

The number of fires that occur during the 30-year time period is also useful information to detect differences attributable to the various treatment regime schedules. Tables 21:A-G summarize the proportion of all predicted fires with percentages by decade and severity class. Beyond revealing interesting information about the distribution of fire hazards to homes in the study area WUI, this information is useful to understand how values at risk other than residences might be protected by the suite of silvicultutal treatment regimes modeled at each budget level. For example, a shift towards light severity fire from mixed and stand replacement fire may indicate elevated protection for important wildlife habitat.

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[39] Recall that the averages for the three classes from 39 visited structures modeled in SIAM are used in these calculations for the 252 unvisited homes.

Table 21:A-G. Number of fires in severity classes and decade by proportion

Schedule A: $184,080 budget constraint

Timing	Decade 1	Decade2	Decade 3
	29.0%	42.6%	28.4%
Severity	LSF	MSF	SRF
	11.0%	83.3%	5.6%

Schedule B: $2,135, 048 budget constraint

Timing	Decade 1	Decade2	Decade 3
	32.8%	27.6%	39.6%
Severity	LSF	MSF	SRF
	8.1%	75.6%	16.2%

Schedule C: $2,319,128 budget constraint

Timing	Decade 1	Decade2	Decade 3
	35.7%	37.7%	26.5%
Severity	LSF	MSF	SRF
	16.9%	70.0%	13.1%

Schedule D: $1,235,075 budget constraint

Timing	Decade 1	Decade2	Decade 3
	35.6%	26.2%	38.2%
Severity	LSF	MSF	SRF
	18.4%	66.5%	15.2%

Schedule E: $3,370,123 budget constraint

Timing	Decade 1	Decade2	Decade 3
	37.2%	21.4%	41.4%
Severity	LSF	MSF	SRF
	13.4%	81.6%	5.0%

Schedule F: $3,284,920 budget constraint

Timing	Decade 1	Decade2	Decade 3
	33.0%	35.9%	31.1%
Severity	LSF	MSF	SRF
	11.7%	75.3%	13.0%

Schedule G: $5,604,048 budget constraint

Timing	Decade 1	Decade2	Decade 3
	37.9%	29.6%	32.5%
Severity	LSF	MSF	SRF
	13.4%	73.1%	13.6%

The results in this section indicate that despite a low average existing 30-year ignition hazard across the 291 study area homes both suites of mitigations have the potential to effectively reduce this hazard. Increasing fiscal aggressiveness of HIZ mitigation options generally provides increasing levels of reduction for this study area whereas the hazard does not appear to decrease as linearly following the application of increasingly aggressive silvicultural treatment schedules. While this may be an artifact of the nature of the two modeling tools (SIAM is deterministic, SIMPPLLE is stochastic) it can be interpreted as a statement about the reliability of each mitigation suite at this study site when the goal is reducing wildfire hazard to homes. Siding improvements and HIZ fuel conversions appear to be more reliably effective than silvicultural thinning and prescribed burning treatments in the vegetated areas surrounding this study area WUI.

Objective 4: Cost Effectiveness Analysis

The first section of this chapter revealed the existing 30-year hazard of WUI structure ignition results in the study area. The subsequent two sections reported the predicted costs and effectiveness potential of various mitigation options. These pieces of information allow comparisons and a cost-effectiveness analysis (CEA) of mitigation strategies. For this dissertation, the comparison is between two sets of effectiveness results at seven levels of cost. The application of the same seven budgets has produced two sets of impacts on modeling results. The HIZ mitigations affect the SIAM modeling results, whereas the scheduled silvicultural treatment regimes affect the 30-year fire probabilities in SIMPPLLE modeling results. The three CEAs that follow are based on the effectiveness modeling results plus cost information reported above for the two suites (A&B) of mitigation options that appear as the upper and lower paths in Figure 1.

HIZ Cost Effectiveness Results

Judging by the cost effectiveness ratios, the full fuels conversion option is the best HIZ mitigation investment option in this study area. When the $3,284,920 for option F, is divided by 63.7 percent effectiveness at reducing structure ignition probabilities the result is that it takes $51,569 to achieve each percent of effectiveness. Table 22 shows the seven HIZ options ranked in order of cost effectiveness using the reduction in the average SIAM probabilities for the 291 homes as the definition of effectiveness. The cost of each mitigation option is divided by the percentage effectiveness to generate cost effectiveness ratios. The CE ratios are reported in Table 22 as the cost in dollars to attain each one percent effectiveness for a given mitigation option. Table 22 also shows the number (out of 291) of study area homes with this option, the reduction in average ignition probability across the study area and the approximate cost to implement each option. The full fuels conversion option in combination with building upgrades ranks second in this study area when using the CE ratios. However, there are no additional effectiveness gains beyond those of the fuels conversion, yet the cost increases. This points out one of the problems of relying too heavily on CE ratios as the single metric for interpretation. The light fuels conversion option is the next most cost effective investment, followed by the light fuels conversion plus siding replacement. For this light fuels and siding option investment, when the $3,370,123 million is divided by 19.6 percent effectiveness the ratio is $171,945 for each percent of reduction achieved. Both the window upgrade alone and the window upgrade added to the siding replacement add no additional effectiveness. These are the two least cost effective HIZ mitigation options in this study area.

Table 22. The seven home ignition zone mitigations, listed in order of cost effectiveness ratios

	Number of Houses with option of 291	Cost per option ($million) 2006 Dollars	HIZ Mitigated hazard average for 291 homes (effectiveness)	HIZ CE Ratio[40] Cost / 1 percent Effectiveness / (RANK)
Existing Average	NA		0.994	
F. Full Fuels Conversion	291	3.284920	0.361 (-63.7%)	$51,569 (1)
G. Full Fuels Plus Siding and/or windows	246	5.604048	0.361 (-63.7%)	$87,976 (2)
D. Light Fuels	269	1.235075	0.898 (-9.0%)	$137,231 (3)
E. Light Fuels and Siding	242	3.370123	0.799 (-19.6%)	$171,945 (4)
B. Siding replacement	242	2.135048	0.927 (-6.7%)	$318,664 (5)
C. Windows and Siding	242	2.319128	0.927 (-6.7%)	$346,139 (6)
A. Window Upgrade	51	0.184080	0.993 (0.00%)	NA

Figure 20 charts the CE points of various home ignition zone mitigations on two axes. The vertical axis represents the cost for each option while the horizontal axis shows mitigation effectiveness. Effectiveness is the reduction below the existing average ignition probability of 0.994 for the 291 study area homes. The farther to the right a point is, given the budget, the more cost effective the investment as modeled with SIAM. Note that options D, and F represent the most cost effective possibilities, whereas options B, C, and E are identified as inferior HIZ mitigation options.

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[40] Although these ratios use $1 million as the denominator, this does not actually represent a possible scale of each mitigation option. This is used for comparison purposes only and should not be interpreted as indication that the application of each mitigation option is scaleable.

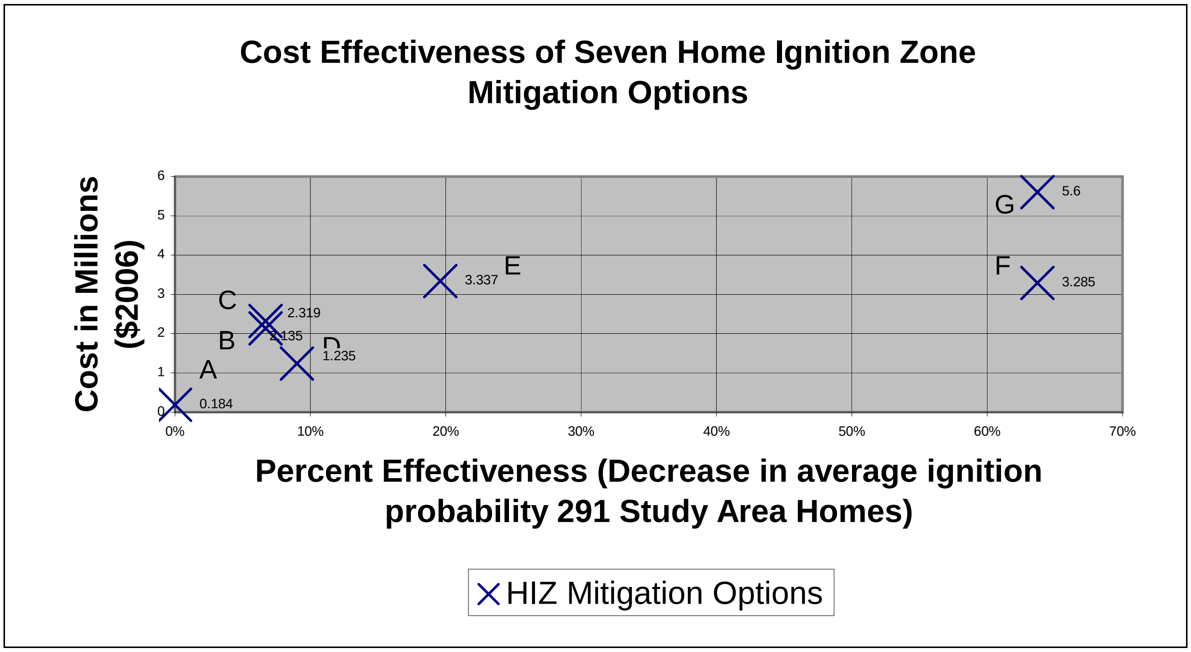

Figure 20. Cost effectiveness points for each home ignition zone mitigation option, modeled with the Structure Ignition Assessment Model.

Silvicultural Forest Treatment Cost Effectiveness Results

The effectiveness of MAGIS thinning and burning treatment regime schedules modeled with SIMPPLLE at changing wildfire probability is extremely variable. The range of change in the average 30-year wildfire probability for all the polygons hosting houses is from positive 20.2 percent to negative 22.1 percent. The budget for each schedule is divided by the percentage effectiveness for that schedule to derive cost effectiveness ratios. Table 23 shows the set of CE ratios for each of the scheduled treatment regimes using the reduction in the average 30-year wildfire probabilities for the 243 polygons[41] hosting the 291 homes. Schedule C, which costs approximately $2,319,128 is the most cost effective schedule with costs of $104,938 for each one percent reduction in average 30-year fire probability for the 291 polygons hosting study area houses. Schedule E, at a total cost of $3,370,123 dollars is the next most cost effective schedule with a cost of

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[41] The polygons hosting more than one house are included in these calculations with multiple records.

$152,494 for each one percent reduction. Schedules G and B are the only other cost effective schedules. At a total cost of $5,604,048 the CE ratio for Schedule G implies that each one percent reduction costs $1,514,608. At a total cost of $2,135, 048 the CE ratio for Schedule B implies that each one percent reduction costs $22,273,849. All treatment schedules are reported above in Chapter IV.

Table 23. The seven silvicultural mitigations options ranked by cost effectiveness ratios as modeled with MAGIS v1.2.3 and SIMPPLLE v2.3.

	Cost per option ($million) 2006 Dollars	MAGIS Mitigated average 30-year fire probability (effectiveness)	MAGIS CE Ratio Cost/ 1 percent Effectiveness (rank)
Existing Average		0.00486	
Schedule C	2.319128	0.00377 (-22.1%)	$104,938 (1)
Schedule E	3.370123	0.00377 (-22.1%)	$152,494 (2)
Schedule G	5.604048	0.00466 (-3.7%)	$1,514,608 (3)
Schedule B	2.135048	0.00480 (-0.01%)	$22,273,849 (4)
Schedule A	0.184080	0.00507 (+4.8%)	NA (5)
Schedule D	1.235075	0.00507 (+4.8%)	NA (6)
Schedule F	3.284920	0.00582 (+20.2%)	NA (7)

Figure 21 charts the CE points of various silvicultural forest treatment regime schedules on two axes. The vertical axis represents the cost for each option while the horizontal axis shows mitigation effectiveness. Effectiveness for this chart is defined as the reduction in the average 30-year wildfire probabilities for the polygons hosting structures, modeled with 100 SIMPPLLE simulations. The farther to the right a point is, given the budget, the more cost effective the investment as modeled with MAGIS and SIMPPLLE. By looking at the difference in the cost effectiveness between schedules (e.g., B and D, with budgets separated by only $184,000), note that small changes in the scheduling or the stochastic nature of the fire probabilities in the SIMPPLLE model make huge differences in the cost effectiveness of the seven treatment regime schedules.

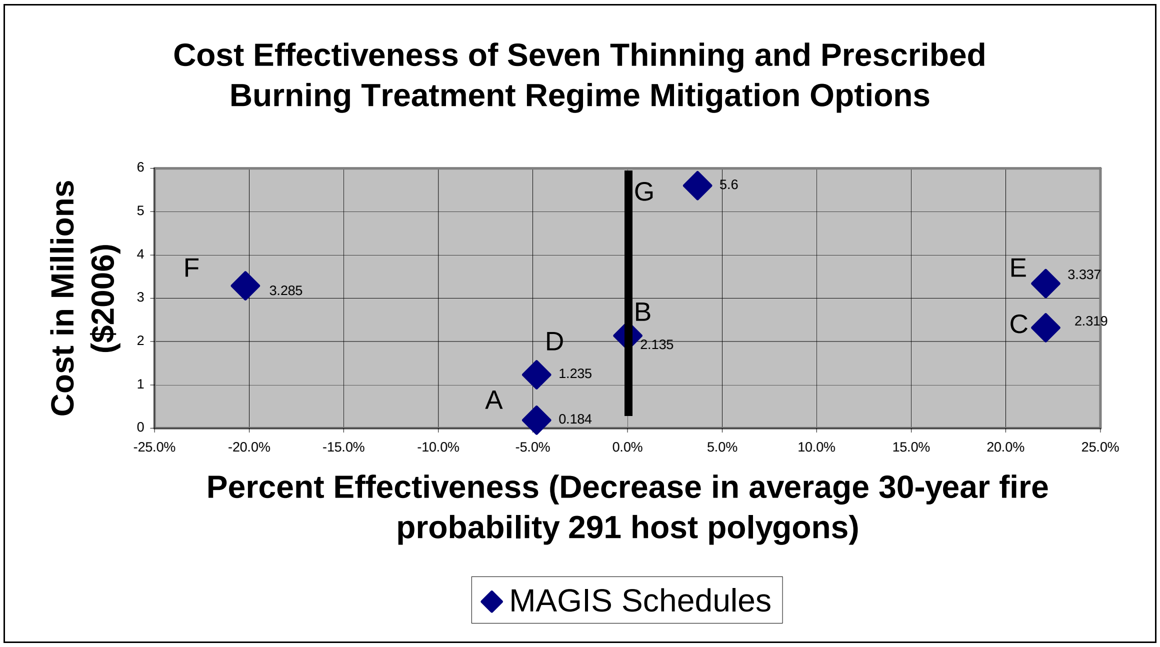

Figure 21. Cost effectiveness points for each silvicultural forest mitigation schedule, modeled with MAGIS v1.2.3 and SIMPPLLE v2.3.

Modeling System Hazard Cost Effectiveness Results

Now that the cost effectiveness has been assessed above for each model independently, the combined impact on the modeling system is evaluated to accomplish study Objective 4, a CEA comparison of the two mitigation suites (the rightmost block in Figure 1: the study design flowchart). When the cost effectiveness of the two suites of mitigation options are compared using the recombined full modeling system the HIZ full fuels conversion appears as the best investment. Indeed most of the HIZ mitigation options have lower cost effectiveness ratios than the silvicultural treatment schedules based on the same seven budget levels. Table 24 reveals the change to the 30-year existing hazard estimates for both the HIZ[42] and MAGIS treatment regimes at the same seven budget levels. The cost for each mitigation option is divided by the percent effectiveness to derive study area 30-year hazard reduction CE ratios. The mitigation options are ranked using parentheses in the table based on their CE ratios. A side-by-side comparison of the two suites of mitigation options is possible by reviewing the effectiveness and CE ratio at seven budget levels.

As stated above, the most cost effective mitigation is HIZ full fuels conversion, which costs $3,284,920. This mitigation cost $52,142 to achieve each percent of effectiveness. By using the CE ratios alone it is followed by the HIZ full fuels conversion with building upgrades. At a cost of $5,604,048 this option costs $88,953 to achieve each percent of effectiveness. However, realizing that this is no more effective than the HIZ full fuels conversion alone, the next best investment option is the $2,319,128 silvicultural forest treatment schedule which costs, $103,997 to achieve each one percent effectiveness. These are followed by another home ignition zone mitigation option, and then the third most expensive silvicultural schedule. Then the next three most cost effective options are HIZ mitigation options followed by the most expensive silvicultural forest treatment schedule. After this the cost effectiveness reaches zero for the window replacement HIZ option and even becomes cost ineffective for three of the silvicultural forest treatment schedules. These CE ratios indicate that there is no clear mitigation suite that seems most cost effective in this study area based on modeling. However, six of the seven HIZ

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[42] All HIZ mitigations are assumed to occur at the start of the 30-year analysis period and to persist for the full 30-year duration.

options decrease the hazard whereas the silvicultural options can either be very cost effective, not cost effective at all or very cost ineffective.

Plotting the total effectiveness versus cost is again a useful analysis technique. Figure 22 charts the cost effectiveness points of all of the mitigation options on two axes. In this case, effectiveness is the reduction achievable below the exiting average 30-year wildfire caused structure hazard estimate of 0.00484 for 291 study area homes. The vertical axis represents the cost for each option while the horizontal axis shows percents of mitigation effectiveness. The farther right a point is, given the budget, the more cost effective the investment as modeled by SIAM and SIMPPLLE. The HIZ mitigation options are shown with blue X's and the silvicultural forest mitigations are shown with black diamonds.

Note that the HIZ options are farther right than the silvicultural forest treatment options at all but two budget levels ($2.319 and $3.370 Million). This indicates that HIZ mitigations would generally be more cost effective in this study area. Also note that the two most costly HIZ options are aligned vertically on the plot. This indicates that no additional effectiveness is attained with the additional cost for building upgrades than is possible through full fuel conversion alone.

As an alternative to spending this additional 2.319 million (beyond the 3.28 million for full HIZ fuels conversion) on the building upgrades, it could be invested in silvicultural forest treatment schedule C. This can be done because the two suites of mitigation options are independent. When money is invested this way the modeling system predicts that the effectiveness attainable for the maximum budget ($5.6 million) increases to 70.9

percent with a cost effectiveness ratio of $79,086/each percent effectiveness. Although this is the second lowest cost effectiveness ratio, it is far lower than that for this level of investment in either of the two mitigation suites. This CE point is represented by the star on Figure 22.

Table 24. Costs, effectiveness and cost effectiveness ratios for all mitigation options

	Cost per option ($million) 2006	HIZ Mitigated hazard average for 291 homes (effectiveness)	HIZ CE Ratio Cost / 1 percent effectiveness	MAGIS Mitigated hazard average for 291 homes (effectiveness)	MAGIS CE Ratio Cost / 1 percent effectiveness
Existing Average		0.00484		0.00484	
Window Upgrade / Sch. A	0.184080	0.00484 (-0.0%)	NA	0.00505 (+4.3%)	NA
Siding replacement / Sch. B	2.135048	0.00450 (-7.0%)	$305,007 (7)	0.00477 (-1.4%)	$1,525,034 (10)
Windows and Siding/ Sch. C	2.319128	0.00450 (-7.0%)	$331,304 (8)	0.00376 (-22.3%)	$103,997 (3)
Light Fuels / Sch. D	1.235075	0.00439 (-9.3%)	$132,804 (4)	0.00505 (+4.3%)	NA
Light Fuels and Siding / Sch. E	3.370123	0.00383 (-20.9%)	$161,250 (6)	0.00579 (+19.6%)	NA
Full Fuels Conversion / Sch. F	3.284920	0.00179 (63.0%)	$52,142 (1)	0.00374 (-22.7%)	$144,710 (5)
Full Fuels Plus Siding and/or windows / Sch. G	5.604048	0.00179 (63.0%)	$88,953 (2)	0.00463 (-4.3%)	$1,303,266 (9)

These modeling system hazard reduction effectiveness results indicate that many of the mitigation options conducted in the home ignition zone are more cost effective than silvicultural forest treatments based on the same budgets. They also indicate that the SIMPPLLE and MAGIS modeling tools used to investigate the impacts of treatment schedules on 30-year fire probabilities portray a great deal of variability. While this result may not be especially satisfying it may reflect an important reality; there is greater certainty that HIZ mitigations will reduce the hazard to WUI structures. However, the silvicultural forest treatments may have as great of potential to mitigate wildfire caused structure ignitions in the future, as shown by schedule C in this analysis.

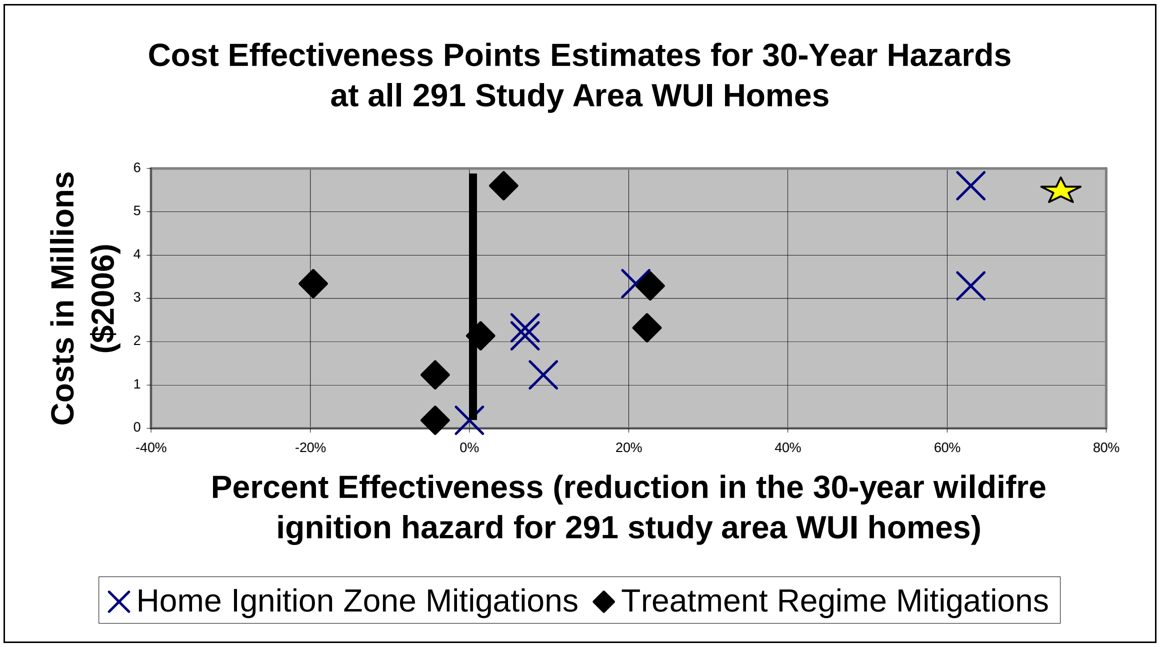


Figure 22. Cost effectiveness points for all mitigation options, modeled with SIAM, MAGIS v1.2.3 and SIMPPLLE v2.3.

The same modeling results can be used to demonstrate the change in the expected number of homes destroyed by wildfire in the study area during the next thirty years. In this case, the top four options according the CE ratios in from Table 24 are used in Table 25 to demonstrate the cost effectiveness on a reduced expected home loss basis. The results in this table indicate is that the most cost effective preventative mitigation option costs several million dollars to reduce the expected losses to wildfire by a single house. The findings in this study of high mitigation costs to protect WUI structures from wildfire have strong implications for future research needs.

Table 25. Mitigation cost effectiveness at preventing home ignitions

	Cost per option ($million) 2006	Mitigated hazard average for 291 homes (effectiveness)	Mitigated Expected Home loss	Change in expected loss	CE Ratio Cost / 1 house saved
Existing Average		0.00484	291*0.00484 = 1.408	NA	
HIZ Full Fuels Conversion	3.284920	0.00179 (-63.0%)	0.52	0.888	$3,698,524
HIZ Full Fuels Conversion with Building Upgrades	5.604048	0.00179 (-63.0%)	0.52	0.888	$6,310,865
Schedule C	2.319128	0.00376 (-22.3%)	1.094	0.314	$7,385,758
Schedule E	3.370123	0.00374 (-22.7%)	1.088	0.32	$10,531,634

The next chapter discusses many of the assumptions upon which these results are built and the limitations this creates for the modeling system. The final chapter explains what these results mean and includes important discussions regarding suggested future research.

CHAPTER V- DISCUSSION

The results chapter (IV) provides useful cost, effectiveness and cost effectiveness analysis findings for an economic comparison of preventative mitigation options for WUI homes threatened by wildfire. While the results are important findings for the selected study area west of Darby Montana, they need to be considered within the context of important modeling system assumptions and limitations. For example, use of different wildfire modeling tools would likely produce different cost effectiveness results. The same modeling tools used to achieve objective 1 for this dissertation are also used to achieve objectives 2 and 3, the design of two suites of mitigation options. The findings that result from achievement of objectives 1-3 form the basis for the demonstration cost effectiveness analysis results. Therefore, the following discussions are organized by modeling tools instead of objectives.

Notable SIAM/HIZ Assumptions and Limitations

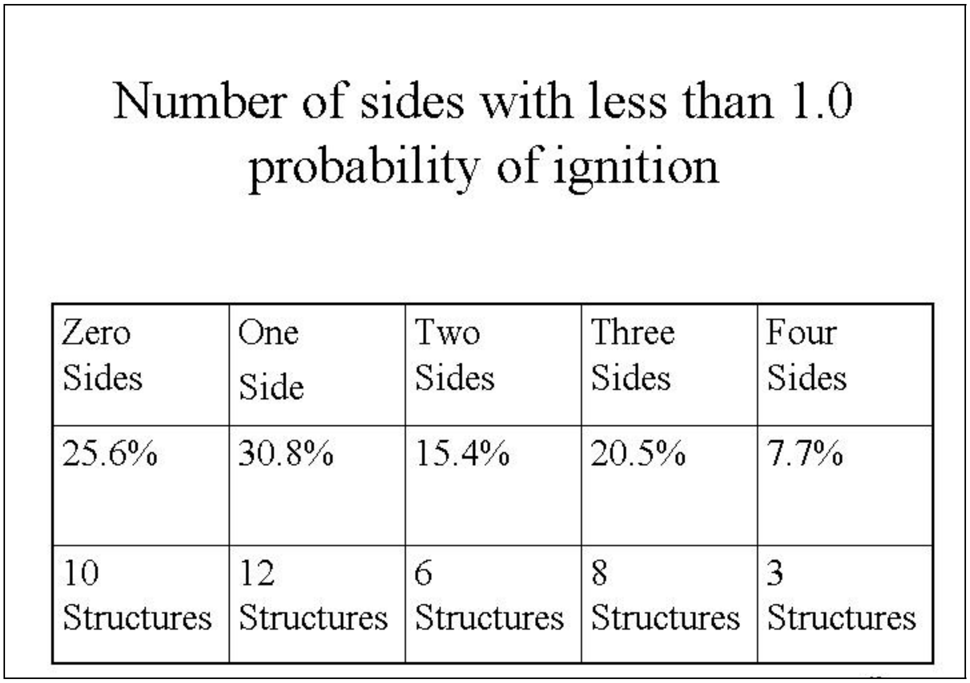
The key SIAM assumptions and limitation that affect both existing and mitigated ignition probabilities are bulleted and described below.

- Extreme Weather
- Fuel Mapping
    - data collection accuracy
    - home ignition zone size
    - data analysis with rectangles
- Subjective modeling inputs
- Extrapolation approach
- Cost estimation approach
- Lack of true optimization of HIZ mitigation options
- Roofs, not a factor in the study area
- HIZ Mitigation timing

The extreme weather is discussed as a major limitation in the introduction to SIAM (see Chapter II) and it is explored in the sensitivity analysis (Appendix C). However, it is worth noting again that this model is designed to overestimate the risk to homes because it relies on extreme weather, so extreme that it prevents suppression. It may therefore only be suitable to conditions that exist for a few days every couple of years. Not only does the model use extreme weather, these conditions may in fact be impossible to experience. Generating winds that are perpendicular to all four sides of a structure is likely not possible at one point in time; at least until the heat rising from the burning structure helps carry these winds. Not only are the winds expected to be moving at 20 MPH towards each side of each house, they are assumed to carry heat from fuel sources that are all burning concurrently. This is unlikely given that in reality fires advance as fronts. However, this simplification is used to allow computations that could occur in uncountable combinations.

Although multiple sides of a house would likely be challenged by any encroaching wildfire, looking individually at sides provides some useful information regarding the magnitude of the assumption that each house's most vulnerable side represents its ignition probability. When we look at sides individually, note SIAM predicts that 81 of the 156 sides have some probability of survival. Table 26 indicates the number of homes with 0, 1, 2, 3 or 4 sides with any expectation of survival. Note that most houses have at least two sides with no chance of survival in their existing state.

Table 26. Number of modeled sides that had a less than 1.0 probability of ignition.



Number of sides with less than 1.0 probability of ignition

Zero Sides	One Side	Two Sides	Three Sides	Four Sides
25.6%	30.8%	15.4%	20.5%	7.7%
10 Structures	12 Structures	6 Structures	8 Structures	3 Structures

By comparing average survival expectation using the maximum side probability to the average survival of all sides tested one can see the sensitivity of this assumption. The average survival expectation for the existing situation is 0.994; when all the sides of all visited houses are averaged this falls to 0.754. This suggests a very high probability for home ignitions given a wildfire with 20mph winds perpendicular to each side, and a 90 degree Fahrenheit ambient temperature. It also illustrates how important the assumption of the highest vulnerability for each structure is to this analysis.

The SIAM estimates are based on the assumption that all ignition sources in the HIZ are aflame simultaneously. While the model developer realizes that suppression resources are often operating at some level, the uncertainty associated with predicting suppression effort makes the worst-case scenario the only obvious modeling choice. This limitation has implications for the combination of SIAM with the aggregated SIMPPLLE wildfire severity probabilities. For each severity (light severity fire, mixed severity fire, and stand replacement fire), all the fuel sources inside the HIZ are assumed to be burning. As a result, only the trees with low branches or ladder fuels were drawn and included in the SIAM analysis.

Fuel sources, especially ones located close to a structure, contribute strongly to the ignition expectation. It is worth noting that structures must take the shape of a four-sided house in SIAM . In reality, the fieldworker is forced to reduce complex shapes to a simple four-sided house, adjusting not only the structure but the estimated distance to real fuels based on this simplified structure. The time required to draw, label and attribute these sources forces the fieldworker to count strides and do simple multiplication to estimate distances. This is the first time this version of SIAM is used to model structure ignition probabilities for real homes, and no accuracy assessment for the fuel mapping protocol was executed. The result is less than perfect confidence that the fuel distances modeled properly reflect flux-time product estimates, which vary substantially within small distances. This fact, although it might appear academic may also be accentuated by the rectangle problem described in the SA Appendix (C).

As mentioned earlier, the HIZ is set by extending the plan view 100 feet perpendicularly from each of the four sides of each structure. This is done because previous research indicates that fuel sources should make ineffective contributions to ignition potential beyond this distance (Cohen and Stratton 2003, Foote 1994, Howard et al. 1973). However, exploratory SIAM modeling for this project reveals that fuels beyond 100 feet and even 200 feet can impact modeled ignition expectations substantially. This runs contrary to the definition of the HIZ proposed by Cohen in the literature (Cohen 2001) as well as personal communication when the model designer suggested using a distance of 100 feet (Cohen Pers. Comm. 2005). In the current version of SIAM, at 100 feet the threshold for height of trees that impact overall ignition probability appears to be 30 feet, for 200 feet of distance the threshold height appears to be 90 feet. The fuels are only drawn to 100 feet for this project and all visited homes are modeled with only this information.

While most of the limitations and assumptions lead to overestimation of ignition potential at least two factors operate in the opposite direction. Although the current version of SIAM allows the user to draw adjacent structures[43] as fuel sources, they cannot be included in calculations with the current software version. The author recognizes that the various structures in this fuel source category do contribute significantly as ignition sources but they are not included. A review of the 39 residences visited reveals an average of three adjacent structures within the 100'HIZ for these 39 homes. Only six of the 39 homes have no adjacent structures inside the HIZ. There are adjacent structures present in 72 of the 156 sides modeled in SIAM. Future versions of SIAM may include these structures, but at this point thermal characteristics describing this wide category of fuels have not been programmed in SIAM for calculations.

In addition to adjacent structures, many investigators relay information to preparedness advisors regarding the importance of annual maintenance for fire safety. While gutters

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[43] Adjacent structures include a variety of buildings and other manmade structures including: garages, sheds, neighboring houses, fences, gazebos, propane tanks, planter boxes and arbors.

filled with dry pine needles are a common example of a factor that would elevate the real threat of home ignition, such factors are not embedded in the SIAM software. Some people attending presentations about SIAM comment on the irony that many of the small factors that can really make a difference are not included in this model. However, it is the designer's opinion, that although these are important considerations for ignition potential, modeling these factors is impossible (Cohen Pers. Comm. 2004). Even if some ratings describing annual maintenance are included in the model they will add to the existing subjectivity of ignition calculations. This version has the subjectivity of firebranding potential and nook and cranny scores restricted. Only three options exist for firebranding and five for nook and crannies, yet numerous factors contribute to these scores. For example, decks, porches, ignitable roofing ends, railings, vent screening, and ignitable windowsills are all considered in the nook and cranny index. Results regarding the interaction of firebranding and nook and cranny ratings are noted in Appendix C. It is worth mentioning that collectively the potential impact[44] is from 0 to 0.505.

The subjectivity of the firebranding data used to run the model is another important identified weakness. Although firebrands can travel farther than one mile with sufficient energy to ignite structures (Albini 1983), the area this creates around a home is frequently beyond the fieldworker's visual realm, making it difficult to assign a firebranding rating. Compounding the problem for firebranding scores, each side is assigned its own score (1-3), yet the chances that firebrands could be delivered from one side to a receptive ignitable surface of any adjoining side seems quite high.

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[44] In this case the impact refers to one of the components of the total calculations. If this number is the highest probability of ignition it is used as the overall probability, if it is not the highest then the higher probability estimates from flux-time product piloted ignition are used.

The next assumption affecting the SIAM results is that a sample of visited houses can be used to construct estimates for 291 homes. Thirty-nine of 291 or approximately 1/7th of all study area WUI homes were visited. As a result of having neither a random sample nor a comprehensive sample, a technique is used in this dissertation to estimate ignition probability for the remaining 252 homes in the study area. While the visited home sample of 39 is intended to saturate design categories and the gradients of fuels and topography that exist across the study area it is not clear that this is the case. A more systematic approach should be developed in the future that permits statistically valid extrapolation from a reasonable sample of homes to a community, and this is suggested as future research.

Cost estimates were developed in consultation with several contractors. However the desire to create several generalized mitigation options in the home ignition zone that could be modeled with SIAM led to the design of mitigation options that are not often performed by single contractors. Considering that according to several of these contractors with many years of experience, up to 50 factors[45] affect fuels mitigation cost estimates, and that jobs are underestimated nearly half the time, the cost estimates used in this dissertation can likely be improved in the future. After visiting with several fire hazard reduction professionals it became clear that fuels removal costs are very site

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[45] The factors mentioned most often are: equipment access, steepness, project size, stem density, human-made obstacles, and disposal technique.

specific. Six fuels contractors[46] provided advice regarding the cost estimation of fuels removal. The replacement of fuel sources with non-flammable substitutes[47] in particular appears to be rare in the area. None of the contractors offered cost estimates on the replacement of these fuels with non-flammable alternatives. This makes the estimation of costs for the fuels conversion mitigation options questionable. This lack of fuel conversion requests in the local area is also troubling given that this full HIZ fuels conversion appears to be the most cost effective option modeled in this dissertation.

Another mitigation cost not described in this dissertation is the replacement of roofs. This is important because the factor with the strongest impact in SIAM is roof ignitability. A flammable roof leads to an ignition probability of 1.0 regardless of all other information in SIAM. While this may be a concern in some parts of the country, no ignitable roofs are found during fieldwork, and the Montana cadastral mapping project database suggests none of these roofs exist in the study area.

The SIAM model’s four-sided approach provides an opportunity to refine the optimization of HIZ mitigation efforts. Remember that the ignition expectation for each residential structure is the maximum probability of ignition from any of its four sides. Because modeling the existing hazard and mitigation effectiveness for each structure is done this way it is possible to optimize across the modeled structures side by side using

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[46] The six contractors include: High Mountain Logging , Horizon Tree Service, Inc., Johnson Bros., Montana Forest Stewardship Services, Sprinkler Man Services, Inc. and Wildwood Forestry & Thinning, LLC.

[47] This mitigation option was designed based on a review of literature that suggests that fuel removal in home ignition zones to achieve wildfire protection is often moderated by the other values provided by fuel sources, such as shade, noise control, privacy and aesthetics.

marginal costs and effectiveness per side and per structure. This level of optimization would allow a superior cost effectiveness comparison between mitigation efforts in the home ignition zone and thinning and prescribed burning treatments within a mile and a half buffer of study area structures. The reason is that dollars could be spent side-by-side and house-by-house to make the greatest reductions in ignition probability at any given cost level. However, this project is intended to demonstrate that cost effectiveness can be used versus actually creating a mitigation strategy. In addition, modeling results from only 39 houses are extrapolated to 291 structures in the study area. Both of these reasons prevent this additional work, which could surely improve estimates and strategic prioritization in the future.

The timing of all of the HIZ mitigation options is another important assumption in this research. The mitigations are all assumed to occur in the first year of the analysis. In the absence of some new law forcing this behavior, the reality of all homeowners upgrading building and converting fuels in their home ignition zones (at a high cost) in the first next year is questionable. While this assumption reflects a virtual impossibility it is applied due to the deterministic aspect of the SIAM model. It could be assumed that mitigations are applied across the three-decade period with one third occurring in each decade. However, the uncertainty regarding implementation and the added math required has precluded any change to this assumption. These are the most important assumptions to keep in mind when looking at SIAM results.

Notable SIMPPLLE Assumptions and Limitations

The key SIMPPLLE assumptions and limitations that affect both existing and mitigated ignition probabilities are also bulleted and described below.

- Modeling with Suppression
- Extreme Fire Spread Probability
- Use of results at the scale of the individual polygon
- No explicit modeling of dead fuels
- Use of historical data to represent the future
- Prevailing wind selection
- Stochasticity in the response to silvicultural treatments

Several key assumptions are made within the SIMPPLLE model to allow for tractable modeling system design and analysis. These can be separated into assumptions that can be manipulated by the user and those that cannot. The assumptions that can be manipulated include ones that are set by the author to reflect conditions in the modeling area. Examples include the selection of suppression and 0.05 probability of extreme fire spread, both described in the results section of the previous chapter.

The most important limitation for the SIMPPLLE modeling results used in this modeling system is that individual polygons are used in combination with SIAM results for each structure. The SIMPPLLE model is designed to investigate succession and disturbance levels across landscapes. By using the number of simulations (out of 100) when fires burn in individual polygons that host residential structures, the scale of the analysis is stepped down to the lowest limit. Fine-scale analysis is not the intent of the data that is used to make size class, density, dominant species, and habitat type determinations for SIMPPLLE. The result is that the wildfire probability for any given polygon may have a greater degree of error than is obvious to the reader. This implies that a range may be more appropriate way to report the results than a point estimate for the average hazard.

The next limitation of SIMPPLLE is one that may trouble some fuel modelers. There are no dead fuels specifically modeled in the fire contagion logic. The SIMPPLLE model relies on fire spreading to adjacent stands based on combinations of habitat type, dominant species, size class, density, average elevation, selected wind direction and past processes. Although fire spread is affected by treatments that change one, two, or three vegetative attributes of a stand and its likelihood of each of three severity fires (given an ignition or fire spreading into it from a neighbor), attributes do not explicitly change to reflect the amount of dead fuels. This may be important when trying to understand the impact of fuel treatments on fires of the future. For example, a broadcast burn is often done to remove excess dead fuels, but removal of this material is not explicitly captured in SIMPPLLE. However, the severity of fire is set to differ based on this information. For example, recent insect and disease infestations can also affect the probability of fires. Fire can spread easier into these stands following infestation, based on SIMPPLLE fire spread logic that encapsulates the idea that there is an increase in standing or downed fuel.

SIMPPLLE uses historical information as the basis for the probabilities and the spread of fire in the future. For example, the number of ignitions during the last decade is used to generate a probability per acre per decade for fire starts during each decade for the duration of the simulations. By relying on data from the recent decade it is implicitly assumed that the types and amount of disturbance in the future will be similar to that of the past. With background climate change (Westerling et al. 2006) there is reason to believe that weather will be different in the future. However, there is presently no clear expectation of the amplitude or direction of future change at this point.

Another important assumption is the prevailing wind selection. While local winds change constantly in speed and direction, a general prevailing wind may be observed in some locations, representing the interaction of climate and topography. It is important to remember that winds driving fires during the most threatening fire events may not be of the same direction as the prevailing winds. For example, the Foehn winds, known also by local names (e.g., the Santa Anna winds in California), generally represent a high-speed wind event blowing in the opposite direction of the prevailing wind, lasting from several hours to several days. The SIMPPLLE model must have a single prevailing wind selected, which is used for the duration of the simulations for each run. Unlike work done by Butler et al. (2004) to enhance FARSITE modeling, wind in SIMPPLLE affects the fire spread logic similarly in all terrain and at all times during the simulation. A southwest wind is selected for the study area based on experience from residents and in consultation with the local fire management officer at the Darby Ranger District. The only time that the simulated wind driven fire is adjusted is in the event of a fire greater than 1,000 acres or if a fire spreads under extreme conditions based on probability and a random number draw.

The effectiveness results (Chapter IV) following the application of seven silvicultural treatment schedules indicate that the stochasticity in the simulation modeling appears to overwhelm the impact of the various treatment regimes. There are several reasons why increased hazard that accompanies some treatment schedules may reflect reality. The first explanation is that the structure and composition modifications made by the treatment regimes result in a shift in the severity of fire. There may be fewer stand replacement fires but more mixed and light severity fires as a result of the treatment. Another possibility is that prescribed fires themselves also have the potential to escape into polygons hosting houses. A third plausible explanation is simply that the real stochasticity of future ignitions may overwhelm the changes made to stand conditions.

Although there are plausible explanations, the stochasticity in the modeling is problematic for this analysis. Consider that when the same treatment schedule, unconstrained by budget or area limits, is simulated twice with SIMPPLLE the change in 30-year hazard results vary from 0.00484 to both 0.00449 and 0.00480. This variability in the predicted response of hazard estimates to the same treatment schedule creates a small problem for the comparison of the two suites of mitigation options at each of the seven budget levels. The best way to represent this variability in the response in fire probabilities to the various silvicultural treatment schedules is to use box plot or average from a sample of 100 simulations instead of a single point estimate. However, while it can be acknowledged that the range of response is great enough to wildly impact the cost effectiveness results described in the previous chapter, dealing with this reality by using a 30-sample approach is also problematic. In order to get this information 240 (8 * 30) 100-simulation SIMPPLLE runs are needed. This requires approximately 1,200 hours of processing time and 240 gigabytes of storage memory. Although this effort could stabilize the SIMPPLLE modeling of the existing hazard and the response to MAGIS treatment schedules it may not. The variation in the additional modeling results would need to be considered along with the change in the mean or median to determine if this intensified modeling approach effectuates stabilization. Therefore, with appreciation of this ranging response as a weakness in the modeling system this is recommended as a good area for future research. These are the most important assumptions to be aware of when reading the SIMPPLLE results section.

Notable Modeling System Assumptions and Limitations

Like the sections describing limitations for each of the modeling tools, this section has bulleted key points of awareness needed to appreciate the modeling results used in this demonstration.

- System for model combination
    - Assignment of houses to polygons
    - Single polygon use for wildfire probabilities
    - HIZ mitigation approaches apply to houses with zero wildfire probability

The process of locating study area houses in SIMPPLLE polygons contributes some notable approximation error to the project. The 2-meter color imagery used for this task (obtained from the 2004 National Agriculture Imagery Program) is a composite of quarter quad tiles compressed as a Ravalli County mosaic. This aerial imagery is distorted slightly based on the seam connection process. It will eventually be corrected and 2005 imagery will also eventually be available. However, the best data available at the time is used. In general, the 2004 images are shifted south and east of where they should be registered[48] to match the state library cadastral layer, which has superior geographic registration. As a result, all structure locations are entered slightly north, northwest of image locations. After all clearly visible homes are mapped with the aid of aerial images; the ownership attribute of the cadastral layer is used to check the map. An additional layer is created, where any of the three classes of residential property are missing a home. Each questionable polygon is reviewed and several homes are added with the aid of this data layer.

After this step, 330 structures appear in the study area WUI. Because Montana cadastral database information for each residence is used to classify homes into hazard categories, this number needs to be reduced to match the number of area structures found in the tax records. Parcels with multiple structures are isolated and then all but what appears to be the main residence is deleted[49].

Although it is acknowledged that adjacent vegetative communities also pose a firebranding threat to some homes, uncertainty regarding the variable contributions to firebranding hazard from these adjacent polygons prevents its inclusion as an explicit link between the two modeling tools in this project.

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[48] Registration refers to the process of properly geographically aligning a digital map layer.

[49] There are also some residences that are inside the area being analyzed with SIMPPLLE but which are not in the case study WUI area. These homes are not included in the analysis. They are within an area modeled with the landscape disturbance software because of the need to extend the SIMPPLLE analysis area geographically beyond the area of interest to prevent distortion of disturbance process contagion affected modeling results inside project WUI area.

After describing all the assumptions that limit the use of SIAM, SIMPPLLE and the combination of the two models it is important to remember that the results are not as important as demonstration that tools like this can be combined in current versions to address very interesting policy questions. When these questions and preliminary findings are found to be interesting, the awareness of results will drive model refinement.

The Limitations of the CEA in this Dissertation

Similar to the sections describing limitations for each of the wildfire modeling tools, this section has bulleted key points of awareness needed to appreciate the limitations of the economic analysis tool used in this demonstration.

- Effectiveness versus efficiency
- Variable costs
- Joint costs
- Spatial and temporal scale selection
- Generalized HIZ mitigation options
- Extrapolation of HIZ mitigation success prevents cost adjustment
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One of the most notable weaknesses for a CEA is that results are not comparable to other projects. Because a CEA transforms the analysis from an overall analysis of efficiency to a relative analysis of efficiency you cannot tell if the project is efficient overall, but you can compare how cost effectively different management options meet your objectives. When the government is deciding how to allocate scarce money, it will have difficulty deciding between cost effective options for two different projects. For example, the results of two CEAs will do little to help the analysts decide how to allocate money between the most cost effective alternative to meet a forest management agency’s legal mandates, and the most cost effective alternative to save more lives for a government emergency response agency. Because the analysis does not yield an efficiency measure, it is difficult to compare results to those of other possible projects. Although you give up the ability to make clear statements about efficiency, CEA allows you to identify superior and inferior alternatives in light of your project objective.

The fact that included cost information can vary is another important weakness of CEA. Should costs include direct costs, indirect costs, tangible costs, intangible costs, and/or joint costs? In CBA, cost information is typically limited to monetary and opportunity costs. But the CEA framework is used to address important non-market benefits, so the question arises how well does it capture non-market costs? Critics could argue that cost manipulation in the CEA could be used to influence the outcome, especially when management alternatives have important differences in cost structure. This variability in cost structure is indeed the case for this research. The estimated costs for the silvicultural forest treatment regime options include administrative costs, planning costs, and implementation costs, whereas the home ignition zone mitigation options only include estimated contractor costs to complete the mitigation tasks.

Next consider the problem of joint costs. For example, the fuel treatment regime options would typically be used to meet several objectives. For sake of argument, imagine that the following ecosystem management goals are typically in place for most fuel treatment projects: reduce fuels, increase wildlife forage, control invasive weeds, control insect and disease, and produce biomass. There are joint costs involved in this project, and they will increase the costs above the most basic costs to only reduce fuels. To apply cost estimates from projects like these in the comparison to contractor estimates will skew the cost effectiveness away from silvicultural fuel treatment options.

Another weakness of all the cost analysis tools is that spatial and temporal scale can affect the results. For example, mitigation CEA for a single home will produce one result. If the analysis is scaled up to a community (as is the case for this research), the same CEA framework may produce a different result. Because the CEA results depends on the spatial scope of the analysis, there should to be a reason to select the scale to prevent manipulation. For example, this research is designed to demonstrate the application of an economic analysis tool for communities exploring wildfire hazard mitigation strategies in a CWPP. This selection of spatial scale has clear impacts on the cost effectiveness analysis results.

Likewise, if temporal scope dramatically affects the results then the analyst needs to be careful to provide justification for the temporal scope selected, or to show how changing the timeframe of the analysis would affect the results of the CEA. In this research, the selection of the 30-year time period for this analysis (justified in Chapter I) has implications for the comparison between HIZ and surrounding wildland mitigation activities. In the case of the HIZ mitigations, they are expected to occur at the start of the 30-year time period. In the case of the silvicultural treatments, they are scheduled for the start of each of the three simulated decades. Yet both the mitigated conditions are expected to persist throughout the 30-year time period. Although this spatial and temporal scale issue is important, it is an issue with the full family of cost/benefit economic decision tools.

The ideal cost effectiveness comparison between HIZ and silvicultural treatments would account for a multitude of mitigation options and combinations to determine an optimal prioritization based on all values. However, the objective of the research is to demonstrate that existing modeling tools can be used to help prioritize mitigation options, not to develop a site-specific prioritization strategy for the study area. As a result only structure protection is included in the definition of effectiveness. If a site-specific prioritization strategy were the stated goal, additional effort to identify values at risk and elevated optimization efforts for both the HIZ and silvicultural forest treatment suites would be necessary.

The design of this study simplifies the HIZ mitigation possibilities to the home and the proximate fuels to a suite of seven possibilities applied to all candidate homes. Recall that the existing hazard for each home is the product of the wildfire probability for its host polygon modeled with SIMPPLLE and the likelihood of ignition given a wildfire modeled with SIAM. The cost effectiveness analysis of the mitigations on the combined modeling system in this dissertation does not adjust costs for the cases where the existing wildfire probability is zero. Ideally, the estimated 69 percent of the houses with a zero 30-year wildfire probability would be removed from each of the HIZ mitigation options to reduce the costs of each mitigation option in the recombined CEA. The problem is that extrapolation is used in the dissertation to estimate the structure ignition probability for 252 of the 291 houses, complicating this retrospective calculation. This explains why this is only suggested as a potential improvement in any future cost effectiveness analysis.

Comparing Budgets to the Existing Community Wildfire Protection Plan

It is interesting to compare the budget levels in this research with information in the CWPP that applies to the study area. The Bitterroot Valley CWPP has been helpful securing roughly $1.92 million for hazard reduction in the Bitterroot Valley between 2001 and 2005. Of this $930,000 was been spent doing fuel mitigation work on private and public lands. At this rate, the amount that will be spent during the 30-year period analyzed in this dissertation is roughly $5.6 million. This is almost exactly the amount used when an unconstrained silvicultural forest treatment scheduler is given the task of minimizing the 30-year fire probability by thinning and prescribed burning all possible vegetative units within 1.5 miles of the 291 study area homes ($5.86 million). This could be interpreted to mean that this CEA analysis is using realistic budgets levels. However, keep in mind that the analysis area modeled in this dissertation represents only a small part of the entire area covered by the Bitterroot CWPP.

CHAPTER VI – CONCLUSIONS

Key Findings

This dissertation demonstrates that a cost effectiveness analysis can be performed to help guide mitigation efforts in low elevation communities across the western US. By introducing an economic analysis that can assist with the selection of mitigation strategies, society can either reduce the cost to achieve a given level of home protection effectiveness or increase the effectiveness for a given cost. The findings in the study area demonstration, where budgets were limited and effectiveness varied, suggest that most of the HIZ mitigation options have superior reliability over silvicultural forest treatments when compared at seven budget levels ranging from $184,000 to $5,604,048.

The range in predicted cost-effectiveness (CE) ratios from $52,142 /1% effectiveness to infinity/1% effectiveness[50], which accompanies the fourteen mitigation options, suggest that economic analysis must be addressed in mitigation planning. One example provided at the end of the last chapter demonstrates that a combination of two independent mitigation options, one from each of the two suites, has the potential to reduce hazard more than that same budget applied exclusively to one suite or the other. Given limited money to address the problem of WUI structure protection, this is exactly the type of information needed to protect the increasing number of western US WUI homes from wildfires in the future. While these results are interesting and may be useful for the local community wildfire protection plan, it remains unclear whether this pattern of cost effectiveness between the two suites of options holds across the western US. Only by

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[50] Infinity is assigned because several of the modeled mitigations generated either no reduction in existing hazard or an actual increase in the hazard.

replicating this approach in numerous study areas representing a range of building types, home ignition zone fuel configurations, and landscape vegetation conditions will general statements comparing the two suites be permissible.

Although the modeling in this dissertation draws conclusions about the potential cost effectiveness of various mitigation strategies it thus far has not included a needed discussion about the feasibility of these strategies. One important result of this dissertation is that the existing risk to homeowners may be quite low, averaging only 0.00484 for the next 30 years across the 291 study area homes. Even the maximum existing hazard of 0.05 may not be sufficient incentive to mitigate wildfire at a cost.

While results and discussion are designed to reveal the comparison of relative effectiveness, the results in chapter IV point to the absolute effectiveness attainable. The cost estimation results in chapter IV of this dissertation describe the cost to make structures more fire resistant and remove HIZ fuels. Even by removing and replacing all the fuels in the home ignition zones across the study area this mitigation option only reduces the existing hazard to 0.00179 at an average cost of $11,288 per home. On average, siding upgrade to non-flammable material costs $8,670 per house, and just the light fuels conversion option averages $4,591 per house. If you consider that homeowner’s insurance will replace the house if it is destroyed by wildfire, the reason for inaction by many WUI homeowners becomes clear.

If a trend of findings such as those in this document suggest that steps taken by homeowners are generally more cost effective than silvicultural treatments to the surrounding public lands this has implications for future wildfire protection planning. Circulation of information regarding the site-specific predicted cost effectiveness of various mitigation options may persuade communities to increase pressure on 1) existing homeowners to modify their homes and surroundings, and 2) new residents to construct homes and plan the surrounding landscape in a more fire resistant manner. This increased emphasis on homeowner mitigation could allow land management agencies to allocate scarce budgets to other protection and land management priorities.

However, there are also many additional values provided by HIZ fuel sources, such as the provision of shelter, shade, temperature and moisture control, noise control, privacy, firewood supply, aesthetics, and wildlife habitat, that all restrict the amount of fuel conversions undertaken in home ignition zones across a given WUI community. On the other hand, some fire mitigation is viewed as providing complementary progress in restoring forests to some reference condition and thought to contribute to forest health goals that extend beyond fire hazard mitigation goals. Nelson et al. (2004) report that crime-control, gardening, and pet needs were also given as reasons to have open areas surrounding a home.

Considering all of the factors affecting fuel mitigation decisions listed above, it seems that economic benefits really need to outweigh costs, or something else needs to motivate homeowners to mitigate fuels. Although an evaluation of efficiency is a logical extension of the findings in this dissertation there are numerous reasons that need to be mentioned to avoid this analysis for this study. The first is that the emerging modeling tools used in the dissertation have not been fully tested and vetted for the purpose of economic analysis. The cost estimates used for the mitigations are also in early stages of evolution. More importantly, a threat to life of residents and firefighters also accompanies the threat of future WUI structure ignition. The valuation of these lives is contentious. Another important limitation is that these mitigation options are simplified to accommodate this dissertation goal of CEA demonstration and they lack optimization that would improve the cost-benefit ratios. Finally, there are numerous benefits in addition to home protection accrued through mitigation (e.g., enhancements in forest resistance to insects and disease, provision of big game winter range forage, and improved firefighter suppression capability) that are not easily monetized and therefore are not captured in this economic analysis. Many of these reasons explain why the cost effectiveness analysis tool is chosen in the dissertation to address the question of how to best allocate the money being spent to protect WUI structures.

Transferability of Study Findings

This research is targeted to the scientific and management communities as well as low elevation WUI communities hoping to reduce expected home loss from wildfire. It should provide a new way to compare options for achieving the goal of improved home survival in high frequency fire regime WUI areas. The ability to apply this approach to different WUI areas across Montana and the western US will be limited at first by model and data availability. Once this is resolved, portability will be a matter of time and budget constraints to execute this type of analysis. Both data availability and portability point to the question of transferability of the findings.

Community Plans as a Vehicle for CEA

The ten-year cohesive strategy drafted by the Western Governor's Association provides guidance on administration of the National Fire Plan after the dramatic WUI fires of 2000. As a result of all of this political attention to the mitigation issue, including the Healthy Forest Restoration Act of 2003, many communities and groups of communities are drafting community wildfire protection plans (CWPP). The third *minimum requirement* for any CWPP provides a direct incentive to get information about mitigation to homeowners. It is called treatment of structure ignitability and each CWPP must recommend measures that homeowners and communities can take to reduce the ignitability of structures throughout the area addressed by the plan (US Congress 2003). The assessments conducted pursuant to this language in the CWPPs could easily be modified to collect input information needed to run SIAM. With the creation of a sampling protocol tied to an ignition probability classification system, assessment of the existing hazard across a community and the potential cost effectiveness of various mitigation options could be ascertained with little additional effort. If the wildfire probability modeling could be based on wall-to-wall data, such as the LANDFIRE data available for the US, a nationally consistent approach could be generated.

Warnings for Misapplication of Study Area Findings

Results for the study area used for this demonstration will differ from other WUI areas based on several characteristics. The size of the area will affect the scale of all possible treatment options. The housing density and cooperation of neighbors will be a major factor. Land ownership patterns will dictate what type of treatments that can be applied. The existing vegetation will impact the baseline and potential gains of all treatments. The topography and weather of an area will also affect the ability to make changes in fire severity. Any building codes that may constrain or mandate HIZ and/or home conditions will also affect transferability. These all point to a need to reiterate that this study is merely an example of how economics can help address a multidisciplinary research question.

This assessment is intended to diagnose the existing risk of home ignition loss during extreme fire weather. This study looks at an area roughly defined by a community as their wildland urban interface. People living in areas with different risk of wildfire would not want to use findings from this study to make decisions. This combination of models is designed to address the case when there are many homes at risk of loss to wildland fires burning with extreme conditions. If one were trying to model a situation without homes, one would not use the SIAM model, and would likely be framing the question with a different effectiveness metric, or even a different economic tool, perhaps economic efficiency versus cost effectiveness.

Although many land management projects appear to focus on fuel reduction, these projects are often designed to realign fire regimes with some reference condition to concurrently improve forest health and enhance community safety. This study was designed to address the case where wildfire-caused structure hazard reduction is the overriding objective. Incomplete consideration of other important land management objectives could lead a person to misinterpret the results in this dissertation. There are now many integrated land management projects that strive to improve multiple resource conditions simultaneously through combinations of vegetation management, road improvements or decommissioning, and recreation infrastructure improvements. Hazardous fuel management is often only one of several objectives of these integrated efforts.

Suggested Future Research

The preliminary modeling system used in this dissertation is built on many assumptions and there is much room for improvement in the future. Throughout the dissertation, shortcomings and limiting assumptions are highlighted to provide adequate caution in the application of the results. All three of the modeling tools used in the research are still being developed. The following is a list of the most important potential modeling system improvements:

SIAM

- Include adjacent structures as fuel sources
- Improve the user interface to allow easier modeling
- Allow polygon modeling versus rectangular fuel source modeling
- Allow for modeling at various weather conditions
- Write the code needed to model plate versus tempered window types
- Check software to allow adjustments in wind speed and temperature adjustments

SIMPPLLE

- Create the option to automate multiple scenarios to reduce set up time for each set of simulations that would allow the analysts to easily take an average from a sample 30 sets of 100 simulations to reduce the variability in the existing fire probabilities and the fire probabilities following the application of MAGIS silvicultural treatment schedules.
- Generate a comprehensive fire probability sensitivity analysis for all parameters under various regions with different vegetation types.
- Create a report with a record for each polygon that describes the average wildfire hazard in all adjacent polygons. This would allow the analyst to connect probabilities from adjacent polygons to the host polygons to the SIAM estimates for a more complete consideration of firebranding potential.

MAGIS

- Improve the optimization fire reduction factors based on SIMPPLLE output.

This dissertation has pioneered a technique to combine fire probability estimation with structure ignition estimation to conduct a cost effectiveness analysis of mitigation options. The research question can be revised in any number of ways to address the needs of the planning community. For example, the question of what is the existing risk could be answered in many ways. In this case, a 30-year planning horizon has been applied, and this implies that a temporal modeling system is needed. If a community were more interested in the chances that a certain known wildfire scenario would destroy houses, then other fire behavior tools in the FARSITE family could easily be substituted to address the fire probability estimation.

On the other hand, if communities are more interested in the structure ignition estimation a methodology to randomly sample homes could be employed that permits the development of a classification system that simplifies the data collection needs for remaining homes in that area, allowing for a low cost comprehensive evaluation of community risk.

There are numerous reasons cited within this document describing why a CEA was conducted instead of a cost-benefit analysis. As described above, the jump to a more elaborate economic analysis could be taken. Optimization of the HIZ mitigation options could be done with the existing cost and effectiveness data. The HIZ mitigation strategies would also benefit by excluding homes modeled with zero wildfire probability from consideration. If these changes are made, a future CBA could address the general issue of spending on the protection of WUI homes from wildfire. The issue of who should be spending the money and how it should be divided between preventative and suppression could be explored further in this manner as well. Consider that it took one person two and a half years to design, execute, and report results for this study. This should hopefully give the reader the impression that with very little financial resources some of society's important forest multidisciplinary management questions can be addressed through the application of innovative study designs that use economics analyses.

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LIST OF ACRONYMS AND ABBREVIATIONS

Ac. - Acres
ADS - Aerial Detection Survey
BC - Benefit/cost
BEHAVE - Fire Behavior Prediction System
BNF - Bitterroot National Forest
CBA - Cost benefit analysis
CE - Cost effectiveness
CEA - Cost effectiveness analysis
CWPP- Community wildfire protection plan
D1 - Decade 1 year 1-10 (2005-2014)
D2 - Decade 2, years 11-(2015-2024)
D3 - Decade 3 years 21-30 (2025-2034)
DBH - Diameter at breast height
DFB - Douglas fir beetle
ESRI - Environmental Systems Research Institute
GIS - Geographic information system
F - Fahrenheit
FARSITE - Fire Area Simulator for Fire Managers
FETM - Fire Emissions Tradeoff Model
FLAMMAP - Fire Behavior Mapping and Analysis Program
FMZ - Fire management zone
HFRA - Healthy Forest Restoration Act of 2003
HIZ – Home ignition zone
LANDFIRE - Landscape Fire and Resource Management Planning Tools
LANDSUM - Spatial successional modeling tool
LSF - Light severity fire
MAGIS – Multi Attribute Geographic Information System
MPH - Miles per hour
MSF - Mixed severity fire
MT - Montana
NA - Not applicable
NAIP – National Agricultural Imagery Project
NIFC - National Interagency Fire Center
NC- Nook and cranny (part of the SIAM model)
P( ) - probability
Pers. Comm. - Personal communication
PICO MPB - Lodgepole pine mountain pine beetle
R1-VMP- USFS, Northern Region's vegetation map
SA – Sensitivity analysis(es)
SIAM – Structure Ignition Assessment Model
SIMPPLLE – Simulating Patterns and Processes at multiple Scales Modeling tool
SO- SIAM One
SRF - Stand replacement fire

USDA - United States Department of Agriculture
USFS – Unites States Forest Service
US – United States of America
VDDT - Vegetation Dynamics Development Tool
WUI – Wildland urban interface

APPENDIX A. SIAM DATA COLLECTION WORKSHEET

Structure Ignition Assessment Model (SIAM)
Home Evaluation Worksheet

1. Descriptive Information

Property Owner Name(s) ____

Property Number_______ Phone Number (   ) _____ -   _______

Street Address: ____

Town _______________, Zip Code _________ - _____

GPS coordinates _____ ____._____N   _____ _____.____W

Date: Month_______ Day_________ Year__________ Time ___:___

Evaluator___________________________ Aspect of Front Wall ________ Deg.

Have you made wildfire mitigation efforts in the past? HIZ Y N, Intermix Y   N

Notes: ____

Are you willing to allow photographs to be used in presentations?   Y   N

2. Fire Branding Index (Worst Case within ¼ mile)

Side 0___   Side 1___   Side2___   Side3___

1 = low (grasses), 2 = moderate (tall cured grasses, open forest), 3 = high (closed forest)

(☐ P.V = fire branding numbers for all directions drawn on plan view

Notes ____

3. Roof Information

Roof Type: Ignitable (wood shakes, sawn shingles)

Non-ignitable (metal, composite, terra cotta, etc.)

Lowest Height________ ft.   Highest Height____________ ft.

Exposed flammable surfaces	Y	N
Debris Present	Y	N

Notes:____

____

SIDE 0, House Back

0.4. Siding Information

Siding Type: Ignitable (wood, vinyl, other_______, Painted Y N

Non-ignitable (metal, composite, masonry, brick, hardyplank, stucco, other)

Height variance over ‘wall 0 origin’ __0____ ft. Wall length______ ft.

Wall origin (right end) Height over Grade____ ft. Wall End Height over Grade____ft.

Flam. surfaces - Origin height over grade: ____ ft. Wall End Height over Grade____ft.

Gable height above wall____ ft. Width____ ft. Dist. from center ____ft R / L of Peak

Clino Reading_____ Distance_____ Notes: ____________________________________

____

0.5. Window Information

(> 2’x2’, starting low and to the right of side ☐ E.V = drawn on elevation view)

Window Type (Glass Temper (P = plate, T= tempered), Glazing I = single pane, II = double pane, a = sashes b = no true sashes, (# of lenses). Example: PIa8, TIIb

0.1. Type:______ Height___ in. Width___ in. Hi___’ Left___’ Exp. Sill Y N ☐ E.V.

0.2. Type:______ Height___ in. Width___ in. Hi___’ Left___’ Exp. Sill Y N ☐ E.V.

0.3. Type:______ Height___ in. Width___ in. Hi___’ Left___’ Exp. Sill Y N ☐ E.V.

0.4. Type:______ Height___ in. Width___ in. Hi___’ Left___’ Exp. Sill Y N ☐ E.V.

0.5. Type:______ Height___ in. Width___ in. Hi___’ Left___’ Exp. Sill Y N ☐ E.V.

0.6. Type:______ Height___ in. Width___ in. Hi___’ Left___’ Exp. Sill Y N ☐ E.V.

0.7. Type:______ Height___ in. Width___ in. Hi___’ Left___’ Exp. Sill Y N ☐ E.V.

0.8. Type:______ Height___ in. Width___ in. Hi___’ Left___’ Exp. Sill Y N ☐ E.V.

0.9. Type:______ Height___ in. Width___ in. Hi___’ Left___’ Exp. Sill Y N ☐ E.V.

0.10. Type:_____ Height___ in. Width___ in. Hi___’ Left___’ Exp. Sill Y N ☐ E.V.

0.11. Type:_____ Height___ in. Width___ in. Hi___’ Left___’ Exp. Sill Y N ☐ E.V.

0.12. Type:_____ Height___ in. Width___ in. Hi___’ Left___’ Exp. Sill Y N ☐ E.V.

0.13. Type:_____ Height___ in. Width___ in. Hi___’ Left___’ Exp. Sill Y N ☐ E.V.

0.14. Type:_____ Height___ in. Width___ in. Hi___’ Left___’ Exp. Sill Y N ☐ E.V.

0.15. Type:_____ Height___ in. Width___ in. Hi___’ Left___’ Exp. Sill Y N ☐ E.V.

Notes:____

- Extra Window Data Sheet Required (☐ data sheet is labeled, and attached)

0.6. Home Ignition Zone Characteristics:

Slope Offset Distances Up:____________ Down:______________

Slope beyond offset Up:________ deg. Down:_________ deg.

Fuel Type (<100 ft., starting left and close to structure, moving clockwise)

- 45^0 lines are drawn for the plan view based on the elevation view dimensions

A. Surface litter, **B**. Short grass (< 6”), **C**. Med. Grass (6-24”), **D**. Tall grass (>24”), **E**. Shrubs, **F**. Underbrush, **G**. Trees, **H**. Woodpiles, **I**. Debris Piles, **J**. Adjacent Structure

N = Natural (forest), O = Ornamental (e.g., GN = natural tree, GO = ornamental tree)

0.1. Fuel Type____ Ignition hazard Y N, Fuel width_____ ft., height____ft. ☐ P.V

Fuel Depth _____ ft. Dist. to structure_____ ft. Notes____________________________

0.2. Fuel Type____ Ignition hazard Y N, Fuel width_____ ft., height____ft. ☐ P.V

Fuel Depth _____ ft. Dist. to structure_____ ft. Notes____________________________

0.3. Fuel Type____ Ignition hazard Y N, Fuel width_____ ft., height____ft. ☐ P.V

Fuel Depth _____ ft. Dist. to structure_____ ft. Notes____________________________

0.4. Fuel Type____ Ignition hazard Y N, Fuel width_____ ft., height____ft. ☐ P.V

Fuel Depth _____ ft. Dist. to structure_____ ft. Notes____________________________

0.5. Fuel Type____ Ignition hazard Y N, Fuel width_____ ft., height____ft. ☐ P.V

Fuel Depth _____ ft. Dist. to structure_____ ft. Notes____________________________

0.6. Fuel Type____ Ignition hazard Y N, Fuel width_____ ft., height____ft. ☐ P.V

Fuel Depth _____ ft. Dist. to structure_____ ft. Notes____________________________

0.7. Fuel Type____ Ignition hazard Y N, Fuel width_____ ft., height____ft. ☐ P.V

Fuel Depth _____ ft. Dist. to structure_____ ft. Notes____________________________

0.8. Fuel Type____ Ignition hazard Y N, Fuel width_____ ft., height____ft. ☐ P.V

Fuel Depth _____ ft. Dist. to structure_____ ft. Notes____________________________

0.9. Fuel Type____ Ignition hazard Y N, Fuel width_____ ft., height____ft. ☐ P.V

Fuel Depth _____ ft. Dist. to structure_____ ft. Notes____________________________

0.10. Fuel Type____ Ignition hazard Y N, Fuel width_____ ft., height____ft. ☐ P.V

Fuel Depth _____ ft. Dist. to structure_____ ft. Notes____________________________

0.11. Fuel Type____ Ignition hazard Y N, Fuel width_____ ft., height____ft. ☐ P.V

Fuel Depth _____ ft. Dist. to structure_____ ft. Notes____________________________

0.12. Fuel Type____ Ignition hazard Y N, Fuel width_____ ft., height____ft. ☐ P.V

Fuel Depth _____ ft. Dist. to structure_____ ft. Notes____________________________

0.13. Fuel Type____ Ignition hazard Y N, Fuel width_____ ft., height____ft. ☐ P.V

Fuel Depth _____ ft. Dist. to structure_____ ft. Notes____________________________

0.14. Fuel Type____ Ignition hazard Y N, Fuel width_____ ft., height____ft. ☐ P.V

Fuel Depth _____ ft. Dist. to structure_____ ft. Notes____________________________

0.15. Fuel Type____ Ignition hazard Y N, Fuel width_____ ft., height____ft. ☐ P.V

Fuel Depth _____ ft. Dist. to structure_____ ft. Notes____________________________

0.16. Fuel Type____ Ignition hazard Y N, Fuel width_____ ft., height____ft. ☐ P.V

Fuel Depth _____ ft. Dist. to structure_____ ft. Notes____________________________

0.17. Fuel Type____ Ignition hazard Y N, Fuel width_____ ft., height____ft. ☐ P.V

Fuel Depth _____ ft. Dist. to structure_____ ft. Notes____________________________

0.18. Fuel Type____ Ignition hazard Y N, Fuel width_____ ft., height____ft. ☐ P.V

Fuel Depth _____ ft. Dist. to structure_____ ft. Notes____________________________

0.19. Fuel Type____ Ignition hazard Y N, Fuel width_____ ft., height____ft. ☐ P.V

Fuel Depth _____ ft. Dist. to structure_____ ft. Notes____________________________

0.20. Fuel Type____ Ignition hazard Y N, Fuel width_____ ft., height____ft. ☐ P.V

Fuel Depth _____ ft. Dist. to structure_____ ft. Notes____________________________

- ○ Extra Fuel Type Data Sheet Required (data sheet is labeled _______)

Fuel Sources: (☐ P.V = drawn on plan view, ☐ photo numbers listed in notes)

Repeated for sides 1, 2, and 3

7. Nook and Cranny Information

Deck Y (#___) N, railing height____ ft. Length____ ft. Material____ ☐ P.V.

Attached Fence, lattice Y N, height____ ft. Length____ ft. Material____ ☐ P.V.

Vents, Screened Y (Number____) N (Number____), Sizes___________

Locations____

Ignitable window sills Y N, Number____ Painted Y N

Firewood Pile Location: ____________ Gaps in Roofing, Y N Flashing Y N

Potential for materials rolling into structure Y N Other:________________________

Notes:____

____

1 = none (no nooks or crannies), 2 = some, 3 = moderate 4 = abundant, 5 = high

☐ Plan Views (0-3) Completed

☐ Elevation Views (0-3) Completed

☐ Photograph dates and numbers listed in each sections notes

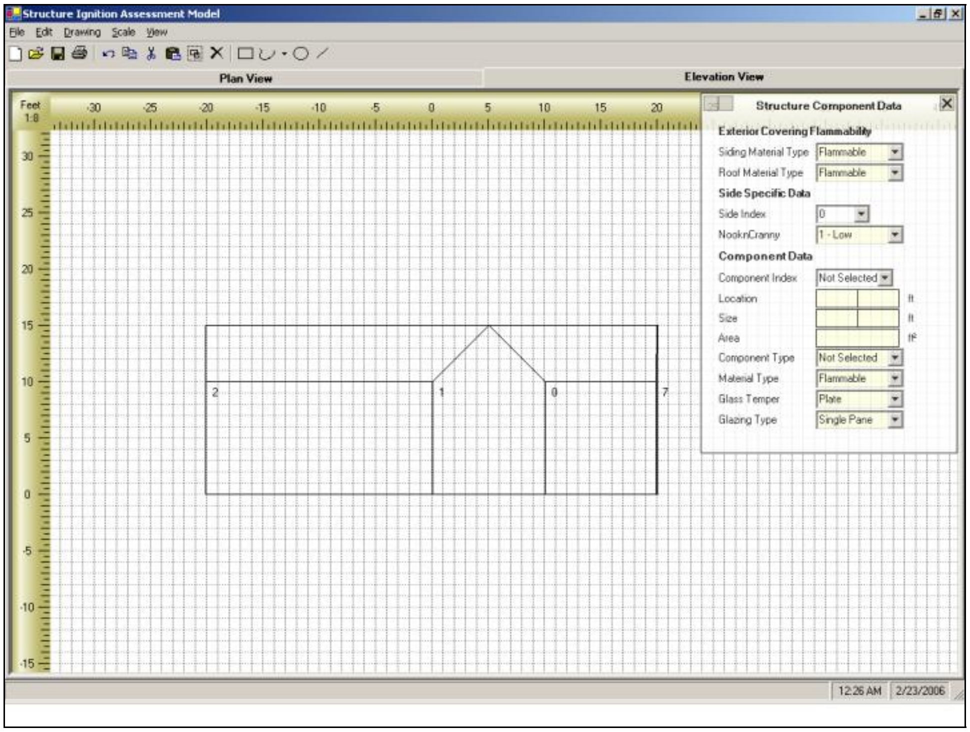
APPENDIX B - EXPANDED METHODS DESCRIPTION

Defining the home ignition zone

The designer of SIAM, Jack Cohen recommended using a HIZ extending 100 feet out from structure walls both in literature (Finney and Cohen 2003) and with personal communication (Cohen Pers. Comm. 2005). Several of Cohen's reports describing the SIAM and results from wildfire investigations and experiments note that crown fires are unable to ignite flammable surfaces without flame contact and even at distances of only 20-30 meters little if any scorch occurs (Cohen 2000). In addition, several other authors support a decision to use a small area to define a home ignition zone based on post-fire assessments. For example, Howard et al. (1973) reported 95 percent survival for homes in the path of wildfire with fire resistant roofs and vegetation clearing 10-18 meters around residences. Foote (1994) had similar findings with a different fire path where an 86 percent survival rate is reported for structures with fire resistant roofing and a ten-meter clearing.

Converting visited homes to SIAM data

When walls are more complicated than a simple rectangle, they are forced to a four-sided structure and the distances from each fuel source to the new sides are adjusted and drawn. The drawings are then used as exactly as possible for data entry. The structure is initially constructed with the computer mouse using a rectangle tool. Fine adjustments are made to the location of the four corners using dialog boxes (Figure B-1). Nodes are inserted into walls where heights or base levels change. Roofs are automatically generated based on wall height information entered in dialog boxes. Windows are entered as rectangles and then modified with the structure component data dialog box. Ignitability/non flammability for siding and roof material are also selected using the structure component data dialog box.



Structure Component Data

Exterior Covering Flammability

Siding Material Type: Flammable
Roof Material Type: Flammable

Side Specific Data

Side Index: 0
NooknCranny: 1 - Low

Component Data

Component Index: Not Selected
Location: ft
Size: ft
Area: ft²
Component Type: Not Selected
Material Type: Flammable
Glass Temper: Plate
Glazing Type: Single Pane

Figure B-1. Elevation views are constructed with mouse and dialog boxes in SIAM.

Once the structure is constructed in the elevation view, the user switches to the plan view to enter fuels and terrain data. Topographic information is entered for each side of the structure using a slope and distance from the structure to the slope offset. All fuels within 100 feet of each side of each structure, and the rectangle that this area creates (i.e., the HIZ) are then entered using computer mouse digitizing in SIAM.

Rating Nook and Crannies for SIAM

Decks are a major component in the nook and cranny index. A score of one represents very little nook and cranny susceptibility to firebrands. An example is a side of a house with metal siding, metal windowsills and vents screened with fine metal mesh. A score of five indicates abundant firebrand ignition opportunity. An example is a side of a house with a wooden deck, firewood piled against checked log siding and unpainted wooden windowsills. This information is recorded for each side of each structure.

Modeling Fire Probabilities in SIMPPLLE

Fire management zones are the way that SIMPPLLE uses past fire information to develop expectations for future fire ignitions. The simulations can be based on a single fire management zone or multiple fire management zones. The process to develop these zones requires a listing of all the fires that have occurred in the analysis area during a measurable period of time in the past. The number of fires is then standardized to one decade using multiplication or division.

Using Recent Forest Management To Initialize The Modeling

Codes describing these activities are used to crosswalk to initial treatments in SIMPPLLE to define existing stand conditions on which simulations will be based. Note that not all acres in each stand selected received the silvicultural treatments, so the acres for each treatment may be exaggerated in the simulations. Table B-1 is a crosswalk for all the activities obtained from the local USFS ranger district to relate Bitterroot National Forest treatments acknowledged by SIMPPLLE as initial treatments.

Table B-1. Crosswalk between local ranger district activity codes and the SIMPPLLE model initial treatment and initial process categories.

ACTIVITY_C	ACTIVITY_N 1995-2004	Initial Treatment	Initial Process
4961	Ecosystem Burning - Grassland	ECOSYSTEM-MANAGEMENT-BROADCAST-BURN	
4962	Ecosystem Burning - Shrubland	ECOSYSTEM-MANAGEMENT-BROADCAST-BURN	
4963	Ecosystem Burning - Stand Modification	ECOSYSTEM-MANAGEMENT-BROADCAST-BURN	
4978	Broadcast Burn	ECOSYSTEM-MANAGEMENT-BROADCAST-BURN	
4980	Understory Burn	ECOSYSTEM-MANAGEMENT-UNDERBURN	
4981	Wildland Fire Not Managed for Resource Objectives	See intial process	MIXED-SEVERITY-FIRE
4992	Wildland Fire Managed for Resource Objectives	See intial process	MIXED-SEVERITY-FIRE
4993	Burning For Range Improvement	ECOSYSTEM-MANAGEMENT-UNDERBURN	
4995	Shrubland/Grassland Burning	ECOSYSTEM-MANAGEMENT-UNDERBURN	
Harvest Related Activities	ACTIVITY_N 1995-2004		
4111	Patch Clearcut	GROUP-SELECTION-CUT	
4114	Clearcut with Reserves	CLEARCUT-WITH-RESERVES	
4121	Shelterwood Preparatory Cut	SEEDTREE-SEEDCUT	
4131	Shelterwood Seed Cut	SHELTERWOOD-SEEDCUT	
4132	Seed Tree Seed Cut	SEEDTREE-SEEDCUT	
4133	Shelterwood Seed Cut with Reserves	SHELTERWOOD-FINAL-WITH-RESRVES	
4134	Seed Tree Seed Cut with Reserves	SEEDTREE-SEEDCUT	
4148	Shelterwood Final Cut with Reserves	SHELTERWOOD-FINAL-WITH-RESRVES	
4151	Individual Tree Selection Cut	INDIVIDUAL-SELECTION-CUT	
4152	Group Selection Cut	GROUP-SELECTION-CUT	
4210	Improvements	IMPROVEMENT-CUT	
4211	Liberation Cutting	LIBERATION-CUT	
4220	Thinning	COMMERCIAL-THINNING	
4230	Sanitation (Salvage)	SANITATION-SALVAGE	
4231	Mortality(Dead Trees Cut)	SANITATION-SALVAGE	
4232	Sanitation	SANITATION-SALVAGE	
FIRE HISTORY 1995-2004			
	Fire History Perimeters 1995-2004		MIXED-SEVERITY-FIRE
ADS SURVEYS 1995-2004			
11006	Mtn. Pine Beetle		PP-MPB or LIGHT-LP-MPB
11007	Douglas-fir Beetle		DF-BEETLE
11009	Spruce Beetle		SPRUCE-BEETLE

Mitigation Cost estimates

The cost estimates for mitigation efforts modeled for the 291 structures in this research ranged from $184,080 to $5,600,467.

Window Upgrades

The first mitigation option is upgrading windows. The size and number of all single pane windows encountered in the field are measured. These measurements are used to calculate the average number and area of single pane windows that could be upgraded to double pane at each of the visited houses with this opportunity for mitigation. The proportion of visited homes with this option is applied to the 291 study area homes to develop a cost estimate for the full set of homes. There are seven houses that could have single pane windows upgraded to double pane windows. Fifteen is the average number of windows to upgrade at each house with this option. The average area of each of the 105 windows that could be replaced at these seven houses is 833.7 square inches. Because this is very close to a two by three foot window (864 square inches) the estimate to replace this size window, obtained from a local source, is used. The costs to remove an existing window and replace it with a wood framed two by three-foot window is estimated at $236. When this is multiplied by the number of windows (15) at the average house with this opportunity and then by the number of houses in the study area that likely have this potential (52) the result is a cost estimate of $184,080.

Siding Upgrade

For siding, each house has four walls, two have the same average length measurements (averages are 61.5 and 45.3 feet), but all four have different average height measurements (averages are 16.9, 19.2, 17.4 and 20.6 feet). The height and length measurements are multiplied for each side of each house to generate a total wall area for each house with flammable siding. These area estimates are divided by 100 square feet to create a number of Squares, where a square is equal to one ten foot by ten foot section of wall material. Locally obtained labor costs representing average removal and installation ($80/Square) costs per square are added to material costs ($135/Square) per Square and multiplied by average squares per house visited to derive the average siding replacement cost per WUI residence. The number of Squares per house is averaged for all homes that have the siding replacement opportunity. By first multiplying the average number of squares (40.33) times the cost estimate of $215/Square an average siding replacement cost of $8,670 per house is derived. An average cost per house to replace the siding is then extrapolated to the proportion of homes in the study area that have this mitigation option. The estimated number of the houses (246) that have a siding replacement mitigation opportunity across the study area is next multiplied by this cost figure. The result is an estimated cost of $2,135,048.

In order to estimate the cost of HIZ option C, which is upgrade of windows at seven houses and siding replacement at 33 houses the window upgrade cost estimate is added to the cost estimate for siding. An estimated cost of $2,319,128 is calculated by adding the $184,080 window upgrade cost to the $2,135,048 siding replacement cost.

Full fuel conversion costs estimation procedures

All the houses modeled in the SIAM plan view have a four foot-by-four foot grid overlaying all the mapped fuels. The number of these cells removed for each mitigation option (light and full fuel removal) in any of 22 fuel categories is counted for each side and recorded. Several of the basic nine fuel categories available in SIAM are split into additional categories. Three height classes of shrubs and five height classes for trees are used. Trees are further broken into two classes (single tree or groups of trees) in each height class.

The author consulted several contractors in an attempt to derive area-based cost estimates for each fuel type. Unfortunately, contractors rarely perform the full fuel conversion activities modeled in this dissertation nor do they perform cost estimation with the approach used in this dissertation. As a result, contractors are asked to evaluate the author's best guess at these costs. Sprinkler installation costs are used as part of the total to convert short dry grasses to watered, non-flammable grass. Medium and long grass requires some additional costs to transform this fuel into a lawn type vegetation area. The number of sixteen square foot fuel cells removed for both the light and full fuels conversion mitigation options is counted for each side of each home and these counts are recorded. The light fuels removal is estimated to cost $1,235,075 with an average of $4,591 for each house. The full fuels conversion option is estimated to cost $3,284, 920, with an average cost of $11,288 per house.

The aggregated cost estimates for the 291 study area houses in the study area, and used to calculate the budgets that accompany each potential HIZ fuel conversion mitigation option. The number of sixteen square foot fuel cells removed for both the light and full fuels conversion mitigation options is counted for each side of each home and these counts are recorded.

Modeling Effectiveness

In the case of the HIZ mitigations, the impacts on the SIAM model results are multiplied by the 30-year fire probability estimates for each house's host polygon, obtained from the existing hazard SIMPPLLE simulations. In the case of the silvicultural forest treatment regime schedules, the impacts that the MAGIS generated schedules have on the SIMPPLLE fire probabilities are multiplied by the existing ignition SIAM for each house.

APPENDIX C - SENSITIVITY ANALYSES FOR MODEL PARAMETERS

Each modeling tool used here is currently in development; however, land managers are using this (2.3) and subsequent versions of SIMPPLLE. Ideally, each model would have a documented (SA), describing the impact of various changes to model parameters; this is not the case. In order to better understand each model's parameter sensitivity, SAs are devised. They are not intended to be comprehensive, but rather to provide context needed to understand the modeling system. The sensitivity of the modeling system must be considered when results from two independent models are combined to form existing hazard estimates in the case study area.

SIAM sensitivity analysis methods

Although complete testing of any model is the designer's responsibility, several key SIAM parameters are tested using real field data to provide a better understanding of the model's sensitivity. Five of the 39 structures are randomly selected. Local sensitivity analyses are then conducted by varying ambient temperature and wind speeds. Ranges are selected to represent realistic summer weather possibilities in the study area during the fire season. Both 80F and 100F temperatures are tested and wind speeds ranging from 0 to 40 miles per hour are tested at five mile per hour (mph) intervals. Combinations of these temperature and wind speed changes from default settings[51] are then used to detect synergistic impacts on the model. The ignition expectations are recorded for all changes, as is the impact of the nook and cranny and fire branding probability, a component of the calculations that represents the interaction of the two subjective ratings (firebranding

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[51] SIAM default settings: 90F and 20 mph

potential (1-3) within ¼ mile of each side, and nook and cranny ratings (1-5) for each side).

One additional concept is tested with this SA. When fuels are entered using polygons in SIAM they appear to accurately represent fuel position relative to each structure. Although the fuels appear as polygons in SIAM's plan view, the physics equations used to calculate the flux time products are actually modeled using the largest rectangle possible from the polygon. In other words the most distant x and y coordinates are used to generate a rectangle. Figure C-1 shows the rectangle that would actually be used for a polygon fuel source. This feature of SIAM might lead one to believe that both the proximity of fuel sources to walls would be underestimated and fuel source size would be overestimated. The expected impact is flux time product overestimation, leading to inflated ignition expectations. To test how strongly this affects the estimates, all fuel sources in the five test structures are converted into many smaller rectangles. Then all rectangles are selected in a separate modeling effort and results are compared.

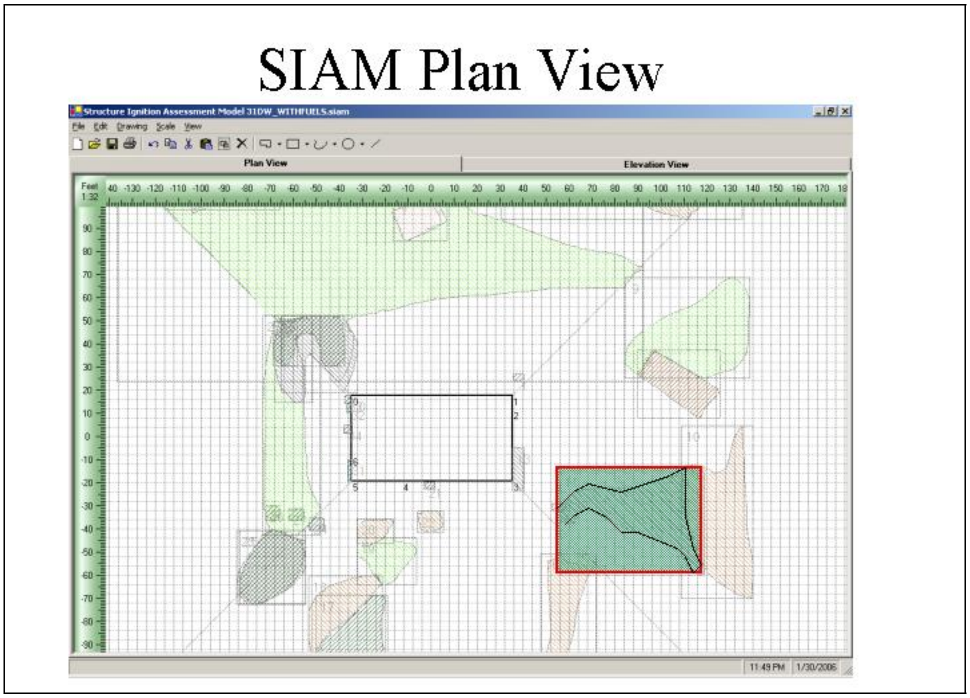

Figure C-1. SIAM model rectangle interpretation of mouse digitized irregular polygons.

SIMPPLLE sensitivity analysis methods

Conducting a complete SA is the responsibility of any model designer. A limited SA is conducted for this study to provide context regarding the sensitivity of simulation-based fire probabilities to various parameters that help the author decide what settings to use for this project.

With recognition that SIMPPLLE is typically used at the landscape scale and that it is being used here at the polygon scale, the sum acreage of fire across three decades is tracked in multiple areas for the SA. The entire area modeled with landscape disturbance software is broken into four nested special areas for analysis purposes (Figure C-2). The special areas are: (1 – Blue, 243 stands) those acres in only the polygons that host homes in the study area, (12 – Green, 1,137 stands) those acres in polygons that have portions within 1/4 mile = 402.336m (a high probability firebranding distance) of homes in the study area and, (123 – Orange, 4,173 stands) those acres in polygons within one and a half miles of the study area WUI structures, and (1234- Red, 52,570 stands) all remaining acres in the study area.

Each special area serves a purpose in the analysis. For example, the special area that includes the area extending one and one half miles from all 291 structures is used to restrict the thinning and prescribed burning treatments to the default area specified in the Healthy Forest Restoration Act. Figure C-2 below shows the study area broken into four special areas with the 291 residences shown as light blue points.

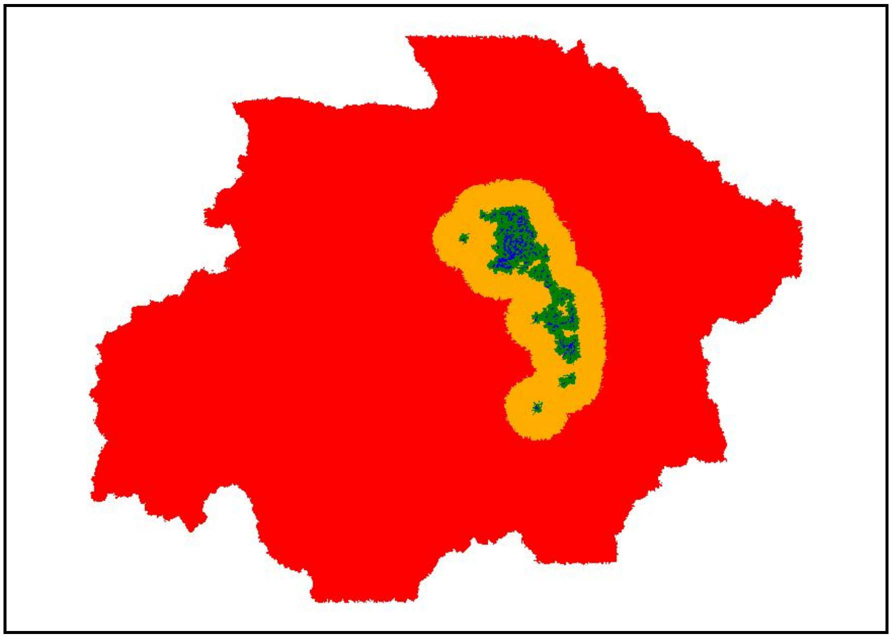

Figure C-2. The SIMPPLLE study area broken into nested special areas.
Blue = 1, Green = 12, Orange = 123, and Red = 1234.

The SIMPPLLE SA is conducted using all polygons in the modeling area (58,123 polygons totaling 381,362 acres) as well as only the polygons that host a residence in the study area (243 polygons totaling 1,361 acres). The three fire severity class outputs for each simulation (light, mixed and stand replacement) are summed, to create a combined or ‘total fire’ acreage of all severity fire predictions. This has been done for other SIMPPLLE modeling efforts and appears logical, given that these severity delineations span a gradient of vegetative mortality and because any fire can cause a home ignition. To summarize the mean number of acres that burn for 30, three-decade simulations, in two nested collections of polygons (total and those hosting a residential structure) are used as the output for each parameter change. Results are reported with the ranges of 30 simulation averages that result from parameter changes. They are also shown with charts that show these averages connected with best-fit lines.

The limited SA employs mainly local (changing one variable at a time) parameter changes in the SA. Suppression is the one discrete parameter tested. All other parameter changes are tested with suppression turned off. For continuous variables a reasonable range for each parameter to be tested is first determined. Both the range for each input parameter and the range of average output of total fire are provided below in tables C-1 and C-2 for the entire SIMPPLLE analysis area and the special area 1, respectively.

Table C-1. Sensitivity of simulated fires within the entire SIMPPLLE study area to changes in important model parameter levels.

Parameter	Range of parameter levels analyzed	Average area burned from 2004-2034	Percent Range of total area (381,320ac.) burned, 2004-2034
Basecase		123,908	32%
Extreme Fire Spread Probability	0.1-100	119,051-339,922	31-89%
Weather Ending	0.5-1.5* x’s default	114,930-129,869	30-34%
Insect Logic	0.5-1.5* x’s default	112,122-115,495	29-30%
FMZ 1	0.5-1.5 x’s default	96,131-141,539	25-37%
FMZ 2	0.5-1.5 x’s default	112,981-116,562	30-31%
30 Year Fire Record FMZ Single Probability /acre		118,874	31%

* Some infestation probability settings are restricted below 150% by hitting the 1.0 maximum.

Table C-2. Sensitivity of simulated fires within polygons hosting residences to changes in important model parameter levels.

Parameter	Range of parameter levels analyzed	Average area burned from 2004-2034	Percent Range of total area (1,361 ac.) burned, 2004-2034
Base case		75	6%
Extreme Fire Spread Probability	0.1-100	102-1,361	7-100%
Weather Ending Events	0.5 – 1.5 x's default	75-122	5-9%
Insect Logic	0.5-1.5* x'sdefault	81-111	6-8%
FMZ 1	0.5-1.5 x's default	58-87(93 FMZ 1 Basecase)	4-6% (7%)
FMZ 2	0.5-1.5 x's default	72-235 (177 FMZ 2Basecase)	5-17% (13%)
30 Year Fire Record FMZ Single Probability /acre		114	8%

* Some infestation probability settings are restricted below 150% by hitting the 1.0 maximum.

The first parameter tested is the probability of extreme fire spread. The next set of parameters tested is the probability that fires of various sizes greater than 0.25 acres are extinguished by weather ending events. All fires smaller than 0.25 acres are kept at default settings.

One of the attractive features of SIMPPLLE is the model's interaction between stochastic insect and disease activity and stochastic fire events. There are two main species of insects active in the SIMPPLLE study area. Therefore, the sensitivity of the simulations to various insect infestation rates common in the modeling area, namely lodgepole pine mountain pine beetle (PICO MPB) and Douglas-fir beetle (DFB) levels is tested. The PICO MPB logic uses two (light and severe) probabilities for three plant community hazard groups (low, moderate, high hazard). These groups are based on past process information in each vegetative community as well as information about the number of adjacent communities with past or current PICO MPB process. The DFB logic is based on the species composition of vegetative communities and has two hazard probability groups (light or mixed severity fire in the past and other processes in the past) used to assign various probabilities to the range of size classes for each species mix. All the default insect and disease information is based on work by Fischer and Bradley (1987). All the probabilities are varied in 10 percentile increments[52] simultaneously for these two common insects.

Most simulations used for the SA are run based on a single fire management zone (FMZ). There are also two sets of fire management zones created for the SA. The first is an area of R1-VMP stands that intersects a ¼ mile buffer applied to all roads open to motorized use during the fire season on the public lands in the modeling area (Figure C-3). This is done to examine the variability in fire probability outputs if areas where campers and recreational visits could increase the potential for future fire starts. Roads are selected based on codes that describe the dates of various motorized restrictions. The second FMZ is an area of R1-VMP stands that intersects the area ¼ mile around all WUI structures in the study area; this area is the same as special areas 1 and 12 (Figure C-2). In both cases a step is taken to separate fires during the last decade into those that occurred inside the distinct FMZ area and those in the remainder of the modeling area, and each FMZs is recalculated to reflect historical observations of the different probabilities of fire per acre per decade in the two areas.

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[52] Probability numbers are entered with a series of dialog windows and all are rounded up from 0.5 to accommodate data entry. Several probabilities entered in these windows reach a maximum at 1.0 before the upper limit (one and one half times the default parameter levels) of the parameter testing is reached.

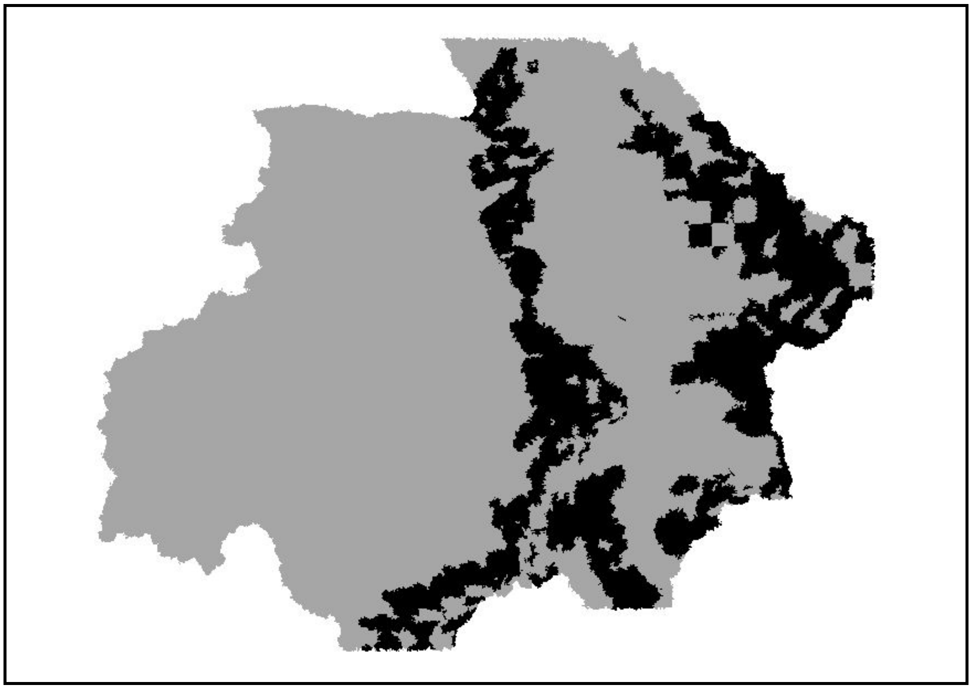

Figure C-3. Fire Management Zone (FMZ) 1, the area within ¼ mile of roads open during fire season.

While using historical ignition data for the modeling area seems useful, it raises the question of how long of a historical period to use as a reference. Factors like changes in fuels, climate, suppression effort and detection capabilities all make the selection of the best reference period challenging. Records of ignitions in the modeling area exist from 1970 to the present. The SA described thus far are based on records abbreviated to just the most recent decade. One simulation scenario in the SA uses a single FMZ with the full 35-year record standardized to one decade.

SIAM sensitivity analysis results

Changing temperature alone has no impact at all on overall ignition probabilities. Wind speed selection influences both the nook and cranny impacts and overall ignition probabilities, with probability changing thresholds varying between sides of each structure, but all occurring below the 20 mph SIAM default wind speed. Figure 30 shows probability changing thresholds, with windspeeds affecting overall SIAM ignition estimates in green triangles and those affecting the nook and cranny ignition probabilities below with blue diamonds. All of these wind speed thresholds are below the 20MPH default setting for SIAM.

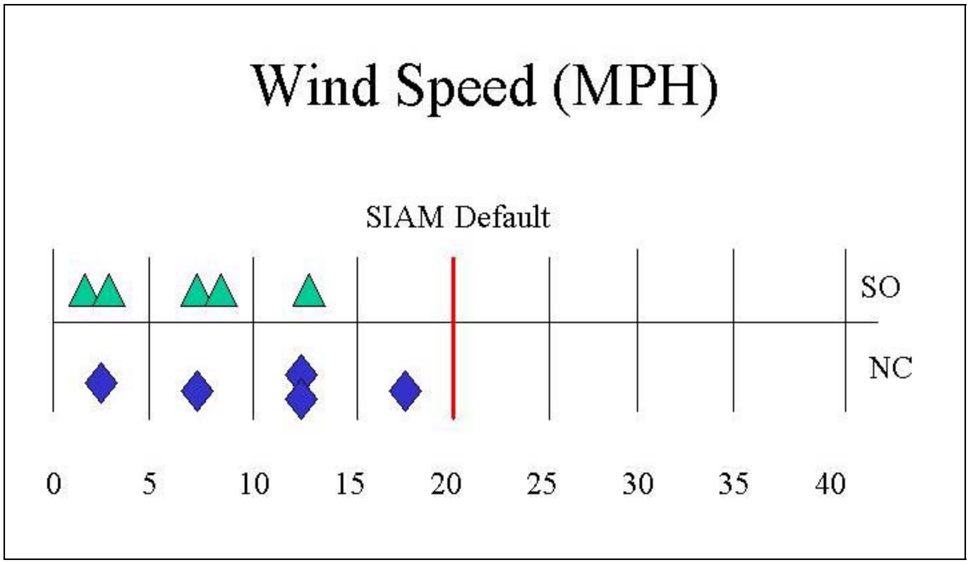

Figure C-4. Nook and Cranny (NC) and SIAM (SO) wind speed probability thresholds.

Results from the SA show that the default settings are indeed on the extreme end of the analysis spectrum. When combinations are tested against the default conditions, lower temperature (80F) combined with lower wind speeds reduce the ignition expectations, whereas higher temperature (100F) combined with higher wind speeds do not increase ignition expectations beyond those at default levels. In summary, the default SIAM weather conditions appear to provide the upper limit of ignition probabilities possible with SIAM.

Contrary to expectations, not all sides of the structures have lower ignition expectations following the polygon to small rectangle conversion. Only three of the twenty (four sides of five houses) sides converted show any impact. While two sides show decreased ignition probabilities, one side shows an increased probability following conversion. Although this feature of the software is a recognized weakness, the impact on the findings does not seem to warrant conversions for all sides in the modeling effort.

Nook and cranny results provide some additional insight into the SIAM ignition probability calculations. The current version of the software reports a nook and cranny probability, which is part of the overall ignition probability. This is itself a combination of the firebranding rating, the nook and cranny rating, and fuel source proximity. Ignition probabilities for 44 of the 156 sides modeled are dominated[53] by nook and cranny probabilities. The minimum impact is 0.0 for a firebranding score of one and a nook and cranny score of one. The maximum impact is 0.505 for a side with a firebranding rating of three and a nook and cranny of five. Yet, not a single visited home has a maximum ignition probability for all sides dominated by a nook and cranny probability. Modeling various homes, indicates that including specific fuel sources close to structures enhances the nook and cranny ignition probability levels as well as the variability within nook and cranny ignition probability levels; all fifteen combinations of the two factors bear this out. Table C-3 is a nook and cranny probability matrix for modeled residences with various nook and cranny and firebranding ratings. The numbers reported in Table C-3 are only part of the overall SIAM ignition probability calculations.

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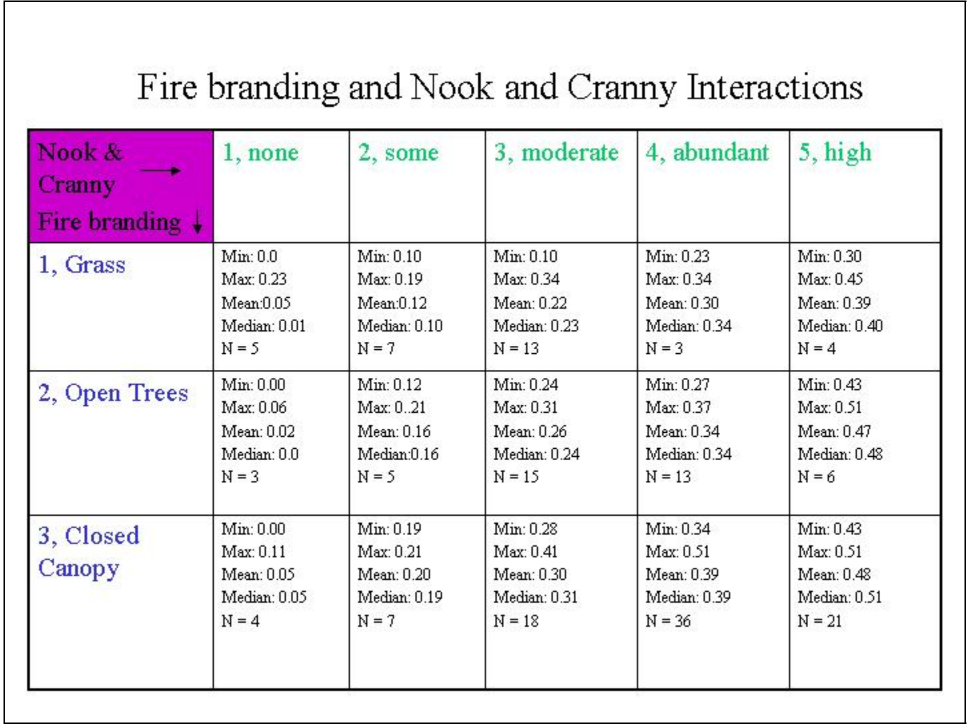
[53] Nook and Cranny is said to dominate the overall probability when they are equal. The overall probability is always elevated to the level of the nook and cranny, but often is higher based on flux-time product calculations.

Table C-3. The nook and cranny / firebranding score results matrix



Fire branding and Nook and Cranny Interactions

Nook & Cranny → Fire branding ↓	1, none	2, some	3, moderate	4, abundant	5, high
1, Grass	Min: 0.0 Max: 0.23 Mean:0.05 Median: 0.01 N = 5	Min: 0.10 Max: 0.19 Mean:0.12 Median: 0.10 N = 7	Min: 0.10 Max: 0.34 Mean: 0.22 Median: 0.23 N = 13	Min: 0.23 Max: 0.34 Mean: 0.30 Median: 0.34 N = 3	Min: 0.30 Max: 0.45 Mean: 0.39 Median: 0.40 N = 4
2, Open Trees	Min: 0.00 Max: 0.06 Mean: 0.02 Median: 0.0 N = 3	Min: 0.12 Max: 0..21 Mean: 0.16 Median:0.16 N = 5	Min: 0.24 Max: 0.31 Mean: 0.26 Median: 0.24 N = 15	Min: 0.27 Max: 0.37 Mean: 0.34 Median: 0.34 N = 13	Min: 0.43 Max: 0.51 Mean: 0.47 Median: 0.48 N = 6
3, Closed Canopy	Min: 0.00 Max: 0.11 Mean: 0.05 Median: 0.05 N = 4	Min: 0.19 Max: 0.21 Mean: 0.20 Median: 0.19 N = 7	Min: 0.28 Max: 0.41 Mean: 0.30 Median: 0.31 N = 18	Min: 0.34 Max: 0.51 Mean: 0.39 Median: 0.39 N = 36	Min: 0.43 Max: 0.51 Mean: 0.48 Median: 0.51 N = 21

SIMPPLLE sensitivity analysis results

Results from the SA are summarized in two tables above. Table C-1 conveys information about results across the entire SIMPPLLE analysis area whereas Table C-2 shows the sensitivity to parameter changes in polygons hosting study area WUI structures. The most important parameter for the modeling system is the selection of suppression[54]. The second most potent parameter in SIMPPLLE's fire logic is the probability that a given fire[55] spreads with extreme wind conditions (conceptualized by model designers as spreading with increased contagion ability). The full range of this parameter is tested, with 1 percentile changes between 0.01 and 0.1 and ten percentile

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[54] There is a table below in the modeling system sensitivity section that discloses the summary statisitics for the modeling system when suppression is turned off.

[55] Note that all fires that grow to 1,000 acres are also assumed in SIMPPLLE simulations to spread across the landscape with extreme wind conditions.

changes between 0.1 and 1.0. The three-decade range of mean total fire area for this parameter is 119,051 – 339,922 ac. (Figure C-5) and 102 – 1361 ac. (Figure C-6) for the total area and residential host polygon area, respectively. These ranges correspond to ranges of 31 - 89% and 7 – 100% for these two areas.

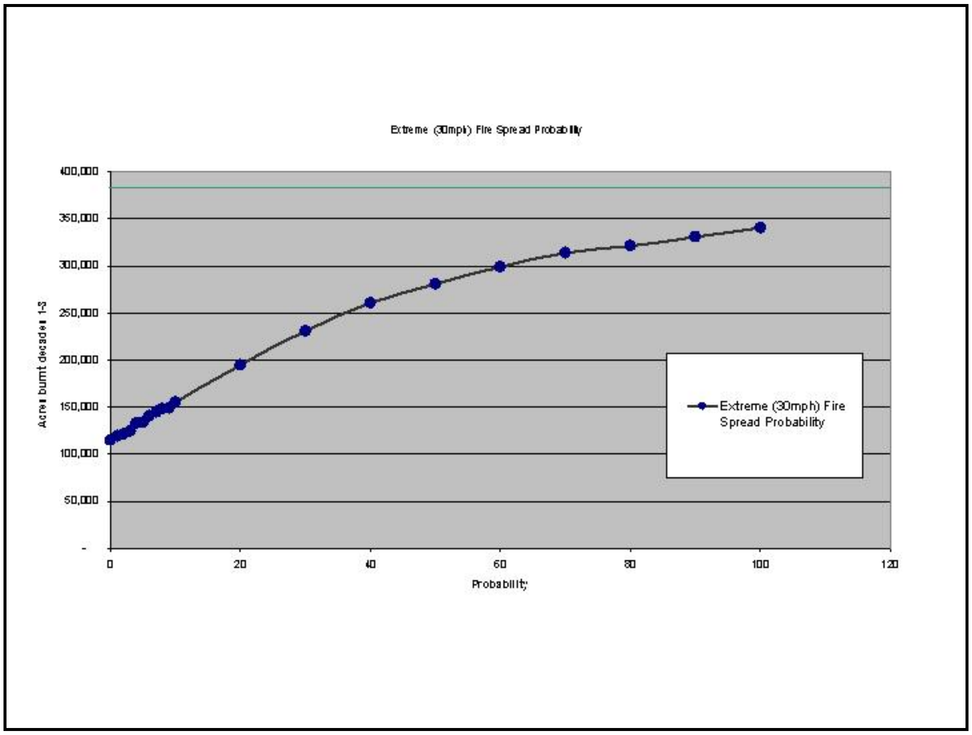

Figure C-5. Extreme fire spread parameter sensitivity in total modeling area.

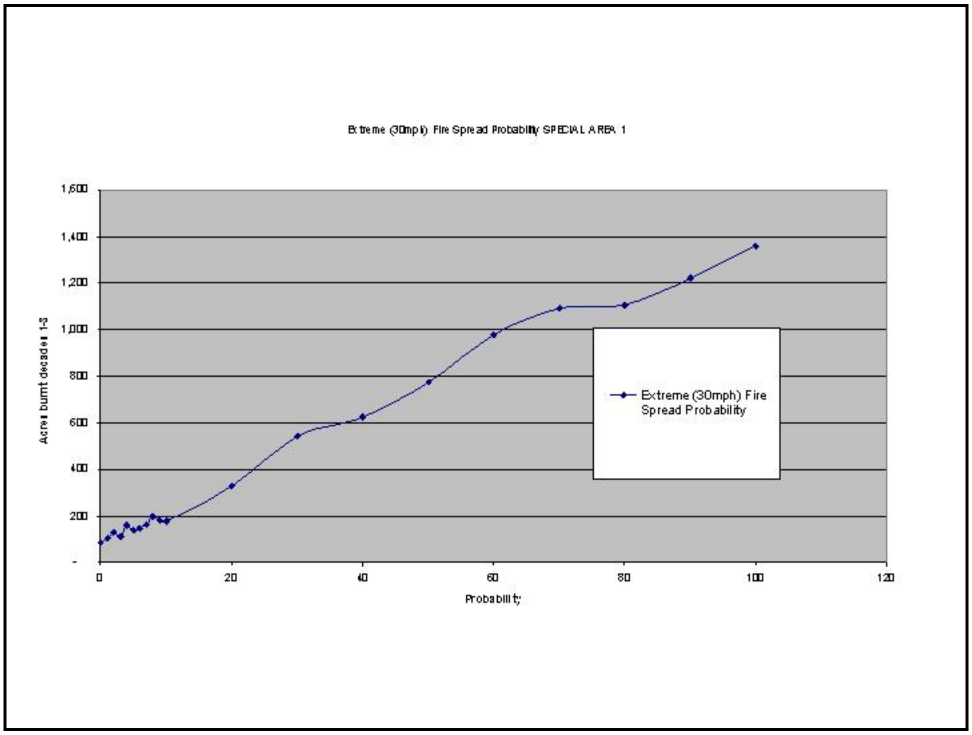

Figure C-6. Extreme fire spread parameter sensitivity in polygons hosting residences.

The probability that fires greater than 0.25 acres in size are extinguished by weather-ending events (fall rains or snow) is another parameter that is tested in the SA. The full range of this parameter is tested from 0 to 1.5 times the default settings at 10 percentile increments. The range of mean total fire area for this parameter is 114,930 – 129,869 ac. and 75 - 122 ac. for the total area (Figure C-7) and residential host polygon area (Figure C-8), respectively. These ranges correspond to 30 - 34% and 5 – 9% for these two areas. Changing the probabilities used to model this variable creates a relatively small effect on in the acreage of fire during the three decades modeled.

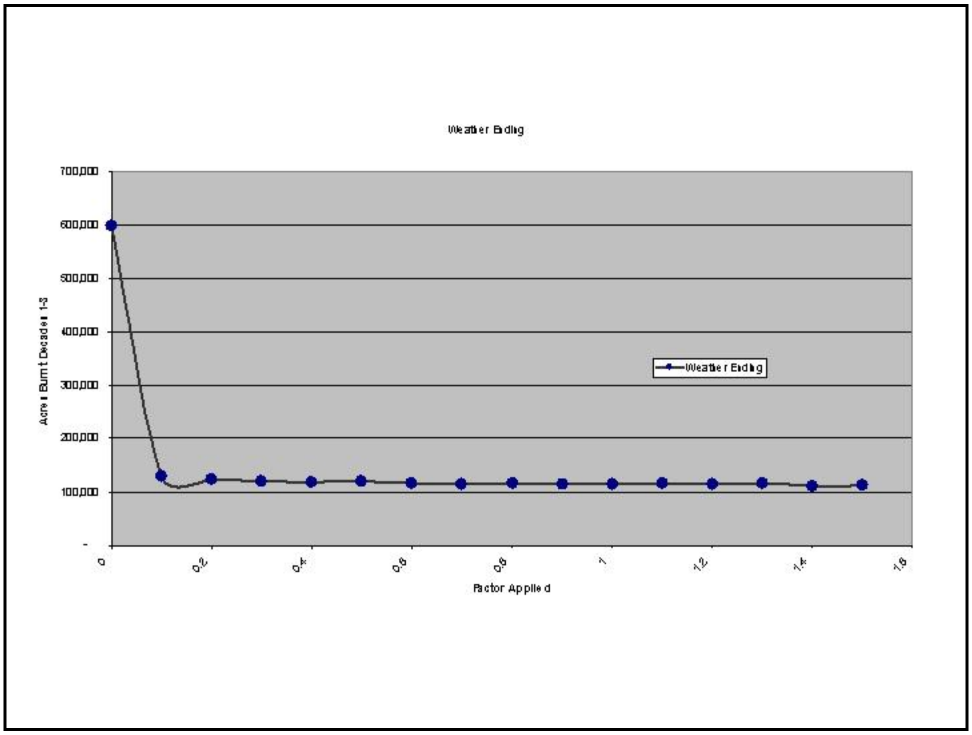

Figure C-7. Changes in area burned based on changes to default settings (0.5 – 1.5) for probabilities of weather extinguishing fires of various sizes greater than 0.25 acres, for the total modeling area.

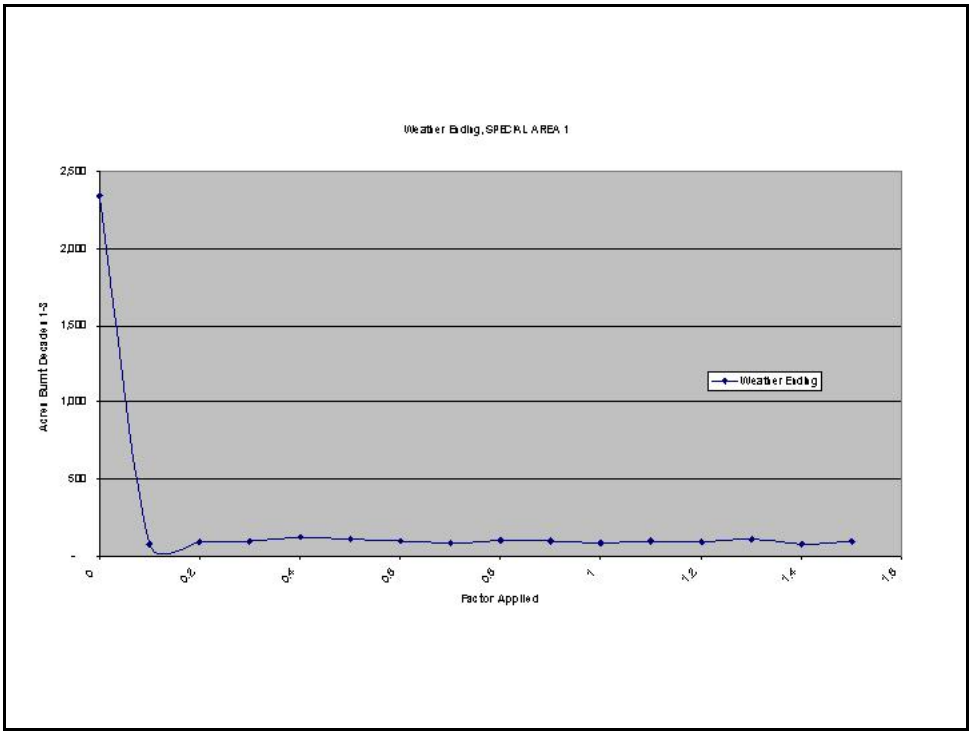

Figure C-8. Changes in area burned based on changes to default settings (0.5 – 1.5) for probabilities of weather extinguishing fires of various sizes greater than 0.25 acres, for the polygons hosting houses.

The range of average total fire area for the Douglas-fir and mountain pine beetle infestation parameters is 112,122 – 115,495 ac. (Figure C-9) and 81 - 111 ac. (Figure C-10) for the total area and residential host polygon area, respectively. These ranges correspond to 29 - 30% and 6 – 8% for these two areas. Changing this parameter not only generates very small changes in the acreage of fire during the next three decades, it also shows no obvious pattern of fire acreages in the smaller area of polygons hosting residential structures. The lowest and highest total fire acreages modeled in the critical area hosting homes occur within one ten percentile change (0.6 to 0.7) in these parameters, suggesting that the interactive stochasticity of infestations and fire overwhelms the changes in these parameters settings.

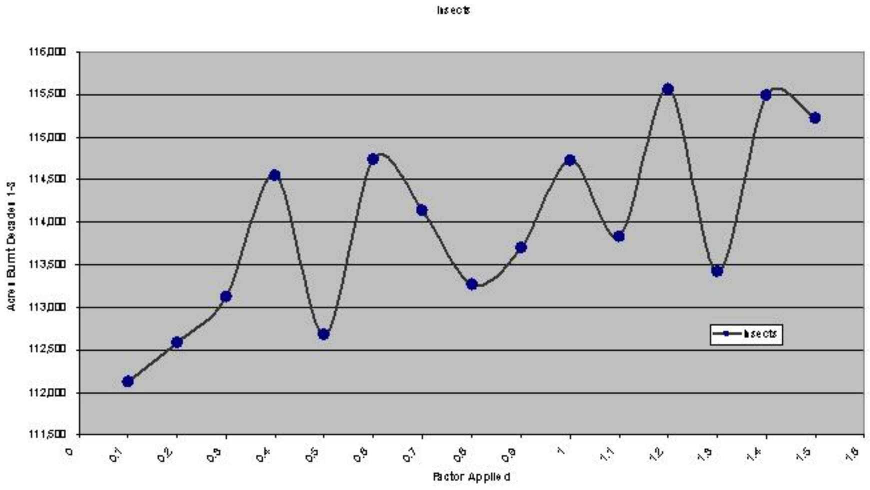

Figure C-9. Changes in area burned based on changes to default settings (0.5 – 1.5) for mountain pine beetle and Douglas-fir beetle logic, for the total analysis area.

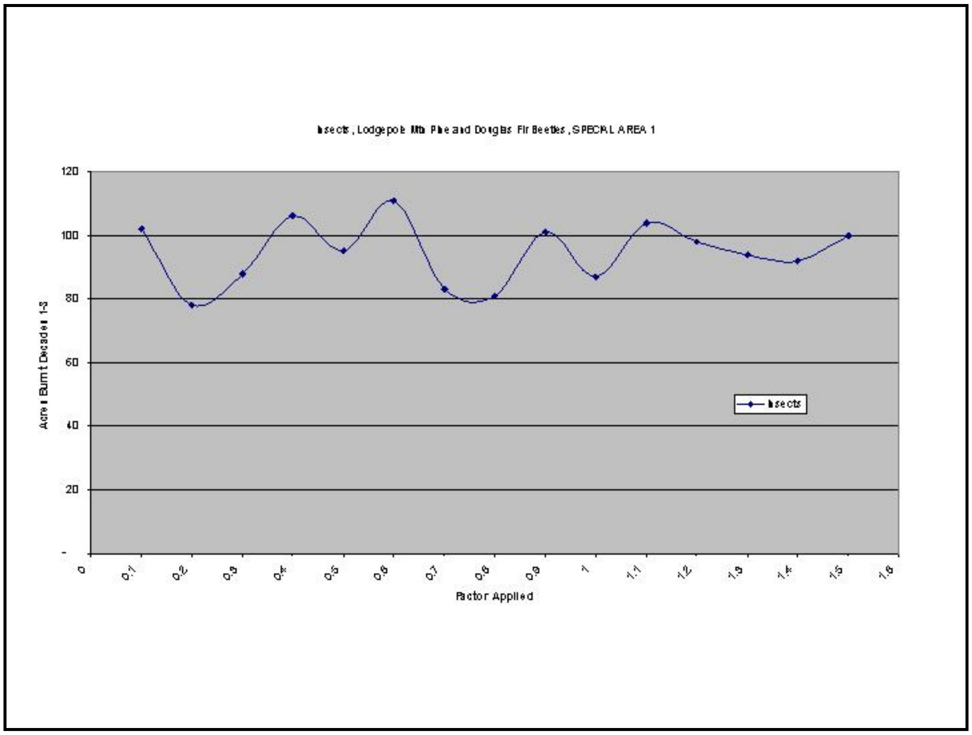

Figure C-10. Changes in area burned based on changes to default settings (0.5 – 1.5) for mountain pine beetle and Douglas-fir beetle logic, for the polygons hosting houses.

Sensitivity of ten percentile changes to probability per acres for both fire management zones are also tested within the range of 50 percent to 150 percent of the historic ignitions per acre for the most recent decade. The first FMZ separates the area into polygons within a quarter mile of all roads crossing public lands in the modeling area that are open to motorized travel during the fire season and those not in this area. This roaded area comprises 79,915 acres or roughly 21% of the area modeled. The range of total fire acres for the next three decades is from 96,131 – 141,539 ac. (Figure C-11) for the entire SIMPPLLE analysis area and 58 – 87 ac. (Figure C-12) in the vegetative communities hosting residential structures, respectively. These ranges are quite different than the two average outputs for the no suppression base case for this fire management zone, of 113,738 ac and 93 ac., suggesting that the acreage burning for 30 years is highly sensitive to the number of ignitions in the FMZ.

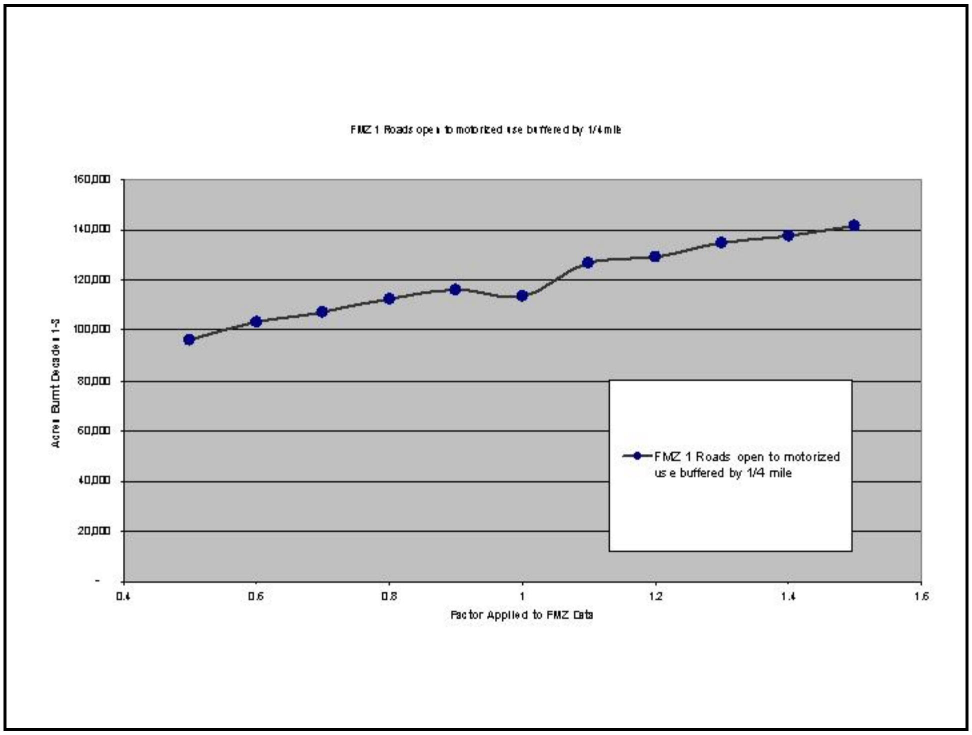

Figure C-11. Changes in area burned based on changes to default FMZ settings (0.5 – 1.5) for the buffered open road area only, for the total analysis area.

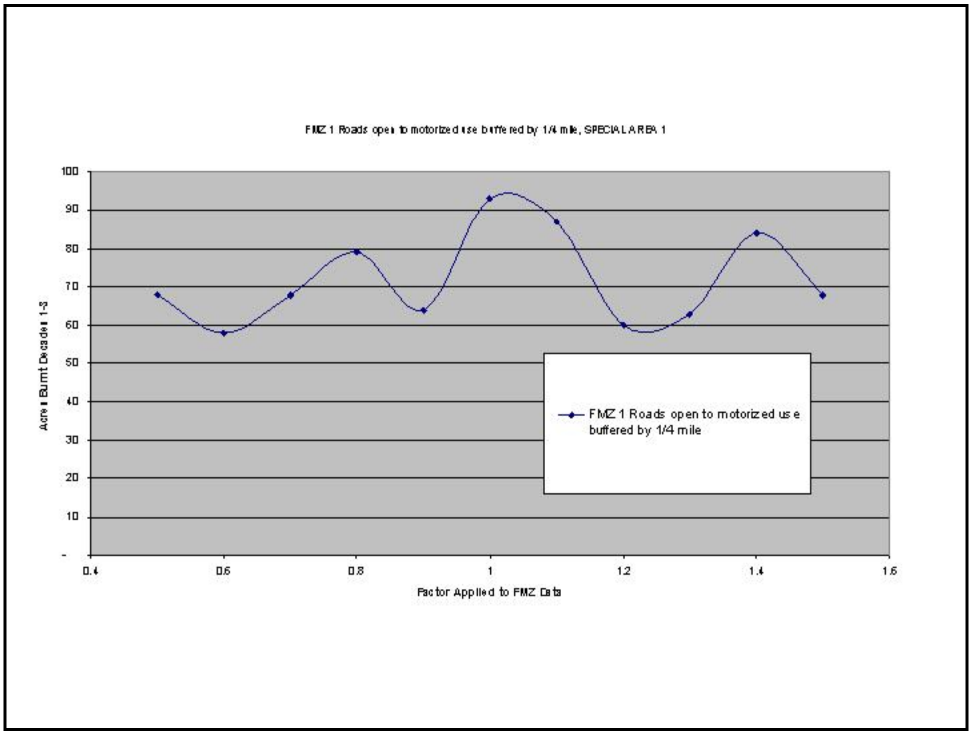

Figure C-12. Changes in area burned based on changes to default FMZ settings (0.5 – 1.5) for the buffered open road area only, for polygons hosting houses.

A second FMZ separates the SIMPPLLE analysis area into one part within a quarter mile of all WUI residential structures defined as the study area structures for this project and one part outside these buffers. This area comprises a much smaller area, only 8,073 acres in size or roughly 2% of the modeled area. The range of total fire acres for the next three decades ranges from 112,981 – 116,562 acres in the total analysis area (Figure C-13) and 72 – 235 acres in the vegetative communities hosting residential structures (Figure C-14). These ranges are not very different than the output for the base case for this fire management zone, based on historical ignitions, of 114,697 ac and 177 acres. The large increase in the amount of fire in the vegetative communities hosting residential structures from 177 to 235 is no surprise given that the upper limit of parameter the change here multiplies the historical ignitions in this area by 1.5.

Modeling mean acreage for total fire area for the longer 1970-2004 period, holding all other parameters at default levels, generates slightly different results of 118,874 ac and 114 acres. These changes result in slightly less fire in the total area, but more fire in the smaller WUI structure polygon area. While all the parameters changes are tested without suppression, the area-based results they generate are used to determine which case to carry forward to the final analysis.

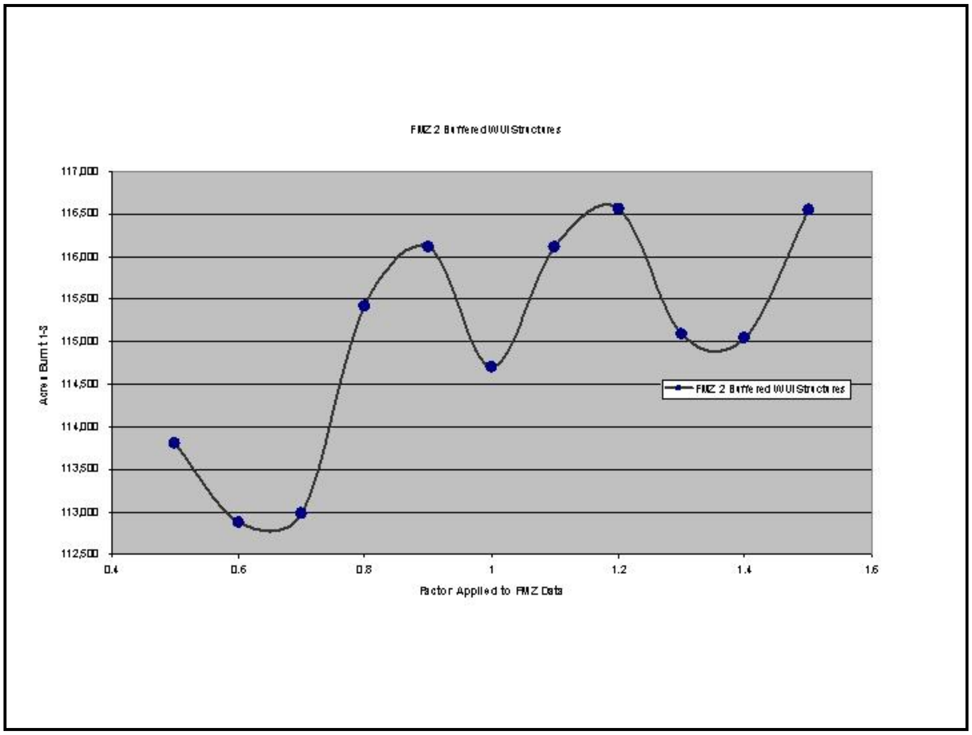

Figure C-13. Changes in area burned for the total analysis area based on changes to default FMZ settings (0.5 – 1.5) for special area 1, the area when 291 structures are buffered by ¼ mile.

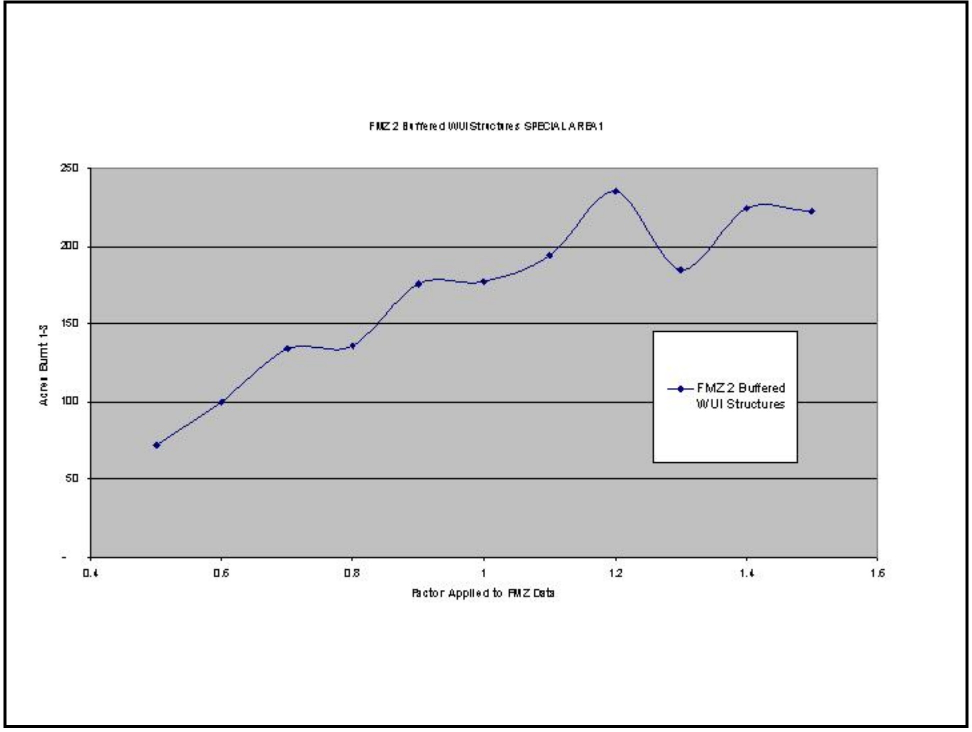

Figure C-14. Changes in area burned for special area 1 based on changes to default FMZ settings (0.5 – 1.5) for special area 1, the area when 291 structures are buffered by ¼ mile.

One of the most important decisions in the modeling system is the use of suppression in the SIMPPLLE modeling. Table 13 shows summary statistics of the modeling system results when suppression is turned off. The distribution of existing hazard estimates are clearly much higher than results obtained when modeling with suppression. The maximum and average probabilities are roughly seven and sixteen times, respectively, as high as those estimated with active suppression. The median probability is also much higher at 0.03, and the number of houses with zero probability is much lower than the non-suppression modeling results for the 30-year period. This demonstrates how important suppression is in SIMPPLLE for modeling system estimates of existing hazard.

Base case modeling decisions were made by conducting SAs on the two primary modeling tools (SIMPPLLE and SIAM) and reviewing the results. For example, suppression is selected for the SIMPPLLE modeling. The decision to include this was made late in the dissertation effort. Although there are reasons to expect that the fires that make their way to homes may not be suppressed as forces are overwhelmed, the possibility of having no suppression in the SIMPPLLE modeling area during the next 30 years is so small that it does not make sense to build the modeling system this way. Several lessons are also gleaned for how individual models could be applied differently in the modeling system. Many of these potential model modifications are suggested priorities for future research and described in the final chapter.