Guiding preventative wildland fire mitigation policy and decisions with an economic modeling system

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A B S T R A C T

The protection of private residences from wildland fire produces high levels of cost and safety risk to firefighters, especially with the expanding ex-urban settlement pattern in the wildland urban interface (WUI). Economic information on probable structure losses can help guide efficient wildfire management, policy, and investments. However, no single existing modeling tool is capable of accurately predicting existing wildland fire ignition risk to WUI residences, nor are there broadly accepted models to calculate needed investments to reduce risk to WUI structures. To fill this void, a representative set of rural residences in western Montana was selected to estimate a baseline, 30-year wildland fire ignition hazard and the cost effectiveness of optional investments to reduce risk from wildfire damage to these residences. The study applied a modeling system combining outputs from a structure ignition assessment model (SIAM) with wildland fire probabilities from an ecological disturbance model (SIMPPLLE). Results indicate that the probability of structure damage to a home when a fire visits a residence is 1.0 under conditions of extreme wildland fire weather. This contrasts with the low probabilities (0.0–0.05) that wildland fire will reach vegetation surrounding the residence.

Cost-effectiveness analysis of two suites of preventative mitigation strategies demonstrated that home mitigation zone investments (modifying houses or fuels within 30.5 m (100 ft) of a residence) are generally more cost effective in reducing risk to WUI structures than investments in silvicultural operations in surrounding forests (within 2.4 km (1.5 mi) of homes). The effectiveness of the mitigation options in modifying average home loss due to wildfire ranges from negative 19.6% to positive 63% (some silvicultural treatments did increase the probability of wildfire in simulations). While both home ignition zone mitigations and silvicultural treatments can markedly reduce wildland fire hazard estimates, the former appear to provide a more pronounced reduction in hazard as correlated with expenditures.

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1. Introduction

Residential developments in western US unincorporated areas adjacent to public lands have expanded substantially in recent years (Stein et al., 2005, 2007; NFAEB, 2005; US Census, 2001), raising a series of questions for land managers and planners. What actions should be taken to reduce wildfire risk to homes in the Wildland Urban Interface (WUI)? How can residents and fire suppression organizations reduce the costs of fighting fire? How does structure protection fit into a broader picture of public land management, including demands to sustain fire-adapted ecosystems? This research examines one of the most salient questions regarding human developments in areas with high levels of wildfire occurrence: How can individual homeowners and the public most effectively allocate available financial resources to protect residential WUI structures from wildland fire? By linking models of structure ignition and wildfire probability in the most common forest type surrounding western WUI developments, this research examines the cost effectiveness of various preventative mitigation measures to protect structures from wildland fire.

Implementation of the two most common approaches to reduce wildfire risk – Firewise activities, and thinning and prescribed burning silvicultural treatments – was modeled for a study area in the Bitterroot Valley of western Montana. Firewise mitigation efforts are actions taken to modify the residence itself as well as fuel conversions within the home ignition zone (HIZ). The HIZ was 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 30.5 to 61 m (100 to 200 ft) (Cohen, 2001). In this study, the HIZ is defined as the area extending 30.5 m (100 ft) from each side of each structure. Firewise mitigations may be restricted by cost, ownership boundaries

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in the HIZ, action or inaction by adjacent landowners, subdivision covenants, and tradeoffs with other values provided by fuels, such as shade, wildlife habitat and privacy. Silvicultural treatments in the forest and grassland areas surrounding residences are intended to modify the behavior of a wildfire within and adjacent to the HIZ treated areas and are generally considered the responsibility of public land management agencies funded mainly with tax revenues.

Forest managers and researchers observe that population expansion and fire protection activities have substantially modified fire regimes in the high fire frequency landscapes of the western U.S. (Romme et al., 2003; Swetnam et al., 1999; Arno et al., 1997; Covington and Moore, 1994). Many authors note how fire management policies preventing low intensity fire in dry ponderosa pine (Pinus ponderosa) landscapes have, ironically, 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, 1993, 1994; Arno, 1980).

Extreme fire behavior, partially attributable to a century of fire-suppression, has already collided with many human communities nestled in and around flammable forests in the wildland urban interface (WUI), resulting in increasing home losses to wildland fires in recent years. Despite these losses, an increasing number of homes are being built in low elevation ponderosa pine forested areas in unincorporated places in the western US that often have limited fire protection resources (Stein et al., 2007; Stein et al., 2005; NFAEB, 2005). Hedonic pricing model research suggests that homes in close proximity to forested areas are highly desirable (Kim and Johnson, 2002), indicating a sustained demand for homes in the WUI and the likelihood of increasing development. However, Loomis (2004) identified reduced housing value due to proximity of recent fire and Donovan et al. (2007) demonstrated that housing values decreased following heightened awareness of high wildfire risk.

The proximity of houses to flammable forests places them at risk of ignition. Structure ignitions from forest wildfires occur through several vectors of heat transfer. Large wildland fires produce firebrands that can reach a house from more than a mile away (Albini, 1983). Fires approaching a structure can also affect wind and temperature factors that impact the radiant and convective heat fluxes, all affecting ignition risk. Therefore, home ignition probability varies at the home ignition zone scale (Cohen and Butler, 1998).

Table 1 indicates that during the period 2000–2007, annual US wildland fire suppression costs were roughly $1 billion and hundreds of primary residences were destroyed annually by wildland fire. During 2003 alone, wildland fires burned 4090 primary residences in the US, mainly in fires near San Diego, California. Resident and firefighter lives have been lost to wildland fires that destroy WUI homes. Fire hazard is expected to remain stable or grow in these areas, thus compounding the risk to lives and homes. Recent research on climate change suggests higher temperatures and longer summers may elevate North America’s annual forest fire acreage (Westerling et al., 2006). With continued growth of the WUI and increasing fire hazard, the number of WUI residences threatened each year by wildland fire and inflation-adjusted wildland fire suppression expenditures devoted to defending these structures will likely continue to rise.

Wildland fire suppression is a dangerous, expensive activity undertaken for myriad reasons other than simply the protection of homes. Other protection considerations include critical infrastructure, sensitive wildlife habitat, soil productivity, aesthetics, and air quality (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, as there are many benefits derived from wildland fire. Ecosystems rely on the wildland fire process, as do human communities, since frequent low intensity fire reduces woody fuels and the types of fires that may cause widespread structure loss. Although the benefits of fire are well recognized, rural residents and their property are simultaneously threatened by fire, creating an ongoing social dilemma on the extent of costly suppression activities. The range of risk-reduction strategies must be carefully evaluated with criteria including efficiency and effectiveness, to which this study is intended to make a contribution.

2. Area description

We applied a cost-effectiveness analysis (CEA) of preventative mitigation strategies to a case study area in the Bitterroot Valley of western Montana. Of the 136,945 ha (338,400 ac) within the study area, roughly 70% is forest, 11% is shrub land, and 8% is grass land. The residential area is a subset of this landscape, covering 550 ha (1360 ac) with 291 WUI residences. The composition of the vegetative communities in the residential area is roughly 38% forest, 24% shrub land, 37% grass land, and less than 1% non-vegetated (4 ha (10 ac)). This area has experienced extensive large wildland fire activity during 2000, 2003, and 2007.

3. Methods

The overall cost-effectiveness evaluation can be distilled into three steps: (1) a baseline wildfire structure ignition hazard calculation as the average product of a baseline wildland fire probability at each house and a baseline ignition probability given exposure to wildland fire for each house; (2) estimation of modified home ignition hazard probabilities following the implementation of mutually exclusive HIZ or mechanical and prescribed fire mitigation options for seven expenditure levels; and, (3) a cost-effectiveness analysis (CEA) to determine treatments with the lowest cost per percentage point reduction in average wildfire ignition hazard to structures.

A modeling system to estimate home ignition probability must both describe expectations for future wildfire at the landscape scale and predict the probability of home ignition at the scale of a residential lot, given a passing fire. Currently, no single model exists; however, this research utilized two existing models to perform this task. The Structure Ignition Assessment Model (SIAM; Cohen 1995) was used to identify the likelihood that a structure would ignite in the presence of wildfire and to design HIZ treatments that reduce this likelihood. The Simulating Patterns and Processes at the Landscape Scale (SIMPPLLE; Chew et al., 2004) model was used with records of past fire events in the study area to estimate future fire expectations. It is important to note that SIMPPLLE is an ecological process prediction-modeling tool, not a fire behavior-modeling tool. A third model, the Multiple-resource Analysis and Geographic Information System (MAGIS; Zuuring et al., 1995), a treatment scheduling model, was used in conjunction with SIMPPLLE to design wildland

<table>
<thead>
<tr>
<th>Year</th>
<th>Number of fires</th>
<th>Primary residences burned</th>
<th>Acres burned (millions)</th>
<th>Total federal agency suppression costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>2007</td>
<td>85,705</td>
<td>5401</td>
<td>9.3</td>
<td>$1.31 billion</td>
</tr>
<tr>
<td>2006</td>
<td>96,385</td>
<td>2357*</td>
<td>9.9</td>
<td>$1.08 billion</td>
</tr>
<tr>
<td>2005</td>
<td>66,552</td>
<td>402</td>
<td>8.7</td>
<td>$0.88 billion</td>
</tr>
<tr>
<td>2004</td>
<td>77,534</td>
<td>315</td>
<td>6.8</td>
<td>$0.89 billion</td>
</tr>
<tr>
<td>2003</td>
<td>85,943</td>
<td>4090*</td>
<td>4.9</td>
<td>$1.33 billion</td>
</tr>
<tr>
<td>2002</td>
<td>88,458</td>
<td>835</td>
<td>6.9</td>
<td>$1.66 billion</td>
</tr>
<tr>
<td>2001</td>
<td>84,079</td>
<td>731 (all structures)</td>
<td>3.6</td>
<td>$0.92 billion</td>
</tr>
<tr>
<td>2000</td>
<td>122,827</td>
<td>861 (all structures)</td>
<td>8.4</td>
<td>$1.36 billion</td>
</tr>
</tbody>
</table>

* Five firefighters killed protecting WUI structures.
** 15 people killed in association with Cedar Fire.
mechanical and prescribed fire treatments intended to reduce the probability of wildfire entering the residential area.

A means to compare costs associated with alternative treatments for reducing probability of home ignition hazard is necessary to identify efficient HIZ and wildland treatments. Economists have proposed CEA as an alternative to benefit–cost analysis (BCA) when benefits cannot easily be quantified in dollars (Boardmann et al., 2001; Levin and McEwan 2001; Rideout and Hesseln 2001). CEA is often used to compare costs to achieve various objectives in medical, healthcare, education, and national defense studies. Since the threat of wildland fire to WUI structures includes a threat to human life, CEA is a sound alternative to BCA, as it removes the need to value human life. Additionally, current preventative wildland fire protection planning is based on social equity considerations that do not allow a prioritization of protection based on house values. Targeting public wildland fire hazard mitigation resources in proportion to home values would be a difficult policy to defend.

All existing and modified home ignition hazard probabilities were estimated for a 30-year time period (2005 to 2034). Using a shorter time period would be insufficient to assess how changes in the fuels and vegetation arising from treatments affect fire hazard. However, using a longer time period would introduce bias by not accounting for the likely change in housing density from continuing in-migration. For the HIZ, Firewise mitigation measures are assumed to occur in the first decade and persist for 30 years. Mechanical thinning and burning treatments that change tree density, size class, species composition and vegetative wildfire severity are permitted to occur in any of the next three decades and are assumed to persist for two to three decades, depending on the scheduled treatment regime.

3.1. Estimation of existing home ignition probabilities

Of the 291 houses in the study area, 39 were visited for direct data collection, which was limited largely by the willingness of study area residents to participate in somewhat obtrusive household measurements. Ocular and stride estimates were combined with tape measurements to draw necessary elevation and plan views of each home and HIZ for SIAM. Structural and fuel characteristics within each HIZ, and fire branding potential within a ¼ mile were spatially documented for each home. These data were entered into SIAM to generate ignition probability estimates for each side of each house. The maximum probability for any side of each home was accepted as the probability of ignition from an extreme wildland fire.

Visited homes were placed into either a flammable or non-flammable category based on the flammability of their roofs1 and exterior walls (siding). Unvisited homes were classified as flammable, non-flammable or unknown based on sizing characteristics obtained from the Montana State Library’s Cadastral Map Project database. The average probability of ignition for visited homes in the flammable category was accepted as the probability of ignition for unvisited homes in the flammable category. The average probability of ignition for visited homes in the non-flammable category was accepted as the probability of ignition for unvisited homes in the non-flammable category. The average probability of ignition of all visited homes was accepted as the probability of ignition for all unvisited homes in the unknown category.

The R1-VMP (Brewer et al., 2004) vegetation polygons that host each residential structure were determined by locating structures manually in ESRI, ArcView 3.2, using 2-meter digital orthoquad imagery overlaid with property lines from the Montana Cadastral Map Project database. Subsequently, wildland fire probabilities, given current landscape conditions according to the R1-VMP and historical disturbance information (ignition probabilities per acre, recent fire perimeters, recent harvest and fuel treatment perimeters, and current insect and disease infestation locations), were modeled for the period 2005–2034 using SIMPPLLE. All SIMPPLLE modeling for the project was conducted under an assumption of active suppression, since approximately 98% of wildland fires in the western US are suppressed before they grow to a large size (Calkin et al., 2005).

To estimate the probability of wildfire for three serial decades, 100 three-decade simulations were run. The probability that a polygon ignited each decade was controlled by the historic rate per acre for the entire landscape, and therefore did not change. Due to the stochastic nature of disturbance initiation and spread, a single polygon could potentially burn up to three times, once in each of the three sequential decades. However, a single fire did change the vegetation structure and composition attributes substantially for forested polygons in a given simulation run, limiting fire potential in subsequent decades for that simulation. The number of simulations (1–100) in which wildfire occurred for each decade was recorded to generate a burn probability for each polygon (each polygon was limited to one disturbance process or succession per decade). For the second and third decades, the landscape was updated to reflect succession or disturbance, including fire, mountain pine, Douglas-fir beetle or spruce budworm infestation, or western root rot development. Decade specific results listed the succession or disturbance change for each vegetative polygon in a text file. These text files were used in a spreadsheet to estimate the 30-year wildfire probabilities. A total 30-year wildland fire probability specific to each polygon hosting a structure was calculated by combining the probabilities for each polygon for each decade with Eq. (1).

\[
p(D_{1−3}) = p(D_1) + (1−p(D_1))p(D_2) + (1−(p(D_1) + (1−p(D_1))p(D_2)))p(D_3)
\]

(1)

where \( D \) represents the simulation period (decade) and \( p(D_{1−3}) \) equals the 30-year wildfire occurrence probability at each house.

Since the research question addresses the 30-year probability of fire reaching a polygon hosting a structure, the single probability across three decades is needed, not the average probability across the time period. When fire enters a polygon with a home, there is a probability that the home will burn. Part of our modeling process is modifying that probability. Since we do not know with certainty if a home will exist after the initial fire enters the polygon and whether the home will be rebuilt following ignition, we must restrict the probability of fire burning a home in the 30-year period to less than or equal to one. In other words, the three-decade probability cannot exceed one, and it also should not be less than the highest probability for any given decade. This explains why these numbers are combined with Eq. (1).

The existing wildfire structure ignition hazard of each residential structure in the study area for the next 30 years was estimated as the product of the probability of wildfire occurrence in the polygon hosting a particular house and the probability that wildland fire will ignite that particular structure (Eq. (2)).

\[
30−year \text{ home ignition hazard} = p(D_{1−3})p(\text{ignition if house encounters wildfire})
\]

(2)

The average 30-year home ignition hazard of these 291 structures is then used as the starting point for the next two steps: estimating modified home ignition probabilities; and estimating the cost effectiveness of treatments.

3.2. Estimating modified home ignition probabilities

The two mutually exclusive sets of mitigation options are now described. For convention sake, the HIZ treatments are listed with numbers, whereas the silvicultural treatment schedules applied to the

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1 None of the visited houses had flammable roofs, nor were any flammable roofs found in the Cadastral database.
wildlands surrounding the residential area are listed with letters. In
addition, the silvicultural treatment regimes included at variable
levels in these optimized treatment schedules are denoted with
Roman numerals.

Countless combinations of building improvement and fuel con-
versions inside HIZs are possible. By consulting with local contractors
who perform fuel mitigation work, and with consideration of the
modeling limitations, seven general HIZ treatments were developed
and described in Stockmann (2006). In summary, these HIZ
treatments were:

1. Replacing single pane windows with double pane windows;
2. Upgrading flammable siding to non-flammable siding;
3. A combination of 1 and 2;
4. Conversion of light fuels to watered lawn;
5. Combination of building upgrades (3) and light fuel conversion in
the HIZ; and
6. Full fuel conversion with replacement using non-flammable
alternatives;
7. Combination of building upgrades (3) and full fuel conversion in
the HIZ.

The treatment effectiveness of each of these seven possible HIZ
mitigations was estimated by altering attributes of the plan and
elevation views for each visited house in SIAM, and recalculating
ignition probabilities. Modified home ignition hazard probabilities
were then estimated by multiplying the existing probability that
wildfires burn the host polygon ($p(D1–3)$) by the modified SIAM
probability of home ignition. The total costs of performing each of the
seven HIZ mitigation options for all 291 structures were calculated
with unit costs estimated following consultation with local contractors
and businesses. The percent effectiveness is defined as the change
from existing condition wildfire structure ignition hazard to
mitigated wildfire structure ignition hazard. This requires taking the
mitigated hazard figure, subtracting the existing hazard figure, and
dividing the result by the existing hazard figure. This yields the percent
effectiveness for each mitigation option modeled.

To model possible reductions in the probability that vegetation in
polygons hosting homes would burn, the MAGIS (Zuurig et al., 1995)
treatment scheduling software was used with spatially specific
vegetation data, net treatment costs per acre (where treatment regime
costs are reduced by estimated revenue per acre for treatment regimes
IV and V), and expected burn probability reduction factors by decade
to develop optimal treatment schedules over three decades in forests
extending up to 1.5 mi from, but not including polygons hosting, the
291 structures. The seven HIZ expenditure levels were adopted as
expenditure constraints for potential mechanical and prescribed
vegetation data growth and disturbance simulations were performed.

Modified probabilities that vegetation polygons hosting structures
would burn were then calculated with Eq. (1). Next, modified wildfire
structure ignition hazard probabilities were estimated by multiplying
the modified wildland fire probabilities by the existing probabil-
ities ($p(ignition if house encounters wildfire)$) of home ignition using
Eq. (2).

### 3.3. Estimating cost effectiveness of treatments

A CEA can be applied in two ways. Analysts can select a target
effectiveness level and let expected costs float, or select an expend-
diture constraint and let expected effectiveness float. The former
approach is untenable for this study design, due to the complexities of
combining several wildfire modeling tools to obtain an effectiveness
measure. In this study, the cost-effectiveness ratios of the HIZ and
silvicultural treatment mitigation options are compared for the seven
expenditure levels. Expenditure levels required for each mitigation
option were divided by the total percent reduction in average 30-year
home ignition hazard relative to the existing average 30-year home
ignition hazard to derive cost-effectiveness (CE) ratios for the study
area. Note that this CEA evaluates discrete treatment options and
is therefore not a marginal analysis. A marginal assessment would

### Table 2

<table>
<thead>
<tr>
<th>Cost</th>
<th>Amount ($)</th>
<th>Treatment regime</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ecosystem maintenance burn(s)</td>
<td>259/445/ha</td>
<td>X</td>
</tr>
<tr>
<td>hand line construction</td>
<td></td>
<td>XX</td>
</tr>
<tr>
<td>hand line overhead</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Prethinning overhead</td>
<td>36/ha</td>
<td>X</td>
</tr>
<tr>
<td>Thinning—timber stand improvement</td>
<td>162/ha</td>
<td>X</td>
</tr>
<tr>
<td>Timber stand improvement overhead</td>
<td>20/ha</td>
<td>X</td>
</tr>
<tr>
<td>Ecosystem management thin and</td>
<td>344/ha</td>
<td>X</td>
</tr>
<tr>
<td>underburn, hand line construction,</td>
<td></td>
<td></td>
</tr>
<tr>
<td>hand line overhead</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Monitoring</td>
<td>2/ha</td>
<td>X</td>
</tr>
<tr>
<td>Sale preparation</td>
<td>17/CCF</td>
<td>X</td>
</tr>
<tr>
<td>Sale administration</td>
<td>9/CCF</td>
<td>X</td>
</tr>
<tr>
<td>Yarding, deducted from revenue</td>
<td>Variable/CCF</td>
<td>X</td>
</tr>
<tr>
<td>Yarding</td>
<td>Variable/CCF</td>
<td>X</td>
</tr>
</tbody>
</table>
require that the analyst could scale options up or down by marginally adjusting the expenditures. This would require an expanded optimization analysis, which was beyond the scope of this study.

4. Results

4.1. Existing probability of home ignition

SIMPPLLE modeling revealed that the existing probability that polygons hosting houses in the study area will experience wildland fire during the period 2005–2034 is extremely low. The 30-year wildland fire probabilities for individual homes ranged from 0.0 to 0.0496 for these polygons, with 201 homes having a zero probability. Although few study area houses are expected to face a wildland fire between 2005 and 2034, SIAM modeling for the 39 homes visited revealed that only three residential structures have any probability of surviving an extreme weather wildland fire in their current condition. The average ignition probability for the 39 modeled houses given a wildfire in the polygon hosting the home is 0.994. The average ignition expectation for all 291 homes is also 0.994, because the distribution among flammability classes (classified by roof and siding characteristics from the cadastral data) for the 39-house sample matched the distribution of the 291-house population.

Table 3 summarizes the existing 30-year wildfire hazard statistics for all 291 houses in the study area for the period 2005–2034. The average 30-year wildfire ignition hazard probability for all polygons with homes is 0.00484. Multiplying 291 houses by this average implies that 1.41 homes in the study area are expected to face a wildfire ignition between 2005 and 2034.

4.2. Estimation of modified home ignition probabilities

4.2.1. Firewise treatments in the home ignition zone

Table 4 reports the effectiveness of the seven Firewise HIZ treatments in reducing home ignition hazard, as modeled by SIAM, given extreme weather conditions and a wildfire in the polygon occupied by a house. The fifth column of Table 4 reports the modified 30-year average hazard of home ignition in the study area assuming all homes needing the HIZ treatment are treated and all homes in the study area continue to face the existing probability of a wildfire in the polygon hosting the home. All HIZ treatments except window improvements are effective at reducing the existing structure ignition probabilities, and total treatment expenditure levels are typically positively related to ignition probability reduction. The full HIZ fuel conversion option is much more effective than either the light fuel conversion or any of the building improvements, reducing mean ignition probability from 0.994 to 0.36. With full fuel HIZ mitigation (6), modified home ignition hazard probabilities decreased from 0.00484 to 0.00179. This represents a 63% reduction, a much greater reduction than the other HIZ treatment options.

4.2.2. Mechanical and prescribed fire fuel treatments in wildlands surrounding homes

Table 5 summarizes seven new SIMPPLLE burn probability averages for the polygons hosting homes in the study area. These new SIMPPLLE probability averages were modified following the application of seven silvicultural treatment schedules devised with MAGIS. Treatments in the table are listed in order of expenditures that correspond with HIZ expenditure levels (1–7). The table also reports modified home ignition hazard probabilities for each fuel treatment assuming existing HIZ conditions. The effectiveness of silvicultural mitigations varies considerably. Four forest treatment schedules reduce wildland fire probability estimates, while three increase the hazard. The most effective treatment reduces the average 30-year ignition hazard by 22.7% from 0.00484 to 0.00347.

4.3. Cost effectiveness of treatments

Comparison of cost effectiveness of HIZ and forest treatments in reducing the probability of home ignition is facilitated by reference to Tables 4 and 5, and Fig. 1. Note in Fig. 1 that the HIZ options (X) are farther right (larger reduction in average home ignition hazard) than the silvicultural forest treatment options (●) at all but two expenditure levels ($2.319 million and $3.370 million). This indicates that HIZ mitigations modeled would generally be more cost effective in the study area. Also note that the two most costly HIZ treatments (5 and 7) are aligned vertically in the figure. This indicates that no additional effectiveness is attained with the additional cost for building upgrades than is possible through full fuel conversion alone.

The HIZ full fuel conversion emerges as the best investment, requiring $3.28 million to reduce combined wildfire hazard by 63%. When cost effectiveness is normalized to a 1% reduction in wildfire structure ignition hazard, each 1% reduction from the existing (0.00484) to mitigated (0.00179) average 30-year hazard of home ignition for all 291 study area homes requires a $52,000 investment. This compares to $104,000 to achieve each 1% reduction through the application of the most cost-effective silvicultural treatment schedule (C) in the wildlands surrounding the study area homes. The cost effectiveness is zero for the window replacement HIZ option. Three of the silvicultural forest treatment schedules are cost ineffective (the probability of home ignition is actually predicted to increase).

It appears that at the $5.640 million expenditure level, a combination of two independent mitigation options, one HIZ and one silvicultural treatment, has the potential to reduce hazard more than if the expenditure was applied exclusively to either HIZ or silvicultural treatments. As an alternative to spending an additional $2.319 million (beyond the $3.28 million for full HIZ fuel conversion) on the building upgrades, this money could be invested in silvicultural forest treatment schedule C. When money is invested this way, the modeling system predicts that the effectiveness attainable for the maximum
expenditure increases to 70.9% with a cost-effectiveness ratio of $79,086 for each 1% reduction in home ignition probability. Although this hybrid approach yields a higher cost-effectiveness (CE) ratio than the smaller investment associated with the full fuel conversion alone, its CE ratio is far lower than other options where the maximum investment is put solely in either of the two mitigation suites. This CE point is represented by the star in Fig. 1.

investment is put solely in either of the two mitigation suites. This CE ratio is far lower than other options where the maximum investment is put solely in either of the two mitigation suites. This CE point is represented by the star in Fig. 1.

Table 5
Silvicultural treatment schedule effectiveness.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>SIMPELL average</th>
<th>SIMPELL median</th>
<th>SIMPELL maximum</th>
<th>Host polygons, Where P = 0.00</th>
<th>Modeling system average</th>
<th>Modeling system maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Existing</td>
<td>0.00486</td>
<td>0.000</td>
<td>0.0496</td>
<td>201</td>
<td>0.00484</td>
<td>0.0476</td>
</tr>
<tr>
<td>Schedule A $184,080</td>
<td>0.00507</td>
<td>0.000</td>
<td>0.0592</td>
<td>189</td>
<td>0.00505 (+4.3%)</td>
<td>0.0592</td>
</tr>
<tr>
<td>Schedule B $2,135,048</td>
<td>0.00480</td>
<td>0.000</td>
<td>0.0493</td>
<td>199</td>
<td>0.00477 (−1.4%)</td>
<td>0.0473</td>
</tr>
<tr>
<td>Schedule C $2,319,128</td>
<td>0.00377</td>
<td>0.000</td>
<td>0.0492</td>
<td>211</td>
<td>0.00376 (−22.3%)</td>
<td>0.0492</td>
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<td>0.000</td>
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<td>196</td>
<td>0.00505 (−4.3%)</td>
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<td>0.00466</td>
<td>0.000</td>
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<td>197</td>
<td>0.00463 (−4.3%)</td>
<td>0.0474</td>
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5. Discussion

The large range in predicted cost-effectiveness ratios for all mitigation options suggests that economic analysis can provide useful information to support wildfire mitigation planning. The findings in this case study suggest that most of the HIZ mitigation options have superior performance over silvicultural forest treatments when compared for seven expenditure levels ranging from $184,000 to $5,604,048. Given limited budgets to address the problem of WUI structure protection; this is exactly the type of information needed to efficiently protect the increasing number of western US WUI homes from future wildland fires.

While these results are interesting and may be useful for the local community wildland fire protection plan, it is unclear whether the observed pattern of cost effectiveness between HIZ and wildland fuel treatments holds across the western US. Only by replicating this approach in numerous study areas representing a range of building environments and vegetation conditions will general statements comparing the two suites of treatments be permissible. If the pattern does hold or is observed in other locations, then from an economic perspective, there is little sense in spending money conducting forest treatments in forests surrounding structures if structure protection from wildfire is the sole objective. If as a society we decide to subsidize wildfire risk reduction in the US, grant programs that facilitate work in the HIZ seem to be a wiser investment.

If steps taken by homeowners are generally more cost effective than silvicultural treatments in surrounding public lands, this has important implications for future wildland fire protection investment planning. Circulation of information regarding the site-specific predicted cost effectiveness of various mitigation options may persuade communities to increase pressure on existing homeowners to modify their homes and surroundings, and require 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 resources to other protection and land management priorities. Safer, new home construction and landscaping design standards for homeowners, specifically, the use of non-flammable building materials and conscious removal of flammable vegetation surrounding houses, could reduce both fuel treatment and suppression expenditures aimed at house protection.

Considering that homeowner’s insurance will typically reimburse the owner for the value of the house and much of its contents if destroyed by wildland fire, the reason for inaction by many WUI homeowners is made clear by this case study. Existing probability of home ignition faced by homeowners is low, averaging only 0.00484 for the next 30 years. Even the most cost-effective treatment option, removing and replacing all the fuels in the HIZs across the study area, only reduces the existing hazard to 0.00179 at an average cost of $11,288 per home. The low probability of a fire occurring at a given house site and the remarkable capacity of fire suppression personnel to contain fires (at least under current conditions), make widespread preventative treatments a tough sell to homeowners and public officials. Other incentives for clearing hazardous fuels around a house, such as crime-control, gardening opportunities, and pet needs may be more compelling reasons for homeowners to choose open areas surrounding their homes (Nelson et al., 2004). Yet these incentives are frequently offset by the values provided by vegetation left adjacent to houses, such as the provision of shelter, shade, temperature and moisture control, noise control, privacy, aesthetics, and wildlife habitat.

Modeling system assumptions include assignment of houses to single polygons, the complexity of the modeled mitigations (including both the fact that HIZ mitigation approaches apply to all houses including those with zero wildland fire probability, and that all HIZ mitigations are modeled to persist for the entire 30-year period), and the use of average cost-effectiveness ratio analysis versus optimized marginal analysis. Although adjacent vegetative communities also pose a firebranding threat to some houses; uncertainty regarding the variable contributions to firebranding hazard from these adjacent polygons prevented their inclusion as an explicit link between the modeling tools in this project. The cost-effectiveness analysis of the mitigations on the combined modeling system in this study does not adjust costs for the cases where the existing wildland fire probability is zero based on a stochastic modeling run. Ideally, the estimated 69% of the houses with a zero 30-year wildland fire probability would be
removed from each of the HIZ mitigation options to reduce the costs of each mitigation option in the recombined CEA. The twofold problem complicating this retrospective calculation is that the set of houses with a zero probability shifts with different stochastic modeling runs, and extrapolation was used in the study to estimate the structure ignition probability for 252 of the 291 houses; which explains why this is only suggested as a potential improvement in any future cost-effectiveness analysis.

In contrast with many HIZ treatments, some wildland fuel reduction treatments can achieve multiple complementary goals. Therefore, there are joint costs involving wildland fuel reduction treatments that may be associated with satisfying wildfire forage production, invasive weed control, insect and disease control, and biomass production goals. These joint costs will increase the costs of wildland fuel reduction treatments above the most basic costs to only reduce fuels. To compare wildland fuel treatment costs to contractor costs for specific HIZ treatments will bias the cost-effectiveness analysis in favor of HIZ treatments where structure protection is the only definition of effectiveness.

Effectiveness could be expanded in the future to include additional measures, such as expected change to highly valued natural resources.

6. Conclusion

This study has pioneered a technique that combines wildfire probability with structure ignition probability given a passing wildfire to conduct a cost-effectiveness analysis of preventative home ignition mitigation options. The study demonstrates the utility of cost-effectiveness analysis to help guide mitigation efforts in low elevation communities across the western US. The case study area in the Bitterroot Valley, Montana, revealed that, for the particular expenditure levels examined, most of the HIZ treatments have superior cost effectiveness to wildland fuel treatments. Combinations of independent HIZ and wildland fuel treatments may have the potential to reduce home ignition hazard more than when the same level of expenditure is applied exclusively to one type of treatment. A surprising finding is the low existing wildfire ignition risk to structures over a 30-year period. Also notable is the extraordinary expenditures ($3.7 million) required to reduce expected home loss, among these 291 case study houses, by a single home over the 30-year study period. Given limited resources to address the problem of WUI structure protection, the analysis framework developed in this paper is useful in providing information needed to more efficiently protect the increasing number of western US WUI homes from future wildland fires. The conceptual modeling system could easily be modified to address other policy questions. For example one could substitute other fire behavior-modeling tools (e.g. FARSITE (Finney 2004) derivatives) for SIMPPLIE. This would allow the analyst to modify the questions which can be addressed.

Acknowledgments

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References


### Table 6

<table>
<thead>
<tr>
<th>Cost per option (in $M) 2006</th>
<th>Mitigated hazard average for 291 homes (effectiveness)</th>
<th>Mitigated expected home loss</th>
<th>Change in expected loss</th>
<th>CE ratio cost/1 house saved</th>
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<tr>
<td>Existing average</td>
<td></td>
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<td>HIZ full fuel conversion</td>
<td>3.28</td>
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