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Quantifying the net economic benefits of mechanical wildfire hazard treatments on timberlands of the western United States

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ABSTRACT

Mechanical treatment of vegetation is done on public and private lands for many possible reasons, including enhancing wildlife habitat, increasing timber growth of residual stands, and improving resistance to damaging pests. Few studies, however, have focused on the circumstances under which mechanical wildfire hazard reduction treatments can yield positive net economic wildfire benefits for landowners and managers. This study describes an economic assessment tool built from a representative area sample frame inventory of hazardous and potentially treatable timberland in twelve western states of the U.S. Base case parameter assumptions about values at risk, timber product prices, stand re-growth following treatment and wildfire impacts enable an initial estimate of the amount of timberland with positive discounted expected net economic benefits under four policy scenarios. These assumptions are then varied in a Monte Carlo simulation to provide some bounds of uncertainty around base case levels. A policy that allowed optimal prescriptions and product sales and which incorporates wildfire costs and benefits would result in more than 25% of treated area with positive net benefits. This is reduced somewhat if wildfire reduction costs and benefits are not considered, and reduced again to 14% when large trees are excluded from product sales. A policy that prohibits sale of products from these treatments results in less than 1% of area with positive net benefits.

1. Introduction

Federal agencies in the United States have embarked on a widespread program to reduce forest stand densities in an effort to decrease wildfire severity and enhance forest health. These wildfire hazard reduction goals are part of the National Fire Plan (Secretaries of the Interior and of Agriculture, 2000; USDA Forest Service, 2000) and cover both public and private lands. Although stand density reductions may be an attractive way to reduce wildfire hazard to levels that would support less intense wildfires, enable more effective fire suppression, and possibly facilitate a shift to more desirable environmental conditions, costs for implementing a large scale program have not been scientifically assessed across broad landscapes or over long times. Forest thinning projects are often done to achieve objectives other than reducing wildfire damages, such as enhancing stand growth, increasing forage for ungulates, or improving pest resistance. However, thinning focused on wildfire objectives has rarely been evaluated, at large spatial scales, from the perspective of the net economic wildfire benefits they yield for landowners, where these net benefits include treatment costs, reduced wildfire damages, and reduced suppression expenditures. Understanding how treatments might be arrayed across large landscapes to achieve the best use of agency budgets or the greatest benefit to private landowners is crucial to designing effective wildfire management programs.

Available evidence suggests that some kinds of wildfire hazard reduction treatments are economically beneficial in some locations, such as prescribed fire in the southeastern U.S., where the long-run benefits exceed the costs of prescribed fire in Florida (Mercer et al., 2007). Part of the reason prescribed fire can pay off in the South is because of its low cost. In the western United States, prescribed fire is more expensive and more constrained by the region's weather and terrain (Cleaves et al., 2000). Consequently, attention by the USDA Forest Service in the West has been directed toward mechanical treatments. Some of these treatments remove woody biomass and others alter its form and leave it on site. Managers need to justify expenditures for mechanical treatments and must develop priorities for implementing these treatments. Justifying and prioritizing treatments is difficult because mechanical treatments can cost thousands of dollars per hectare (USDA Forest Service, 2005; Abt and Prestemon, 2006; Prestemon et al., 2008; Skog et al., 2006), treatment lifespans are uncertain, and effects on wildfire damages in the long-run are not well understood. A comparison of treatment costs to their long-run expected benefits is essential to properly assess

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economic efficacy and to develop economically informed priorities about where and how much to treat.

The objective of this paper is to describe the plausible range of the long-run expected net economic benefits of mechanical wildfire hazard reduction treatments in the western U.S. and to outline under what conditions such treatments are likely to be economically efficient. Economic efficiency in our study is defined as the net of long-run discounted expected benefits through avoidance of damaging wildfire and associated suppression costs, and the initial costs of treatment (referred to in shorthand in this article as expected net economic benefits, or ENEB). The geographical and biophysical focus of our study is on non-reserved timberlands of all ownerships in the contiguous western United States.

To quantify ENEB, we utilize a model originally published by Prestemon et al. (2008) and Huggett et al. (2008). The original model, which we refer to as the Economics of Biomass Removals (EBR) model, was designed to quantify the timber market impacts of large scale mechanical wildfire hazard reduction treatments in productive forests of the western and southern U.S. The modified EBR model in this paper is used to address a research question: how much timberland in the western U.S. can be mechanically treated with positive long-run net economic benefits? To do this, we use a Monte Carlo simulation approach that assesses, for each spatial modeling unit, the plausible range of ENEB of hazard treatments. Monte Carlo simulations are performed by jointly varying several assumptions about treatment costs and benefits that contribute to an assessment of ENEB. Using this process we identify conditions and places in the West where treatments may be cost effective under four alternative policy environments. This research provides a method for understanding the extent and location of timberlands with positive ENEB. In addition, we provide a method to prioritize treatments across a broad landscape given a finite budget. Our empirical analyses require making several assumptions that, if varied, may work either to increase or decrease the net economic benefits of wildfire hazard reduction treatments. These include assumptions regarding the ecological damages and benefits from wildfires, which are difficult to establish, in addition to assumptions about how fuels may affect wildfire occurrence probabilities, and the large-scale and long-run impacts of these treatments on overall wildfire occurrence and suppression effectiveness.

2. Methods

2.1. Theoretical model of wildfire hazard reduction

We begin by describing the long-run expected net economic benefits of wildfire hazard reduction treatments as deriving from an economic decision on how to allocate scarce inputs to the wildfire hazard reduction process. This allocation depends on the prices of the inputs and on the value of the outputs. Wildfire outputs consist of damages to resources and property and benefits to ecosystems, resources, and society, and these damages and benefits also have prices. Below, we quantify the conceptual framework previously described by Kline (2004).

Wildfire is produced on the landscape from a combination of what economists identify as purchased and free inputs. Free inputs include things outside the direct influence of the manager, including weather, human and natural wildfire ignitions, oxygen, and natural fuels. Purchased inputs, meant to influence (mainly reduce) wildfire activity, are defined as any input intended to alter wildfire activity. Often, inputs are described as baskets of activities that are formed from the most basic inputs, capital, labor, and materials. These activities themselves have defined prices per unit of activity, thus wildfire management involves choices about how much of these activities to undertake. These activities could include wildfire hazard reduction (prescribed fire, mechanical fuel treatments, fire break construction and maintenance), firefighting (suppression), wildfire prevention education, law enforcement actions, and actions that rearrange firefighting resources across landscapes before fires occur. Taken together, the sum of the unit prices of these activities times their amounts equal the purchased costs of fire management. An economic decision that natural resource managers make is how to allocate these activities across space and over time so that the overall sum of the long-run discounted purchased costs and losses is minimized. Rideout and Omi (1990) provide a rigorous description of the decision process implied by this cost plus loss model.

For this analysis, we abstract from the overall cost plus loss model to describe a subset of manager decisions regarding only mechanical wildfire hazard reduction treatments. Managers are assumed to follow benefit-maximizing behavior (and this may apply to a public land manager, acting on behalf of a benefit-maximizing public) by seeking to maximize the discounted sum of the timber revenues from the treatments and the hazard reduction benefits (avoided losses from wildfire) of the treatments less the costs of implementing the treatments.

$$max_x ENEB = R(x) - C(x) + \lambda(x) \int_{t=1}^{T} NB(x) e^{-rt} dt. \quad (1)$$

ENEB is the Expected Net Economic Benefits from treatment and is comprised of the revenues from treatment (R), less the cost of treatment (C), plus the discounted sum of the net benefits resulting from reduced wildfire due to treatment (NB), all of which are a function of the treatment level (x) times the annual wildfire probability (λ). A more complete model would include a term that would account for the benefits and costs to future final harvest volumes or future treatment volumes if retreatment is necessary. We chose to exclude these benefits and costs and focus on the medium-term returns to treatments. Effects of treatments on final harvest volumes are only relevant to stands which will be final harvested, and few public forests are final harvested (<0.5% per year according to the 2007 RPA database). For private lands, the final harvest rate approximates a 100 year rotation, which could affect the optimal management strategy and could result in changes in ENEB. We expect that any changes would be small however, and the analytical difficulties of determining optimal rotations in infrequently harvested landscapes combined with the unknowns regarding the effects of these thinning treatments on 50–150 year ahead outcomes would overwhelm the more important question of the long-run effects of the treatments on wildfire costs and benefits.

Eq. (1) contains an overall assumption that treatments alter wildfire activity. Given an understanding of the revenues generated upon treatment ($R(x)$), cost of the treatment ($C(x)$), and the form and elements contained in $NB(x)$, the long-run economic net benefits can be calculated. The elements contained in $NB(x)$ include the gains from avoided losses and costs of wildfire occurring in a hazardous stand of timber: avoided timber losses, reduced suppression costs, reduced property damage, and reduced ecosystem damage. Also among the elements of $NB(x)$ are the losses associated with the reduced rate of "free" fuel treatment provided by wildfire and the reduced ecosystem restoration benefits from wildfire. T represents the life of the treatment and r the discount rate.

Assuming that ENEB is continuous and twice-differentiable and assuming that the decision maker operates under risk neutrality, first order conditions for an optimum of Eq. (1) is shown in Eq. (2), and leads to the familiar result that the marginal costs of treatment should be set equal to the marginal benefits of treatment, where marginal benefits includes both marginal revenues and marginal net benefits from reduced wildfire in order to maximize the expected net economic benefits from treatment.

$$\frac{\partial ENEB}{\partial x} = R_x - C_x + \lambda_x \int_{t=1}^{T} NB(x) e^{-rt} dt_x + \lambda NB_x \int_{t=1}^{T} e^{-rt} = 0. \quad (2)$$

The second order conditions are those needed to identify a minimum—i.e., they must be positive.

2.2. Simulation model for wildfire hazard reduction

The modified EBR model provides a method for assessing the costs of mechanically treating individual parcels within large landscapes. The original EBR assessed the net costs of hazard reduction treatments—that is, it contained information sufficient to determine only the first two terms on the right side of Eq. (2): R_x and C_x. The original EBR was also designed to target simulated treatments according to a wildfire hazard rating and wildland–urban interface status of a land parcel, if desired. Wildfire hazard ratings in the modified EBR are retained from the original model, with 4 levels: high, medium and low hazard as well as a no-hazard level. Hazard ratings are based on a two-dimensional combination of the torching index and the crowning index.

The basic sampling unit of the original EBR model is the Forest Inventory and Analysis (FIA) plot information of non-reserved status timberland plots, provided by the Forest Service. Plots are aggregated up to spatial modeling units defined at sub-state levels by forest type, owner group, wildland–urban interface status, and wildfire hazard classification. Wildfire hazard in the EBR model is generated from the tree-level information on the FIA plots. Wildfire hazard reduction treatments are based on three alternative prescriptions. The implementation of the treatment is simulated and a cost of treatment is generated for each plot. Similarly, the plot-level information contains data on the timber products (pulpwood and sawtimber by species group) potentially removed upon treatments. Market information includes timber prices and distances to consuming product mills. The plot-level information on treatments and timber products is aggregated up to the spatial modeling units. The EBR model was designed in this manner to evaluate the effects of alternative programs focusing on such treatments, and to quantify their overall costs.

Not included in the original EBR model was information on wildfire probability or the net benefits of conducting such treatments to achieve wildfire hazard reduction and forest health goals. The modifications we made to the EBR model for this analysis include this additional information. The modified EBR is therefore designed to capture not only the benefits of treatments in terms of potential timber product sales, but also the benefits of these treatments in terms of reduced suppression costs and reduced rates of wildfire damages to property and resources.

The modified version of the EBR allows for three alternative silvicultural prescriptions. These prescriptions are described in detail by Huggett et al. (2008) and include (a) a stand density index-based prescription that favored removing large diameter materials (SDI-Large) to achieve torching and crowning index-defined hazard reduction objectives, (b) SDI-Small, favoring removing smaller-diameter trees to achieve the hazard objectives, and (c) a thin-from-below (TFB) prescription that was designed to achieve the hazard reduction objectives. The SDI-Large prescription allows removal of trees greater than 21 in. d.b.h. Because removal of trees of this size from forests on the east side of the Cascades in Oregon and Washington is restricted through what are referred to as the Eastside Screens (USDA Forest Service, Region 6, 1994), we assume that special circumstances will allow the removal of trees larger than 21 in. in diameter. The SDI-Small prescription limits removals from all stands to trees smaller than 21 in. in diameter, which results in much many more small trees removed in order to reach the hazard reduction goals for torching and crowning. In much of the interior West, this prescription would require a break from normal practice where diameter limits of 16 in. or less are common. As discussed by Noss et al. (2006) such treatments are not generally effective in restoring ecological structure and function, so we chose to use a more progressive prescription in this analysis. The thin-from-below treatment removes the smallest trees first until hazard reduction goals are met, up to a maximum removal of 50% of original stand basal area.

We evaluated ENEB by simulating a 10 year policy window using a set of base values. However, because these values are highly uncertain, we then used a Monte Carlo simulation approach to assess the plausible range of ENEB of hazard treatments. The Monte Carlo simulations were performed by jointly varying several assumptions about treatment costs and benefits that contribute to an assessment of ENEB. Using this process, we identified conditions and places in the West where treatments may be cost effective under alternative policy environments, which we call scenarios.

We developed four scenarios which vary (a) the type of treatment allowed, (b) the sale of timber products from the treatment, and (c) the inclusion of wildfire reduction costs and benefits. The first scenario (Optimal) specified that products removed upon treatment could be sold, and the highest ENEB prescription (SDI-Large, SDI-Small, TFB) for the location was applied. This scenario was expected to result in the highest ENEB.

The second scenario (No products) specified that products removed upon treatment could not be sold, and the highest ENEB prescription without product sale for the location was applied. This scenario recognized that sale of products from hazard reduction treatments are often challenged through administrative appeals (Laband and González-Cabán, 2006), and would lead to a managerial disincentive to include product removals.

The third scenario allowed for product sale but limited the prescriptions considered to SDI-Small and TFB only (Harvest constrained). This scenario reflects a political reality that removal of large diameter timber in hazard reduction treatments is administratively limited in some areas and that even where allowed, often results in project appeals. This scenario mimics a policy that prohibits the harvest of trees with a d.b.h. greater than 21 in.[3]

A fourth scenario (Short-run) excluded wildfire related costs and benefits that occur due to fuel reduction, instead considering only the costs of treatment and the value of timber removed. In this scenario, in which timber products from treatment could be sold, the costs of wildfire suppression and the losses of timber and nontimber values experienced in a wildfire are set to zero in the ENEB calculation. This assumes that landowners and land managers will not include the immediate non-monetary benefits or costs of the treatments.

These four scenarios were applied to all non-reserved timberlands that could be treated mechanically and for which such treatment was consistent with ecological adaptations to fire (i.e., treatments were not simulated for some forest types found in coastal Washington and Oregon or for forest types that are subject to natural stand-replacing wildfires—e.g., lodgepole pine, except in the wildland–urban interface).

To build a net benefit framework into EBR, we assembled the parameters on each plot needed to quantify the terms after the plus sign on the right side of Eq. (2), the discounted sum of the wildfire-related net benefits of treatments. Additional parameters include estimates of the following: wildfire probability; wildfire damages to standing timber; costs of wildfire suppression, both with and without treatment; wildfire damages to non-timber values such as structures, habitat, scenery, etc.; fuel reduction effect of a wildfire in an untreated stand, and forest growth following wildfire hazard reduction treatments.

However, because the exact magnitude of these additional parameters are not known for all landscapes that might be treated, simulation techniques that vary these parameters are used to provide analysts with useful information. In particular, simulations can reveal the sensitivity of ENEB to these maintained parameter assumptions. Moreover, if multiplier ranges chosen for the simulations can bracket the plausible

[3] The value of old-growth for wildlife, scenery and existence value is frequently cited as a reason to preserve large-diameter stems in western forests in appeals of hazard mitigation treatments proposed for national forest areas subject to the Eastside Screens which administratively limits the removal of stems 21 in. d.b.h. or greater except under specific circumstances (USDA Forest Service, Region 6, 1994; USDA Forest Service, Region 6, 2009), as well as appeals for treatments not subject to these administrative limits (USDA Forest Service, Kaibab National Forest, 2009).

magnitudes of the parameters, the simulations can identify in which sub-state regions are such treatments most likely to yield positive or negative ENEB. The simulations or calculations of the ENEB given some base set of assumptions can also produce a list of locations that can be ranked according to their ENEB; such a list could be used to prioritize locations for a program of treatment on public lands or for the design of a system of incentives to encourage treatment on private lands.

To develop an equation that could be simulated with EBR, we simplify Eq. (1) by converting to discrete time. Thus, for each plot in each spatial unit we calculate the following ENEB:

$$ENEB = P^{'}V_{F} - C + \lambda\sum_{t=1}^{T}\left[P^{'}V_{U,t}k + N_{t} + S_{t} - Y_{t}\right]\tau_{A}(1+r)^{-t} \quad (3)$$

where P = vector of timber product prices ($/unit)

V_F vector of timber product volumes per hectare sold from hazard reduction treatment
C treatment cost plus timber product transport cost ($/ha)
T useful life of a mechanical wildfire hazard reduction treatment
V_U vector of untreated stand timber product volume per hectare
λ annual wildfire probability
k salvage discount factor in case of a fire, where k ranges from zero to 1: $k = 1$ complete timber volume loss upon wildfire, $k = 0$ no timber volume loss upon wildfire in a hazardous (untreated) stand
$(1+r)^{-t}$ discount factor for year t, where r is the discount rate
N net nontimber value ($/ha) that would be lost in the event of a wildfire ($/ha) (i.e., losses minus the nontimber value of the gains experienced upon advent of a wildfire in a hazardous (untreated) stand)
S suppression cost ($/ha) in the event of a wildfire in a hazardous stand
Y suppression cost ($/ha) incurred in the event of a wildfire in a treated stand
τ_A annual wildfire fuel treatment factor.

The wildfire fuel treatment factor, τ_A, merits further explanation. Research by Mercer et al. (2007) indicated that one unit area of wildfire reduced future wildfire by about 0.63 units, and that this effect was spread out over approximately 7 years after a wildfire. In other words, if a management action (say, fire suppression) averted the occurrence of 1 ha of wildfire in year t, there would be, on average, an additional 0.09 ha of wildfire each year for years $t+1$, $t+2$,…,$t+7$, compared to no management action. For Florida, the annual fuel treatment factor would be (Mercer et al., 2007): $\tau_A = 1–(0.63/7) = 0.91$. In other words, 91% of the untreated fire risk remains for each year after treatment. Higher levels of τ_A in our model correspond to a weaker wildfire fuel treatment effect.

To allow the parameters of this model to vary in simulations, we developed multipliers of the parameters. The multipliers are represented in Eq. (4) as η_n. The allowable ranges of the multipliers are shown in the middle two columns of Table 1. Base values of the parameters are shown in the last column of the table.

$$ENEB = \eta_1 P^{'}V^{F} - \eta_2 C + \eta_3\lambda\sum_{t=1}^{T\eta_4}\left[\eta_1 P^{'}V_t^{F}\eta_5 k + \eta_6\eta_7 w_t N_t + \eta_8 S_t - \eta_9 U_t\right]\eta_{10}\tau_A(1+r\eta_{11})_t^{-t}\bigg\} \quad (4)$$

where the amount of volume remaining is estimated as a proportion of the volume removed through treatment ($V_t^F\eta_5 = V_{U,t}$). In the Monte Carlo simulations, the multipliers shown in Table 1 were sampled from uniform distributions, because we have little information regarding their central tendencies. Random sampling across the uniform distributions was done independently, as we had no a priori information regarding their joint distributions. We caution, as well, that some of these values would not be identifiable through any observational study, and that a change in one value accompanied by an opposite change or an identical change in another value could generate the same ENEB.

Table 1
Base case and multiplier values used in the simulations.

	Unfavorable multiplier	Favorable multiplier	Base case parameter
Timber price (η_1)	0.50	2.00	[a,b]
Treatment cost (η_2)	3.00	0.33	$494/ha to $5189/ha[a,c]
Wildfire probability (η_3)	0.50	2.00	0.006/year to 0.030/year[d]
Treatment life multiplier (η_4)	0.33	3.00	4 to 30 years[c]
Standing volume (total merchantable stand volume/treatment volume) (η_5)	0.50	2.00	5.95 to 12.91[e]
Nontimber net losses from wildfire (η_6)	0.25	5.00	$495/ha to $1485/ha[a,f]
WUI nontimber loss factor (η_7)	0.5	2.00	5
Suppression cost in untreated stand (η_8)	0.50	2.00	$1297/ha to $3981/ha[a,d]
Suppression cost in treated stand (η_9)	0.50	2.00	$242/ha[a]
Wildfire fuel treatment factor (η_{10})	0.67	1.27	0.75
Discount rate (η_{11})	1.75	0.50	4.00

[a] Values in 2002 dollars.
[b] Varies by timber product.
[c] Varies by spatial modeling unit.
[d] Varies by Forest Service Region.
[e] Varies by treatment prescription.
[f] Varies by hazard rating.

2.3. Base case parameter values and Monte Carlo multipliers

Each location had a vector of base case values for each of the 11 parameters listed in Table 1. These base case values were allowed to vary in the Monte Carlo simulations as shown ranging from unfavorable to favorable as labeled in Table 1 and identified as $\eta_1 - \eta_{11}$ in Eq. (4).

Timber product prices (P) are the same as those used in Prestemon et al. (2008), and they vary by product (species group) and location. Product prices enter into Eqs. (2)–(4) in terms of possible timber product revenues from treatment and in terms of the potential losses upon wildfire occurrence in the stand. Prices were allowed to vary in simulation from one-half to twice these product specific values (η_1).

Treatment costs (C) in the model varied from location to location based on the volume and diameter of removed from the stand as well as other site-specific factors. In the timberlands of the western U.S., the base case per hectare costs for each location varied from just under $500 to more than $5000. These were allowed to vary in simulation from one-third to three times these site-specific values through η_2.

Base case wildfire probabilities (λ) varied by location and were calculated as the average probability of wildfire, 1992–2006, on national forests of Regions 1–6. Spatial modeling unit locations were matched to Forest Service regions, and the underlying value from those units were assigned from that historical data. To accommodate uncertainty about actual probabilities in the Monte Carlo simulations, these were allowed to vary by half or double (η_3) from the underlying values.

A weakness of this approach of ascribing the same wildfire probability to all locations within a spatial modeling unit is that it ignores how fuel conditions and other smaller scale spatial variables may ultimately affect wildfire probabilities. Although, we contend, the range of variation allowed in the Monte Carlo experiments reported in this article adequately brackets the range of actual values. In future applications, having detailed models that relate fuel conditions to wildfire probability would enhance the quality of this application of EBR (e.g., Rodríguez y Silva and González-Cabán, 2010).

The base case number of years for which wildfire hazard reduction treatments are assumed to last in each location was determined by the ecological conditions found in spatial units where the FIA plots are found. The modified version of the EBR used in this research incorporates into the model a stand growth algorithm that differs from that originally implemented (Prestemon et al., 2008). In particular, pre- and post-treatment stand growth of the original modeling method was based on a limited set of timber stands. Instead the new approach uses growth algorithms that vary by LANDFIRE Map Zones, adjusting pre- and post-treatment hazard re-growth according to the climate, soils, and extant forest types present in each Map Zone (LANDFIRE, 2010). However, although the Map Zone-based approach represents an improvement over previous methods, it is still an approximation. In the Monte Carlo simulations, these values (η_4) were therefore varied from one- to triple the rate reported in Abt et al., 2011. We use these Map Zones by state to delineate our spatial units.

Because treatment volumes form only a portion of the standing timber volume, and because that volume is uncertain even upon measurement, we incorporate a simple additional multiplier to calculate removal volume upon salvage harvest (η_5)—a measure of the standing timber found on the forest inventory plot that could be sold for timber products. The base case timber volume/treatment volume ratio differed across locations. This multiplier ranges from about 6 to almost 13 across locations in the base case. In the Monte Carlo simulations, the random multiplier of this ratio ranges from 0.5 to 2.0.

Another layer of uncertainty surrounds losses of this standing timber in the advent of wildfire (η_5). We make the simple assumption that timber losses that occur in a hazardous stand can be mitigated partially through timber salvage. Lacking reliable information about how the hazard level existing previous to a wildfire relates to timber losses, we applied one salvage discounting procedure regardless of hazard: if a wildfire burns a hazardous stand, the timber has a probability of being salvaged at 15%, while the timber removed is reduced in per unit value by 36%, which is consistent with the wildfire related salvage observed in recent years on federal lands (Prestemon et al., 2006; Prestemon and Holmes, 2008). This assumption is not varied. Losses were assumed to be zero for forests that had such elevated TI and CI values that they were classified as having no hazard.

Base case values for non-timber net losses (N_t) were uniform across the landscape but varied according to whether the stand lay in the wildland–urban interface/intermix (WUI) and the stand's hazard rating. The non-timber loss value was estimated from the limited studies available. Butry et al. (2001) indicate that these losses—related to impacts on the broader economy, health, and structure damages—may be $1000 ha, after factoring out timber losses. While wildfires are known to affect other goods and services valued by people, their impacts are highly uncertain (e.g., Hesseln et al., 2003; Brown et al., 2008; Stetler et al., 2010). For simplicity, in the base case these were set at $495/ha (allowing for greater wildfire ecosystem benefits, aside from the fuel treatment effect) for a hazard rating of 1, while hazard rating 2 has a base case value of $990/ha and hazard rating 3 has a base value of $1485/ha of non-timber net losses. In-condition timberland was assumed to experience zero non-timber net losses in the event of a wildfire. The $495/ha is about half of the 2002 dollar value of the non-timber losses generated in Florida in 1998 by their intense wildfires (Butry et al., 2001), and this is slightly more than half of what we estimate was lost ($907/ha) (not including timber) in the Hayman fire of 2003, based on figures from Kent et al. (2003).[4] In the Monte Carlo simulations, however, these were allowed to vary from one-fourth to five times (η_6).

[4] Kent et al. (2003) report 133 residences lost (we set at $100,000 per residence), 466 outbuildings ($2000 per outbuilding), and burned area emergency response ($26.7 million) in this 57,000 ha wildfire in 2000. The losses therefore total $51.7 million, or $907/ha, in 2002 dollars. This does not include tourism or health effects.

Because wildfires occurring in WUI tend to threaten a greater density of valuable assets as well as subject more people to health impacts, we also apply a WUI value (w_t) to our analyses. The base case WUI value is 5.0 and is only applied to spatial units in the EBR classified as WUI. This WUI value, we contend, should account for the relatively higher rates of structure losses, infrastructure losses, evacuation impacts on the broader economy, and adverse health effects of wildfires occurring closer to where people live and work (e.g., Butry et al., 2001; Rittmaster et al., 2006). In the Monte Carlo simulations, it is allowed to vary from 2.50 to 10 (η_7).

Wildfire suppression costs for wildfires in untreated stands in dollars per hectare (S_t) were defined in the base case geographically in the same manner as wildfire probabilities. The base case values varied by location according to historical Region averages of suppression costs per unit area burned. Underlying suppression cost assumptions in dollars per hectare were calculated as the average real dollar costs per hectare reported, 1992–2006, by the Forest Service in the Region in which the spatial unit was found. In Monte Carlo simulations, suppression costs were allowed to vary uniformly from half to twice the base case values (η_8).

Wildfires occurring in treated stands are assumed to be similar to "use fires" which are unplanned ignitions managed for resource benefits (see USDA Forest Service, 2008) and are assumed to result in minimal wildfire damages. We assign a base suppression cost of $242/ha for these fires, allowing them to vary randomly and uniformly through their multiplier (η_9) from $121 to $484/ha.[5] The fuel treatment factor (τ_A) is highly uncertain for western timberlands, as there is no published empirical evidence about either its existence or its persistence. In the case of western timberlands in our model, the base case value is set at 0.75. In Monte Carlo simulations, multipliers (η_{10}) range from 0.67 to 1.27, allowing for either no fuel treatment from a wildfire ($\tau_A = 1$) or extensive treatment ($\tau_A = 0.5$). We note, however, that an omitted factor relevant to fuel treatments is how treatments may affect losses in locations near the treatment zone. As is the case with wildfire, it could be that treated areas could reduce overall amounts of wildfire in a large region around a treatment area. We found no empirical evidence to support this idea, although experimental evidence exists (e.g., Finney, 2001; Stratton, 2004).[6]

There is inherent uncertainty in economics about the appropriate discount rate (r). This rate could vary from location to location, depending on the alternative best uses for land. In our analyses, we assume for the base case an annual rate of 4%, but this is allowed to vary in Monte Carlo simulations (η_{11}) from 2% to 7%.

3. Results

The results of the simulations of ENEB from mechanical wildfire hazard reduction prescriptions under the four scenarios are shown in Figs. 1 to 5 and in Tables 2 to 4. Fig. 1 displays the results of the Monte Carlo simulations as a probability distribution of the highest ENEB prescription across all locations in the West. The median, upper and lower

[5] The occurrence of a low-intensity wildfire in the location of a treated area during its period of treatment viability could extend the useful life of the fuel treatment, increasing the long-run economic net benefits of these wildfire hazard reduction treatments, overall. Using Monte Carlo methods, the effects of these treatment life-extending wildfires were simulated under one of four scenarios evaluated in this research (Optimal scenario). Compared to results that did not account for this useful life extension, the base case treatable area did not significantly increase. The Monte Carlo-generated probability density of timberland, on the other hand, showed an increase by 1.1 percentage point in the area of timberland with positive discounted expected net benefits. To simulate the effects of these wildfires on treatment life extensions, we used a Monte Carlo approach to develop statistical response functions. These response functions and the treatment simulation results are available from the authors.

[6] This idea implies large scale application of fuel treatments across broad landscapes. The analysis we are providing is on the economic efficiency of fuel treatments in individual locations, without regard to landscape scale designs. As Finney (2001) indicated, random placement has a muted effect on simulations of fire spread.

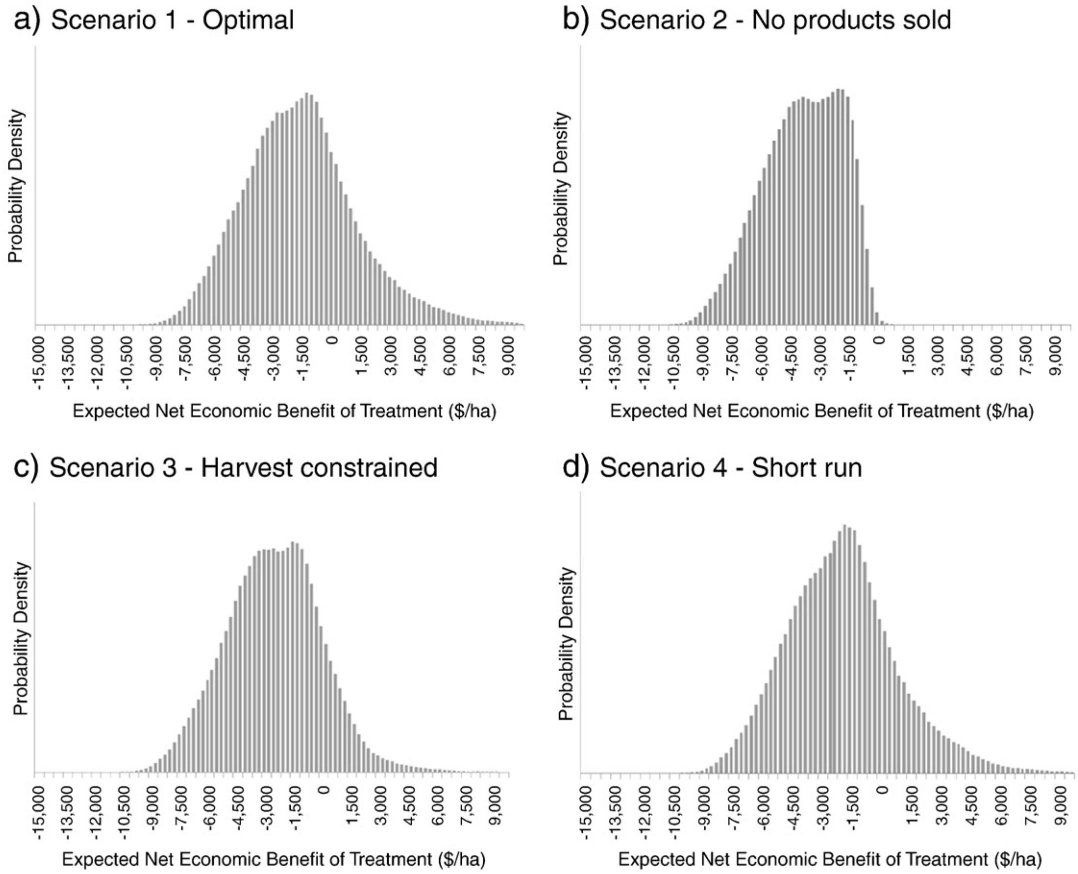

Fig. 1. Monte Carlo simulation of the proportion of timberland area at different levels of expected net economic benefit of treatment for (a) scenario 1—Optimal (optimum prescription; products sold; wildfire costs and benefits included), (b) scenario 2—No products (optimum prescription; no products sold; wildfire costs and benefits included), (c) scenario 3—Harvest constrained (optimum prescription excluding SDI-Large; products sold; wildfire costs and benefits included), and (d) scenario 4—Short run (optimum prescription; products sold; wildfire costs and benefits excluded).

bounds of a 95% simulation density distribution, and the percentage of stands across all simulations with positive ENEB in each simulation are shown in Table 2. Table 3 shows the average output values from the base case parameters and allows us to compare the four scenarios. Table 4 shows the area treated under each of the scenarios by state, owner and WUI status. We also generate maps (Figs. 2–5) that display the locations in the West according to their highest ENEB prescription under the four scenarios using base case parameters (see Table 1). Each of these results is described further below.

Fig. 1a and Table 2 indicate that the amount of timberland in the West with positive ENEB under scenario 1 (Optimal, with optimum prescription choice, products are sold, and wildfire values included) is more than 27.%. However, when treatment products are not sold in scenario 2 (see Fig. 1b and Table 2), less than 1% of the area has positive ENEB. For scenario 3 (Harvest constrained), which excludes SDI-Large but allows products to be sold (Fig. 1c), however, the proportion of simulated landscape with a positive ENEB falls by nearly half, to 16% (third row of results in Table 2). Finally, under scenario 4 (Short run), when the wildfire related costs and benefits are not considered but prescriptions can include SDI-Large and products can be sold, the amount of timberland with positive ENEB is 24% (Fig. 1d, fourth row of Table 2). What this shows is that (1) sale of timber products is a primary determinant about whether treatments yield positive net benefits for landowners, (2) excluding the harvest of larger diameter timber significantly reduces the amount of timberland where such treatments would have positive ENEB, but (3) excluding wildfire related costs and losses is a modest factor affecting ENEB, reducing economically viable treatment options when products can be removed by about four percentage points (from 27.3 to 23.5 percentage points, or by one-sixth compared to the scenario that included these wildfire related costs and benefits).

The simulated 95% density distribution limits (Table 2) shed further light on the likelihood that timberland in the West can be treated with positive ENEB. In scenario 1, with all three prescriptions available and products sold, the Monte Carlo simulations result in a median per hectare ENEB of −$1625 and a 95% confidence limit on ENEB ranging from −$6625/ha to $5125/ha (Fig. 1a). Without sale of products, however, as simulated in scenario 2 and shown in Table 2 and Fig. 1b, both the median (−$3625/ha) and the range (−$7825 to −625/ha) shifted lower. Eliminating the option of applying an SDI-Large prescription (scenario 3) resulted in a lower median than in scenario 1, but higher than scenario 2 (Fig. 1c). Dropping consideration of wildfire related costs and benefits (scenario 4) shifted median and range of ENEB slightly lower when compared to scenario 1 (Fig. 1d and Table 2).[7]

[7] A criticism of evaluating ENEB with spatial aggregates is that fine-scale information about the specific parcels comprising the spatial aggregate is averaged. For instance, the distances to mills that form part of the timber benefits are assumed to be the same across all timberland contained in the spatial aggregate, while they vary across parcels within the spatial aggregate, some with lower transport distances and others with higher transport distances, leading to a more peaked simulation density. The result of this is to flatten the tails in the simulated density figures, producing an underestimate of the amount of timberland with the most positive ENEB (and an underestimate of timberland with most negative ENEB). We tested the impact of this assumption for the Scenario 1 only by setting transport costs to zero and evaluating how the simulation density distribution shifted. We found that the proportion of the simulation density distribution with positive ENEB when timber products from treatment are sold for the SDI-Large prescription increased by 7.3% percentage points, to 34.6%, compared to the comparable value for a simulation that included transport costs (27.3%).

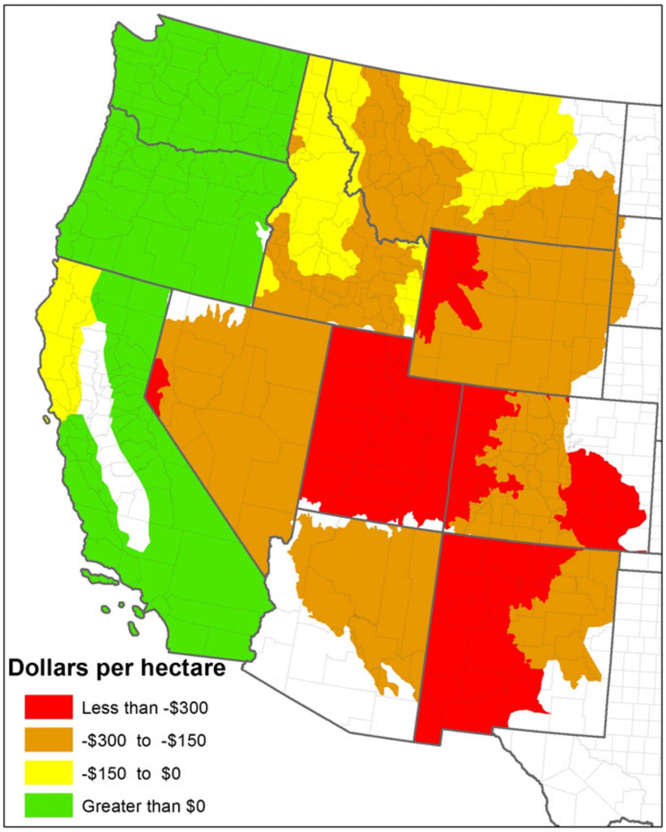

Fig. 2. Map of expected net economic benefits (ENEB) of mechanical wildfire hazard reduction treatment under Scenario 1 (Optimal, with optimum prescription, products sold, and wildfire costs and benefits included). State and county boundaries are indicated. Red colors indicate lowest net value of treatment, and green is highest, with brown and yellow intermediate. Areas in white have no significant out-of-condition timberland area.

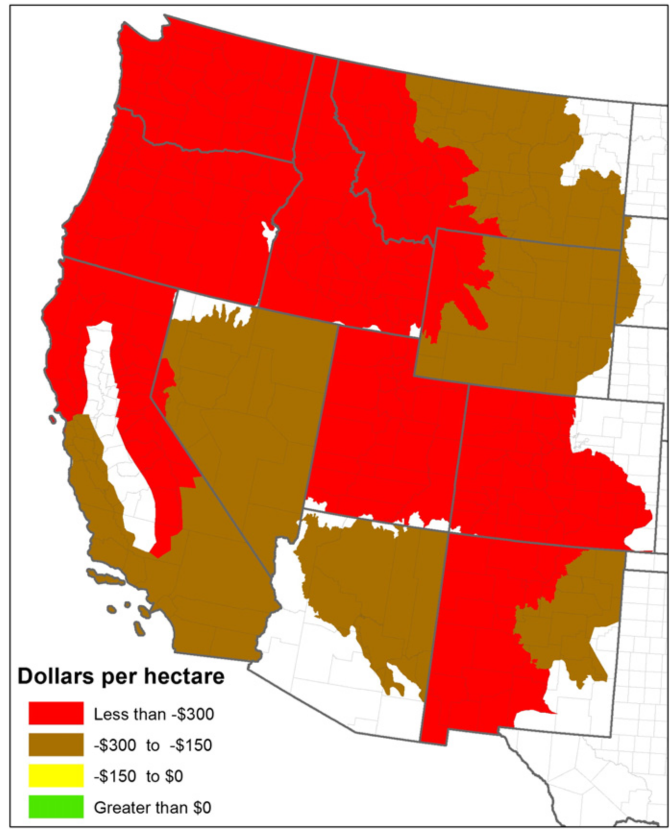

Fig. 3. Map of expected net economic benefits (ENEB) of mechanical wildfire hazard reduction treatment under Scenario 2 (No products, with optimum prescription, no products sold, and wildfire costs and benefits included). State and county boundaries are indicated. Red colors indicate lowest net value of treatment, and green is highest, with brown and yellow intermediate. Areas in white have no significant out-of-condition timberland area.

A key attribute of the EBR model is its ability to link stand and site conditions and proximity to timber product consuming facilities with ENEB of treatments. Figs. 2–5 present a spatial, rather than a density, distribution of these locations under the four scenarios. Table 3 documents features of spatial units where the ENEB was positive in each of the four scenarios under base case assumptions; Table 4 shows where the areas of positive ENEB are located under base case assumptions. Fig. 2 indicates that, at base-case values for all parameters, many locations in the West had positive ENEB, with these areas concentrated in California, western Oregon, western Washington, and southern Idaho. Places where the ENEB of treatments was most negative were in the interior West, even with products sold upon treatment, especially Nevada, Utah, Wyoming, and New Mexico. Fig. 3 illustrates how little timberland would have positive ENEB if no products were sold upon treatment—essentially nowhere in the West would treatment yield positive ENEB. Fig. 4 shows the effect of dropping consideration of the SDI-Large prescription, which resulted in negative ENEB in parts of California and southern Idaho, and other parts of the West have more negative ENEB. Finally, Fig. 5 illustrates some small shifts in ENEB when wildfire related costs and benefits were not considered. This figure indicates that some places where timber product markets are weak were less likely to be treated with positive ENEB. Note that the EBR model includes only out-of-condition timberland in the locations that are mapped; many places in the West are either in-condition timberland or are non-timberland forest, and so they were excluded from our analyses. Further, Figs. 2–5 were developed under base-case assumptions, so under situations of higher timber prices or higher suppression costs, for example, the area of the West with the highest ENEB (in green) would expand to include parts of Arizona, and Montana. In contrast, weak timber product markets could make many of these places with positive ENEB when products are sold into places with negative ENEB.

The tabular representation of the locations of out-of-condition timberland in the West that had positive ENEB of treatment under the base case under all four scenarios under base case assumptions (Tables 3 and 4) has the following implications:

(1) when timber products were not sold, no timberland in the West had positive ENEB;
(2) when timber products were sold, nearly 4.6 million hectares of timberland had positive ENEB (29% of available timberland under scenario 1, 11% under scenario 3, and 27% under scenario 4);
(3) under scenario 1, 1.99 million hectares (or 43% of area with positive ENEB) were on private lands, with 54% and 39% under scenarios 3 and 4 respectively;
(4) stands with the highest ENEB tend to grow quickly, with expected length of useful treatment life lasting on average three years or less (sites with negative values, not shown in Table 3, had treatment lives lasting nearly twice as long, averaged across scenarios 1, 3, and 4), hinting that these stands were those with highest pre-treatment product volumes, fastest growth rates, and highest volumes of treatment removals, which are found mainly along the West Coast and in the northern Rockies;
(5) when timber products were sold in scenario 1, less than 4% (171,533 ha) of the timberland area with positive ENEB was found in the wildland–urban interface, and similarly low shares were found with other scenarios;

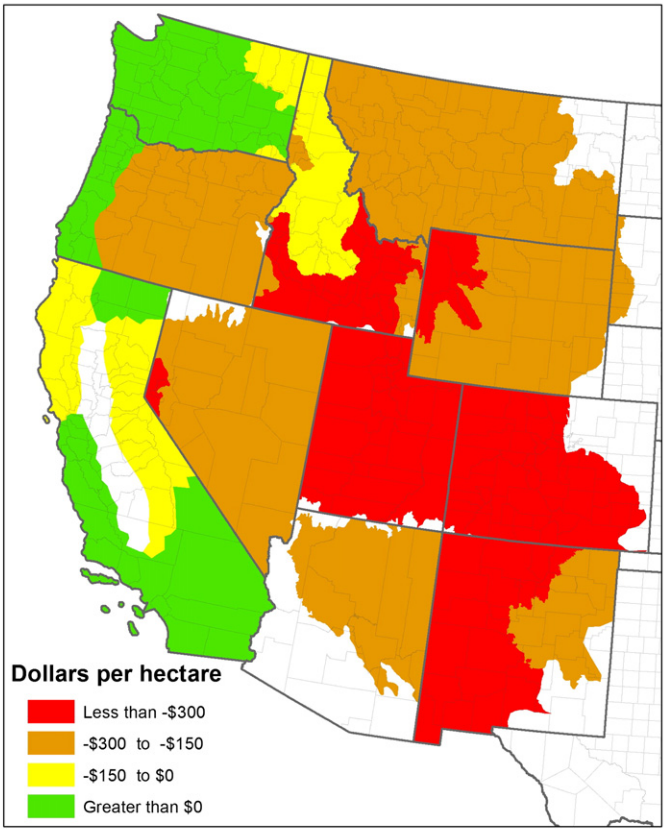

Fig. 4. Map of expected net economic benefits (ENEB) of mechanical wildfire hazard reduction treatment under Scenario 3 (Harvest constrained, excluding SDI-Large, products sold, and wildfire costs and benefits included). State and county boundaries are indicated. Red colors indicate lowest net value of treatment, and green is highest, with brown and yellow intermediate. Areas in white have no significant out-of-condition timberland area.

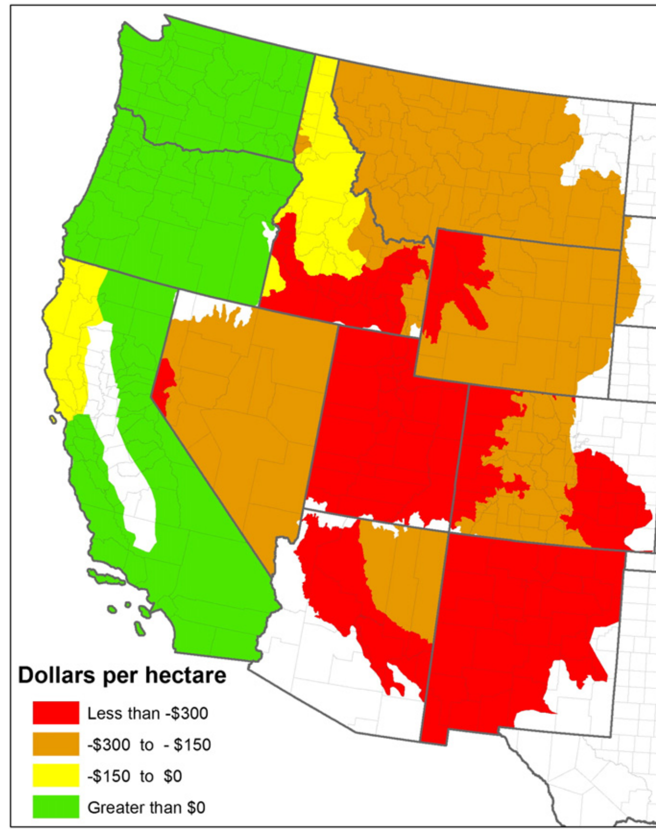

Fig. 5. Map of expected net economic benefits (ENEB) of mechanical wildfire hazard reduction treatment Scenario 4 (Optimal, with optimum prescription, products sold, and wildfire costs and benefits excluded). State and county boundaries are indicated. Red colors indicate lowest net value of treatment, and green is highest, with brown and yellow intermediate. Areas in white have no significant out-of-condition timberland area.

(6) where treatments of timberland had positive ENEB when timber products were sold in scenario 1, stands were found only in the primary timber producing states of the West: California, Oregon, Washington, Montana, and Idaho, which highlight the importance of having a vigorous market for timber products in the vicinity of a treatable stand if economic efficiency is an important criterion in site selection.

One result not shown in Table 4 relates to the share of total hazardous timberland receiving treatment with positive ENEB under base case assumptions. When timber products were sold, 43% of all WUI timberland was treated with positive ENEB under scenario 1, 33% under scenario 3, and 43% under scenario 4. This is compared to the comparable shares on non-WUI timberlands: 29%, 11%, and 26%. This implies that a larger share of the WUI is treatable when timber products are sold compared to the non-WUI. Still, WUI timberlands represent fewer than 3% (399,099 ha) of available hazardous timberland in the EBR modeling domain, so this somewhat more positive ENEB timberland could be quickly completed in an aggressive program of treatment across the West.

4. Discussion and conclusions

There are many challenges to treating landscapes in ways that restore valued ecosystem structures and functions and simultaneously yield the greatest economic net benefits to society. Land managers, especially of public lands, have long been asked to design timber harvest and vegetation management prescriptions that achieve multiple use objectives, including those focused on enhancing forage, timber, water, esthetic and recreational values. It is only more recently that large scale programs of treatments have been contemplated that have focused specifically on reducing the costs and losses from wildfire (USDA/USDI, 2006). Our simulations show that, under a wide range of plausible assumed values of influential parameters, there are places where such treatments would have positive ENEB. Across the western U.S., the timberland with positive ENEB from treatments can only be found if timber products can be sold. Further, these lands are only in five states, along the West Coast and the North. Even there, however, most stands have negative ENEB. How treatments are carried out and the constraints in selling timber products that may derive from the treatments will influence the expected net benefits that could result from mechanical wildfire hazard reduction programs.

This highlights the challenges facing government agencies. Land management policies, in many cases, require agencies to devote a large share of wildfire hazard reduction treatment funds to areas with higher densities of buildings, people, and private lands. Yet, if agencies seek to focus treatments only on timberland where hazard reduction treatments yield positive net benefits, and the implementing programs do not have timber product sales as a possible design feature, then such programs are not likely to affect a significant portion of the western landscape. According to our analyses, the area estimated by our model to have positive ENEB under base case parameters in scenario 2 (No products) was zero. Even allowing for alternative assumptions about driving parameters in our simulations, we found a very low probability (less than 1%) that any particular timberland hectare could be treated with positive net benefits.

If timber product sales are possible, then under base case assumptions this area rises to nearly 4.6 million hectares. Monte Carlo

Table 2
ENEB of treatments by scenario from Monte Carlo simulations.

Scenario	Timberland ENEB				
	95% lower bound	Median	95% upper bound	Share of area with positive ENEB	Hectares (out of 15.49 million) with positive ENEB
	$/hectare[a]			Percent	Million hectares
1-Optimal optimum of SDI-L, SDI-S, TFB; with products; with wildfire values	−6625	−1625	5125	27	4.23
2-No products optimum of SDI-L, SDI-S, TFB; without products; with wildfire values	−7875	−3625	−625	<1	0.03
3-Harvest constrained optimum of SDI-S, TFB; with products; with wildfire values	−7125	−2375	2625	16	2.49
4-Short-run optimum of SDI-L, SDI-S, TFB; with products; without wildfire values	−6875	−1875	4625	24	3.64

[a] Values rounded to the nearest $25, in 2002 dollars.

Table 3
Mean area weighted values for inputs and outcomes of all lands with positive ENEB of treatments by scenario using base-case parameter values.

Scenario	Units	1-Optimum	2-No products	3-Harvest constrained	4-Short run
Prescription		Optimal of 3 prescriptions	Optimum of 3 prescriptions	Optimum of SDI-Small, TFB	Optimum of 3 prescriptions
Wildfire-related costs and benefits included?		Yes	Yes	Yes	No
Sale of timber products allowed?		Yes	No	Yes	Yes
Distance to nearest 5 sawmills	km	85	NA	86	86
Distance to nearest pulp mill	km	157	NA	162	153
Treatment cost	$/ha[a]	2219	NA	2077	2185
Average treatment life	Years	1.7	NA	1.6	3.1
Treatment revenues	$/ha[a]	3544	NA	3061	3626
Net value of treatment	$/ha[a]	1383	NA	990	1429
Wildfire probability	Annual	0.021	NA	0.023	0.021

[a] Values in 2002 dollars.

simulations further support the idea that economically efficient treatment can only occur widely when products are sold, which also correlates with states with vigorous timber growth rates. These findings are consistent with those of Ince et al. (2008), Barbour et al. (2008), and Prestemon et al. (2008). Given this, the market prices of timber products are important determinants of positive ENEB. Yet, given recent trends in forest products markets in the United States (e.g., Howard and Westby, 2009), it is not likely that this key determinant of net benefits will adjust substantially upward in the coming years.

This simulation exercise also highlights the potential utility of the EBR model for identifying the circumstances under which mechanical hazard reduction treatments could have positive ENEB. In a first approximation of the prioritization emerging from the model, we see that these stands generally grow in coastal states of the West. The EBR model, appropriately calibrated to match what managers consider to be the values of the most important parameters affecting ENEB of treatments, could be used as a tool for prioritizing treatments across broad areas of the western U.S., where the majority of mechanical fuel treatments are being considered. As an economic optimization tool, rules on allocations across space (e.g., funding levels across states or national forests regions), and other constraints or priorities can be added that would allow this model to serve as one among a broader array of decision support tools.

Table 4
Hectares of treatable area with positive ENEB by scenario by WUI status, ownership and state.

Scenario	1-Optimal	2-No products	3-Harvest constrained	4-Short run
Prescription	Optimum of 3 prescriptions	Optimum of 3 prescriptions	Optimum of SDI-Small or TFB	Optimum
Wildfire-related costs and benefits included?	Yes	Yes	Yes	No
Sale of timber products allowed?	Yes	No	Yes	Yes
Total treatable hectares	4,592,592	0	1,748,010	4,237,527
WUI	171,553	0	133,490	171,232
Non-WUI	4,421,039	0	1,614,520	4,066,295
National forest	2,061,902	0	502,481	1,738,110
Other public land	540,550	0	296,145	532,888
Private land	1,990,141	0	949,384	1,966,529
Arizona	0	0	0	0
California	1,260,953	0	730,851	1,260,953
Colorado	0	0	0	0
Idaho	510,486	0	38,407	510,486
Montana	365,756	0	28,377	15,557
New Mexico	0	0	0	0
Nevada	0	0	0	0
Oregon	1,402,476	0	569,628	1,402,155
South Dakota	0	0	0	0
Utah	0	0	0	0
Washington	1,052,922	0	380,748	1,048,377
Wyoming	0	0	0	0

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