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Market impacts of a multiyear mechanical fuel treatment program in the U.S.

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A B S T R A C T

We describe a two-stage model of global log and chip markets that evaluates the spatial and temporal economic effects of government-subsidized fire-related mechanical fuel treatment programs in the U.S. West and South. The first stage is a goal program that allocates subsidies according to fire risk and location priorities, given a budget and a feasible, market-clearing market solution. The second stage is a quadratic welfare maximization spatial equilibrium model of individual State and global product markets, subject to the fuel treatment allocation. Results show that the program enhances timber market welfare in regions where treatments occur and globally but has an overall negative economic impact, once fuel treatment program costs are included. The overall cost of a mechanical fuel treatment program, when considering timber market welfare, transport costs, treatment costs, and timber receipts, exceeds $1000 per acre, implying that the long run fire effects and ecosystem net benefits of a treatment program would need to exceed this figure in order to justify widespread implementation.

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1. Introduction

Both scientists and policy makers have suggested that forest restoration can reduce the overall negative impacts from wildfires by reducing wildfire intensities when fires burn through these treated stands (e.g., van Wagtendonk, 1996; Office of the President of the United States, 2002; One Hundred Eighth Congress of the United States of America, 2003). Stands could be treated by eliminating vegetation, through either mechanical treatments or prescribed fire, which would not exist in fire-adapted ecosystems where fire frequencies are high and intensities are modest. Ecological and societal benefits are believed to derive from moderated wildfire intensities resulting from lower fuel levels. These lower intensities may result in cheaper or more effective suppressions strategies, lower vegetation mortalities, lower amounts of soil damage, and reduced post-fire rain runoff.

Mechanical treatments are done to quickly convert stands from high fire danger to low fire danger conditions and to return stands to a state where they can then be allowed to burn by a wildfire or can be prescribe burned with greater ease, potentially lowering the subsequent landscape maintenance costs (Brown and Kellogg, 1996; Lynch and Mackes, 2003). Unfortunately, use of prescribed fire is limited by financial, ecological and legal factors (González-Cabán and McKetta, 1986; Rideout and Omi, 1995; Cleaves et al., 2000). Mechanical treatment strategies, however, face their own significant challenges, including public opposition, operational difficulties, environmental constraints, and expense. Some members of the public view these treatments as just another way for wood processors to gain access to public lands for their own profit (e.g., Vaughn, 2003; Natural Resources Defense Council, 2003), with significant consequences for agency actions (Laband and González-Cabán, 2006), but this opposition is not always widespread (Vogt et al., 2001). With respect to operations, these treatments sometimes require vehicle access when heavy equipment is used in the thinning operation. Heavy equipment is used to cut and chip trees onsite, and sometimes it is needed to pile trees at log landings. Without heavy equipment, these treatments are labor intensive, requiring hand and sometimes supervised burning of hand-thinned materials. Mechanical treatments may be limited by extreme drought during warm months of the year (due to risk of igniting a fire during treatment operations) and by wet soil conditions at other times. Although the temporal window of opportunity is often larger than that of prescribed fire, mechanical methods are more expensive (e.g., Keegan et al., 1995; Brown and Kellogg, 1996; Drews et al., 2001; Lynch and Mackes, 2003). Our analyses have shown that costs range from several hundred to several thousands of dollars per acre. Extreme costs of such treatments strain the plausibility that the net benefits of mechanical treatments will exceed their costs in some locations.

But mechanical treatments also have the possibility of obtaining marketable products from the thinning operation, which can offset the high cost of treatment. It is possible that introducing treatment materials into timber markets can lead to net positive timber market impacts (Abt and Prestemon, 2006). Market effects depend on who you are: non-participant timber producers can be harmed through lower market prices and lower output by them; the U.S. treasury may be helped, through higher treatment revenues (after accounting for the costs of subsidies to treat); and wood consumers can benefit because of lower prices and higher total final product output.

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The primary objective of this paper is to describe some of the multiyear impacts of mechanical treatment programs on timber markets in the U.S. This study therefore expands the foundational work by Abt and Prestemon (2006), who evaluated the timber market impacts of a one-time western U.S. national forest mechanical fuel treatment program. Left unanswered were questions of long-run impacts, inclusion of other regions, the effects of constraints on the institutional capacity to manage large-scale treatment programs, or the effect of expanding timber demand on the welfare impacts of such programs. To meet our objective, we: (1) include a greater total area of land available for treatment, including non-National Forest federal lands and federal lands in the southern U.S., a region where more wood is produced than in any single other country in the world (Prestemon and Abt, 2002); (2) model the treatment program and market impacts over several decades; and (3) quantify the effect of expanded timber market demand that could result from a sustained treatment program. Additionally, our analysis differs from Abt and Prestemon (2006) by implementing a stand-level prioritization strategy based on stand-level wildfire risk measures, the torching and crowning indices. Finally, this study also evaluates the effect on model outcomes of accounting for fire risk change over time.

To perform our analyses, we divide the West and South's timberland into 2501 “locational aggregates” and treat the landscape according to our priorities for treating each of these locational aggregates. Because forest inventory data are provided for points, or plots, that are sampled across the landscape, such point data must be expanded, using acre and timber volume expansion factors, in order to describe the landscape in aggregate. Hence, a locational aggregate is a collection of all of the plots that are in the same State and have identical owner, broad forest type, wildland–urban interface (WUI) status, and fire risk levels. Priorities for treatment are based on the WUI status and the fire risk level.

To address issues of parameter uncertainties and program size, we conduct sensitivity analyses that evaluate the impacts of a treatment program under different supply and demand elasticities, evaluate these impacts across different program sizes (aggregate spending to achieve treatment on government lands), quantify the effects of including southern forests in a nationwide program, and measure the overall effects of limiting the treatment program to high risk or WUI lands only.

Our research provides information for government decision makers, who need to know the market impacts of introducing treatment products. The research also provides information for decision makers at the national level who seek to understand how mechanical treatment programs of different sizes might affect the rate of fire risk reduction occurring from treatments. This can help managers prioritize how to spend scarce federal dollars to achieve maximum societal benefits. Our research does not, however, address private land treatments.

2. Methods

Timber markets in the U.S. West and South differ substantially, both in terms of the kinds of forest growing there and in terms of the relative shares of production deriving from public and private lands. In the West, nearly half of production derives from private timberland and is more than 90% softwood. Mills are concentrated in Oregon, Washington, California, Montana, and Idaho (Spelter and Alderman, 2005; Prestemon et al., 2005). In the South, production from private lands accounts for 98% of total timber product output, and it contains a larger share from hardwood species (Smith et al., 2004). Fire risk also differs across regions. In the South, southern pine stands of certain types are frequently prescribe burned (Cleaves et al., 2000). Nonetheless, many forests in the South are left untreated by any fuels management strategy. In the West, narrower weather windows and more difficult terrain limit the opportunities for prescribed fire. In both cases, there exists the opportunity to use mechanical methods to reduce wildfire fuels, aiding in ecosystem restoration and leading to lower overall damages to these stands in the event of a wildfire.

In both the South and the West, wildland managers seeking to reduce fuels and restore ecosystems to fire-adapted states could prioritize treatments according to risk criteria. These criteria include proximity to built-up areas such as the WUI and places where fuel accumulations and stand structures would lead to catastrophic outcomes in the case of a wildfire. These managers would logically prioritize or limit their treatments to particular fire-adapted forest types. In the modeling described here, all forest types in the West are potentially treatable; in the South, we limit our treatments to pine types, as fire is used as a primary management tool in pine forest ecosystems (Stanturf et al., 2002).

If materials are removed from stands following fuel treatment, then the effects of these treatments would be expected to differ between the West and the South. In the West, a sizeable government mechanical treatment program would be expected to affect prices and aggregate welfare significantly. In the South, where doubling output from federal lands would still amount to a very small change in aggregate timber product output, the effects on prices and welfare would be less. In the results section, we report the separate price impacts of such a program in each region.

2.1. Timber markets in fire prone landscapes

In this study, we represent aggregate timber supply in fire prone landscapes as consisting of a price-responsive private supply and a price unresponsive public supply. Added together, these comprise the aggregate schedule of timber supply at different prices. See Abt and Prestemon (2006) for a detailed description of the market dynamics of a treatment program on producer and consumer welfare and prices.

Abt and Prestemon (2006) modeled treatment materials as adding to regular timber harvests from national forests. In this analysis, we recognize instead the likelihood that timber removals for treatments would substitute for regular removals on government lands. In other words, land managers will replace regular harvests with treatment harvests, until treatments exceed historical regular harvests. This recognizes that timber harvest programs on some federal lands may be constrained by available personnel (e.g., Prestemon et al., 2006). Compared to Abt and Prestemon (2006), then, the modeled timber market impacts in this study would be expected to be smaller than would be found under the “add-to” assumption in that study. Additionally, to capture the effect of treatments that exceed even historical harvests, we further add an administrative cost per unit area of land treated ($300 per acre), based on conversations with managers. Because the aggregate impacts on prices and welfare will depend on the size of the program, we vary the size of the program across a range, with most simulations from $300 million to $1200 million per year.

The effect of removal programs on prices and private producer and consumer welfare depends on how responsive supply and demand are to prices. The more elastic demand is to prices, the smaller the impact that a program would have on the welfare of mills. The more elastic supply is to prices, the more completely they reduce output in response to a price decrease. On the other hand, the opportunity to benefit from treatment materials could provide an incentive for manufacturers to expand their input capacities, effectively expanding derived demand for timber at every price level. This kind of expansion would increase the size of the timber market. To test how important such demand expansions would be, in one simulation scenario we also evaluate the effects of new investments on overall producer and consumer welfare.

2.2. Theoretical considerations

An ideal model of fuel treatment spending by a government would optimize how the government devotes resources to affect losses,

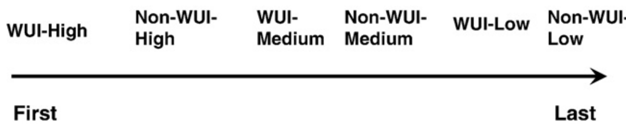

Fig. 1. Treatment priorities applied in all simulations. Where lower risk levels or non-WUI acres are not included in certain simulations, the risk or WUI priorities remain.

perhaps by minimizing costs plus losses (e.g., Donovan and Rideout, 2003). We contend, however, that the information and modeling demands of such a program are large and, today, insurmountable. Short of this, we can design a cost-minimizing program that comprehends national policy priorities. For these, we can look to the Healthy Forest Restoration Act of 2003 (HFRA) (One Hundred Eighth Congress of the United States of America, 2003) and previous analyses done by the U.S. Forest Service for guidance. The HFRA emphasizes treating higher risk forests and forests near built-up areas—the wildland–urban interface (WUI). In our study, we simulate treating only the high priority stands, or, alternatively, treating all stands that are out-of-condition (e.g., have low crowning and torching indices or fire regime condition class values that are 2 or 3) but prioritize how we spend our money on them, according to fire risk and WUI status. Given limited resources, higher fire risk and WUI sites would receive the most attention, which would be consistent with the heuristic valuation of the HFRA (Fig. 1).[1]

2.3. Empirical model

We have developed an empirical model that prioritizes treatments on government lands based on WUI status and fire risk. The first stage of the model is a goal program, attaching weights to acres according to their risk and WUI status and maximizing the sum of these weighted acres; the weights serve to set the treatment priority for a given risk and WUI status. This stage is subject to a feasible market solution, including market-clearing and maximum spending constraints. The second stage, occurring after treatment, is a quadratic programming problem that maximizes consumer plus producer welfare less transport costs, subject to the treatment solution from the first stage (and other constraints) (Samuelson, 1952; Takayama and Judge, 1964; Just et al., 1982). The second stage therefore allocates log removals from public lands in the treatable set of all stands. Sawlogs are required to enter timber markets, but pulpwood logs may be disposed of locally when no local market exists for it (i.e., the pre-solution pulpwood value minus haul cost must be positive). However, we also can simulate the effects of a program that would not have any removed timber consumed in timber markets.[2]

This model is specified as an annual maximization of a weighted sum of acres, found by finding a $(I+J+K+M)\times 1$ vector $\mathbf{d}_t>0$, subject to non-negativity, state program cost, total program cost, market feasibility, and mill capacity constraints, where I is the total possible owner types, J is total possible WUI classifications, K is the total forest types available for treatment across all States, and M is the total U.S. States receiving treatment. The problem is solved for all acres that are allowed to be treated, of ownership i, of WUI status j, forest type k, in state m:

$$Y_t = \max_{\mathrm{d}_t} \sum_{m=1}^{M}\sum_{k=1}^{K}\sum_{j=1}^{J}\sum_{i=1}^{I} d_{i,j,k,m,t} w_{i,j,k} a_{i,j,k,m,t} \tag{1a}$$

subject to:

(1b) Non-negative proportion of acres treated each year: $0\leq d_{i,j,k,m,t}\leq 1$ $(\forall\ i,j,k,m,t)$.

(1c) Non-negative acres available to treat each year: $a_{i,j,k,m,t}\geq 0(\forall\ i,j,k,m,t)$.

(1d) A nationwide annual program maximum treatment cost constraint:

$$-\sum_{m=1}^{M}\sum_{k=1}^{K}\sum_{j=1}^{J}\sum_{i=1}^{I} a_{i,j,k,m,t} c_{i,j,k,m} + C_t \geq 0$$

(1e) State annual program minimum treatment spending proportion constraints:

$$\sum_{k=1}^{K}\sum_{j=1}^{J}\sum_{i=1}^{I} \frac{a_{i,j,k,m,t} c_{i,j,k,m}}{C_t} - s_{m,t} \geq 0(\forall m)$$

(1f) State annual product consumption capacity constraints:

$$\sum_{k=1}^{K}\sum_{j=1}^{J}\sum_{i=1}^{I} a_{i,j,k,m,z,t} v_{i,j,k,m,z} - K_{m,z,t} \geq 0(\forall m,z)$$

(1g) State market material balance constraints for the volume of each timber product z:

$$\sum_{k=1}^{K}\sum_{j=1}^{J}\sum_{i=1}^{I} d_{i,j,k,m,t} a_{i,j,k,m} v_{i,j,k,m,z} + s^{r}_{m,z,t}(p_{m,z,t}) + s^{u}_{m,z,t} - \sum_{n=1}^{N} T_{m,n,z,t} + \sum_{m=1}^{M} T_{n,m,z,t} - d_{m,z,t}(p_{m,z,t}) \geq 0(\forall m,z)$$

(1h) State minimum federal harvest constraints:

$$\sum_{k=1}^{K}\sum_{j=1}^{J}\sum_{i=1}^{I} a_{i,j,k,m,t} v_{i,j,k,m,z} + s^{u}_{m,z,t} - F_{m,z,t} \geq 0(\forall m,z)$$

where:

$d_{i,j,k,t}$	the proportion of acres treated of the acres in ownership i of WUI status j in forest type k in year t;
$w_{i,j,k}$	a nonnegative priority weight placed on acres in ownership i of WUI status j in forest type k;
$a_{i,j,k,m,t}$	the acres in ownership i of WUI status j in forest type k in state m, in year t;
C_t	the maximum program spending available for all treatable stands in all states, in year t;
$s_{m,t}$	the minimum spending allowed in state m in year t;
$v_{i,j,k,m,z}$	volume of timber of timber product z on the acre in ownership i of WUI status j in forest type k in state m, in year t;
$c_{i,j,k,m}$	the total treatment cost (local haul plus site costs) of acres in ownership i of WUI status j in forest type k in state m;
$K_{m,z,t}$	state m's input capacity constraint for timber product z in year t;
$p_{m,z,t}$	the price of timber product z in state m in year t;
$s^{r}_{m,z,t}(p_{m,z,t})$	private timber production quantity in state m in year t of timber product z;
$s^{u}_{m,z,t}$	public timber production quantity in state m in year t of timber product z;
$d_{m,z,t}(p_{m,z,t})$	public timber production quantity in state m in year t of timber product z;

[1] Other possible programs could exist that would address both fire risk and market impacts. For example, a mechanical fuel treatment program generating timber products could be designed to maximize timber market welfare given an overall program cost and a required set of treatment priorities based on fire risk and the WUI.

[2] Operationally in the simulation, this "local" dumping only occurs for pulpwood because of its low value, relative to that for sawtimber sized materials, and it only happens in the West because of the very thin western pulpwood markets in parts of the West. This occurs only for stands in which the pre-solution stumpage value of the pulpwood in a stand is negative. Making this decision a function of the final price of pulpwood in the market would endogenize the decision in the mixed integer program and make it non-linear and hence not solvable using the solution algorithm applied.

$T_{n,m,z,t}$ the volume of timber product z shipped from state n to state m in year t;

$T_{m,n,z,t}$ the volume of timber product z shipped from state m to state n in year t;

$F_{m,z,t}$ the minimum federal timber product volume removed (treatment plus regular harvests) of product z from government lands in state m in year t.

The second stage of the model maximizes consumer plus producer welfare globally, across all markets defined in this model: 25 states, western Canada (British Columbia and Alberta), and the rest of the world (including the rest of the U.S., Canada, and world). This is solved as a spatial optimization problem, across multiple products, where we maximize the total value of consumption, production, and trade less the costs of production and product transport. This is accomplished by maximizing social net welfare in each year (W_t) by allocating production (the quantity supplied, S at price P) and consumption (the quantity demanded, D at price P) across consuming and producing regions by moving quantities of product (T) among regions:

$$W_t = \max \sum_{m=1}^{M} \sum_{z=1}^{Z} \int_{p}^{pmz\max} D_{m,z}(P_{m,z,t})dP - \int_{0}^{p} S_{m,z}(P_{m,z,t})dP - \sum_{n=1}^{N} \sum_{m=1}^{M} \tau_{m,n,z} T_{m,n,z,t} \qquad (2)$$

subject to the solution found in the first stage (goal program) and constraints (1a)–(1h), allowing only trade and therefore prices and production to be altered compared to the solution found in the first stage. The variable $p_{mz\max}$ is the vertical axis intercept of the demand curve, specified as a linear projection from pre-treatment program equilibrium supply and demand intersection defining pre-treatment program price and quantity. The variable $\tau_{m,n,z}$ is the transport cost to move one unit of product z from state m to state n. The local haul cost proportion of $c_{i,j,k,m}$ is proxied by the distance to the nearest five sawmills and the nearest two pulpwood consuming mills (pulp, particleboard, chip mill) from the forested center of the county in which U.S. Forest Service Forest Inventory and Analysis (FIA) plots are located. The source of the mill location data is Prestemon et al. (2005)—see Fig. 2. Again, material balance constraints are required in this second stage. Demand and supply curves can be approximated with linear functions projected from the point of pre-program equilibrium.

Two versions of the two-stage model are used, and both allow for the model to solve progressively, over time, until the entire landscape is treated (given an annual treatment budget). One version does not "grow" stands so that the area represented by the set of plots defining a "location" (the multiple plots comprising an owner-WUI status-forest type-risk aggregate) cannot change over time. Locations comprised of only "in-condition" plots (stands with negligible fire risk) cannot go "out-of-condition" (stands with significant fire risk). Once treated, this area is permanently defined as "treated" in the model. In this version, it is always possible to treat all available stands in the simulation scenario.

A second version recognizes that stands can grow into condition, grow out of condition following treatment or if left untreated, or be treated but not completely remove all stands out of risky status. Movement between risk categories is allowed each year for all stands, based on a Markov process; a portion of the stands change risk status, some remain in the same status. Depending on the risk growth rate (the values identified in the Markov transition matrix), it is possible, given a small treatment program (small budget), that the entire landscape of risky stands can never be fully treated and put into in-condition status. Note that this growth transition Markov process is calibrated on torching and crowning indices, which (we explain below) are only available for western forest types. Hence, we implement risk growth only for the western U.S., not the southern U.S. When this version of the model is implemented, the South is "turned-off" (not treated) in the simulations. Although the second

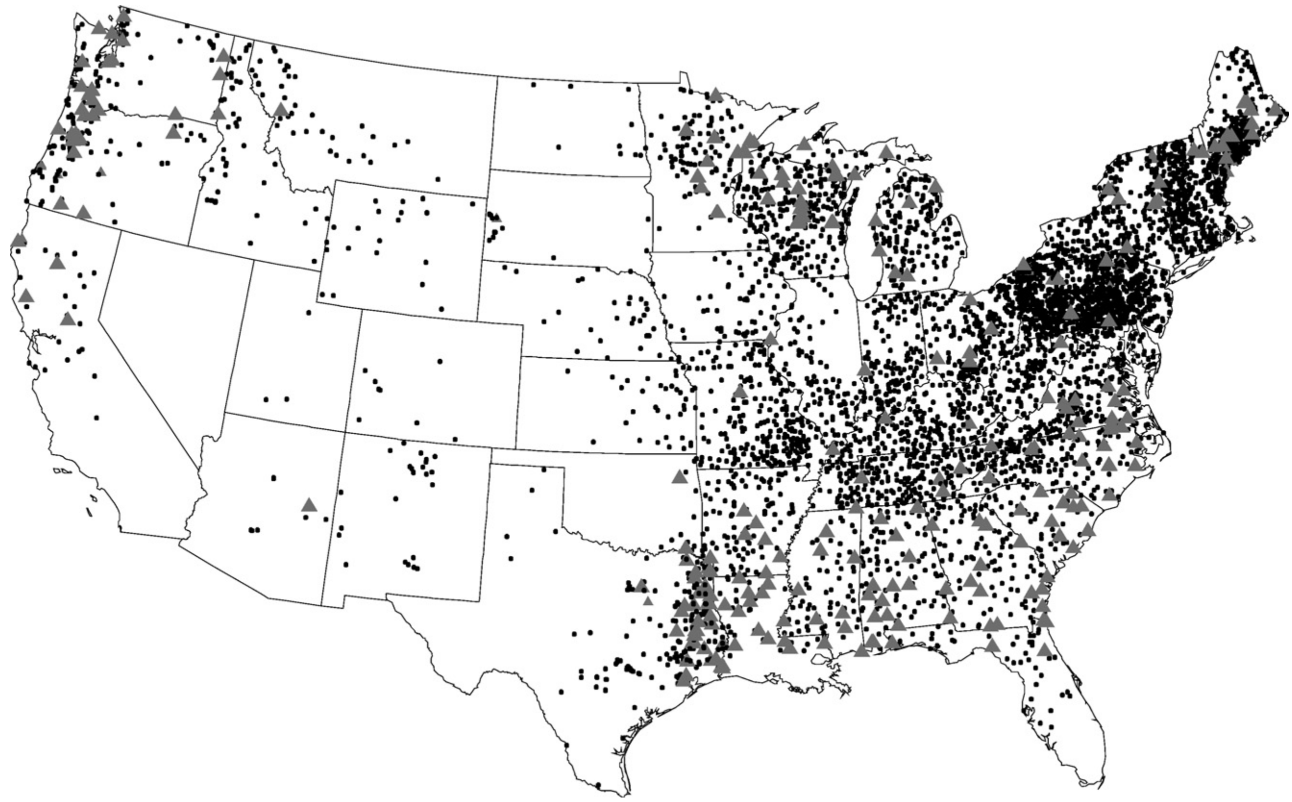

Fig. 2. Mills in the continental U.S. Triangles are pulp mills, dots are sawmills. (Source: Prestemon et al. (2005). Available at www.srs.fs.usda.gov/econ/mills/mill2005.htm).

Table 1
Simulation scenarios for evaluating the impacts of different assumptions on timber market welfare and treatment costs and length

Scenario	Treatments allowed	Treatment products sent to market required	Federal timberlands treated	Western federal timberland is treated	Southern federal timberland is treated	Subsidy level (mill. $, 2005)	Allow risk growth of stands	Allow demand capacity growth	Market supply elasticities	Market demand elasticities
1	Yes	Yes	All	Yes	Yes	300	No	No	Base case	Base case
2	Yes	Yes	All	Yes	Yes	900	No	No	Base case	Base case
3	Yes	Yes	All	Yes	Yes	1200	No	No	Base case	Base case
4	Yes	Yes	All	Yes	Yes	900	No	No	Base case	Base case × 2
5	Yes	Yes	All	Yes	Yes	900	No	No	Base case × 2	Base case
6	Yes	Yes	All	Yes	No	900	No	No	Base case	Base case
7	Yes	Yes	All	Yes	No	900	Yes	No	Base case	Base case
8	Yes	Yes	High risk only	Yes	Yes	300	No	No	Base case	Base case
9	Yes	Yes	WUI only	Yes	Yes	300	No	No	Base case	Base case
10	Yes	Yes	All	Yes	Yes	900	No	Yes	Base case	Base case

version may seem more realistic, the growth model is calibrated on a limited set of stands and forest types, and limits the applicability of the model outcomes. Differences in outcomes compared to the non-growth version can be used to illuminate the importance of further investigations into fire risk growth transitions before and after treatment across many forest types and locations.

2.4. Simulations scenarios

Given our research goal of quantifying the market impacts of treatment programs under a base set of program structures and assumptions, it is important to understand the effects on the market outcomes of varying this base set. To do this, we conduct ten scenarios (Table 1). Comparison across scenarios allows for detection of the effects of program variations and maintained assumptions. Fig. 1 documents the ordering of our treatment program, enabled through weights in the first-stage goal program, starting from high risk WUI stands to low-risk non-WUI stands.

2.5. Modeling assumptions

The 25 states included in the model incorporate 12 forest types in the West and 12 in the South. From these stands can be obtained four softwood products, which are grouped here as (1) ponderosa pine, including ponderosa pine (*Pinus ponderosa*) and sugar pine (*P. lambertiana*), (2) lodgepole pine (*P. contorta*), (3) southern pine (especially, *P. taeda*, *P. echinata*, *P. elliottii*, and *P. palustris*), and (4) other softwoods. In the current model, two principal stumpage products are modeled: sawlogs, and wood chips. Sawlogs are derived from softwood species only; all hardwood logs and non-sawtimber size materials are modeled as mixed hardwood–softwood chips (i.e., pulpwood).

Western Canada is comprised of Alberta and British Columbia, but these two provinces' timber volumes are modeled simply: Northern Alberta and Northern BC are modeled as containing mainly lodgepole pine, southern Alberta as containing mainly ponderosa pine, and southern British Columbia as containing other softwood. Prices are set at prices described in FAO (2005). Trade with the rest of the world is allowed only by the coastal states, southern border states with Mexico, and easternmost states of the U.S., while trade with western Canada is allowed only by the northern border states. Although tariffs on logs are zero between the U.S., Canada, and most of their trading partners, exports of such logs are restricted. Public softwood logs from both Canada and the western U.S. cannot be exported, although eastern U.S. public softwood logs can be. The model addresses these restrictions by imputing a prohibitively large transport cost between states that cannot export and potential foreign destinations. By construction, however, this effect could not be implemented for exports from the West or South to non-U.S. locations outside of Western Canada. Including the northern and northeastern U.S. as separate regions remains an area for further research.

2.6. Survey data

Data on forest conditions in the West and South are state-level inventories from the U.S. Forest Service's Forest Inventory and Analysis (FIA). A single periodic Resource Planning Act (RPA) inventory[3] is used for each of the twelve Western states. The Southern states use the latest available FIA periodic or annual inventory.[4] Table 2 lists the surveys by state.

2.7. Assignment of hazard and WUI classifications

The RPA data in the West included variables which indicated if a plot is in the wildland–urban interface (WUI). Hazard classification in the West is based on the torching index (TI) and crowning index (CI). The hazard targets for the West, based on inventoried plot conditions, are

- $TI \geq 25$ mph and $CI \geq 25$ mph or
- $TI < 25$ mph and $CI \geq 40$ mph.

If a plot meets one of these two conditions, then it is not identified as "risky"—i.e., it is defined as "in-condition", and the area associated with this plot is allocated to the "in-condition" stands in the landscape. These thresholds allow us to define hazard levels for plots that do not meet these criteria pre- or post-treatment. In the results section,

- plots with $TI < 25$ and $25 < CI \geq 40$ are classified as low hazard,
- plots with $TI \geq 25$ and $CI < 25$ are classified as medium hazard, and
- plots with $TI < 25$ and $CI < 25$ are classified as high hazard.

Because the South has no TI and CI calculator available, we use plot-level fire regime condition class (FRCC, or, simply, condition class) identified by FIA. Condition class indicates the degree of departure (1 ≡ low, 2 ≡ medium, 3 ≡ high) from natural, historical conditions and is most appropriate as a coarse-scale measure of hazard. Neither condition class nor WUI classification are included in the FIA surveys, so subsequent processing using data from a Geographical Information System (GIS) is used to assign condition class and WUI status to each plot. The condition class grid[5] is converted to a point file where each point is the centroid of a grid cell. This point layer is overlaid on a WUI map[6] for the South and the National Atlas grid of forest types.[7] Each

[3] Available at http://www.fia.fs.fed.us/tools-data/data/.
[4] Available at http://www.ncrs2.fs.fed.us/4801/fiadb/.
[5] Available at http://www.fs.fed.us/fire/fuelman/.
[6] State-level maps available at http://silvis.forest.wisc.edu/projects/WUI_Main.asp.
[7] Available at http://nationalatlas.gov/mld/foresti.html.

Table 2
FIA surveys used to develop baseline stand-level information

Region	State	Survey
South	Alabama	FIA periodic, 2000 cycle 7
	Arkansas	FIA annual, 2001 cycle 3
	Florida	FIA periodic, 1995 cycle 2
	Georgia	FIA annual, 2001 cycle 4
	Kentucky	FIA periodic, 1988 cycle 1
	Louisiana	FIA periodic, 1991 cycle 1
	Mississippi	FIA periodic, 1994 cycle 1
	North Carolina	FIA periodic, 1990 cycle 2
	Oklahoma	FIA periodic, 1993 cycle 1
	South Carolina	FIA annual, 2001 cycle 3
	Tennessee	FIA periodic, 1999 cycle 6
	Texas	FIA annual, 2002 cycle 3
	Virginia	FIA annual, 2001 cycle 3
West	Arizona	RPA periodic, 1999 cycle 2
	California	RPA periodic, 1994 cycle 1
	Colorado	RPA periodic, 1983 cycle 2
	Idaho	RPA periodic, 1991 cycle 1
	Montana	RPA periodic, 1989 cycle 1
	New Mexico	RPA periodic, 1999 cycle 2
	Nevada	RPA periodic, 1989 cycle 1
	Oregon	RPA periodic, 1992 cycle 1
	South Dakota	RPA periodic, 1995 cycle 4
	Utah	RPA periodic, 1995 cycle 1
	Washington	RPA periodic, 1991 cycle 1
	Wyoming	RPA periodic, 1984 cycle 1

Condition Class point is assigned the corresponding WUI classification and forest type. The total number of points for each forest type is determined for each FIA survey unit. The percent of land area for a survey unit in each forest type, Condition Class, and WUI combination is calculated as the number of points in each Condition Class and WUI combination within a forest type divided by the total number of points for that forest type. These percentages are then attached to the FIA treatable acres and removal volumes aggregated by survey unit and forest type. This allows the allocation of area and volume to Condition Class and WUI classifications within the survey unit, which can then be aggregated to the state level.

In our simulations of the South (described below), only Condition Classes 2 and 3 are allowed to be treated. Condition Class 1 is assumed to be approximately "in-condition" for purposes of our simulations and not treated in simulation. As well, plots with inventoried basal area of 50 ft^2 or less are excluded from treatment because they meet or fall below the recommended minimum basal area target for the restoration of one southern pine forest type (Outcalt, 2005).

Table 3
Treatable acres (all ownerships) for the twelve Western states by forest type and hazard level

State	Forest type	Acres (in thousands) by hazard level			
		Low	Medium	High	Total
AZ	Douglas fir	37.2	38.9	67.8	143.9
	Fir-spruce	38.4	29.1	109.2	176.6
	Other hardwoods	29.9	6.5	10.7	47.1
	Ponderosa pine	322.7	186.7	126.0	635.3
	Unclassified and other	4.6	0.0	13.6	18.2
CA	Douglas fir	84.2	140.5	81.1	305.8
	Fir-spruce	139.2	264.6	542.6	946.4
	Hemlock-sitka spruce	1.0	7.7	9.1	17.8
	Lodgepole	56.4	58.0	83.2	197.5
	Non-stocked	11.9	1.2	0.0	13.1
	Other hardwoods	197.6	98.7	169.6	465.9
	Pinyon-juniper	0.0	0.7	0.2	0.9
	Ponderosa pine	690.0	457.5	1,014.2	2,161.7
	Redwood	91.1	53.6	61.3	206.0
	Unclassified and other	707.9	640.4	935.2	2,283.4
	Western white pine	13.8	0.0	1.6	15.4
CO	Douglas fir	183.8	463.0	450.5	1,097.3
	Fir-spruce	229.5	611.6	930.4	1,771.5
	Lodgepole	78.7	460.2	218.2	757.1
	Other hardwoods	165.7	50.6	97.8	314.1
	Ponderosa pine	202.1	136.5	150.6	489.3
	Unclassified and other	9.8	23.2	29.3	62.3
ID	Douglas fir	410.1	921.2	639.5	1,970.8
	Fir-spruce	589.3	705.9	1,170.2	2,465.4
	Hemlock-sitka spruce	165.1	201.2	369.4	735.7
	Larch	55.5	38.0	24.5	118.0
	Lodgepole	214.1	303.6	293.8	811.5
	Other hardwoods	10.0	7.6	0.0	17.6
	Ponderosa pine	64.9	37.1	14.2	116.1
	Unclassified and other	6.8	0.0	6.8	13.6
	Western white pine	14.8	0.0	18.2	33.0
MT	Douglas fir	560.7	1,944.7	869.0	3,374.5
	Fir-spruce	329.3	337.2	672.4	1,338.9
	Hemlock-sitka spruce	38.6	39.5	57.3	135.3
	Larch	81.1	94.3	81.6	257.0
	Lodgepole	312.0	651.4	498.0	1,461.4
	Other hardwoods	5.7	0.0	1.7	7.4
	Ponderosa pine	273.4	136.5	85.1	495.0
	Unclassified and other	25.8	28.9	116.9	171.6
NM	Douglas fir	93.6	171.6	278.8	544.0
	Fir-spruce	30.8	164.1	410.6	605.5
	Other hardwoods	29.7	27.8	75.6	133.1
	Ponderosa pine	221.7	218.1	226.0	665.8
	Unclassified and other	20.8	10.4	30.4	61.5
NV	Douglas fir	7.0	0.0	0.0	7.0
	Fir-spruce	6.2	11.7	30.0	47.9
	Lodgepole	0.0	0.0	3.5	3.5
	Ponderosa pine	3.5	8.2	0.0	11.7
	Unclassified and other	2.2	0.0	1.1	3.3
	Western white pine	3.3	0.0	0.0	3.3
OR	Douglas fir	902.7	2,533.6	685.3	4,121.6
	Fir-spruce	352.4	402.5	951.4	1,706.3
	Hemlock-sitka spruce	175.9	382.3	217.2	775.5
	Larch	20.4	5.7	13.3	39.5
	Lodgepole	300.2	24.5	160.2	484.9
	Other hardwoods	65.8	111.6	11.0	188.4
	Pinyon-juniper	9.5	0.0	10.5	20.1
	Ponderosa pine	521.9	110.5	204.1	836.5
	Unclassified and other	3.2	1.9	0.0	5.1
SD	Ponderosa pine	77.7	84.9	27.3	190.0
	Spruce-fir	14.7	12.9	6.4	34.0
UT	Douglas fir	104.4	73.4	124.5	302.3
	Fir-spruce	107.4	107.0	386.4	600.7
	Lodgepole	22.4	12.1	43.7	78.2
	Other hardwoods	58.3	13.4	83.1	154.7
	Ponderosa pine	34.1	2.6	9.9	46.6
	Unclassified and other	5.9	9.6	8.1	23.6
WA	Douglas fir	750.6	1,893.0	863.4	3,506.9
	Fir-spruce	199.3	165.6	562.7	927.7
	Hemlock-sitka spruce	272.0	868.3	671.1	1,811.5
	Larch	25.6	5.9	28.8	60.3
	Lodgepole	95.1	45.4	98.8	239.3
	Non-stocked	5.7	0.0	3.8	9.5
	Other hardwoods	66.1	39.9	19.7	125.8
	Ponderosa pine	157.1	62.0	59.3	278.4
WY	Douglas fir	29.4	66.2	93.7	189.3
	Fir-spruce	72.7	91.4	297.1	461.2
	Lodgepole	102.5	184.2	153.2	439.9
	Other hardwoods	13.4	0.8	19.4	33.7
	Ponderosa pine	86.5	68.4	57.4	212.2
	Unclassified and other	69.1	34.2	82.6	185.9
Total		11,593.7	17,201.7	17,030.2	45,825.5

2.8. Fuel treatments

Treatments are simulated at the plot level. Lodgepole and fir-spruce forest types in the West are treated with an even-aged treatment that removes trees, beginning with the smallest diameter

Table 4
Treatable acres (all ownerships) for the thirteen Southern states by forest type and Condition Class

State	Forest type	Acres (in thousands) by Condition Class			
		CC 1	CC 2	CC 3	Total
AL	Elm/ash/cottonwood	174.7	99.6	67.8	342.1
	Loblolly/shortleaf pine	2454.6	1571.9	908.8	4935.2
	Longleaf/slash pine	487.2	253.2	39.5	779.9
	Oak/gum/cypress	1329.9	356.5	220.8	1907.2
	Oak/hickory	1983.2	1246.8	1800.0	5029.9
	Oak/pine	1054.3	1112.2	566.6	2733.0
	Pinyon/juniper	13.5	9.2	2.3	24.9
AR	Elm/ash/cottonwood	534.5	104.1	130.4	769.0
	Loblolly/shortleaf pine	3842.5	447.1	507.1	4796.7
	Oak/gum/cypress	1321.1	220.4	131.9	1673.4
	Oak/hickory	3478.1	1076.4	1704.2	6258.6
	Oak/pine	1257.7	455.1	291.9	2004.7
	Pinyon/juniper	93.9	45.7	43.2	182.7
FL	Elm/ash/cottonwood	185.6	11.7	0.0	197.3
	Loblolly/shortleaf pine	669.1	219.3	0.0	888.4
	Longleaf/slash pine	2795.9	196.0	0.0	2991.9
	Oak/gum/cypress	2394.2	164.7	0.0	2558.9
	Oak/hickory	930.8	55.5	0.0	986.4
	Oak/pine	552.2	138.1	0.0	690.2
	Tropical hardwoods	105.5	2.9	0.0	108.4
GA	Elm/ash/cottonwood	161.1	79.9	10.3	251.4
	Loblolly/shortleaf pine	3350.3	1458.8	87.2	4896.3
	Longleaf/slash pine	2030.4	176.3	2.1	2208.8
	Non-stocked	3.4	1.4	0.0	4.8
	Oak/gum/cypress	2191.5	627.7	37.2	2856.5
	Oak/hickory	1846.9	1383.2	692.5	3922.6
	Oak/pine	1397.1	1067.0	68.0	2532.0
	Pinyon/juniper	0.8	1.0	0.2	2.0
	Tropical hardwoods	10.5	1.1	0.0	11.6
	White/red/jack pine	27.3	4.4	8.8	40.5
KY	Elm/ash/cottonwood	345.8	63.8	102.9	512.4
	Loblolly/shortleaf pine	361.5	13.6	15.9	391.0
	Maple/beech/birch	359.7	64.3	124.5	548.5
	Oak/gum/cypress	8.5	11.1	33.3	52.9
	Oak/hickory	7757.9	224.8	185.5	8168.2
	Oak/pine	650.3	37.9	42.9	731.1
	Pinyon/juniper	96.6	7.8	13.6	118.0
	White/red/jack pine	23.5	0.9	4.4	28.8
LA	Elm/ash/cottonwood	972.1	50.2	6.4	1028.7
	Loblolly/shortleaf pine	2428.9	756.4	51.0	3236.3
	Longleaf/slash pine	479.2	91.5	1.4	572.1
	Oak/gum/cypress	2851.8	202.1	17.8	3071.7
	Oak/hickory	863.2	340.0	48.7	1251.9
	Oak/pine	1077.5	276.2	27.6	1381.3
MS	Elm/ash/cottonwood	405.6	101.0	67.1	573.7
	Loblolly/shortleaf pine	2004.1	1132.5	243.7	3380.4
	Longleaf/slash pine	458.1	160.9	2.4	621.4
	Oak/gum/cypress	1679.6	558.8	137.1	2375.4
	Oak/hickory	2026.3	948.2	607.6	3582.1
	Oak/pine	1233.3	869.0	162.6	2264.9
	Pinyon/juniper	11.9	9.6	2.7	24.3
NC	Elm/ash/cottonwood	189.2	67.2	83.0	339.4
	Loblolly/shortleaf pine	2561.7	1191.6	553.0	4306.2
	Longleaf/slash pine	223.3	76.1	13.7	313.1
	Maple/beech/birch	146.2	29.0	19.6	194.8
	Oak/gum/cypress	1315.3	396.9	61.2	1773.4
	Oak/hickory	3164.8	830.6	1904.4	5899.7
	Oak/pine	1012.0	550.8	237.1	1799.9
	Pinyon/juniper	7.9	2.9	6.6	17.4
	Spruce/fir	8.5	0.0	0.6	9.1
	White/red/jack pine	145.6	33.0	32.0	210.6
OK	Elm/ash/cottonwood	234.6	64.2	65.1	363.9
	Loblolly/shortleaf pine	714.7	96.9	129.2	940.8
	Non-stocked	4.3	1.1	1.1	6.4
	Oak/gum/cypress	264.7	13.3	66.2	344.3
	Oak/hickory	2475.0	454.8	594.0	3523.8
	Oak/pine	334.3	219.6	73.8	627.6
	Pinyon/juniper	17.2	8.3	8.2	33.7
SC	Elm/ash/cottonwood	214.7	38.9	8.2	261.8
	Loblolly/shortleaf pine	3029.8	740.2	99.9	3870.0
	Longleaf/slash pine	227.5	53.6	3.3	284.5
	Non-stocked	1.2	0.2	0.0	1.3
	Oak/gum/cypress	1547.9	125.5	11.5	1684.9

Table 4 (*continued*)

State	Forest type	Acres (in thousands) by Condition Class			
		CC 1	CC 2	CC 3	Total
SC	Oak/hickory	1060.9	260.8	383.2	1704.9
	Oak/pine	695.2	294.0	31.1	1020.4
	Pinyon/juniper	14.6	2.8	0.8	18.2
	Tropical hardwoods	0.9	0.2	0.0	1.1
	White/red/jack pine	23.1	4.8	1.7	29.6
TN	Elm/ash/cottonwood	206.1	76.1	73.7	355.8
	Loblolly/shortleaf pine	754.1	143.9	2.3	900.3
	Maple/beech/birch	16.1	0.0	0.0	16.1
	Non-stocked	2.6	0.0	0.0	2.6
	Oak/gum/cypress	311.8	6.1	3.3	321.2
	Oak/hickory	8134.8	502.4	55.1	8692.3
	Oak/pine	1137.4	189.0	9.0	1335.3
	Pinyon/juniper	176.4	5.4	0.7	182.5
	White/red/jack pine	80.2	11.6	10.8	102.6
TX	Elm/ash/cottonwood	273.3	23.7	84.8	381.9
	Exotic hardwoods	20.0	2.5	3.7	26.2
	Loblolly/shortleaf pine	3,018.7	343.1	293.6	3,655.5
	Longleaf/slash pine	111.0	21.8	0.8	133.6
	Non-stocked	1.1	0.1	0.4	1.6
	Oak/gum/cypress	999.3	107.0	105.4	1211.7
	Oak/hickory	572.1	41.7	603.2	1217.0
	Oak/pine	1490.1	171.9	326.4	1988.4
VA	Elm/ash/cottonwood	112.2	40.3	69.2	221.7
	Loblolly/shortleaf pine	1211.1	486.0	553.4	2250.4
	Maple/beech/birch	82.9	39.9	24.1	146.9
	Oak/gum/cypress	216.5	32.0	26.8	275.3
	Oak/hickory	4448.8	1250.0	2212.6	7911.3
	Oak/pine	788.4	525.4	261.9	1575.6
	Pinyon/juniper	39.2	13.2	14.3	66.7
	Spruce/fir	3.2	1.5	0.9	5.5
	White/red/jack pine	119.5	53.9	58.5	231.9
Total		106,734.7	28,153.5	18,403.7	153,291.8

and moving up, until one of the two targets above are met or a maximum of 25% of beginning basal area is removed. All other forest types are treated with an uneven-aged treatment that removes trees proportionately across all diameter classes until one of the two targets above are met or a maximum of 50% of beginning basal area is removed.[8] Table 3 shows the breakdown of treatable area by forest type and hazard classification in the Western States. Overall, there are 46 million acres in the West that do not meet our target conditions for TI and CI. Around 37% of treatable western acres are high hazard, 37% are medium hazard, and 26% are low hazard.

Each plot in the South is treated with an even-aged treatment that removes trees, beginning with the smallest diameter and moving up, until the residual basal area is 50 ft^2. If a plot's inventoried basal area is less than or equal to 50 ft^2 then it is excluded from treatment. The detail of treatable acres for the Southern states is given in Table 4. There are 153 million treatable acres in the South, of which 70% are Condition Class 1, 18% are Condition Class 2, and 12% is Condition Class 3. The federal portion of those 153 million acres is a very small part of this, however.

[8] Applying these treatments to out of condition plots across all ownerships and WUI categories removes 155×10^6 mbf of sawtimber volume and 59×10^6 mbf of chipped volume. Median basal area is reduced from a pre-treatment level of 139 ft^2 to 100 ft^2 post-treatment. Although the market impacts are not considered here, we developed an alternate set of treatments: an even-aged treatment that removes a maximum of 50% of beginning basal area for lodgepole and fir-spruce forest types and an even-aged treatment with no basal area removal limit that removes trees until one of the target conditions are met for all other forest types. These alternate treatments remove 56×10^6 mbf of sawtimber volume and 64×10^6 mbf of chipped volume and reduce median basal area per acre to 87 ft^2. The sharp reduction in sawtimber volume and modest increase in chip volume compared to the modeled treatments are due to a decrease in large diameter trees removed and an increase in small diameter trees removed in the dry forest types. Overall timber market and social welfare impacts are smaller and have a different spatial and temporal distribution under the alternate treatments.

Table 5
Wildland–urban interface (WUI) acres (all ownerships), by state

Region	State	Acres (in thousands)
South	AL	3384
	AR	1817
	FL	1629
	GA	4324
	KY	3119
	LA	1723
	MS	2343
	NC	6013
	OK	447
	SC	2782
	TN	3489
	TX	1505
	VA	4128
	Total	36,702
West	AZ	24
	CA	260
	CO	248
	ID	1222
	MT	159
	NM	42
	NV	11
	OR	292
	SD	6
	UT	10
	WA	545
	WY	11
	Total	2831
Total		39,533

WUI acres by state are shown in Table 5. Treatable WUI comprises about 24% of the total treatable area in the South and 6% of the treatable area in the West. A note on our estimate of treatable WUI acres is necessary. Western WUI acres are based on the assignment of interface or intermix to each plot in the RPA database. FIA plot volume and area expansion factors[9] are not adjusted for WUI status, hence the resulting area in interface and intermix obtained by summing across all plots (treatable and untreatable) in a state does not match published estimates of WUI area found in Radeloff et al. (2005).

In the West, treatable acres and removal volumes are summed from the plot level to state, forest type, WUI classification (in or out), owner (federal, other public, private and other), and hazard aggregates for use in the optimization model. In the South, removal volumes are first summed in survey unit, forest type, and owner aggregates. It is assumed that treatable acres and removal volumes across Condition Class and WUI classifications are proportional to the estimated percentages of land by Condition Class and WUI at the survey unit level (described above). Acres and volumes are allocated to Condition Class and WUI via these percentages, and then summed to state, forest type, WUI classification (in or out), owner (federal, other public, private and other), and Condition Class aggregates for use in the optimization model.

2.9. Treatment costs

Treatment costs for each plot in the West are generated by the Fuel Reduction Cost Simulator (FRCS) (Fight et al., 2006) in the Fuel Treatment Evaluator[10] (FTE). FRCS is not able to provide a valid estimate for approximately 25% of the plots.[11] Ordinary least squares (OLS) linear regression is therefore used to generate an estimated equation for treatment cost on the other 75% of plots using the FRCS costs per acre by plot as the dependent variable and plot slope, trees removed by diameter class per acre, and volumes removed per diameter class per acre as independent variables. The results of this estimation are shown in Table 6. These parameter estimates are applied to all 12,753 treatable plots in the West to generate an estimated cost per acre. The mean estimated cost per acre for each state, forest type, owner, WUI, and hazard level aggregate is calculated for use in the optimization model based on the number of plots in each of these aggregates. These cost equations are also applied to all 31,211 treatable plots in the South. The mean estimated cost per acre for each state, forest type, owner, WUI, and Condition Class aggregate used in the optimization model is based on the number of plots in each of these aggregates. Table 7 shows the minimum, maximum, and mean cost per acre across the aggregate categories in each region.

Table 6
Results of OLS treatment cost estimation for n=9,594 plots in the West; adjusted R^2=0.94

Variable	Parameter estimate	Standard error	*t*-value
Plot slope	5.1984	0.3138	16.57
Square of plot slope	0.1520	0.0049	30.75
Number of trees removed per acre, 2″ diameter class	−0.0190	0.0153	−1.24
Number of trees removed per acre, 4″ diameter class	0.0190	0.0291	0.65
Number of trees removed per acre, 6″ diameter class	1.8299	0.1097	16.68
Number of trees removed per acre, 8″ diameter class	2.7192	0.2547	10.68
Number of trees removed per acre, 10″ diameter class	2.8117	0.4668	6.02
Number of trees removed per acre, 12″ diameter class	5.9756	0.8985	6.65
Number of trees removed per acre, 14″ diameter class	4.6760	1.3064	3.58
Number of trees removed per acre, 16″ diameter class	5.2012	2.2391	2.32
Number of trees removed per acre, 18″ diameter class	3.4489	3.4572	1.00
Number of trees removed per acre, 20″ diameter class	5.0783	4.3772	1.16
Number of trees removed per acre, 25″ diameter class	8.2434	2.5959	3.18
Number of trees removed per acre, 30″+ diameter class	−7.2937	4.3978	−1.66
Volume removed per acre, 6″ diameter class	0.2127	0.0388	5.49
Volume removed per acre, 8″ diameter class	0.5280	0.0402	13.14
Volume removed per acre, 10″ diameter class	0.4746	0.0417	11.38
Volume removed per acre, 12″ diameter class	0.2748	0.0461	5.96
Volume removed per acre, 14″ diameter class	0.3285	0.0447	7.35
Volume removed per acre, 16″ diameter class	0.2821	0.0562	5.02
Volume removed per acre, 18″ diameter class	0.3442	0.0640	5.38
Volume removed per acre, 20″ diameter class	0.2995	0.0696	4.30
Volume removed per acre, 25″ diameter class	0.2598	0.0228	11.41
Volume removed per acre, 30″+ diameter class	0.3654	0.0160	22.85

2.10. Growth modeling

Growth and regeneration modeling, to account for risk change over time, is constrained by the availability of valid regeneration models for all forest types. As a first approximation and an initial first step, we model

Table 7
Mean, minimum, and maximum treatment costs per acre across the 610 state, forest type, owner, WUI, and hazard aggregates in the West and the 1499 state, forest type, owner, WUI, and Condition Class aggregates in the South

Region	Mean	Minimum	Maximum
South	771	17	3699
West	837	8	13,012

[9] These are the acres or tree volume that the sampled plot and tree represent on the sampled landscape. Multiplying by the expansion factors allows a complete assessment of all timberland areas surveyed by the USDA Forest Service.

[10] See http://www.ncrs2.fs.fed.us/4801/fiadb/FTE_Version3/WC_FTE_version3.asp.

[11] FRCS did not return a cost for plots where all trees removed were under 5″ dbh or if the average volume per tree or slope constraint was violated. See Fight et al. (2006) for a detailed list of constraints.

Table 8
Market parameters assumed

Market elasticities		CA, OR, WA	Rest of U.S. West	Southeast U.S.	South–Central U.S.	Western Canada	Rest of world
Softwood sawtimber besides southern pine	Supply with respect to own price	0.43	0.3	0.2405	0.3055	2	3
	Supply with respect to inventory volume	1	1	1	1	1	1
	Demand with respect to own price	−0.5	−0.5	−0.5	−0.5	−2	−4
Southern pine sawtimber	Supply with respect to own price	0.43	0.3	0.2405	0.3055	2	3
	Supply with respect to inventory volume	1	1	1	1	1	1
	Demand with respect to own price	−0.5	−0.5	−0.5	−0.5	−2	−4
Chips	Supply with respect to own price	0.43	0.3	0.2405	0.3055	2	3
	Supply with respect to inventory volume	1	1	1	1	1	1
	Demand with respect to own price	−0.5	−0.5	−0.5	−0.5	−4	−8

risk change for two fire prone forest types in Colorado, ponderosa pine and Douglas fir forest types. The uneven-aged fuel treatment with a removal limit of 50% of beginning basal area is implemented on plots, and it therefore represents approximately 1.6 million acres of timberland in our model. TI and CI are calculated post-treatment and following each 5-year growth step over a 25-year simulation. Growth and regeneration on plots in these forest types that initially meet the hazard targets are also simulated, and TI and CI are calculated following each 5-year growth step. Using the frequency distributions of land area moving from one hazard category to another over the 25-year simulation as growth and regeneration change plot conditions, we produce a transition matrix for untreated stands and for mechanically treated stands following treatments. These matrices are then converted to annual risk transition matrices and applied to all western U.S. stands. While the widescale application of the risk transition matrices is an imperfect long-term assessment of risk changes across all stands over many years, we believe that it provides inferences regarding the order of magnitude of risk changes over time and is useful as a simulation tool. The growth version of the model, we note, is applied in only one scenario.

2.11. Baseline simulation data

Current harvest data are developed using the removals and product data from Smith et al. (2004). Hardwood removals account for only 4% of all timber removals in the western U.S. states and 35% in the South (Smith et al., 2004). However, we do not consider the timber market impacts on hardwood log markets. Because our treatments require chipping all hardwood roundwood, the only effect on hardwood markets is through the chip market.

Mill production and capacity data are from Spelter and Alderman (2005), adjusted upward by state to match the consumption by non-included mills. Outside the U.S. and Canada, softwood log production and processing capacities are set at 100 and 110% of production, respectively, as reported by FAO (2005) for 2002. Capacities are allowed to adjust to increased log processing due to rising treatment harvests, however. These capacities are allowed to expand to 140% of stated capacities, consistent with a movement along the supply curve rather than a shift out. In the simulation involving investment increases in response to a treatment program, we allow for increases in capacity of 1% per year, beyond the physical limits set by existing plant and equipment, and this capacity increase therefore involves an outward-shifting timber derived demand curve.

Product prices in the western U.S. are from National Forest System Cut and Sold reports (U.S. Forest Service, 2004) for the second quarter of 2003. Regional prices are adjusted by the percentage of harvest from each species group to provide species prices. Prices differ by state and species, ranging from \$39 per thousand board feet (mbf) in Arizona and New Mexico for lodgepole pine to \$528 per mbf in Oregon and Washington for ponderosa pine. Chip prices nationwide and internationally are set initially at \$30 per bone dry ton (Rummer et al., 2003). Southern pine sawlog prices are set at the statewide average delivered log prices reported in Timber Mart-South (Norris Foundation, 2005) in 2004.

Trade between states and regions will occur when the net cost to an importing region is less than the cost of procuring logs locally. Thus transportation costs will be essential to development of trade patterns in the model. Following Rummer et al. (2003), we assume the cost of transporting wood between states is \$0.35/bone dry ton (bdt) per mile or \$1/mbf/mile. Distances between states are determined by using the distance between the spatial centers of forestland in each state.[12]

Supply elasticities remained fixed at unity for inventory, while the supply elasticity with respect to price varies across space (Table 8). The inventory elasticity is consistent with theory and the maintained assumption of most long run analyses of timber markets (e.g., Adams and Haynes, 1980; Abt et al., 2000). Price elasticities of supply are based on studies by Adams and Haynes (1980), Abt et al. (2000), Haynes (2003), and Newman (1987). Demands for logs are set at the same level as the demand for timber found by many studies. Because log demand and timber demand are not equivalent concepts, it is important to vary these elasticities from those in the published literature (Adams and Haynes, 1980; Majerus, 1980; Regional Forester, 1984; Wear, 1989; Adams et al., 1991; Newman, 1987; Abt et al., 2000;

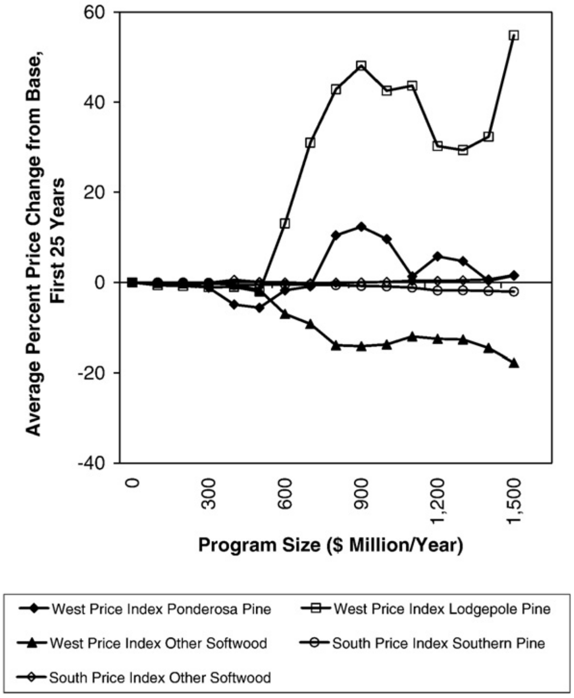

Fig. 3. Regional log price effects, weighted by state or regional production level, by product category for alternative sizes of mechanical fuel treatment programs.

[12] A coverage of forest for all states is used in ArcView to identify the spatially weighted average center of each state. The straight-line distance between each state pair is determined, and a circuity factor of 1.3 is applied to each straight line distance to derive an approximate road distance.

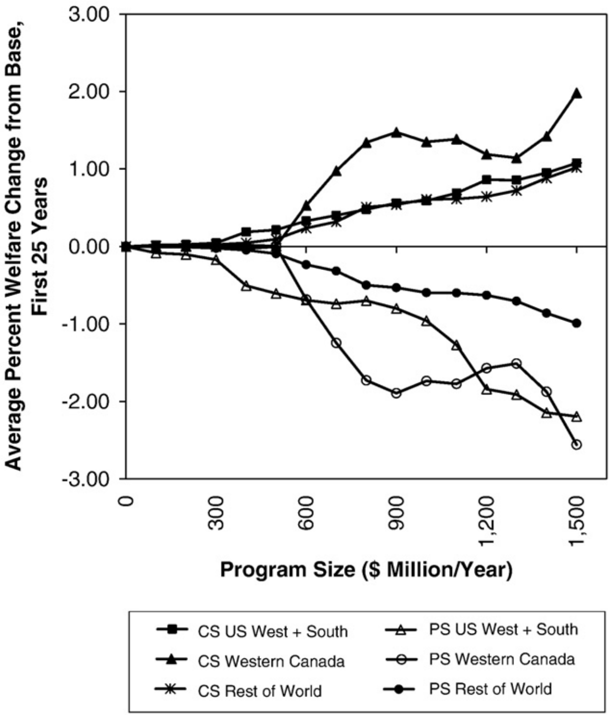

Fig. 4. Consumer surplus (CS) and producer surplus (PS) effects by region for alternative sizes of mechanical fuel treatment programs.

Haynes, 2003). To detect the importance of the assumed levels of elasticities on the welfare impacts of introducing mechanical fuel treatment-derived timber products, we perform simulations that alternately double demand and double supply elasticities.

The structure of our model implies a linear-in-outputs technology (e.g., Chambers, 1988, p. 267–268) for softwood sawtimber demand in the South and the West. A single, region-wide (West-wide and South-wide) mill capacity is available for producing outputs from any combination of softwood species inputs. The linear-in-outputs technology implies infinite substitution elasticities. Effectively, mills will demand the input yielding the greatest consumer surplus per unit first, although all inputs will be provided from harvests due to come-along volumes. Further, mechanical fuel treatment choices on the landscape (in terms of species mixes) ignore this surplus-maximizing choice, implying some supply of lower-priced and lower surplus-generating wood inputs from treatments. Because treatment locations are chosen before the market solution is achieved based on costs and fire and WUI risk priorities, lower surplus-generating material will likely be entering the market.

3. Results

Our simulations show that programs that are funded at less than $500 million per year have low market impacts (Figs. 3 and 4). Price and welfare effects of programs funded under $500 million annually are small partly because of our assumption that treatment materials replace timber products deriving from regular harvests. When treatment timber products exceed base-case regular harvest volumes, price and welfare impacts appear and may grow rapidly.

Simulations show that West-wide prices of ponderosa pine, lodgepole pine, and other softwood in the West change little—negatively, by about 1–2%—until the program size exceeds $300 million per year (Fig. 3). The prices of softwoods other than lodgepole and ponderosa pine in the West decline steadily with the size of the treatment program, dropping on average by more than 20% with a $1.5 billion annual program. Lodgepole pine prices, conversely, exhibit mainly positive changes for programs exceeding $500 million. By the time the program is $700 million per year, the price of lodgepole has risen by over 40%; larger programs have impacts above 40%, as well, although the effect varies over time.[13] The increase in lodgepole and decline in other softwood prices occurs because the fuel treatment program results in higher harvests of other softwood and lower harvests of lodgepole pine than occurred under regular government harvests. The opposite occurs for ponderosa pine: prices for this species drop for moderately sized programs ($300 m to $700 m), as large fuel treatment programs result in more of this species on the market. Larger programs, however, focus instead on other species, replacing ponderosa pine and driving that price up. In the South, government lands have historically produced little volume, compared to private producers. Doubling or even quadrupling timber output from government lands would have small price effects; the simulation results in a 2% drop in the price of southern pine timber when the federal program reaches $1.5 billion annually. Southern prices of “other softwood” also show little sensitivity to the size of the treatment program, due to the small role that government timber plays in southern markets.

Welfare impacts of the program (Fig. 4) grow less in percentage terms with program size than do the price impacts. Non-federal producers of timber in the West experience a steady negative decline in surplus as program size expands, while consumers experience welfare growth. Because the absolute value of the welfare gain is greater for consumers (despite their apparent smaller percentage change) than is the loss for producers, total welfare in the fire prone regions increases. Producers lose, for example, about 0.8% ($72 million) in welfare when the program is $600 million per year, and consumers gain 0.3% ($116 million). Producers in western Canada feel little impact from a program that is limited to $500 million or less annually, but a negative impact results from larger programs. The negative impact occurs because of aggregate North American price declines for timber, due to greater U.S. timber output. Consumers in this case benefit in western Canada, due to lower overall prices and greater consumption there. Nevertheless, the effects of export restrictions for softwood timber from the U.S. and Canadian West are observable when evaluating the effects on markets elsewhere. Consumers in the rest of the world gain less than producers in the rest of the world lose, a net loss. Globally and in fire prone regions, the net effect in terms of social net welfare (i.e., economic surplus minus transport costs) is usually less than 1%, with a global gain of about 0.75% for the largest program evaluated.

The welfare amounts ignore the costs of the program and the effects on net timber receipts received by the federal government, and we find that it is important to account for those when evaluating the overall economic impact of the program (Fig. 5). This assessment shows that the program has overall negative net benefits that grow with the size of the program.[14] Note that all of these assessments ignore the potential positive benefits received by lowering fire risk, as measured by torching and crowning indices, and lowering it in the wildland–urban interface. With each $100 million in program annual spending on mechanical fuel treatments, the net welfare plus government timber sale receipts minus treatment and regular harvest costs increases by less than $100 million each year. For example, a

[13] This price rise implies that the market benefits most by producing and consuming lodgepole pine provided at subsidized cost from public lands. Although arbitrage and interspecies substitutions dampen these impacts, as the model shows, log transport is too expensive to avoid the price rises. In places where lodgepole treatments occur, little ponderosa pine or other softwood volumes are available for substitution.

[14] Alternatively, our modeling approach that forces timber into markets and hence inducing welfare effects that are not everywhere positive could be avoided by simply destroying all materials removed. Scenarios are available from the authors that would quantify these impacts. In net, however, doing this becomes a pure cost and could be seen as deriving little benefit from the program while generating only costs, but this could reduce public opposition to mechanical treatment programs (e.g., Laband and González-Cabán, 2006).

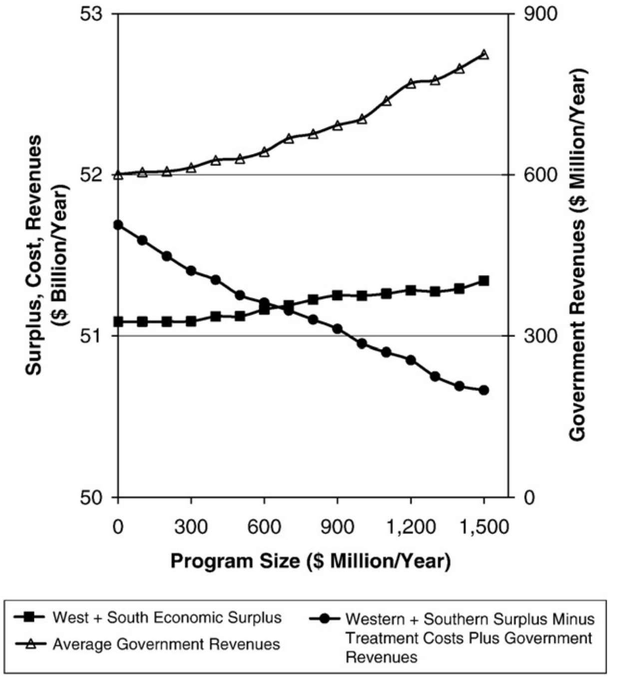

Fig. 5. Overall economic impacts of alternative mechanical fuel treatment sizes, based on western plus southern U.S. social net welfare, annual costs of the program, and annual timber product receipts from government lands.

$300 million annual program, which would mechanically treat slightly more than 300,000 acres per year, has a net benefit of −$280 million. In other words, to justify the $300 million annual program from a purely timber welfare and program cost perspective, it might be prudent to expect that the fire risk and ecosystem restoration benefits should exceed $280 million annually. Translated into per acre terms, each acre treated should be expected, on average, to generate about $950 in additional net annual benefits compared to an untreated acre (Fig. 5).

The kind of rough comparisons presented in the last paragraph depend, perhaps crucially, on underlying assumptions. For this reason, it is important to evaluate the impacts of given treatment programs under differing assumptions (Table 9). The first three scenarios in Table 9 show how programs of different sizes (subsidy amounts) applied in the West and the South affect aggregate social net welfare (ignoring government timber receipts and program costs), timber receipts, overall regular government harvesting costs, the net economic position of the forest sector in the West and South (not accounting for the fire effects of treatments), and the per acre changes in the net economic position in the West and South and globally. The table shows that the effect of the treatments on social net welfare increases nearly linearly, with each $100 million spent, by about 0.05 and 0.03% globally and in the West and South, respectively. Timber receipts grow with the size of the program, as well, though not linearly, rising by 2.6% per $100 million for a $300 million program and by 2.8% per $100 million for a $1200 million program. Regular government harvesting costs decline with the size of the program, logically, as treatment materials substitute for regular timber products harvested from federal lands. When adding in net timber revenues and the costs of the treatment program, the net benefits for the West and the South are larger. They rise by 0.01% for a $300 million program and by 0.31% for a $1.2 billion program. Nonetheless, the program always costs money, although the per acre costs decline slightly, after accounting for domestic U.S. welfare shifts and the effects on other government harvest costs. In welfare plus regular harvest receipts minus harvest costs, there is a decrease in aggregate by 0.42% with a $300 million program and a 1.57% decrease with a $1.2 billion program.

These values can be expressed on a per acre basis, as well, providing the policy analyst with a measure of how changing the size of a program will affect the relative hurdle the program could be required to clear in terms of benefits to justify its existence. On a per acre basis, increasing the size of the program will have variable effects on the net overall costs of the program when considered only from the

Table 9
Summary results for all mechanical fuel treatment program scenarios

Scenario	Size of program	Regions treated, scenario description	Average area treated	Total social net welfare[a]	West+ South social net welfare[a]	West+South government timber receipts	West+South government regular harvest costs	West+South social net welfare[a]+revenues−regular harvest costs	Change, West+south social net welfare[a]−program costs	Change, global social net welfare[a]−program costs
	Million $/year		Acres/year	Percent change with program					$/acre	$/acre
1[b]	300	South, West	208,658	0.13	0.01	7.68	−13.69	−0.42	−1026	−612
2[c]	900	South, West	611,828	0.49	0.19	19.94	−19.04	−1.24	−1040	−620
3[d]	1,200	South, West	802,175	0.58	0.31	28.15	−27.45	−1.57	−1006	−687
4[e]	900	South, West	611,828	0.54	0.30	33.30	−13.56	−0.95	−760	−452
5[f]	900	South, West	622,377	0.16	0.87	9.00	−27.82	−0.41	−318	−814
6[g]	900	West only	617,025	0.50	0.23	17.09	−25.17	−1.20	−997	−604
7[h]	900	West only, growth	617,831	0.46	0.10	16.27	−36.34	−1.28	−1068	−611
8[i]	300	South, West	204,183	0.09	0.09	6.02	−14.10	−0.36	−903	−809
9[j]	300	South, West	205,024	0.06	0.02	5.90	−7.17	−0.46	−1145	−1000
10[k]	900	South, West	611,828	2.09	4.40	−22.14	−66.62	2.71	2274	1042

[a] Social net welfare is consumer surplus plus producer surplus minus inter-market product transport costs.
[b] Treat all risk levels, treat West and South, subsidy of $300 million per year, no stand risk growth, no capacity growth, base case elasticities.
[c] Same assumptions as in Scenario 1 but a subsidy of $900 million per year.
[d] Same assumptions as in Scenario 1 but a subsidy of ,200 million per year.
[e] Same assumptions as in Scenario 2 but double market demand elasticities.
[f] Same assumptions as in Scenario 2 but double market non-federal supply elasticities.
[g] Same assumptions as in Scenario 2 but treat the West only.
[h] Same assumptions as in Scenario 6 but allow risk to grow.
[i] Same assumptions as in Scenario 1 but treat only high risk stands.
[j] Same assumptions as in Scenario 1 but treat only wildland–urban-interface and intermix stands.
[k] Same assumptions as in Scenario 2 but allow capacity to grow by 1% per year.

perspective of western and southern timber markets, revenues, and costs. A $300 million annual program will cost an average of about $1026 per acre when considered from the perspective of just the South and West but $612 when considered from a global welfare perspective. In other words, the program is less harmful to timber market welfare and the government's financial position when considered globally. A large, $1.2 billion program would cost an average of $1006 per acre from the standpoint of the West and South and $687 per acre from the standpoint of global welfare net of government timber receipts.

It is worth noting here that, in spite of the high per acre average costs of a treatment program, a significant portion of stands likely have positive net stumpage values of treated materials upon removal. An analysis of pre-solution timber values—i.e., before treatment materials enter the market—indicates that 31% of government owned western timber stands needing treatments and 19% of government owned southern stands needing treatment have positive pre-solution treatment values (standing timber revenues net of treatment and average haul costs). For "small" programs (e.g., costing less than $300 million per year), which we find have little influence on local prices, approximately one-fourth of the treatable area would be treatable with positive net revenues accruing to the government. High risk acres, which are treated first in our simulations, however, do not as commonly generate positive revenues; only about 23% have positive pre-program net revenues.

The effects of alternately doubling the timber demand price elasticities (Scenario 4) and private timber supply price elasticities (Scenario 5) are mainly to enhance global and regional social net welfare for a given program size. The effects of the assumptions regarding price elasticities are shown as entries for Scenarios 4 and 5 can be obtained by comparing them to Scenario 2 in Table 9. The welfare enhancement impact of making demand or supply more elastic occurs because consumers and producers are more able to change their production and consumption in response to price shifts; technically, it involves flatter supply and demand curves, meaning that price changes have smaller overall impact on surplus values. In the case of more elastic demand and supply, the overall costs (social net welfare, treatment costs, and timber net receipts) are smaller than for the same size program evaluated using our base case elasticities. For demand elasticities with respect to price that are twice the assumed level, the global cost per acre of a $900 million program applied to all risky federal lands in the West and South is $452 and in the West and South is $760 per acre. For doubled non-federal market supply elasticities, it is $814 using global welfare and $318 using South and West welfare in the per acre valuation.

Limiting the program to just the West and excluding treatments in the South has the effect of both increasing the annual rate of treatment in the West (because some expensive southern acres do not have to be treated) and lowering the overall costs of the program (because the South does not have to be treated). The effect of dropping the South is quantified by comparing the West-only simulation, Scenario 6, with Scenario 2. In terms of producer and consumer welfare, the net impact of a West-only program is to just slightly increase global welfare, by 0.01 percentage points, compared to Scenario 2, but increase by 0.04 percentage points the social net welfare gains experienced in the aggregate of the West and South, compared to Scenario 2. The latter occurs because smaller new timber quantities enter the market due to treatment, limiting price drops, and because the West has less material to compete against in Rest of the World markets. Per acre overall program costs, shown in the last column, are lower for Scenario 6 compared to Scenario 2, consistent with the overall lower market distortions and lower treatment costs.

Including risk growth serves to decrease the overall benefits globally (Scenario 7, compared to Scenario 6) in the West. The scenario where growth is included takes 59 years to complete, while the one without growth finishes in 49, for a $900 million program. What this implies is that the additional growth yields less overall average annual benefits than what is found by not taking it into account and slows the speed of treatment of especially high risk stands. In Scenario 6, a $900 million program focused only on the West takes 20 years to completely treat the highest-risk stands (risk level 3) and 29 more to complete the program. With growth, because stands are continuously transitioning into risky status, growing into higher risk conditions without treatment, and transitioning into risky status following treatment, such a program would take 23 years to treat half of the high risk stands and a full 59 years to complete the program. From a cost perspective, the effect of accounting for stand fire risk growth is that the per acre costs of the program are slightly higher, once the timber market effects and effects on net harvest receipts and costs are combined than would be the case without growth: they are about 7% more from a West-only perspective and about 1% higher from a global perspective.

Programs focused on highest-risk acres or on the wildland–urban interface are completed faster, but they have overall smaller global welfare benefits and larger West and South welfare benefits. Their effects on global and West and South-only social net welfare, calculated by comparing Scenario 1 (Fig. 6) with Scenarios 8 and 9 for a high risk-only and a WUI-only program, respectively, are less than 0.1%. Timber receipts generated by such programs increase by less (by 6.02 and 5.90 percentage points for high risk only and WUI-only programs, respectively) with these more focused programs, compared to those without such a focus. The high risk-only program results in costs per acre that are lower than a program that focuses on all risk level stands. This is because denser, high risk stands produce more marketable treatment materials. The WUI-only program, on the other hand, is more expensive than a program that allows treatment of both WUI and non-WUI stands. This result implies that WUI stands are either more expensive to harvest or generate fewer marketable products.

Expanding capacity, perhaps as a response to greater availability of materials in treatment regions, results in overall positive effects on global and West plus South timber market social net welfare. The effects of a capacity expansion that are examined with a $900 million per year program are shown in Scenario 9 and should be compared with Scenario 2, in which no capacity expansion is imputed and for which all other scenario variables are identical. Expanding capacity

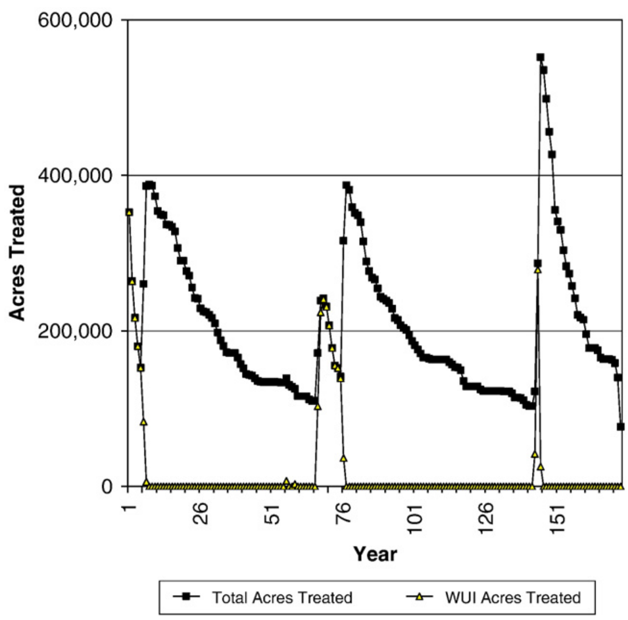

Fig. 6. Area treated annually in the U.S. South and West under Scenario 1, allowing no growth, prioritizing the wildland–urban interface (WUI) and higher risk stands, with a $300 million per year subsidy.

gradually by 1% per year results in global welfare for a $900 million per year program that is 1.60 percentage points higher, on average, than without such expansion. West and South welfare increases by 4.40%, compared to a no-treatment base, in this simulation. Timber receipts on government lands decline, however, due to greater substitution of treatment materials for regular timber receipts, particularly in places with weaker timber markets. If we can assume that the capacity expansion occurs as a response to the treatment program, then instead of the program being a net loss per acre (excluding fire effects), it becomes a net gain. Globally, the gain is $1042 per acre, while for the West and South calculation even more, $2274 per acre.

4. Conclusions

This study has many potential conclusions to highlight. But it bears reiterating what this research set out to accomplish and what it did not. First, the treatments evaluated in this study were not chosen to be optimal from any perspective, and we examined few alternatives—for example, in the manner of Feidler and Keegan (2003). Instead, treatments for our simulations were chosen based on expert judgment, balancing silvicultural as well as fire risk objectives. Exhaustively evaluating the economically best treatment among a large set of possible treatments would require research that is beyond the scope of this paper, although it would be worthwhile and further advance the science. Second, an economically or socially optimal mechanical treatment program in any case would need to address, among other things, the economic benefits of the treatments in terms of fire effects, information that we currently do not have. Instead, this research focused on identifying the costs of mechanical treatments and quantifying the timber market implications of a feasible treatment program which is designed to reduce fire risk, as measured by crowning and torching indices or by Fire Regime Condition Class metrics. The modeling is not exhaustive, and we leave it to others to evaluate what might be the best or optimal treatment design to attain some expression of aggregate wildfire damage reduction objective, ecosystem objectives, or government treatment program cost objectives.

In terms of what we did learn from our simulation exercise, we have several conclusions. First, small programs have small impacts on timber producers and consumers, when spread across space and time. For the western and southern U.S. considered in aggregate, effects on producer and consumer surplus net of transport costs are positive, but they are less than 1% across all program sizes evaluated. Only when capacity expands over time in response to such a program are benefits greater than this.

Second, adding the South to a national treatment program for government lands only slightly increases the cost of the treatment program compared to one limited to the U.S. West. The South produces little timber from government lands, compared to the private sector and compared to public lands in the West (and potentially from treatments in the West), so this effect is expected.

Third, the overall cost, when considering timber market welfare, transport costs, timber receipts, and treatment program costs, is generally over $1000 per acre. This means that the long run fire effects and ecosystem net benefits of a treatment program would be expected to exceed this figure in order to justify implementation of such a program.

Fourth, allowing for growth in fire risk before and after mechanical fuel treatment results in an extension of the length and hence the long run costs of a program. However, the timber market welfare is elevated for a longer time when growth is accounted for, accentuating the timber market welfare effects of a mechanical fuel treatment program. This growth scenario showed that the program length increases by about one-third, implying that the long run discounted costs of a program of fuel treatment are higher than the no-growth simulations would imply.

Fifth, expanding capacity in response to a fuel treatment program can turn its overall costs to a benefit. If the private sector can be induced to invest in plant capacity to consume treatment materials, then the overall per acre losses could be reduced or even changed to a net gain for the market and for the government. Such investments would likely occur only if the government can signal that such a treatment program would be sustained for many years.

Sixth, we find that the international impacts of a mechanical fuel treatment program are small but that they increase with the size of a program. The effects of the program mainly occur through at least three mechanisms. (1) By increasing softwood removals on government lands, our exports to Canada decline because such softwood logs cannot be exported by law from the western U.S. Although private timber producers in the U.S. can make up for part of this loss in exports, they cannot make up for all of the loss. This negatively affects timber producers in western Canada but benefits the region's consumers. (2) By lowering the domestic price of timber in the U.S., such treatment programs would lead to substituting western logs for eastern U.S. logs, which would lower export opportunities for Canadian lumber producers. (3) Canadian consuming mills would experience some lower wood input prices because of the slightly lower Canadian log export opportunities, hence benefiting from the treatment program.

Designing a mechanical treatment incentive program is beyond the scope of our research. But such a program merits discussion here, if only to indicate its complexities. Some analysts have shown recently that mechanical treatments that are distributed randomly across a landscape may be far less effective at reducing fire spread in the context of intense wildfire than mechanical treatments designed specifically to reduce spread (Finney, 2001), indicating just how complex decision making is at fine scales. This fine-scale complexity would be difficult to address at the modeling scale of this study. An effective program of private landowner incentives would need to consider how to achieve landscape level effective designs of treatments that would best utilize taxpayer subsidies. As well, a system of compliance checking and follow-up would be needed to achieve the full value of a large scale mechanical treatment incentive program for private lands. Finally, part of the justification for mechanical treatments has been to return the landscape to a condition wherein fires can be left to burn in some circumstances, restoring a landscape to a fire-adapted, resilient state. Private landowners, particularly those in the WUI, are likely to have fewer incentives to allow fires to burn; these ownerships are smaller, making let-burn strategies more complicated, and they contain higher densities of structures and people, compared to forests managed by the government.

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