A description of the timber-based RTP mixed-integer goal program economic model

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Introduction

Economic impacts from wildfire may be reduced if available fuels are removed from the landscape using fire surrogates such as mechanical fuel treatments. These treatments involve removal of standing trees and other fuels from forest stands with features indicative of high fire damage risk. Previous chapters of this report have shown that mechanical fuel treatments ("treatments") can generate large volumes of merchantable timber. Should this timber enter the market, economic consequences would be expected.

In our modeling, the incentive to produce such materials specifically for fire risk reduction or fire regime restoration, has historically been a secondary objective. Thinnings of forest stands proceeded for a variety of reasons, including enhancing the proportion of larger diameter timber to achieve for economic objectives related to revenue or profit maximization for forest landowners. Thinning also has been done to improve the landscape for wildlife or to encourage growth of forage for range animals (also for profit). On government lands, non-timber objectives may have played a larger role than on non-government lands. Since the late 1990s, with rising costs of fire suppression, mechanical means have been pointed to as potentially useful means of reducing fuels because thinnings have fewer constraints related to weather than other wildland fire surrogates (e.g., prescribed fire) or wildland use fire, they can immediately achieve stand densities that might be closer to those desirable compared to other fire surrogates, and they can generate some revenues (the merchantable timber, in particular) that can help to offset their cost of implementation.

Designing a mechanical treatment incentive program is beyond the scope of our research, and we do not intend to develop it further in this study. 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 2004). 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 have less incentive to allow fires to burn, since these ownerships contain higher densities of structures than government lands (for example), and because such fires would still represent significant risks to residents.

Hence, the focus of our research is the implementation of a treatment program implemented at the landscape level on government lands.

Methods

Timber markets of the western U.S. have long been dominated by harvests from public lands, but the situation has changed in the last decade (Haynes et al. 2001). National forests of the West provided nearly half of all timber harvested during the period 1950-1985. Since the late 1980s, however, harvests in the West are dominated by industrial and nonindustrial forestland owners. Markets in the region have contracted overall, and timber outputs in major producing states have declined. Large-scale biomass removals could result in a near doubling of timber output in many parts of the fire-prone West.

Fire related fuel treatments would tend to be focused on the fire-adapted forest types of the West. In our analyses, mechanical fuel treatments will be focused on all forest types but will tend to prioritize coniferous-dominated stands ahead of others. Among the forest types expected to receive the most attention are ponderosa pine, Douglas-fir, lodgepole pine, and western larch. Hardwood types are more commonly found on non-federal lands than on federal lands (Haynes et al. 2001), so when considering a program that is limited to federal or government lands, it is likely that coniferous stands will receive the vast majority of treatment for any given program.

The western situation contrasts greatly with the South. Federal harvests have always played a minor role in southern markets, providing less than 2 percent of total timber volume to the market (Haynes et al. 2001). The South's production is dominated by industrial and non-industrial production. Recent transitions are away from industry toward a corporate ownership by timberland management and investment organizations (TIMO's) and real estate investment trusts (REIT's) (Wear et al. 2006, Clutter et al.

2006). Most lands owned by industry and now TIMO's and REIT's are industrial style pine plantations managed on relatively short rotations. Fire risk is managed through prescribed fire, thinning, and chemical control of undergrowth. On nonindustrial private lands, fire risk is less likely to be managed, but when managed it is typically done through the same methods as used by industry and corporate owners.

Fire-related fuel treatments in the South are usually done in pure southern pine or pine-oak natural forest types and pine plantations. Hardwood types are less often managed in this way and so lie outside the domain of our analyses.

Timber Markets in Fire Prone Landscapes

Large changes in the amount of wood on local markets can affect the welfare of timber producers and timber consumers by shifting supply (Holmes 1991). Outward shifts in supply decrease prices and increase overall welfare. However, such shifts can have differential impacts on various producer and timber consumer groups, especially when the outward shift in supply results in a contraction in demand for alternative products. Of particular interest is the effect of such shifts on private timber producers, whose outputs compete directly with outputs of national forests (Adams et al. 1996).

Outward shifts in supply such as those associated with salvage removal programs are often short-run, affecting local markets for only a few months to a couple of years (Holmes 1991, Prestemon and Holmes 2004). If such outward shifts in supply are perceived by demanders to be temporary, then demand will not increase (the demand curve will not shift outward) and market responses to supply increases are limited by local mill production capacities and markets for mill outputs. In the case of a short-run supply shift, timber consumers gain but producers not participating in a biomass reduction program may be harmed. This effect is similar to programs such as tree planting incentives which are intended to increase future timber supplies (Boyd and Hyde 1989). If supply shifts are perceived as permanent, then arbitrage can lead to outward demand shifts that return prices to normal and increase economic welfare generally within the sector.

Timber supply in markets where government timber harvests exist can be described as consisting of two components: a price-responsive private supply, which slopes upward in price-quantity space, and a policy-driven public supply, which is essentially vertical in this space. Increased public land timber harvests, represented as shift outward in this nearly vertical public timber supply curve, benefit mills but harm private timber suppliers by driving down the price of timber. In the calculation of timber market effects of treatments, where total supply is equal to the public plus the private supply components, economic surplus is estimated using techniques described by Just et al. (1982). These techniques have been applied frequently in forestry, e.g., Holmes (1991) and Wear and Lee (1993).

From the perspective of public timber supply, there are at least two possible outcomes for the timber market with a biomass removals program in place, and these two outcomes depend on whether biomass removals substitute for regular removals from public lands or merely add to them. There would be no immediate market effects on producers or timber consumers in the aggregate in the short-run if (1) product removals from biomass treatments can substitute for regular harvests, (2) the costs per unit to get the product to markets are the same, and (3) the mix of products going to markets remains the same. Over the long-run, the programs would affect residual stands, including growth rates, final products obtained from a different inventory structure and wildfire salvage volumes obtained from the forests under an altered wildfire risk.

In this analysis, unlike the more spatially and product-limited analysis conducted by Abt and Prestemon (2006), biomass removals are assumed to replace regular public harvests up until biomass removals equal historical regular harvests, wherein total harvests can be larger than historical (and would be pure biomass volumes, not regular harvest volumes). The price effects of these programs would depend on how fast timber demand can adjust to a larger supply obtained from the treatments. Large, brief programs of biomass removals that result in more total volume of timber being removed from federal lands than when most volume was from regular harvests, will depress prices, harming private producers and benefiting wood product manufacturers (the timber consumers). If demand can expand to accommodate (absorb) these greater harvest levels, then private producers and all consumers may not be worse off at all—every market segment would gain or at least not lose. Small programs, on the other hand, would have little if any effect on the market, as the locations but not the origination ownership (government) of timber volume changes: supply would not significantly shift, so prices, production, and product shipment patterns would change little.

From the perspective of timber demand, the impact of biomass removals programs on markets will depend on the demand response, either (1) affecting trade across regions and the process of spatial arbitrage and/or (2) altering capacity utilization rates at existing mills and/or (3) influencing the creation of new capacity in the vicinity of the treatment zones. The current study evaluates only the short-run situation where local demand stays constant. Additional biomass removed from the land and entering timber markets will therefore depress prices and encourage transshipment of logs to outside of the treatment region. Such movement, however, would have economic effects outside the region that should be accounted for (Murray and Wear 1998). Recent research (Prestemon and Holmes 2000, Nagubadi et al. 2001, Bingham et al. 2003) has shown that low product values and high shipping costs or market inefficiencies can limit the transmission of local market changes to more distant markets.

Figure 1 illustrates the welfare, price and quantity effects arising from a fuels treatment program in a market with both public and private harvests but no trade. Private timber supply is price-responsive, increasing in quantity with increasing price. Public supply is symbolized by a vertical line, S_{G0}. Price in the market for timber is set where the curve representing the sum of private supply and public supply, S_0, intersects the timber derived demand curve, D, at point a, resulting in the equilibrium price P_0 and quantity Q_0 without a fire-related biomass removals program. Producer economic surplus is the area above the private supply curve and below price, area P0ac. Economic surplus accruing to timber consumers is the area above price and below the demand curve, area daP0.

Where the harvests from a large scale program of fire-related biomass treatments on national forests replace regular removals, the government supply curve shifts to S_{G1}, so that total supply shifts outward, to S_1. The total quantity offered with the shifted supply curve, including private supply, is Q_1, and price drops to P_1. Producer economic surplus for private timber producers is area feb, while government revenues from treatments and regular harvests amount to area P_1fe. Surplus accruing to timber consumers is larger than without the biomass removals and is now area dbP_1. Note that the producer surplus accruing to private producers is reduced unambiguously by such a treatment program, as the market price declines and their volume sold shrinks. Also, these changes might apply to producers and consumers locally, but the opportunities to ship product outside a region of fuel treatments can reduce the welfare effects of such a program. Emphases on different parts of a treatment region can also have anomalous effects on consumers and producers. If treatment programs effectively substitute less valuable treated material for more valuable untreated material, provided that the government subsidizes such treatments, consumers may be left only marginally better off and producers much worse off.

If supply shifts past the point where demand intersects the horizontal axis, then producers lose all timber market surplus— they sell no timber, as the market price for timber is zero— and public landowners get no value. In fact, the public would have to pay timber harvesters to remove the biomass. Timber consumers would still gain, however, as wood is provided to them at no cost or they would need to be paid to cut it.

A similar story could be told about benefits accruing to producers and consumers if, instead of new capacity developing locally, demand shifts outward as a result of expanded wood product exports out of the region to other parts of the United States or abroad. The timber consumers benefited in that case would reside outside of the treatment region.

Another component of market analysis is identification of intermarket relationships. If markets are integrated, that is, if local market shocks are transmitted (Ravallion 1986), and biomass harvests are large, then the price effects of these harvests can be transmitted across regions, resulting in economic effects of these harvests that go beyond the treatment zone. Unless these intermarket relationships are understood and quantified, single market analyses would reach erroneous conclusions. One method of evaluating the degree of market linkages is by examining the costs of transfer of various forest products among producing and consuming markets. These are the methods outlined by Samuelson (1952) and Takayama and Judge (1964).

Theoretical Considerations

An ideal model of fuel treatment would optimize how the government spends resources, perhaps using a classical least cost plus loss minimization framework. Here, the costs could be comprised of the costs of fuel treatments of all kinds (including mechanical treatments) and the costs of wildfire suppression on all government lands (say). The losses would be comprised of the net negative welfare impacts on log markets and on the environment and society from mechanically treating (e.g., erosion from harvesting) and prescribe burning (smoke, escaped wildfire) and the losses associated with wildfire that burns on treated and untreated lands. Different forests and locations on the landscape would have different losses associated with a wildfire, have different costs of treatment, cause different welfare losses when material from mechanical treatments is pushed into log markets, and cause different societal and ecological losses from doing the fuel treatments themselves (apart from the wildfire losses). Constraints to such an optimization might include log input capacities in mills, on trade, on spending by state, on how many resources should be devoted to treating WUI locations, etc.

Aside from decisions about what should be the universe of consideration for wildfire losses and timber market losses, many pieces of such an optimization program are missing. First, we do not understand well what are the losses associated with wildfire on federal lands, although some attempts have been made for federal (e.g., Kent et al. 2003, Prestemon et al. 2006) and non-federal lands (Butry et al. 2001). Second, we do not have a firm understanding about the landscape level effects of fuel treatments on observed wildfire outcomes in all forest types, although some information exists for some locations (e.g., Prestemon et al. 2002, Mercer and Prestemon 2005). Third, we do not understand how fuel treatments affect wildfire suppression.

Short of this kind of understanding, we can design a treatment program that comprehends policy priorities. For these, we can look to the Healthy Forest Restoration Act of 2003 (HFRA) and previous analyses done by the USDA Forest Service for guidance. The HFRA has placed emphasis on treating higher risk places on the landscape and forests near built-up areas—the wildland urban interface (WUI). In our study, we therefore can either limit a conceived program (simulation) to treating only these kinds of stands. Alternatively, we design a program that seeks to restore all lands with 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 risk and WUI status. Given limited resources, higher risk and WUI sites would receive the most attention, which would be consistent with this heuristic valuation of these sites.

Empirical Model

We have developed an empirical model that allows for prioritization of particular parts of the landscape over others, based on WUI status and fire risk measures. Our model of western and southern timber markets undergoing fuel treatments is designed as an annual two-stage maximization problem. In the first stage is a goal program that maximizes the sum of weighted acres treated subject to a treatment budget constraint and a feasible global log market solution. The second stage is quadratic program that maximizes global log market welfare subject to the treatments found in the first stage. The second stage therefore allocates log removals from private lands in the treatment zones and from all lands globally. Logs removed are generally required to enter timber markets except when no local market exists within a feasible haul distance (the pre-solution timber value minus haul cost must be positive) for pulpwood size material. However, we also can simulate the effects of a program that would not have such removed timber consumed in timber markets.

This model is specified as an annual maximization of a weighted sum of acres, found by finding a (M+K+J+I) × 1 vector $\mathbf{d}_t > \mathbf{0}$, subject to non-negativity, state program cost, total program cost, market feasibility, mill capacity constraints. 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:

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

subject to:

(1b) Non-negative proportion of acres treated: $0 \geq d_{i,j,k,m} \geq 1 \; (\forall\, i, j, k)$

(1c) Non-negative weights on each acre treated: $w_{i,j,k} \geq 0 \; (\forall\, i, j, k)$

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

(1e) Nation-wide program maximum treatment cost constraint:

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

(1f) State program minimum treatment spending proportion constraints:

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

(1g) State annual product consumption capacity constraints:

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

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

$$\sum_{k=1}^{K}\sum_{j=1}^{J}\sum_{i=1}^{I} d_{i,j,k,m,t}a_{i,j,k,m}v_{i,j,k,m,z} + s^{r}_{m,z,t}(p_{m,z,t}) + s^{u}_{m,z,t}$$

$$-\sum_{n=1}^{N} T_{m,n,z,t} + \sum_{m=1}^{M} T_{n,m,z,t} - d_{m,z,t}(p_{m,z,t}) \geq 0 \;\; (\forall\, m, z)$$

(1i) 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*;

$w_{i,j,k}$ = the priority weight placed on acres in ownership *i* of WUI status *j* in forest type *k;*

$a_{i,j,k,m,t}$ = the number of acres in ownership *i* of WUI status *j* in forest type *k* 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 (transport 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*;

$T_{n,m,z,t}$ = 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, the rest of the U.S., western Canada (British Columbia and Alberta), and the rest of the world. This is solved as a standard spatial optimization problem, across multiple products:

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

subject to the solution found in the first stage (goal program), allowing only trade and therefore prices and production to be altered. The variable p_{mzmax} is the vertical axis intercept of the demand curve, specified as a linear projection from pre-treatment program equilibrium supply and demand intersection defining pretreatment 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*. 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 available, and both allow for the model to solve progressively, over time, until the entire landscape is treated (given a 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 completely "in-condition" plots cannot go "out-of-condition." Once treated, this area is permanently defined as "treated" in the model. In this version, it is always possible to "complete" a treatment program, treating all risky stands defined in the simulation scenario.

A second version recognizes that stands can grow into and out of condition or be treated but not completely be removed from risky status. In that case, the model allows for previously in-condition stands in the landscape to move out-of-condition. It also accounts for out-of-condition stands to spontaneously more to in-condition status (due to, say, stand mortality, other phenomena). It is possible, given a relatively small treatment program (small budget) that the entire landscape of risky stands cannot ever be fully treated and put into in-condition status. Note that this latter growth transition is not available for the southern U.S. (southeast), so when this version of the model is run, the South is effectively "turned-off" (not treated) in the simulations.

Risk status is defined by the TI and CI methods described in another chapter of this report. Because the South has no valid TI and CI calculator available, we have adopted the condition class identified by FIA that applies to a plot. Locations were then collections of stands in different condition classes (again by owner, WUI status, and forest type). In our simulations (described below), only condition classes 2 and 3 were allowed to be treated. Condition class 1 was assumed to be approximately "in-condition" for purposes of our simulations.

Simulations Scenarios Implemented

The central goal of the simulations was to identify the sensitivity of overall market welfare and the rate of treatment each year to alternative levels of program subsidies and alternative assumptions about risk, WUI, and regional treatment preferences. Scenarios are summarized in Table 1. Comparison across scenarios allows for detection of the effects of maintained assumptions on outcomes such as impacts on producers and consumers of timber, overall program cost (over many years), and overall program length. These comparisons are summarized in Table 2. Figure 2 shows our priorities for treatment, which generally run from high-risk WUI stands to low-risk non-

WUI stands. Alternative scenarios also allowed for emphases on certain forest types. Those scenarios are available from the authors but are not compiled for this report. Zhou and Barbour (in process) will report some of the results of that prioritization on product assortments deriving from treatments.

Data Sources and Assumptions

Model Details

The 25 states included in the model incorporate 12 forest types in the West and 12 in the South. From these stand 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, chips are mixed hardwood and softwood.

Northern Alberta and Northern BC are modeled as lodgepole pine, southern Alberta as containing mainly ponderosa pine and BC as containing other softwood. Trade with the rest of the world is allowed only by the coastal states and easternmost states, while trade with western Canada is allowed only by the northern border states. Exports of logs from public lands in both the western U.S. and from Canada are restricted by law, and thus are constrained to zero in the model. Exports of logs from private lands are allowed from both countries. Import taxes on logs are set to zero, consistent with the North American Free Trade Agreement and the majority of U.S. and Canadian log export destinations and import sources.

Survey Data

The primary source data for forest conditions in the West and South were state-level inventories from the U.S. Forest Service's Forest Inventory and Analysis (FIA). A single periodic Resource Planning Act (RPA) inventory[1] was used for each of the twelve Western states. The Southern states used the latest available FIA periodic or annual inventory[2] at the time of the simulation. Table 3 lists the surveys by state.

Assignment of hazard and WUI classifications

The RPA data in the West included variables which indicated if a plot was in the Wildland Urban Interface (WUI). Hazard classification in the West was based on the torching index (TI) and crowing index (CI). See the accompanying document "Mechanical Fuel Treatments on Timberland in the Western United States and Their Impact on Wildfire Hazard Ratings" for detailed information on how TI and CI were calculated for Western plots. The hazard targets for the West, based on inventoried plot conditions, were

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

If a plot met one of these two conditions, then it was excluded from consideration. These thresholds allowed us to define hazard levels for plots that did not meet these criteria pre- or post-treatment. In the results section,

- plots with $TI < 25$ and $25 < CI \leq 40$ were classified as low hazard,
- plots with $TI \geq 25$ and $CI < 25$ were classified as medium hazard, and

[1]Available at http://www.fia.fs.fed.us/tools-data/data/.

[2] Available at http://www.ncrs2.fs.fed.us/4801/fiadb/.

- plots with TI < 25 and CI < 25 were classified as high hazard.

Algorithms for calculating TI and CI for Southern species were not available so hazard in the South was based on the Regime Condition Class (FRCC; Schmidt et al., 2002). The FRCC indicates the degree of departure (1 ≡ low, 2 ≡ medium, 3 ≡ high) from natural, historical conditions and is more of a coarse-scale measure of hazard compared to the stand-level hazard assessment of TI and CI. Neither Condition Class nor WUI classification were not included in the FIA surveys. A process using data from a Geographical Information System (GIS) was implemented to assign Condition Class and WUI status to each plot. The Condition Class grid[3] was converted to a point file where each point was the centroid of a grid cell. This point layer was overlaid on a WUI map[4] for the South and the National Atlas grid of forest types[5]. Each Condition Class point was assigned the corresponding WUI classification and forest type. The total number of points for each forest type was determined for each FIA survey unit. The percent of land area for a survey unit in each forest type, Condition Class, and WUI combination was 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 were then attached to the FIA treatable acres and removal volumes aggregated by survey unit and forest type. This allowed the allocation of area and volume to Condition Class and WUI classifications within the survey unit which could then be aggregated to the state level. Treatment was simulated on all Condition Classes. However, plots with inventoried basal area of 50 ft^2 or less were excluded from treatment.

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

Treatments

Treatments were simulated at the plot level. Lodgepole and fir-spruce forest types in the West were treated with an even-aged treatment that removed trees, beginning with the smallest diameter and moving up, until one of the two targets above were met or a maximum of 25% of beginning basal area was removed. All other forest types were treated with an uneven-aged treatment that removed trees proportionately across all diameter classes until one of the two targets above were met or a maximum of 50% of beginning basal area was removed. See the accompanying document "Mechanical Fuel Treatments on Timberland in the Western United States and Their Impact on Wildfire Hazard Ratings" for more information on these treatments. Table 4 shows the breakdown of treatable area by forest type and hazard classification in the Western States. Overall, there were 46 million acres in the West that did not meet our target conditions for TI and CI. Around 37% of treatable acres were high hazard, 37% are medium hazard, and 26% are low hazard.

Each plot in the South was treated with an even-aged treatment that removed trees, beginning with the smallest diameter and moving up, until the residual basal area was 50 ft^2. If a plot's inventoried basal area was less than or equal to 50 ft^2 then it was excluded from treatment. The detail of treatable acres for the Southern states is given in Table 5. There were 153 million treatable acres in the South, of which 12% were Condition Class 1, 18% were Condition Class 2, and 70% were Condition Class 1.

WUI acres by state are shown in Table 6. 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. Plot expansion factors 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 will not match published estimates of WUI area (Radeloff 2005). Our calculation of WUI in the South may also be biased since we applied our estimated percentages of land in WUI to expansion factors (not adjusted to reflect interface or intermix) summed to the survey unit level. We acknowledge these issues and leave the development of WUI-adjusted expansion factors as a venue for future work.

In the West, treatable acres and removal volumes were 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 were first summed in survey unit, forest type, and owner aggregates. It was assumed that treatable acres and removal volumes across Condition Class and WUI classifications were proportionate to the estimated percentages of land by Condition Class and WUI at the survey unit level (described above). Acres and volumes were 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.

Treatment Costs

Treatment costs for each plot in the West were generated by the Fuel Reduction Cost Simulator (FRCS; Fight et al., 2006) in the Fuel Treatment Evaluator[6] (FTE). FRCS was not able to provide a valid estimate for approximately 25% of the plots. Ordinary least squares (OLS) linear regression was 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 7. These parameter estimates were 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 was calculated for use in the optimization model based on the number of plots in each of these aggregates. These results were 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 was based on the number of plots in each of these aggregates. Table 8 shows the minimum, maximum, and mean cost per acre across the aggregate categories in each region.

Growth Modeling

The accompanying document, "The Spatial and Temporal Impacts of Mechanical Fuel Treatments on Wildfire Hazard Ratings in Colorado", describes how growth and regeneration were simulated in Colorado ponderosa pine and Douglas fir forest types. The uneven-aged treatment with a removal limit of 50% of beginning basal area was

[6] Available at http://www.ncrs2.fs.fed.us/4801/fiadb/FTE_Version3/WC_FTE_version3.asp.

implemented on plots representing approximately 1.6 million acres. TI and CI were 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 met the hazard targets was also simulated and TI and CI calculated following each 5 year growth step. Using the frequency distributions of land area moving from one hazard category to another over the simulation as growth and regeneration change plot conditions, we produced a set of transition matrices (Tables 6 -11 in the accompanying document for the treated plots).

Baseline Simulation Data

Current harvest data were developed using the 2001 Forest Resources of the United States removals and product data (Smith et al. [2002]). Hardwood removals account for only 4 percent of all timber removals in the western U.S. states and a larger share in the East. 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.

Base level mill capacities and timber production levels in the U.S. and Canada derive from Spelter and Alderman [2003] and were adjusted for each state to reflect non-included mills. Outside the U.S. and Canada, softwood log production and processing capacities were set at 100% and 110% of production, respectively, as reported by FAO (2004) for 2002. Capacities were allowed to adjust to increased log processing due to rising treatment harvests, however. These capacities were allowed to expand to 140% of stated capacities, understanding that such adjustments could be achieved by adding shifts.

In markets, this adjustment in processing capacity is consistent with a movement along the supply curve rather than a shift out. In one simulation, we also allow for real increases in capacity of 1% per year, beyond the physical limits set by existing plant and equipment.

Product prices in the Western U.S. were derived from National Forest System Cut and Sold reports for the second quarter of 2003. Regional prices were adjusted by the percentage of harvest from each species group to provide species prices. Prices differ by state and major species group, ranging from a low of $39 per thousand board feet (mbf) in Arizona and New Mexico for lodgepole pine to a high of $528/mbf in Oregon and Washington for ponderosa pine. Chip prices nationwide and internationally were set initially at 35 cents per cubic meter, consistent with Rummer et al. (2003). Southern pine sawlog prices are set at the statewide average delivered log prices reported in Timber Mart-South (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 Fight (personal communication [May 2003]) and 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. Distance from stump to mill 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 FIA plots are located. The source of the mill location data was Prestemon et al. (2005). Distances between states for trade purposes are determined by using the distance between spatial-center of forestland in each state. A GIS coverage of these mills was developed for this study; an example map is shown in Figure 3.[7]

Supply elasticities remained fixed at unity for both inventory and price. While the former 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. [2001]) (but not all—see Newman [1987]), we impose the unitary supply elasticity with respect to private supply to simply welfare calculations and limit modeling complexity. Such a private supply specification is represented as in Figure 1, with a ray from the price-quantity price origin (Price = 0, Quantity=0) to base-level prices and quantities for all products and all regions. While this is a simplifying assumption and not consistent with all research regarding timber supply, it may apply to log supply (our market), and it allows for a simple calculation of small changes in producer surplus and avoids the need for piecewise supply function specification (and the increased solution complexity that this carries with it). 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 (log demand should be more elastic, because the harvest and mill transport costs form a wedge between the log price and the timber price), it is important to vary these elasticities from those in the published literature (Adams and Haynes [1980], Majerus [1980], Regional Forester [1984], Adams et al. [1986], Wear [1989], Adams et al. [1991], Newman [1987], Abt et al. [2000], Haynes et al. [2001]). All elasticities are shown in Table 9. The demand elasticities are allowed to double in simulation 9.

[7] All coverage information is available for inspection, at www.srs.fs.usda.gov/econ/mills/mill2005.htm

Results

Summary results are displayed in Table 10. These results are displayed as differences from the Base Case of no treatment program. Results below are briefly described in terms of the effect of the assumption listed in Table 2. Some figures showing the annual treatment amounts and the area in the West and South (depending on the scenario) that remains out of condition—i.e., fire risk levels 1, 2, and 3 in the western U.S. or still in Condition Class 2 or 3 in the South.

The institutional capacity-constraining effect of not introducing treatment materials into the timber market but occupying the efforts of timber planning and sale personnel on government lands are shown in the first two rows of simulation results. These rows show that such a restriction, with a $300 million annual mechanical treatment program, would only very slightly reduce welfare of consumers (by less than one percent in the West but negligibly when the South is included). The effect of such reductions are positive on western producers, as prices rise and the private producers increase their timber sales. When the South is included, though, producers could be harmed, as private producers from the West substitute their production for southern production, in export markets (i.e., markets besides the South and West, which could include other markets in the northern U.S.). Government treatment revenues, however, would be negatively affected in the first case but possibly positively affected in the case where southern markets are included—apparently, southern timber price increases from the government harvest reductions more than offset the quantity reductions experienced when treatments occupy agency time. The last column shows the trivial result—the total size of an initial treatment program—which covers 30.2 million acres in the West and 5.9 million acres in the South, achieved through implementation of such a treatment program. With the West treated only, this program takes 144 years to complete; the South adds 29 years to the program, resulting in a completion time of 173 years (Table 11) and a slight reduction in the average treated area per year by about 1,300 acres.

The effect of requiring treatable products to enter timber markets, compared to no such requirement, is demonstrated in the third and fifth columns. The fourth row of results shows the addition of the South to such a treatment program of $300 million per year. The effect of requiring (or allowing) treatment materials to enter timber markets is to increase consumer surplus, compared to no such program, by 0.27 percent each year of the program, on average. Producer surplus is reduced in this scenario by 1.56 percent each year. As shown in Table 11, requiring or allowing products to enter markets does not affect the total time to completion of the program, indicating that, at $300 million per year in government treatment costs, capacity constraints do not operate to limit program length at all.

Figure 4 shows the timing of treatment acres by WUI and non-WUI in the West only scenario. This chart shows the three jumps in area treated that occurs throughout the simulation: spikes occur where the cheapest acres to treat in the risk category are obtained. As the program progresses through higher and higher cost stands, the amount that can be treated given a budget is progressively less and less, until all acres in the risk category are consumed. Secondary spikes show the effect of treating the cheapest wildland-urban interface acres within each risk category. Figure 5 shows where such treatments happen during this simulation. The line graph shows that much attention is paid early on to states such as Idaho, Colorado, and Washington, states with much high-risk WUI timberland area. Figure 6 documents the number of acres remaining out of condition, by risk category, in the West. This figure shows that it takes nearly six decades to treat all high risk stands (risk = 3), a similar time to treat medium-risk stands, and slightly less time (about 35 years) to treat lower risk stands.

The effect of adding the South to a combined West plus South treatment program is documented in Figures 7 and 8. This figure shows the greater length of time to completion and the timing differences in treating all risk levels in the West and Condition Class 2 and 3 lands in the South. Notable in Figure 8 is that the Southern Condition Class 3 and 2 acres are generally treated faster than the western risk level 3 and 2 (high and medium risk) acres, respectively. This is because the southern treatment costs are generally lower than the western costs, due to different treatments applied and different site conditions (e.g., in the South slopes are lower, usually).

Accounting for simulated stand risk growth (fifth row of results) works to lengthen the time to completion of a program in the U.S. West only (Scenario 6) shows that the total treatment time increases to over two centuries (Table 11) and raises the average treated area per year by nearly 200,000 acres. The area treated, in total, increases from 30.2 million to 80.2 million, a rise of 50 million acres, due to the growth. This growth helps timber consumers in the long run slightly more than in the equivalent case without growth but softens the long-run impact on producers very slightly, by spreading out the negative impact across space and time. Figures 9 and 10 show how regrowth results in persistent requirement to reenter certain stands to maintain in-condition status in the West.

The sixth row of results compares the effect of tripling the size of a treatment program focused only on the West and accounting for stands risk growth. The impact on treatment length (Table 11) is substantial, shortening the program by 182 years, to just 59 years. The timber market effect of this is to reduce producer surplus by an addition 2 percent compared to Scenario 6, with a total producer surplus annual reduction by about 3 percent compared to the base case (Scenario 1). The effect on consumers is small, however, in this case, as consumer benefits are spread out over many, many years, averaging only a 1 percent benefit (but similar in dollar terms to the losses by producers, since producer surplus is generally about one-third that of consumer surplus on average across all scenarios). Government harvest revenues are eleven-fold larger, compared to the base case, however, once the program is tripled in size and accounts for growth.

The seventh row of results shows the net effect of adding the South to a large, $900 million per year treatment program (not accounting for risk growth). This shows additional benefits to timber consumers and additional losses experienced by producers in a manner coincidentally similar to the effect of adding growth to western U.S. stand simulations. The effect is to nearly triple annual area treated, as might have been expected, from about 207,000 acres per year to 621,000 acres per year, a 414,000 acre increment. Harvest revenues double in this scenario, compared to a $300 million per year South plus West treatment program.

Doubling the demand elasticities used in the entire simulation analysis (eighth row of results in Table 10), for a no-growth South plus West treatment program, serves to reduce the benefits to timber consumers in the West and South, as would be expected from a flatter demand curve, by about 5 percent. Producers in these regions would also be harmed more, as consumption (and hence prices) drops and trade is affected more significantly. Government harvest revenues would be only slightly affected, but consumers in the rest of the World (ROW) would be much lower. In short, a flatter demand curve does result in lower consumer surplus and greater trade effects from a treatment program, but there are no effects on the annual size or the speed of such a treatment program.

The length of a treatment program of $300 million per year could be limited by restricting treatments to just wildland-urban interface stands or to just high risk acres. Simulations 10, 11, and 12 evaluate the impacts of these (rows 9, 10, and 11 of the results in Table 10). If a program of $300 million per year were restricted to high-risk stands only (ninth row of results in Table 10, and illustrated in Figures 11 and 12). This West-only program would complete in just 57 years, compared to 144 years (Scenario 4) with all lands in the West. Impacts each year are only slightly smaller, during the 57 years, than an all-risk levels treatment program. Government harvest revenues are slightly larger during these 57 years compared to the annual impact over 144 years. The long run cost of the program, though, is only very slightly less than a 144 year program, due to the steep 7 percent discounting.

The WUI-only focused program results in completion within 8 years if focused on the West and 16 if it also includes the South (Table 11). These small programs result in very slight impacts on producer and consumer groups, overall, and they are very brief compared to all-risk and all government timberland programs. Harvest revenue effects are still much higher, over the 8 or 16 year program, than in the base case no-treatment program—nearly tripling revenues—but this increase is short-lived. These WUI-only programs only involve about 1.5 million acres in the West and another 1.5 million acres in the South. Figures 13-16 show the annual treatment amounts.

The effect of gradually expanding mill input capacity, comparing Scenario 13 with Scenario 8, is to benefit western and southern timber consumers by an additional 1.85 percent and to harm private producers by an additional 2.1 percent. This means that greater amounts of harvests are concentrated earlier in the program, as greater mill capacities allow for greater treatment amounts in this large program of $900 million per year.

Conclusions

This study has many potential conclusions to highlight. First, small programs have small impacts on timber producers and consumers, when spread across space and time. For the western U.S., effects on producer and consumer surplus are less than 2 percent per year. Effects on prices and trade within the U.S. and across national borders are similarly small. However, the program, if sustained, could potentially go on for many decades. When this $300 million per year program is focused on wildland-urban interface stands, the effects are equally small on market variables, but the effect is shorter-lived, effectively completing within 1-2 decades. The western U.S. WUI stands could be completely treated within eight years, while adding southern U.S. WUI stands would add another eight years to the time to completion.

Second, focusing a national-level treatment program on high-risk stands on government lands effectively shortens the time to completion of the program by about two-thirds. However, because stands continually grow into risky condition, accounting for growth implies that such a program would take several decades longer and require constant treatment into the far distant future (assuming that post-treated stands are not maintained through prescribed fire).

Third, mechanical fuel programs for government forests, when adjusted for stand and fire risk growth extend the length to completion by about one-third. For example, a $900 million per year program could be completed within about 58 years if re-growth of stands into risky condition were assumed not to occur but, we estimate, would take nearly 75 years once re-growth were accounted for. This result depends on an assumption that mechanically treated stands are not then subject to regular prescribed fire to potentially maintain "in-condition" status in terms of fire risk. This tripling of the size of a treatment program, from $300 million per year to $900 million per year, increases the positive impacts on western timber consumers by five-fold and more than doubles the negative impacts on private producers in the western U.S. Still, the overall effect of even a $900 million per year program is to reduce western producer surplus by 3.3 percent and increase western consumer surplus by 1.4 percent (the consumer surplus absolute number is larger, however, and this figure ignores government treatment revenues). The program completes in one-third the time, compared to a $300 million annual program. This effect on time-to-completion is essentially linear.

Fourth, government timber receipts with a $300 million per year program limited to the U.S. West increase by $5.4 billion per year, including treatment timber and regular harvests, effectively quadrupling government timber harvest receipts. Adding the South to the program increases these revenues nearly ten-fold. A $900 million per year program more than doubles these figures.

Fifth, international impacts of a mechanical fuel treatment program are small but effectively linearly related to the size of the treatment program. The effects of the program mainly occur through at least three mechanisms. (A) First, 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 consumers in Canada. (B) Second, by lowering the domestic price of timber in the U.S. such treatment programs would tend to substitute western logs for logs used in the eastern U.S. (by small amounts), which would lower export opportunities for Canadian lumber producers (not directly modeled in the timber market modeling chapter but modeled in the wood products market chapter by Ince). And (C) third, Canadian consuming mills would experience some lower wood input prices and hence benefit, because of the slightly lower Canadian export opportunities.

Sixth, allowing for gradually expanding wood demand capacity in the western U.S., a treatment program would primarily benefit western U.S. consumers (mills). On the other hand, private timber producers would be more negatively affected, as a higher feasible rate of government harvests substitutes for private harvests in the market, and prices drop. Consumers in the rest of the world are also very slightly harmed, as more timber processing is concentrated in the western U.S. Similar effects occur after allowing for expanded southern U.S. capacity.

Seventh, accounting for growth of stands back into risky condition following treatment and into riskier condition before treatment effectively doubles the long-run cost of the treatment program. Treating all stands in the western U.S. without accounting for growth has a long-run cost, at a 7 percent discount rate, of $4.6 billion. Accounting for risk growth over time, this cost rises by $8.9 billion, nearly tripling the long run cost of the program.

Eighth, adding the South to a national treatment program for government lands only very slightly increases (by less than 1 percent) the cost of the treatment program compared to one limited to the U.S. West. Addition of the South only added 29 years to the total time to completion of a $300 million per year program, or about 20 percent longer. The cost, however, without accounting for stand risk growth, does not much because of these extra years, due to steep discounting of the costs of those most distant years. Such a South plus West program, however, does shift where treatments occur throughout the duration of the program, with southern condition class 3 stands treated before western risk level 2 stands.

Literature Cited

Abt, R.C., F.W. Cubbage, and G. Pacheco. 2000. Southern forest resource assessment using the Subregional Timber Supply (SRTS) model. Forest Products Journal 50(4):25-33.

Adams, D.M., R.J. Alig, B.A. McCarl, J.M. Callaway, and S.M. Winnett. 1996. An analysis of the impacts of public timber harvest policies on private forest management in the United States. Forest Science 42(3):343-358.

Adams, D.M., C.S. Binkley, and P.A. Cardellichio. 1991. Is the level of National Forest timber harvest sensitive to price? Land Economics 67(1):74-84.

Adams, D.M., and R.W. Haynes. 1980. The 1980 Softwood Timber Assessment Market Model: structure, projections and policy simulations. Forest Science Monograph No. 22. 64 p.

Boyd, R. G., and W.F. Hyde. 1989. Comparing the effectiveness of cost sharing and technical assistance programs. Pp. 48-89. In: Forestry Sector Intervention: the impacts of public regulation on social welfare. Ames, Iowa: Iowa State University Press.

Clutter, M., B. Mendell, D. Newman, D. Wear, J, Greis. 2006. Strategic factors driving timberland ownership changes in the U.S. South. Draft Report.

Fight, R.D., Hartsough, B.R., Noordijk, P., 2006. Users guide for FRCS: fuel reduction cost simulator. Gen Tech. Rep. PNW-GTR-668. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 23 p.

Holmes, T.P. 1991. Price and welfare effects of catastrophic forest damage from southern pine beetle epidemics. Forest Science 37(2):500-516.

Just, R.E., D.L. Hueth, and A.S. Schmitz. 1982. Applied Welfare Economics and Public Policy. Englewood Cliffs, NJ: Prentice-Hall, Inc. 491 pages.

Majerus, G.A. 1980. Econometric estimation of demand and supply curves for timber in Montana, 1962-1980. Unpublished M.S. Thesis, University of Montana.

Newman, D.H. 1987. An econometric analysis of the southern softwood stumpage market: 1950-1980. Forest Science 33(4):932-945.

Prestemon, J.P., and T.P. Holmes. 2000. Timber price dynamics following a natural catastrophe. American Journal of Agricultural Economics 82(1):145-160.

Prestemon, J.P., and T.P. Holmes. 2004. Market dynamics and optimal timber salvage after a natural catastrophe. Forest Science 50(4):495-511.

Prestemon, J.P., J.M. Pye, R.J. Barbour, G.R. Smith, P.J. Ince, W. Xu, and C. Steppleton. 2005. Primary Wood Processing Mill Locations in the Continental U.S. Available at www.srs.fs.usda.gov/econ/data/mills/mill2005.htm

Radeloff, V. C., Hammer, R. B., Stewart, S. I, Fried, J. S., Holcomb, S. S., and McKeefry, J. F., 2005. The wildland urban interface in the United States. Ecological Applications 15,799-805.

Ravallion, M. 1986. Testing market integration. American Journal of Agricultural Economics 68(1):102-109.

Regional Forester. 1984. Montana timber demand and supply: a short-run model of the timber market and an assessment of the economy, employment and fuel wood use. Unpublished report issued to the Montana State Forester from the Northern Region, USDA Forest Service, Missoula, Montana.

Rummer, B.; Prestemon, J.P.; May, D.; Miles, P.; Vissage, J.S.; McRoberts, R.E.; Liknes, G.; Shepperd, W.D.; Ferguson, D.; Elliot, W.; Miller, S.; Reutebuch, S.E.; Barbour, J.; Fried, J.; Stokes, B.; Bilek, E.; Skog, K. and Hartsough, B. 2003. A strategic assessment of forest biomass and fuel reduction treatments in western states. http://www.fs.fed.us/research/pdf/Western_final.pdf. Accessed on November 21, 2004.

Samuelson, P. 1952. Spatial price equilibrium and linear programming. American Economic Review 42(3):283-303.

Schmidt, K.M., Menakis, J.P., Hardy, C.C., Hann, W.J., Bunnell, D.L., 2002. Development of coarse-scale spatial data for wildland fire and fuel management. Gen. Tech. Rep. RMRS-GTR-87. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 41 p.

Spelter, H., and M. Alderman. 2003. Profile 2003: softwood sawmills in the United States and Canada. USDA For. Serv. Res. Pap. FPL-RP-608.

Takayama, T., and G.G. Judge. 1964. Equilibrium among spatially separated markets: a reformulation. Econometrica 32(4):510-523.

Wear, D.N. 1989. Structural change and factor demand in Montana's solid wood products industries. Canadian Journal of Forest Research 19(5):645-650.

Wear, D.N., D.R. Carter, and J.P. Prestemon. 2006. The U.S. South's Timber Sector in 2005: A prospective analysis of recent change. Draft Report.

Zhou, X., and R.J. Barbour. (In Process). Product assortments deriving from risk- and forest type prioritized fire related fuel treatments on federal lands in the U.S. West. Forest Policy and Economics.