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ABSTRACT

The FIA BioSum model was used to simulate three fire-hazard-reduction policies in an area comprising northern California. southwestern Oregon. and the east slopes of the Cascade Mountains in Oregon. The policy scenarios. all subject to a stand-scale fire-hazard-reduction effectiveness constraint. included maximize torching index improvement (Max TI). maximize net revenue recovery (Max NR). and minimize merchantable timber removal (Min Merch). Differences in the area treated under each scenario were considerable. ranging from 15 to 96% of the area for which effective treatments are technically feasible. For each scenario. weight. species. and source tree size of both dirty chips (hogfuel or biomass) and saw logs were estimated. The mix of species and sizes removed under each scenario was surprisingly similar. although the Min Merch scenario did remove more noncommercial species such as hardwoods and more saw logs in the midsize classes (10 to 16in. diameter at breast height (dbh); 25.4 to 40.6cm) than the other two scenarios. Saw logs accounted for 67 to 79% of the weight removed. Under all scenarios. the Douglas-fir *(Pseudotsuga* menziesii)/larch *(Larix)* and white woods *(Piceo* spp.. *Tsuga* spp, and *Abies* spp.) species groups accounted for nearly all of the saw logs removed. Tops and limbs of commercial species and noncommercial species accounted for most of the dirty chips. Stems of low value commercial conifers (7 to 16in; 17.8 to 40.6cm) were also an important source of dirty chips. Trees smaller than 7in. (17.8cm) dbh were a relatively minor component of the dirty chip mix.

1. Introduction

Increasing stand density associated with fire suppression. grazing. and other long-standing forest management practices has resulted in a higher level of fire hazard across much of the Western United States than is believed to have existed prior to European settlement and DeBenedetti, 1979: Bonnicksen and Stone 1982: Parker, 1984; Chang, 1996; Hann et al., 1997; Covington et al., 1997; Fule et al., 1997). As federal and state agencies mobilize to address this issue. some stakeholders worry that even if agency solutions are effective in reducing fire hazard. such solutions may harm other resources that they care about (see for example, Aplet and Wilmer, 2003; Dombeck et al., 2004). Others have warned that without careful planning. agencies may adopt treatment strategies that ultimately prove ineffective and fail to accomplish stated goals (Franklin and Agee. 2003). Cost of treatment programs has also been a concern. and there has been pressure to design cost-efficient and. where possible. self-supporting. programs (Hulsey and Ripley, 2006).

We believe an approach that integrates multiple ecological. social. and economic concerns into a common analytical framework is needed to allow policymakers and the public to evaluate the consequences of alternative strategies for fire-hazard reduction (Barbour et al. 2004a, 2005). This analysis contributes to the understanding of how fire-hazard-reduction treatments can be financed by evaluating the types of wood that could be removed by hazard-reduction treatments. Understanding this aspect of the larger problem is important because the funding available from federal and state governments to address wildland fire hazard is quite limited in relation to the magnitude of the problem. For example. Prestemon et al. (2008-this volume) show that at the current federal funding level. it would probably take decades to make a noticeable difference in the broad-scale fire hazard in the Western United States.

Given that a range of treatments with different net costs may be effective, we want to understand how less expensive treatments can be identified. This analysis considered only mechanical thinning treatments designed exclusively to achieve hazard reduction; however, there is no reason why this framework could not be used to evaluate the costs and effectiveness of other treatment approaches such as prescribed fire; other mechanical methods such as mastication or mowing to alter fuels *in situ;* and thinning treatments designed to yield both hazard reduction and profitable timber volume. We also

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want to understand ways to combine various stand-scale activities into a package that protects a larger landscape from uncharacteristically large or severe fires. This might be done by using information from analyses like the one described here to evaluate stand-scale treatments for use in a landscape-scale fire-spread analyses like that suggested by Finney (2003, 2005). Eventually, we want to understand how to combine the types of financial analyses presented here with analyses of the response of other resources (e.g., wildlife, recreation, aquatic conditions, soil conservation, etc.) under various management scenarios. We feel such an integrated analysis would provide more complete information about how different fire-hazard management policies might influence the array of things people care about on forested landscapes (Barbour et al., 2007).

Toward this end Fried et al. (2005) designed and Daugherty and Fried (2007) refined the Forest Inventory and Analysis Program (FIA) BioSum model. BioSum is a strategic model meant for use on landscapes larger than 10,000km^2 (25,900km^2). BioSum is intended to answer the questions: (1) Could fire-hazard-reduction treatments within a specified area provide enough raw material to fuel one or more 20-megawatt wood-fired electrical power generation plants? (2) Using only revenues from merchantable timber removed during treatments and the sale of electricity, could the package of activities across the landscape (the enterprise) pay for itself? (3) If not, how large of a subsidy would be necessary? (4) What mix of tree species and sizes of merchantable and nonmerchantable timber would be removed during fire-hazard-reduction treatments? The part of the analysis reported here addresses the fourth question.

2. Methods

We evaluated a mostly forested landscape in Oregon and California that includes northern California, southwestern Oregon, and the east slopes of the Cascade Mountains from the California border north to the Columbia River (Fig. 1). For this area, we modeled three stylized fire-hazard-reduction scenarios each reflecting a different point of view about overarching policy objectives (Table 1). The scenarios were (1) maximize net revenue derived from fuel treatments across the landscape (Max NR), (2) maximize the reduction in stand-scale fire hazard across the landscape as represented by improvement in the torching index (Max TI), and (3) minimize the amount of merchantable timber removed during the treatments (Min Merch). These scenarios reflect policy options commonly discussed in the context of the political debate about whether treatments involving the removal of commercial timber have a place in fire-hazard-reduction programs on federal- and state-administered land (Brown, 2000); Western Governors' Association, 2002; Aplet and Wilmer, 2003).

The FIA BioSum analysis framework combines forest inventory data, a treatment cost model, a fuel treatment effectiveness model.

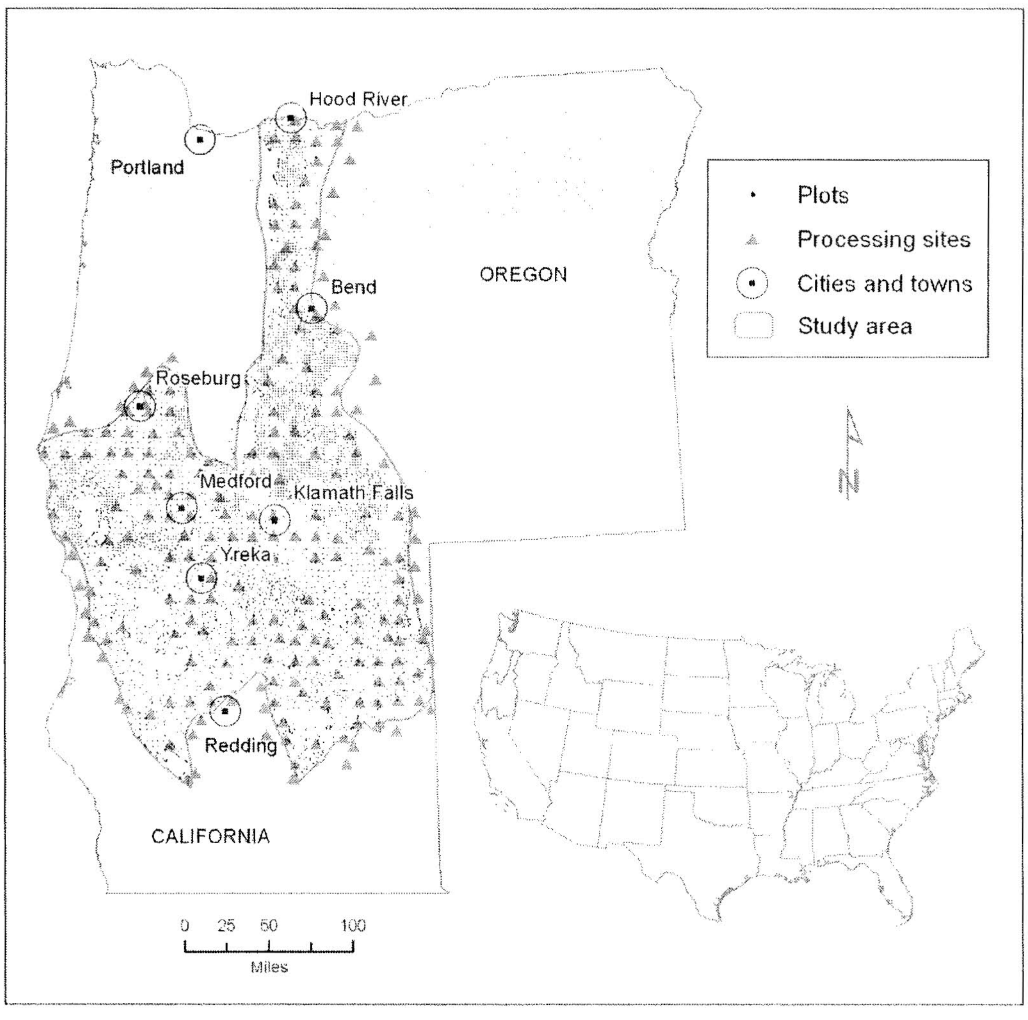

Fig. 1. Study area.

Table 1
Description of simulation scenarios

Scenario	Scenario description
Max NR	Maximum net revenue (NR) for the combination of all plots included in the scenario. Individual plots can have a negative net revenue, and the entire "enterprise" could have a negative net revenue but it would be the highest possible net revenue
Max TI	Maximize the change in torching index (TI) and treat any area where treatments are highly effective regardless of the cost. This scenario picks those plot-treatment combos that contribute to TI change maximization, and omits those that do not. It is designed to achieve maximum TI improvement in the least costly ways, as this is actually a weighted combination of TI improvement and NR max (with nearly all the weight on TI improvement). The inclusion of NR in the weighted objective function ensures optimal location of biomass facilities, thus lowering costs
Min Merch	Maximum net revenue for the enterprise when treatments are limited to plots where treatments are highly effective but allowing only the treatment that minimizes merchantable volume for each selected plot. This scenario reflects the policy choice that only selects fuel treatments that focus on the removal of small-diameter material or at least minimizes the removal of merchantable volume

Each scenario must provide sufficient dirty chips to fire a minimum mill size of 20 MW for 10 years. Each scenario treats plots where treatments are highly effective. "Highly effective" means that it is effective for increasing crowning index without making TI worse, and ending with TI above 25.

and a raw material hauling-cost model with a mixed-integer optimization framework to explore alternative landscape-scale treatment scenarios that achieve a variety of management objectives (Fried et al., 2005). Details of the mixed-integer optimization process used in this analysis are described elsewhere (Daugherty and Fried. 2007). Raw material volumes generated by mechanical fire-hazard-reduction treatments were estimated by applying silvicultural treatments to data derived from forest inventory plots, each of which can be thought of as representing a given area in the landscape. They were evaluated along with multiple siting options for building biomass-fired electrical generating plants.

2.1. Forest inventory plots

A total of 6200 forest inventory plots, representing 22.2million acres (9million ha) of potentially forested land, were extracted for this analysis from the Pacific Northwest Research Station F1A Program's integrated database for periodic inventories (Hiserote and Wadell, 2005). This plot set was culled to remove plots that were observed on the ground to be non forest or located in reserved areas: designated wilderness, natural areas, parks, preserves, monuments, national recreation areas, national wildlife refuges, and inventoried roadless areas. We also omitted plots on steep (> 40%) slopes that were too far from road networks for technically feasible harvest systems, and those with no trees over 5in. (12.7cm) dbh or less than $60ft^2$/ac (14.2m2/ha) basal area. Tree-list data from these variable-radius plots include field measurements and estimates of diameter, height, crown ratio, and species, and model estimates of stem volume and merchantable and nonmerchantable biomass, the latter estimated by using species-specific algorithms (Means et al.,1994).

Treatments on all eligible land were simulated based on nine silvicultural treatment options (Fried et al., 2005). These options were suggested by a group of silviculturists and fire management experts from several federal and state agencies and private firms. The silvicultural prescriptions, all designed to reduce fire hazard, were developed along two broad strategies: (1) fuel reduction or thin-from-below focusing on removing ladder fuels (smallest trees first) and leaving the largest trees untouched, or (2) stand density reduction or thin-across-diameter-classes focusing on canopy density reduction and leaving a residual stand containing the full range of tree sizes that existed pretreatment. Prescriptions under both strategies varied in their residual stand basal area requirements and upper diameter limits for trees to be removed. Residual basal area requirements ranged from $125ft^2$/ac ($29m^2$/ha) down to $60ft^2$/per ac ($14m^2$/ha) and upper diameter limits based on breast height (4.5ft [1.3m] above ground) diameters (dbh) were l0in. (25.4cm), 16in. (40.6cm), 21in. (53.3cm), and no limit (Fried et al., 2005). These data were processed using the Forest Vegetation Simulator (FVS) (Wykoff et al., 1982: Dixon, 2002) to produce a "cut list" (number of trees removed by species and size) for each of up to nine prescriptions for each plot. Some plots had fewer than nine prescriptions because they contained too little basal area to apply prescriptions with higher residual basal area requirements.

2.2. Evaluating fire hazard

The Fire and Fuels Extension (FFE) of FVS (Reinhardt and Crookston, 2003) was used to evaluate pre- and post-treatment fire hazard in terms of torching index (TI) and crowning index (CI). The TI is calculated in FFE as the 20-ft (6.1m) aboveground windspeed at which crown fires are expected to initiate in a specified fire environment; CI is the 20-ft (6.1-m) wind speed at which active crown fire behavior is expected (Scott and Reinhardt, 2001). Although it is theoretically possible to consider hazard as a continuum, the crown fire potential models embedded in FFE are typically applied by silviculturists and fire professionals in a discrete manner. Thresholds are generally selected to demarcate between hazardous and non-hazardous stands or to produce easy-to-understand-and-implement three-class models relative to hazard (e.g., high, medium, or low). We considered plots with either CI or TI less than 25mph (40kph) as high hazard. Treatment effectiveness was evaluated by comparing these modeled indices pre- and post-treatment. A treatment was deemed effective if it increased CI or TI by at least 20mph (32kph), did not decrease either index by more than 10mph (16kph), and neither index was below 25mph (40kph) post-treatment. In addition to tree-list data, FFE requires a surface fuel model (see Anderson, 1932). For this analysis, we used the default fuel model selected by FFE based on current stand conditions.

2.3. Estimating wood product yields

The cut lists generated by FVS (one per plot-treatment combination) were used to estimate the weight of dirty chips and the weight of saw logs from merchantable trees (Means et at., 1994). Saw logs were defined as pieces of stems at least 12ft (3.65m) long with small end diameters of at least 4in. (10.2cm).

2.4. Treatment costs

Estimates of treatment costs were generated via the Fuel Reduction Cost Simulator (FRCS) (Fight et al., 2006). The FRCS model is a regression-based model that synthesizes published harvest cost data for a variety of harvesting systems. Gross product values were calculated as the product of modeled harvest quantities and local product prices. We estimated logging costs based on whole-tree systems for trees smaller than 21in. (53.3cm) dbh. Trees that exceeded this threshold were modeled as being manually felled and delimbed, with tops and limbs left in the woods. We systematically located 221 potential forest bioenergy production facility sites (p-sites) on a 20-x 20-km grid, with minor offsets to ensure that all sites were on private land (Fried et al., 2005; Daugherty and Fried, 2007). We combined, edge-matched, and cleaned geographic information system (GIS) road layers from various government agencies to produce a study-area-wide GIS road coverage with each road segment assigned a rated travel speed. Speeds were converted to unit costs (i.e., cost per unit distance per unit weight of material hauled) by using current cost data for operating log and chip trucks and travel times per road segment. For each potential site, a cost accumulation grid was generated in Arc/

Table 2
Area treated by scenario, proportion of acres eligible for treatment, total green tons removed for the scenario, and the green tons per acre removed

Scenario	Acres treated (×1000)	Proportion of eligible acres	Total removals (green tons×1,000,000)	Green tons per acre
Max NR	2843	0.69	296.2	104
Max TI	3944	0.96	325.9	83
Min Merch	627	0.15	47.6	76

Info, and spatially joined (via overlay) to the plot grid to provide haul cost to that site from every plot in the study area. We assumed that merchantable material would be delivered to the 86 existing wood processing facilities in the study area. and unit haul costs for merchantable material were exogenously assigned for each plot as the average haul cost to the three facilities with the lowest haul cost. We combined results for all p-sites because we were concerned with how much and what kind of material might be removed and how much area could be treated under each policy scenario. not where the processing would take place.

We allocated materials to the highest-valued use by assuming that when all of the saw logs from a given tree size had net values of less than $US18/green ton ($US19.8/green metricton) at the mill gate. these trees would be processed as dirty chips rather than saw logs. The $US18/green ton ($US19.8/green metric ton) threshold was based on the price we assumed a power plant would pay. In reality these saw logs from small trees might end up as posts and poles or pulpwood which could have higher prices than dirty chips. but these options were not included in this version of the BioSum model.

3. Results

None of the silvicultural treatments were effective or the treatments were inappropriate for 4870 of the 6200 F1A plots within the study area excluding them from further analysis. That left 1230 plots representing about 4.1 million acres (1.7million ha) to be considered for treatment. The eligible area included both public and private ownerships and represented slightly more than 18% of the entire analysis area. Summary data for the area treated and total weight of woody material removed under each of the three scenarios are presented in Table 2. Considerable differences among the scenarios are evident even at this level of aggregation. For example. the Max TI scenario treated almost the entire eligible area. whereas the Min Merch scenario treated only a small fraction. Limiting the choice to the minimum merchantable treatment made the majority (85%) of the eligible area uneconomical in terms of treatment. Only the area where the minimum merchantable treatment still produced significant volume was selected. Even so. the Min Merch scenario still removed about 90% of the total weight of wood per unit area removed under the Max TI scenario and nearly three-quarters of the weight removed under the Max NR scenario. This suggests that regardless of the policy goal. removal of a similar amount of material is required to meet the effectiveness criteria.

Table 3
Total projected removals in millions of green tons per acre and proportion of saw logs (stems of trees >7.1 in. [18 cm] dbh), proportion of small trees (< 7.0 in. [17.8 cm] dbh) as a fraction of total removals, and dirty chips from small trees as a proportion by dbh of total dirty chips

Scenario	Saw log proportion	Dirty chips from small trees as a proportion of total removals	Dirty chips from small trees as a proportion of total dirty chips
Max NR	0.79	0.04	0.18
Max TI	0.74	0.05	0.21
Min Merch	0.67	0.04	0.12

Table 4
Weight in millions of green tons of dirty chips from small trees (< 7 in. [17.8 cm] dbh), tops, limbs, low-value commercial conifers (10 to 16 in. [25.4 to 40.6 cm] dbh, and noncommercial softwoods and hardwoods of all sizes (the "other" category) by species

Species group	Max NR	Max TI	Min Merch
Douglas-fir/western larch	12.7	16.8	1.4
Soft pines	2.4	5.2	0.6
Lodgepole	1.1	1.3	0.3
White woods	15.0	17.5	2.8
Other	29.7	44.4	10.4
Total	60.9	85.3	15.5

Results presented in Table 3 break down the data into general wood product categories (saw logs and dirty chips). Saw logs represent most of the weight of material removed. Even under the Min Merch scenario. saw logs account for about two thirds of the total. This implies that removal of substantial amounts of merchantable timber is necessary to accomplish our stand-scale fire-hazard-reduction goals given the nine silvicultural prescriptions the model had to choose from This is consistent with earlier simulations for Montana and New Mexico where treatments that remove only trees less than about 9in. (23cm) dbh are frequently ineffective at reducing stand-scale fire hazard and almost always have negative net revenues (Barbour er 011..20041>. Fight: et .il..)004). Strategies that allow removal of all tree sizes are more effective at reducing stand-scale fire hazard and producing revenue (liedkr <lnc! I(eegan. 2003; Fiedler ct ,11. 20()4).

Small trees (< 7in. [17.8cm] dbh) consistently represented only about 5% of the total weight of material removed. There were. however, differences among the three scenarios in terms of the relative contributions to the total dirty chip yield by small trees and other components of the dirty chip mix. The proportion of small trees in the dirty chip mix ranged from 12% for the Min Merch scenario to 21 % for the Max TI scenario (Table 3).

Dirty chip yields by species for each scenario are shown in Table 4. Hardwoods and noncommercial or low-value commercial conifers (the "Other" category in the table) contributed much more heavily to the dirty chip yield from the Min Merch scenario (about two-thirds of dirty chips) than they did for either of the other scenarios (Table 4). Under all three scenarios. hardwoods and noncommercial and low-value conifers also contributed the highest proportional weight to the dirty chip yield of any species group Table 4). In all cases. the bulk of dirty chips came from tops and limbs of commercial species larger than 7in. (17.8cm) dbh and whole trees of low-value commercial conifers (those with delivered values <$US18/green ton [$US19.8 green metric ton]) between 7 and 16in. (7.8 to 40.6cm) at breast height (table 5). As a consequence of this financial threshold. nearly two-thirds of the trees in the 7 to l0in. (17.8 to 25.4cm) dbh class and 10% of the trees in the 10 to 16in. (24.5 to 39.2cm) dbh class were processed in BioSum as dirty chips even though they had roundwood potential. Noncommercial species and logging slash from merchantable size conifers were also important sources of dirty chips under all three scenarios (Tables 4 and 5).

Results for merchantable timber yields (saw logs) are presented by diameter class in Table 6. Under all three scenarios, by far the largest

Table 5
Weight in millions of green tons of dirty chips from small trees (< 7 in. [17.8 cm] dbh), tops, limbs, low-value commercial conifers (10 to 16 in. [25.4 to 40.6 cm] dbh, and noncommercial species of all sizes by diameter group

Size class (in)	Max NR	Max TI	Min Merch
1.0–7.0	10.8	17.8	1.8
7.1–10.0	21.6	31.6	3.6
10.1–16.0	13.9	19.9	4.0
16.1–21.0	9.3	11.4	3.1
21.1+	5.3	4.6	3.0
Total	60.9	85.3	15.5

Table 6
Weight of saw logs in millions of green tons by tree breast height diameter in inches

Size class (in.)	Max NR	Max TI	Min Merch
1.0–7.0	0	0	0
7.1–10.0	0.9	1.0	0.08
10.1–16.0	56.7	64.4	11.1
16.1–21.0	53.2	57.1	8.0
21.1+	124.4	118.1	13.0
Total	235.2	240.6	32.1

contribution to total saw log removals came from trees in the 21+in. (53.3-cm) class. This diameter class represented 40, 49, and 53% of the total weight For the Min Merch, Max TI. Max NR scenarios. respectively, These trees do not contribute to the dirty chip yield because they are delimbed at the stump, so tops and branches are not collected.

The Douglas-fir/larch and white woods (spruce *[Picea* spp.]. true firs *[Abies* spp.]. and hemlock *[Tsuga* spp.]) species groups are by far the largest source of saw logs under all scenarios Table 7). On a proportional basis, the yields of saw logs by species are practically identical for the Max NR and Max TI scenarios, but the Min Merch scenario had proportionally less Douglas-fir/larch and more pines.

Summarizing yields as proportions by species group and diameter class makes it easy to compare the makeup of the saw log supply among scenarios (Fig. 2). The figure is constructed so that the bars in a scenario (across all species groups and diameter classes) sum to 1, Thus if the bars for a scenario under a single species group are summed and multiplied by the total saw log weight for that scenario from Table 7, the product is the value for that species group given in Table 7. A corresponding calculation can be made for the total saw log weight data given in Table 6. This normalized display makes it possible to assess the relative contribution of different diameters and species of trees to total saw log weight, and to understand differences in these relative contributions among scenarios. The presentation of the data in Fig. 2 demonstrates quite clearly that, on a proportional weight basis, the only major difference among the three scenarios is in the distribution of saw log diameter in the white wood species group. The key difference is that the Min Merch scenario removes the greatest weight of saw logs from the 10.1- to 16-in. (25.4- to 40.6-cm) dbh class. whereas the other two scenarios remove the greatest weight From the largest diameter class.

4. Discussion

Each of the three scenarios we evaluated was intended to represent a different way of looking at the physical, economic, and political drivers that constrain those who manage fire-hazard-reduction activities on public and private lands. Our intent was not to conduct a detailed policy analysis but rather to show how outputs differ with very different policy directions. Other than fire hazard and finances, we did not consider ecological or sociopolitical Factors in this analysis.

4.1. Overview of scenarios

The Max NR scenario (maximize net revenue; Table 1) reflects the point of view that fire-hazard-reduction treatments should not impose a burden on the general taxpayer (Hulsey and Ripley, 2006). Under this line of thinking. people who do not live near the forest should pay as little as possible to protect forest resources or the lives and property of people who choose to live in or near Forests. Removal of merchantable timber to pay for treatments is seen as a way to accomplish this goal. Removal of merchantable timber during fire-hazard-reduction treatments is also an extremely controversial subject in the Pacific Northwest (c.f.. Brown, 2000; Haines, 2004).[2] It is, therefore, important to recognize that analyses that estimate more than the absolute minimum amount of commercial timber removal necessary to accomplish the primary fire-hazard-reduction goal could themselves become controversial (Noss et al.. 2006). Using our techniques, more commercial timber was probably removed under the Max NR scenario than was absolutely necessary to reduce the fire hazard below our stated thresholds in individual stands. An alternative analytical technique (Skog et al., 2006) allows feedback during simulation of the treatment so that the model stops removing trees when the fire hazard goal is achieved. Such a technique probably would be more desirable to those who want to see as little commercial timber removed as possible when implementing fire-hazard-reduction treatments (Brown. 2000: Noss et al., 2006).

The Max TI scenario (maximize the improvement in torching index, Table 1) reflects the point of view that fire-hazard-reduction treatments should be as effective as possible (Franklin and Agee. 2003) and that torching index is the most important factor in preventing surface fires from becoming out-of-control crown fires. Under this scenario, removal of merchantable timber is not a factor. It is interesting that even though small trees, often referred to as ladder fuels, are seen as more important than larger trees in promoting torching (Peterson et al., 2005), about 75% of the weight of material removed under the Max TI scenario was saw logs (Table 3).

The Min Merch scenario (minimize the amount of merchantable timber removed during the treatments. Table 1) reflects the point of view that removal of commercial timber should be avoided whenever possible. By using net revenue to break ties between prescriptions with the same yield of saw logs and requiring that the entire enterprise maximize net revenue, this scenario rewards choices that result in less expensive solutions. It requires the enterprise to be economically efficient. People who ascribe to this type of policy might view commercial timber harvest as generally unnecessary or undesirable to accomplish adequate fire-hazard reduction (Aplet and Wilmer. 2003; Laband et al., 2006) or they might simply fail to see a strong connection between production of commercial timber and fire-hazard-reduction (Brown. 2000). Removal of the net revenue requirements would almost certainly lead to very different outcomes in terms of the silvicultural prescriptions selected by the model. Limiting the amount of hardwood removed would also greatly change the outcomes under this scenario Table 4).

The tactic of removing hardwoods to produce sufficient dirty chips to fire a power plant is likely to be problematic for two reasons. Hardwoods provide an element of biodiversity not offered by commercial conifer species and they are often left in stands to provide sufficient canopy closure to meet requirements for spotted owl (Strix *occidentals)* management on federally administered lands in California's Sierra Nevada Mountains (USD;\ FS, 2001). If hardwoods were removed in the quantities we project, it is also reasonable to assume they would be evaluated for higher value products (c.f., Lowell and Plank. 1996).

A person living within the area would undoubtedly notice a difference in the way forests were being managed under each scenario. For example, under the Max TI scenario. almost all of the eligible area (about 20% of the entire landscape) is treated but under the Min Merch scenario only about 15% of the eligible area, or about 3% of the entire landscape, is treated Table 2). If treatment programs like the Max NR

Table 7
Weight of saw logs in millions of green tons by species group

Species group	Max NR	Max TI	Min Merch
Douglas-fir/western larch	127.3	133.3	16.1
Soft pines	9.2	11.2	2.3
Lodgepole	3.0	2.7	0.8
White woods	95.7	93.4	12.8
Other	0	0	0
Total	235.2	240.6	32.1

[2] Haines, K., 2004. Ninemile fuels reduction scoping comments. Letter to Kevin Moore, Ninemile Interdisciplinary Team Leader Chiloquin Ranger District, Freemont-Winema National Forest, Chiloquin, OR. Klamath Forest Alliance, Somes Bar, CA.

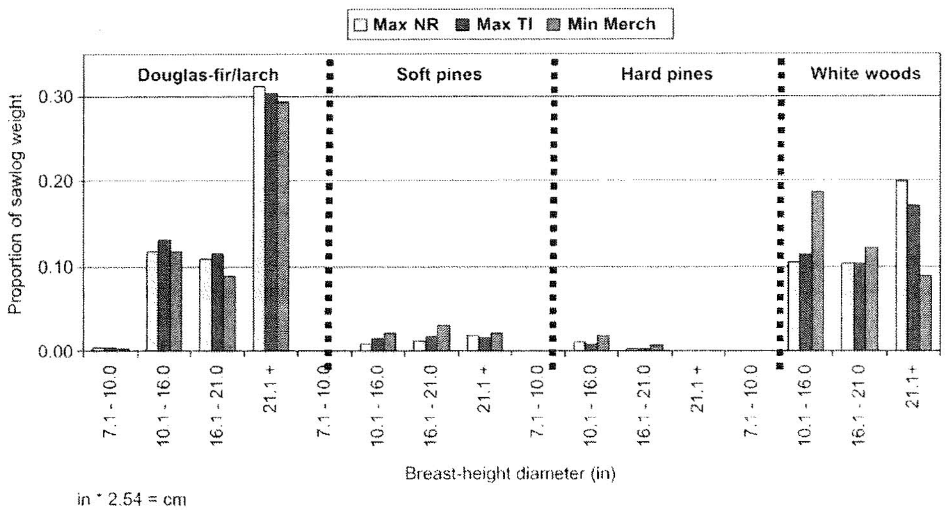

Fig. 2. Proportional weight of saw logs removed for each scenario displayed by species group and breast-height diameter class. Weights of saw logs in each diameter class and species group were normalized based on the total weight of saw logs.

or Max TI scenarios were implemented. they would greatly change the character of the forests over much of this region. Under the Min Merch scenario. management activities would be far less noticeable. but many of the hardwood-dominated stands would be altered. Although it is not our intent to dissect the silvicultural data here. these results suggest that residual stands and the general landscape would look very different under each of the three scenarios. Given these clear differences. it is surprising how similar the species and size distributions of trees removed from each of the scenarios are. Recognition of this similarity is perhaps our most important finding.

The average yields per unit area were quite high under all three scenarios (Table 2.). In places where USDA Forest Service managers want to use wood removals to help pay for fire-hazard-reduction treatments. they typically hope to remove between 10 and 20green tons (9.1 to 18.2metric tons per ha.) of saw logs per acre plus perhaps a quarter of that weight in dirty chips. In this context. it is worth recalling that the silvicultural prescriptions simulated in this analysis were designed by federal. state. and private forest management staff specialists to create ecologically desirable residual stand conditions and greater resilience to fire. They did not include a requirement to remove a specified amount of either merchantable or total woody material. The high average per-acre wood yields reported in Table 2 suggest that many of the FIA plots included in this analysis are currently carrying much greater density than is considered desirable by land managers.

4.2. Characteristics of wood removed

When compared on the basis of the proportion of the total saw log weight there is very little difference among the saw logs recovered from the three scenarios (Fig. 2). This suggests that similarities among existing stand conditions could be as important as policy goals in determining the mix of saw logs. The tendency of the model to select stands with large potential hardwood removals under the Min Merch scenario suggests that there are opportunities to alter the mix of species in the dirty chip mix. This is. however, probably more important in terms of the species composition of the residual stands than any wood processing consideration.

4.3. Sources of dirty chips

Reporting information on dirty chips as a composite for all diameter classes and species is probably sufficient to provide potential manufacturers with the information they need to understand the raw material, because if electrical generation is the goal, total weight, not species or size, is the important driver. Some species will probably generate more ash or cause more corrosion of processing equipment, bur those issues are beyond the scope of this type of analysis. The fact that most of the dirty chips come from tops and limbs of merchantable trees or whole trees of noncommercial species was, however, not really what we expected when we began the study. This result is interesting because the USDAForest Service and other federal and state agencies have placed considerable emphasis on finding uses for stems of small trees (I.!\L)/\ i\ :WOD;We,tem C(IV(,rno(s A,socidtillli. 2002; USD/>, 1\, 2ilt h; I !SUE_Ind USDA, ;>.0(5). To support this effort, the U.S.Congress appropriated $USS million per year for technology grants administered by the US Forest Service to find new uses for or to develop manufacturing technologies for the noncommercial materials (referred to as biomass in much ILS. legislation and in the vernacular of forest managers who work on fire hazard related issues) removed during fire-hazard-reduction treatments (Federal Register. 20(5). Information on the characteristics of that material could become important in guiding the distribution of those funds. The results of our analysis suggest that given the assumptions used here, disposal oflimbs and foliage from trees larger than 1Oin. (2S.4cm) dbh, and perhaps whole trees from noncommercial species. will also constitute a major need in terms of utilization of currently nonmerchantable materials. Disposing of this material presents quite a different processing problem than finding uses for the stems of small trees. Our analysis did suggest. for example. that given current market conditions commercial operators would chip a substantial proportion of commercial conifer trees in the 7- to 16-in. (17.8- to 40.6-cm) diameter class rather than haul them to a sawmill for processing at a loss. Research that could result in higher value uses for these trees or reduced costs for their removal and transportation could shift 5 to 7%of the total weight from dirty chips to saw logs.

4.4. Saw logs

The vast majority of saw logs comes from trees in the Douglas-fir/larch and white woods species groups that are greater than 10in. (25.4cm) dbh. Almost no lodgepole pine (Pinus *contorta)* or soft pines (ponderosa [P.*ponderosa*]. Jeffery [P.*jeffreyi],* white [P.*monticola*]. and sugar pine [P. *lambertiana])* are removed (Table 7). The similarity of the mix of size and species of saw logs among the three scenarios was an unexpected outcome. We chose these scenarios because they represent a reasonable range of policy options that might be followed in addressing the broad-scale fire hazard situation in the analysis area. We assumed that these different approaches would result in different mixes of species and sizes of trees removed, but this was really not the case. This suggests that no matter what policy goal was selected, a similar mix of species would be removed and a similar distribution of saw log sizes would result unless a diameter limit was imposed. In that case, the distribution would be truncated at some upper limit, which would change the proportions of the remaining log sizes. Even in that case, it is probably safe to assume that the distribution would be skewed toward the largest possible log sizes, given the imposed diameter limit and that most of the saw logs would be either Douglas-fir/larch or white woods. What we cannot tell from the current analysis is whether removing all constraints on positive net revenue and imposing a diameter limit could result in effective treatment of a large part of the landscape at higher costs or whether treatments that do not remove high proportions of large trees are simply ineffective.

4.5. Other considerations

Trees that exceeded 21 in. (53.3cm) dbh were modeled as having their tops and limbs removed at the stump. All of the scenarios removed substantial numbers of larger trees (> 21 in.; 53.3cm), and the contribution of their tops and limbs to the post-treatment surface fuel load could be important. Surface fuels are created when small trees or the tops and limbs of larger trees are cut and left on the site. Reducing these "activity fuels" requires their removal from the site or their treatment in place either by grinding or prescribed fire (Peterson et al., 2005). We did not evaluate the difference in costs associated with treating these activity fuels in place.

Another important question raised by our analysis is whether fire-hazard-reduction programs that concentrate on only small trees will accomplish their goals. In many situations, federal forest managers in the Western United States face political pressure to set diameter limits of 9 to 16in. (20.9 to 40.6cm) dbh (for example, American Lands Alliance, 2002; Haines, 2004 [see footnote 1]). Altering our analysis to include such a diameter limit could substantially change the mix of species and sources (small trees or tops and limbs) of material reported in Tables 4 and 5. Maintaining the effectiveness requirement if such limits were imposed would certainly reduce the total area treated, and consequently, amount and type of material recovered. Analyses that evaluate the effectiveness of treatments, such as the one conducted here, suggest that when these types of restrictions are imposed, the area where treatments are effective drops considerably (Barbour et al., 2004b; Fight et al.. 2004; Skog et al., 2006).

If any of the scenarios we modeled were implemented as we designed them, they would contribute a substantial volume of saw logs to existing markets, and this would probably have a noticeable effect on those markets. Private landowners currently supply most of the commercial timber within the analysis area. The Max NR and Max TI scenarios each produce more than a quarter of a billion green tons (about 200million green metric tons) of saw logs, so even if this were spread over 10 or 20years it would still constitute a substantial addition to the region's commercial timber supply. Abt and Prestemon (2006) have suggested that such additions to timber supply would depress prices at least in the short term, and it is conceivable that they could cause the removal of marginal private land from timber production. This could raise political opposition by private landowners to treatments on federally administered land.

5. Conclusions

Our analysis demonstrates the potential of the FIA BioSum model as a strategic planning tool that incorporates objective measures of the effectiveness of stand-scale fire-hazard-reduction with financial aspects of siting and supplying wood products manufacturing plants. Our results for northern California, southwestern Oregon, and the Oregon east Cascades provide a useful foundation for discussions about how this tool could be used in an actual planning process. Under the policy scenarios we examined, this analysis suggests that removal of considerable amounts of commercial size trees is needed to accomplish fire-hazard-reduction goals when objectives are centered on either maximizing net revenue or maximizing treatment effectiveness based on reduction in torching hazard. Even when the objective was to minimize merchantable volume, about two-thirds of the removed weight was in saw logs.

Tops and limbs from merchantable commercial conifers and whole trees of hardwoods and noncommercial conifers were major sources of dirty chips. Opportunities to exploit higher value alternatives to electrical power generation are limited for this type of material. Our financial assumptions also caused a substantial portion of the commercial conifers less than 16in. (40.6cm) dbh to be chipped rather than processed as roundwood. Finding higher value options for these materials shifts 5% or more of the total recovered weight from dirty chips to roundwood.

Substantial differences were found in the total area treated under each scenario, but even so, the types of material removed were not very different. The main differences were seen in the Min Merch scenario. A higher proportion of saw logs from midsize (10- to 16-in, [25.4- to 40.6-cm] diameter trees were removed in comparison to the other two scenarios where larger trees represented a larger proportion of the weight. The Min Merch scenario also removed a much higher proportion of hardwoods and noncommercial conifers, which were converted to dirty chips.

A similar mix of processing capability would probably be required to handle the commercial and noncommercial material removed under any of the three scenarios. The size of the commercial timber operation each scenario could support would however, be, quite different. The total removals from the Min Merch scenario are only about 15% of those from the Max TI scenario which are about 110% of those from the Max NR scenario. This suggests that sizing the industry to fit the potential long-term removals is an important aspect of implementing any broad-scale fire-hazard-reduction program.

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References

Abt, K.l., Prestemon, J.P., 2006. Timber markets and fuel treatments in the Western U.S. Natural Resource Modeling 19. 15-43.

American Lands Alliance. 2002. Fire and fuel reduction on national forest lands in Colorado: recommendations for the future. American Lands Alliance and others, Washington, DC.

Anderson. H.E.. 1982. Aids to Determining fuel Models for Estimating Fire Behavior. Gen. Tech. Rep. INT-l22. Ll.S, Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station, Ogden. UT. www.fs.fed.us/rm/pubs_int/mt_gtrl22.pdf. (September 2007).

Aplet, G.H., Wilmer, B., 2003. The Wildland Fire Challenge: Focus on Reliable Data. Community Protection, and Ecological Restoration. The Wilderness Society, Washington, DC.

Barbour, R.j., Ager, A.A.. Hayes, J.L., 2004a. A framework for the development and application of INLAS: the Interior Northwest Landscape Analysis System. In: Hayes, j.L., Ager, A.. Barbour, R.J. (Eds.), Methods for Integrated Modeling of Landscape Change: Interior Nowthwest Landscape Analysis System. Gen. Tech. Rep. PNW-GTR-610. U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, OR, pp. 1-16.

Barbour, R.J.. Fight. R.D.. Christensen. G.A., Pinjuv. G.L.. Nagubadi, R.v.. 2004b. Thinning and Prescribed fire and Projected Trends in Wood Product Potential. Financial Return, and Fire Hazard in Montana. Gen. Tech. Rep. PNW-GTR-606. U.s. Department of Agriculture Forest Service Pacific Northwest Research Station, Portland, OR.

Barbour, R.J.. Hemstrom, M.A.. Ager, A.. Hayes. J.L. 2005. Effects of spatial scale on the perception and assessment of risk of natural disturbance in forested ecosystems: examples from northeastern Oregon. Forest Ecology and Management 211, 210-225.

Barbour, R.J. Hemstrom, M.A.,Ager. A., Hayes, j.L, 2007. The Interior Northwest Landscape Analysis System: a step toward understanding integrated landscape analysis. Landscape and Urban Planning 80 (3), 333-334.

Bonnicksen. T.M. Stone, E,p. 1982, Reconstruction of a presettlernent giant sequoia-mixed conifer forest community using the aggregation approach, Ecology 63, 1134-1148,
Brown, K, 2000, Thinning, fire and forest restoration: a science-based approach for national forests in the interior northwest. Defenders of Wildlife, Washington, DC.
Chang, C, 1996, Ecosystem responses to fire and variations in fire regimes, Sierra Nevada Ecosystem Project: Final Report to Congress, Vol. II Assessments and Scientific Basis for Management Options, Wildland Resources Center Report No, 37, Centers for Water and Wildland Resources, University of California, Davis, pp, 1071-1099,
Covington, W.W. Fule, P.L, Moore, M.M. Hart, S,c., Kolb, T.E. Mast, J,N. Sackett, S,S. Wagner, M,R. 1997, Restoring ecosystem health in ponderosa pine forests of the Southwest. journal of forestry 95 (4), 23-29.
Daugherty, P,j., Fried.j.S, 2007. jointly optimizing selection of fuel treatrnents and siting of forest biomass-based energy production facilities for landscape-scale fire-hazard-reduction. Information Systems and Operational Research 45 (1),353-372.
Dixon, G.E. 2002. , (Comp.) Essential fVS: A User's Guide to the Forest Vegetation Simulator. Internal Rep.U.S. Department of Agriculture, Forest Service, Forest Management Service Center, Fort Collins, CO.
Dombeck, M.P. Williarns J. Wood, C.A. 2004. Wildfire policy and public lands: integrating scientific understanding with social concerns across landscapes. Conservation Biology 18 (4), 883,
Federal Register, 2005. Request for proposals for woody biomass utilization grant-hazardous fuel reduction on national forest system lands, Federal Register 70 (189), 57250-57252.
Fight, R.D., Barbour, R.J., Christensen, G.A, Pinjuv, G.L., Nagubadi, K.V. 2004. Thinning and Prescribed Fire and Projected Trends in Wood Product Potential. Financial Return, and Fire Hazard in New Mexico. Gen. Tech. Rep. PNW-GTR-605. US Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, OR.
Fight, R.D., Hartsough, B.R., Noordijk, P.,2006, Users Guide for FRCS: Fuel Reduction Cost Simulator Software, Gen. Tech. Rep. PNW-GTR-668. U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, OR.
Fiedler, c.E.. Keegan, C.E., 2003. Treatment effectiveness in reducing crown fire hazard in fire-adapted forests of New Mexico. In: Omi, P.N.. joyce, LA, (Eds.), Fire, Fuel Treatments, and Ecological Restoration: Conference Proceedings, Proc. RMRS-P-29, US. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fort Collins, CO, pp. 39-48,
Fiedler, C.E., Keegan, C.E., Woodall, C.W., Morgan, 'LA .. 2004, A Strategic Assessment of Crown Fire Hazard in Montana: Potential Effectiveness and Costs of Hazard Reduction Treatments. Gen. Tech, Rep, PNW-GTR-622. U,S, Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, OR.
Finney, M,A., 2003. Calculation of fire spread rates across random landscapes. International journal of Wildland Fire 12 (2),167-174,
Finney, M.A. 2005. The challenge of quantitative risk analysis for wildland fire. Forest Ecology and Management 211 (1/2),97-108.
Franklin, j.F .. Agee, j.K .. 2003. Forging a science-based national forest lire policy, Issues in Science and Technology 20 (1), 59-66.
Fried, j.S., Christensen, G.. Weyermann, D., Barbour, K.j .. Fight, K, Hiserote, B., Pinjuv, G.. 2005. Modeling opportunities and feasibility of siting wood-fired electrical generating facilities to facilitate landscape-scale fuel treatment with FIA BioSum (Comps.) In: Bevers, M .. Barrett, TM, (Eds.), Systems Analysis in Forest Resources. Cen, Tech. Rep, PNW-GTR-656. U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, OR. pp. 195-204.
Fule, P,Z., Covington, W.W., Moore, M.M .. 1997. Determining reference conditions for ecosystem management of southwestern ponderosa pine forests, Ecological Applications 7 (3), 895-908.
Hann, W,j., jones, j.L. Karl. M.G .. Hessburg, P.F, Keane, RL Long, D.G., Menakis, j.p .. McNicoll, C.H. Leonard, S.G., Gravenmier, R.A.. Smith, B,G. 1997. Landscape dynamics of the basin, In: Quigley, T.M., Arbelbide, S.j. (Eds.), An Assessment of Ecosystem Components in the Interior Columbia Basin and Portions of the Klamath and Great Basins .. Gen. Tech, Rep, PNW-GTR-405, vol. 2. U.s. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, OR, pp, 337-1055.
Hiserote, B., Wadell, IC, 2005. IDB, a database of forest inventory for California, Oregon, and Washington. USDA Forest Service, Pacific Northwest Research Station, Forest Inventory and Analysis Program. Portland, Oregon, USA.
Hulsey, j., Ripley, K. 2006. Forest Health and Wildfires-a Net Cost Approach to a True Wildfire Protection Program, Washington State Department of Natural Resources, Olympia, WA,
Laband, D.N. Gonzalez-Caban, A .. Hussain, A. 2006. Factors that influence administrative appeals of proposed USDA Forest Service fuels reduction actions. Forest Science 52 (5), 477-488,
Lowell, E.C., Plank, M.E .. 1996, California black oak-from firewood to lumber, 'the lumber recovery story, In: Pillsbury, N,H. Verned, j. Tietje, W.o, (Eds.). Proceedings of a Symposium on Oak Woodlands: Ecology, Management, and Urban Interface Issues, Cen. Tech. Rep, PSW-GTR-160. U.S, Department of Agriculture, Forest Service, Pacific Northwest Research Station, Albany, CA, pp. 457 -464,
Means, J,E., Hansen. H.A. Koerper. G.j., Alaback. P.B.. Klopsch, M.W., 1994, Sottware for Computing Plant Biomass-BIOPAK Users Guide. Cen. Tech. Rep. PNW-GTR-340. U.S. Department of Agriculture, Forest Service. Pacific Northwest Researrch Station, Portland, OR,
Noss, R.F.. Beier,P. Covington, WW. Grumbine, R.E.. Lindenmayer, D.B., Prather, J.W .. Schmiegelow, F., Sisk, T.D. Vosick, D. J. 2006. Recommendations for integrating **restoration ecology and conservation biology in ponderosa pine forests of the** Southwestern United States. Restoration Ecology 14 (1),4-10.
Parker, A,j. 1984. A comparison of structural properties and compositional trends in **conifer forests of Yosemite and Glacier National Parks, USA. Northwest Science 58,** 131-141.
Parsons, DJ, Debenedetti, S.H .. 1979. Impact of fire suppression on a mixed-conifer forest. Forest Ecology and Management 2, 21-33.
Peterson, D.L, johnson, M.C., Agee, J,K. jain,T.B. Mckenzie. D.. Reinhardt, ED., 2005. **forest Structure and Fire Hazard in Dry Forests of the Western United Stares. Gen.** Tech. Rep. PNW-CrR-628. U.s. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, OK.
Prestemon, S.. Abt, j.P.. Huggett Jr, RJ .. 2008. Markel Impacts of a Multiyear Mechanical Fuel Treatment Program in the u.S. Forestry Policy and Economics III, 386-399 (rhis **volume).** doi: 10.1016/j.forpol.2008.01.004.
Reinhardt, E.D.. Crookston. N.L.. 2003. The Fire and Fuels Extension In the forest Vegetation Simulator. Gen. Tech, Rep, RMRS-GTR-116. t.I.S. Department of Agriculture, Forest Service, Rocky Mountain Kesearch Station, Fort Collins, CO,
Scott, J.H. Reinhardt, E.D.. 2001. Assessing Crown Fire Potential by Linking Models of Surface and Crown Fire Behavior. Res. Pap. RMRS-RP-29, U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fort Collins, CO,
Skog, K.E.. Barbour, R.j., Abt,K.L. Bilek, E.M .. Burch, F. Fight R.D.. Hugget, R.J., Miles, P.D. Reinhardt, E.D" Shepperd, WD" 2006. Evaluation of Silvicultural Treatments and Biomass Use for Reducing Fire Hazard in Western States. Research Paper FPL-RP-634.U.S. Department of Agriculture, Forest Service, Forest Products Laboratory, Madison, WI.
U.S. Department of Agriculture, Forest Service [USDA FS]. Forest Products Laboratory, **2000. Forest Products** Laboratory kesearch **Program 0n Small-Diameter** Material, Cen, Tech. Rep. FPL-GTK-110. U.S. Department of Agriculture, Forest Products Laboratory, Madison, WI.
U.s. Department of Agriculture, Forest Service. [USDA FS] 2001. Sierra Nevada Forest **Plan Amendment Record of Decision.** Pacific Southwest **Region. Sacramento, CA.**
US. Department of Agriculture, Forest Service, [USDA FS]. 2005. A Strategic Assessment **of Forest Biomass and Fuel Reduction** Treatments **in Western** States.GenTech. **Rep.** RMRS-GTR-149, Rocky Mountain Research Station, Fort Collins, CO.
U.S, Department of Energy and U.S. Department of Agriculture [US DE andUSDA]. 2005, Biomass as a Feedstock for a Bioenergy and Bioproducts Industry: The Technical Feasibility of a Billion Ton Annual Supply. Washington, DC.
Western Governors' Association, 2002. A collaborative approach for reducing wildland **fire risks to communities and the environment: IO-year comprehensive strategy implementation plan. , Western Governors' Association** http://www.westgov.org/wga/initiatives/fire/final_fire_rpt.pdt, **(1 November 2005).**
Wykoff, W,R., Crookston, N.L, Stage, A,R .. 1982. User's Guide to the Stand Prognosis Model. Gen. Tech, Rep, INT-133, U,S. Department of Agriculture, Forest Service, **Intermountain Forest and Range Experiment** Station. **Ogden, UT.**