MODELING OPPORTUNITIES AND FEASIBILITY OF SITING WOOD-FIRED ELECTRICAL GENERATING FACILITIES TO FACILITATE LANDSCAPE-SCALE FUEL TREATMENT WITH FIA BIOSUM

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ABSTRACT

Utilization of small diameter trees is viewed by many as the key to making landscape-scale fuel treatment financially feasible. But little capacity currently exists for utilizing such material and capacity of sufficient scale to have a significant impact on the economics of small diameter removals will only be added if predictable feedstocks can be assured. The FIA BioSum modeling framework that incorporates Forest Inventory and Analysis (FIA) plot data, a transportation cost model, a treatment cost accounting module, a log valuation model, and a crown fire hazard evaluator was applied to a 28 million acre study area containing 6200 FIA plots spanning the Eastern Cascades, Southern Cascades, Klamath Mountains and Modoc Plateau ecosections of western Oregon and northern California. Up to nine fuel treatment prescriptions with a high likelihood of producing a substantial reduction in crown fire hazard were simulated for each plot, and 221 potential biomass processing sites were considered. With four 50 MW biomass-fueled power plants strategically distributed over the study area, up to 5.3 million acres could be effectively treated with net revenue of 2.6 billion dollars, a merchantable yield of 9.5 billion cubic feet, and a biomass yield of 79 million green tons, if net-revenue maximizing fuel treatments are selected. If merchantable volume minimizing treatments are selected instead for these 5.3 million acres, net revenue would be negative 2.6 billion dollars, merchantable yield would be 3.6 billion cubic feet and biomass yield would be 75 million green tons. With the constraint that every acre generate positive net revenue, only 2.6 million acres would be treated, even if the net revenue maximizing treatment is selected.

INTRODUCTION

As large, stand-replacing fires have become common over the past few years in the western United States, interest in assessing the potential for landscape-scale fuel treatment has intensified. Doubts have grown about the feasibility and/or wisdom of widespread use of prescribed fire due to concerns about air quality, liability, narrow windows of opportunity to implement treatments, and potentially undesirable fire effects. Fuel treatment has for most forestry professionals and most of the public come to be virtually synonymous with mechanical removal or thinning of the forests to reduce fire severity and the likelihood of stand-replacing fire, especially since the advent and passage of the Healthy Forest Restoration Act of 2003.

The conventional wisdom has been that in order to be effective, such treatments would require the removal of large numbers of small stems, at considerable cost, but that this harvested material would have little or no value. In part to address this concern, but also with an eye towards promoting renewable energy options and increasing employment opportunities in rural forests, proposals have been and continue to be floated in many parts of
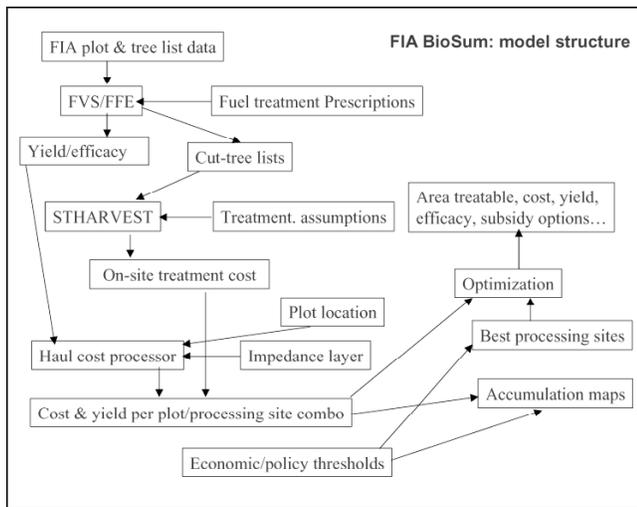
Figure 1—Flow diagram of the FIA BioSum modeling framework.

the U.S. to develop markets for submerchantable-sized trees by promoting the construction of biomass processing facilities of various capacities that would convert biomass to electrical energy via direct combustion or through various intermediate pathways (for example, gasification). However, such facilities require a sizable, up-front investment—one that is unlikely to be made by the private sector without some confidence that there will be an adequate source of supply over a long enough period for the investment to generate a positive financial return.

Fire and forest planners and managers, rural community economic development staff, and potential investors in biomass processing capacity believe they could benefit from knowledge of where the "hot spots" of potential biomass supply are to be found and the kinds of materials, both sub-merchantable and merchantable, that could be reasonably expected to flow from landscape-scale fuel treatments. This analysis was undertaken to identify such hot spots, but has evolved, thanks to wide-ranging discussions with diverse clients, to encompass a great deal more—including comparison of a number of fuel treatment prescriptions, assessment of the economic feasibility of fuel treatments with a complete accounting of harvest and haul costs, and a model-based characterization the fire risk reduction accomplishment of such a fuel treatment program. Questions we sought to address progressed from "how much biomass is out there" and "where is the best place to site a biomass processing facility" to "how much biomass is legally and economically accessible", "how much will treatments cost", and "will a subsidy help".

We constructed a geographically explicit analytic framework for assessing and summarizing biomass production opportunities, dubbed FIA BioSum (fig. 1). We used publicly available, field-collected forest inventory plot data, publicly available road and ownership GIS layers, a suite of publicly available models, and sets of assumptions, parameters and decision rules developed in consultation with local fire, fuels, silviculture, and logging experts as well as biomass plant operators to address the feasibility issue for a 28 million acre, 4 ecosection study area in Oregon and California. These ecosections (Klamath, Modoc Plateau, southern Cascades, and eastern Cascades) were selected because current fire regime condition class maps of the U.S. show much of the area in these ecosections as in condition class 3—lands that have significantly altered vegetation composition, diversity, and structure due to altered fire return intervals so that they verge on the greatest risk of ecological collapse due to loss of key ecosystem components from fire and are thus likely to receive high priority for fuel treatment (USDA, USDI 2002).

METHODS

Forest inventory data for this analysis were drawn from six inventories undertaken at various times during the 1990s by the USDA Forest Service PNW Research Station's Forest Inventory and Analysis Program, USDA Forest Service Region 5, USDA Forest Service Region 6, and the Bureau of Land Management. While there were numerous design differences among these inventories, each was a statistically representative sample of a portion of the total landscape and included measurements of tree attributes such as diameter, height and species with this information compiled to produce plot level estimates of volume, biomass, basal area and density, for example. A total of 6200 field plots representing 22.2 million acres of forested land fell within the study area boundary. This plot set was culled to remove from further analysis plots that were evaluated in the field as non-forest or located in designated wilderness, natural areas, parks, preserves, monuments, national recreation areas, national wildlife refuges, and inventoried roadless areas that had been under consideration for possible protection in the 1990s. We also omitted plots on steep (> 40 percent) slopes that were more than 2000 feet from the nearest mapped road on the grounds that current skyline harvesting systems cannot economically reach beyond this limit, and the cost of building new roads to bring such equipment closer to the plot would likely be prohibitive and is in any case beyond the scope of this analysis. Finally, we omitted plots containing no trees over 5 inches d.b.h.. Due to unforeseen data management problems, the 20 percent of the plots that contained

Table 1—Fuel treatment prescriptions applied in a test of the FIA BioSum analytic framework.

Prescription	Density reduction					Fuel reduction			
	A	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**J**
Target residual basal area ft^2	125	125	90	90	90	80	60	60	60
Maximum d.b.h. (in.) allowed for harvested trees	21	none	21	16	none	21	21	none	10

more than one condition (in other words, the plot contained road or non-forest land in addition to forest or contained more than one type, size or density of forest) could not be processed in time for this analysis, so the results presented here cannot be considered comprehensive over all lands and surely underestimate costs, revenues, area treated and product flows by an unknown amount if considering the entire landscape; still, these results do apply to the 80 percent of the landscape represented by single condition plots. The net result of all these reductions is a set of plots that represents about 10.4 million acres of forest land—8.2 million acres of this federally administered and 2.2 million acres privately owned. We did not account for special use areas with harvesting restrictions such as riparian buffers or late succesional reserves designated under the Northwest Forest Plan. Nor did we include restrictions such as those found in the Healthy Forest Restoration Act of 2003 that attempt to focus treatments within a fixed distance of communities. Either of these types of management restrictions could be accounted for in future analyses if they are accurately mapped.

The plots used in the analysis were loaded into the Forest Vegetation Simulator (FVS) (Stage 1973; Wykoff and others 1982) to simulate fuel treatment prescriptions and, via its Fire and Fuels Extension (FFE) (Reinhardt and Crookston 2003), the likely change in fire hazard these treatments would produce. The two FVS variants applicable to this study area, South-central Oregon and Northeastern California (SORNEC) and East Cascades (EC), were used for modeling and their FFEs were used to derive several fire-related stand attributes and ultimately compute indices of crown fire potential for each plot, specifically, torching index (TI) and crowning index (CI). TI represents the wind speed at which fire could be expected to move from surface fuels into crown fuels and is highly influenced by vertical stand structure (ladder fuels) and height to crown base (derived from crown ratio); CI is the wind speed at which a crown fire could be expected to be sustained and is heavily influenced by crown bulk density. For the purposes of this study, increases in CI or TI brought about by fuels treatment were assumed to reduce fire hazard.

Nine fuel treatment prescriptions representing two treatment approaches were developed in consultation with fire and fuels specialists and applied to all plots for which they were valid (table 1). For example, a prescription calling for a post-treatment residual basal area of 125 ft^2/ac could not be applied to a plot containing only 80 ft^2/ac. Five of the treatments were designed for density reduction (personal communication with John Gerritsma on 3 May 2002), with a primary focus of reducing the propagation of a crown fire, and involved thinning proportionately across all diameter classes to a target residual basal area, with the proviso that 70 percent of the basal area cut be from trees that are 5.5-14.5" d.b.h. with the remainder from trees >14.5 inches. The other three were designed as ladder fuels reduction treatments (personal communication with John Szymoniak, 6 May 2002), with a primary focus of reducing the initiation of crown fire, that thinned from below (>5.5" d.b.h.) to a residual basal area target. The treatments had a range of residual basal area targets (60-125 ft^2/ac) and maximum acceptable diameter for cut trees (10" to no limit). For both kinds of treatments, but mainly for ladder fuels reduction, if the maximum diameter limit was reached before the residual basal area target, then the latter was not achieved. For all prescriptions and on all plots, trees less than 3.5" d.b.h. were cut into pieces and scattered, and trees 3.5-5.5" were cut and scattered on steep slopes (>40 percent) and harvested and collected to the landing as biomass on gentle slopes. Because the most aggressive treatment had a residual basal area of 60 ft^2/ac, plots with less basal area were excluded, leaving 6.9 million acres represented in the analysis.

These prescriptions were applied in FVS-generated "cut lists" for each plot and, with post-processing via various program scripts, numerous plot and tree attributes used at later stages in the analysis (for example, slope, number of stems harvested, average stem size harvested, and volume and biomass by species and size class) were computed and stored. Post-treatment estimates of TI and CI were computed with FFE for each prescription for each plot.

Data extracted from the FVS output was processed with STHARVEST (Fight and others 2003), a spreadsheet model composed of regressions and look-up tables for logging cost components derived from empirical data on small timber sales. STHARVEST requires specification of assumptions regarding logging system (for example, whole tree, cut-to-length, cable), range of tree diameters to be included, volume per acre, and disposition of residue. Miscellaneous costs (for example, "brush-cutting", waterbars) were also accounted for. Whole tree logging systems were assumed for slopes ≤40 percent except for trees too large to be handled without bucking; cable systems were used on slopes >40 percent, with manual felling, bucking and limbing in the woods (in other words, limbs and tops not recovered for biomass utilization). For each plot and prescription, STHARVEST provided an estimated on-site cost of implementing the prescription (in other words, from stump to truck). Harvested material was allocated to one of two categories: Merchantable, which consisted of boles of trees >7.0" d.b.h. to a 5" diameter top, and Biomass, which consisted of trees brought to the landing that were 3.5 – 7.0" d.b.h., the limbs and tops of merchantable trees, and all harvested hardwoods. Delivered biomass was valued at $18 per green ton, the going rate circa 2003 in places like northern California where multiple biomass facilities compete for material, and merchantable material values were assigned from a look-up table based on species group and tree diameter. Plot-treatment combinations that generated less than 300 ft^3/ac of total volume (biomass and merchantable combined) were deemed unrealistic and discarded; for some plots, no treatment cleared this hurdle and these plots were excluded, leaving a set of plots representing 5.7 million acres amenable to one or more of the fuel treatment prescriptions.

Because this analysis targets fuel treatments that reduce the risk of stand-replacement fire, only treatments that are effective in achieving this goal are included. Reaching a consensus among fire and fuel managers on which crown fire potential index is most critical and on how much an index must change for the effect to be significant proved elusive. Consequently, we developed, as a working criterion to demonstrate FIA BioSum's analytic potential, an arbitrary, minimum threshold of fuel treatment effectiveness: a 20 mph improvement (increase) in either TI or CI with no reduction in the other. Treatments that fell short of this threshold were deemed ineffective and discarded; this resulted in some plots being untreatable and reduced the area in the analysis to 5.4 million acres.

Because the problems we tackled are strongly associated with location (where can treatment be feasibly applied, where to site biomass processing facilities) and our plans to eventually integrate this analysis with maps of the wildland urban interface, we chose to pursue a spatially explicit analytical framework that would account for differences in haul costs and identify locations with a sufficient potential accumulation of biomass to justify investment in a processing facility. An approximately 20x20 km grid of 221 potential processing sites (psites) was established over the study area, approximate in the sense that we relocated psites that fell on public lands. GIS road layers obtained from BLM, USDA Forest Service Region 5, USGS and others were combined, edge-matched, cleaned of gross anomalies and massaged to produce a study area-wide, topologically imperfect vector GIS road coverage with each road segment attributed as to likely rated speed. This road coverage was then tessellated into 250 m grid cells, with each cell's value set to the cost per ton-mile of traversing the cell on the fastest (lowest cost of transit) road in that cell, resulting in an impedance surface that formed the basis of haul cost calculations for FIA BioSum. Cells containing no roads were assigned infinite cost of transit, and plots occurring in such cells were "moved" to the nearest road for purposes of haul cost calculation, retaining the distance moved as an input to the yarding cost calculations used by STHARVEST. For each psite, a cost accumulation grid was generated in Arc/Info, and overlaid on the plot grid to provide haul cost in dollars per ton to that psite from every plot in the study area. The haul costs were combined with the outputs from FVS, FFE, and STHARVEST to create a database that stored the biomass and merchantable yields, harvest and haul costs, gross and net revenues, and change in TI and CI associated with every combination of plot, psite and prescription.

To test the simulation framework and develop preliminary estimates of biomass processing opportunities for this broad region, we evaluated seven fuel treatment policy scenarios under the assumption of the construction of 4 biomass processing facilities capable of generating 50MW each. The locations were selected from among the sites with the best accumulation potential – of biomass, merchantable volume, net revenue, and acres treated—with the additional requirement that they be geographically separated (in other
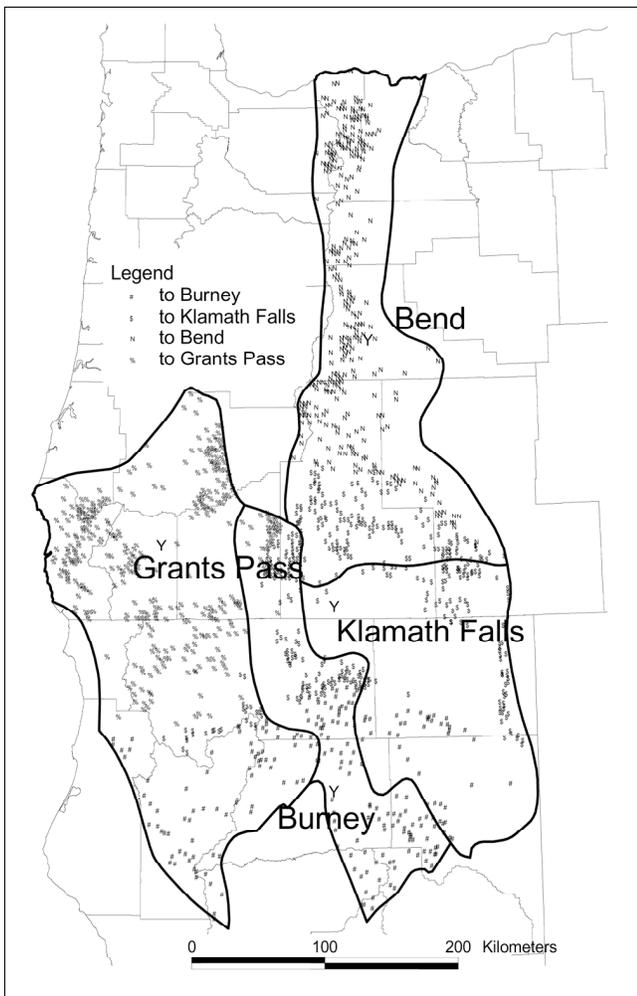
Figure 2—The Oregon-California study area with ecosections, accessible plots and the four potential processing sites considered in this analysis.
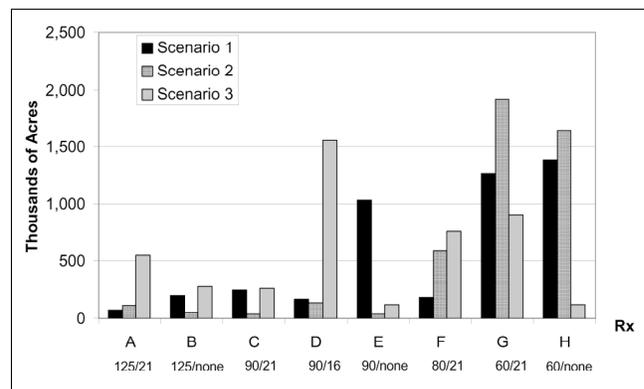

Figure 3—Number of acres for which each fuel treatment prescription was selected; numbers below prescription letters are target residual basal area in ft^2/upper diameter limit.

words, one per ecosection) so as to have little influence on one anothers' markets. Each of the 1556 plots (representing the 5.4 million acres that could be treated effectively) was allocated to the psite with the lowest haul cost: Grants Pass OR, Burney CA, Klamath Falls OR, or Bend OR, and the rest of the analysis proceeds with those allocations (fig. 2). Four of the treatment scenarios were: treat all treatable plots and select the prescription for each plot that 1) maximizes net revenue, or 2) maximizes improvement in TI, or 3) minimizes the merchantable material removed, or 4) maximizes improvement in CI. The other three scenarios 1A, 2A and 3A, corresponded to scenarios 1, 2 and 3, except that only plots with non-negative net revenue would be treated. Scenario 1 was designed to make as much profit as possible subject to the non-trivial constraint that all treatments were designed with an eye towards reducing crown fire potential, not maximizing economic return or even

facilitating a positive cash flow. Scenarios 2 and 4 represent a no-holds-barred policy of reducing fire hazard as the paramount objective, while scenario 3 might be more appealing to groups or individuals who favor the achievement of some measure of fuel reduction but do not support the removal of sawtimber-sized trees and or the generation of profits from fuel treatment activity.

RESULTS

The fuel treatment policy scenarios 1-3 lead to quite different distributions of treatments. The most frequently selected treatments for scenario 1 were H, G, and J, for scenario 2 were G, H, and F, and for scenario 3 were J, G and F (fig. 3). Given the substantial differences in the treatments selected, we expected to see substantial differences in the aggregate results; however, the most substantial differences among scenarios were in net revenue, while the biomass yield was rather robust under this range of scenarios (table 2). Under scenario 1, net revenue was positive for every psite when all effectively treatable plots were treated. Even when selecting prescriptions that minimize merchantable yield (scenario 3), there would still be 3.6 billion ft^3 of merchantable volume produced, though the aggregate net revenue under this scenario is extremely negative. Under every scenario, the acres feeding material to the psite at Grants Pass generated the greatest merchantable volume and the greatest biomass.

With the added constraint that, as proposed in the Healthy Forests Initiative, "every acre pays its own way", the area that could be treated would be reduced to no more than 12 percent of the forested landscape (table 3) in scenarios 1A, 2A and 3A. Of the four sites, Grants Pass again results in the greatest amount of net revenue, acres treated,

Table 2—Aggregate net revenue, area treated, and yields of merchantable volume and sub-merchantable biomass by potential processing site for three, fuel treatment policy scenarios in which all effectively treatable plots are treated.

Scenario 1: Maximize net revenue Processing site	Net revenue (Millions of dollars)	Acres treated (Millions (thousands)	Merchantable volume (Millions of cubic feet)	Biomass of tons)
Burney	542	1,546	2,635	24
Klamath Falls	593	1,101	1,741	14
Bend	343	741	998	12
Grants Pass	1,162	1,962	4,153	30
Total	2,640	5,351	9,527	79

Scenario 2: Maximize torching index improvement Processing site	Net revenue (Millions of dollars)	Acres treated (thousands)	Merchantable volume (Millions of cubic feet)	Biomass (Millions of tons)
Burney	-12	1,546	2,256	30
Klamath Falls	415	1,101	1,602	15
Bend	144	741	822	11
Grants Pass	376	1,962	3,940	37
Total	923	5,351	8,620	94

Scenario 3: Minimize merchantable yield Processing site	Net revenue (Millions of dollars)	Acres treated (thousands)	Merchantable volume (Millions of cubic feet)	Biomass (Millions of tons)
Burney	-795	1,546	974	21
Klamath Falls	-157	1,101	773	12
Bend	-148	741	384	9
Grants Pass	-1,465	1,962	1,444	34
Total	-2,565	5,351	3,574	75

biomass yield, and merchantable yield under scenario 1A. Scenario 3A treats about the same area as scenarios 1A and 2A, but produces less than half the net revenue, largely because there is much less revenue from merchantable volume in the prescriptions selected for this scenario that could be used to offset treatment costs.

All scenarios produced quite different opportunities in terms of the potential longevity of a biomass plant (table 4). Under scenario 2, sufficient biomass could be collected to operate 50 MW generating stations at Grants Pass and Burney for about 50 years, and in all likelihood, much

longer given that this was a static analysis (that did not account for regeneration and continued growth of the residual trees and involved no harvest scheduling component), and preliminary analysis of post-treatment plots modeled forward with FVS indicates a need to re-treat as soon as 20 years after the initial treatment for fire hazard reduction to be maintained. Requiring every acre to pay its own way dramatically cuts the projected longevity of biomass supply, and scenario 3A (minimum merchantable yield and nonnegative net revenue) would appear to all but eliminate the opportunity to attract capital investment for the construction of new biomass generating capacity except at Grants Pass.

Table 3—Aggregate net revenue, area treated, and yields of merchantable volume and sub-merchantable biomass by potential processing site for three, alternate fuel treatment policy scenarios in which only the effectively treatable plots that generate positive net revenue are treated.

Scenario 1A: Maximize net revenue Processing site	NR+ Net revenue *(Millions of dollars)*	Acres treated *(thousands)*	Merchantable volume *(Millions of cubic feet)*	Biomass *(Millions of tons)*
Burney	1,112	735	2,017	11
Klamath Falls	891	524	1,482	7
Bend	536	335	833	8
Grants Pass	2,382	1,023	3,478	16
Total	4,921	2,616	7,809	42

Scenario 2A: Maximize torching index change, NR+ Processing site	Net revenue *(Millions of dollars)*	Acres treated *(thousands)*	Merchantable volume *(Millions of cubic feet)*	Biomass *(Millions of tons)*
Burney	944	711	1,873	12
Klamath Falls	798	516	1,407	7
Bend	486	329	780	8
Grants Pass	2,184	1,014	3,295	17
Total	4,413	2,569	7,355	44

Scenario 3A: Minimize merchantable yield Processing site	Net revenue *(Millions of dollars)*	Acres treated *(thousands)*	Merchantable volume *(Millions of cubic feet)*	Biomass *(Millions of tons)*
Burney	442	735	1,320	12
Klamath Falls	357	524	898	7
Bend	238	335	539	8
Grants Pass	942	1,023	2,182	21
Total	1,978	2,616	4,939	47

Not surprisingly, average effectiveness of fuel treatments in terms of both TI and CI was usually greatest under scenario 2, as shown in figure 4 for CI. What was surprising was that the average improvement in both indices was comparable between with scenario 1, in which the fuel treatment with the greatest net revenue was selected. Scenario 3 was substantially less effective on the plots feeding every psite, with an average CI improvement of 20 to 40 mph, most likely because prescriptions that remove less merchantable material also leave stands with higher canopy bulk-density.

Table 5 summarizes the aggregate results for scenarios 1, 2 and 3 plus scenario 4 (maximize improvement in crowning index). Scenario 4 has greater yields of both biomass and merchantable material, most likely because it favors treatments that reduce canopy bulk density (by removing more of the medium-sized trees greater than 7" d.b.h. and generally less than 21" d.b.h.). It is the additional merchantable component that accounts for the boost in net revenue as compared with scenario 2. The pre-treatment TI and CI averaged 7 and 23, respectively, so on average, all of the scenarios lead to substantial improvements in these indices.

Table 4—Years of feedstock for a 50 MW biomass-based electrical generating plant consuming 1750 green tons per day of biomass an in operation 24/7.

| Scenario	Burney	Klamath Falls	Bend	Grants Pass
1. Maximize net revenue	38	22	18	47
1A. Maximize net revenue, treat only stands with nonnegative NR	18	11	12	25
2. Maximize improvement in TI	47	24	18	58
2A. Maximize improvement in TI, treat only stands with nonnegative NR	19	11	12	27
3. Minimize merchantable yield	33	18	14	53
3A. Minimize merchantable yield, treat only stands with nonnegative NR	19	10	12	33
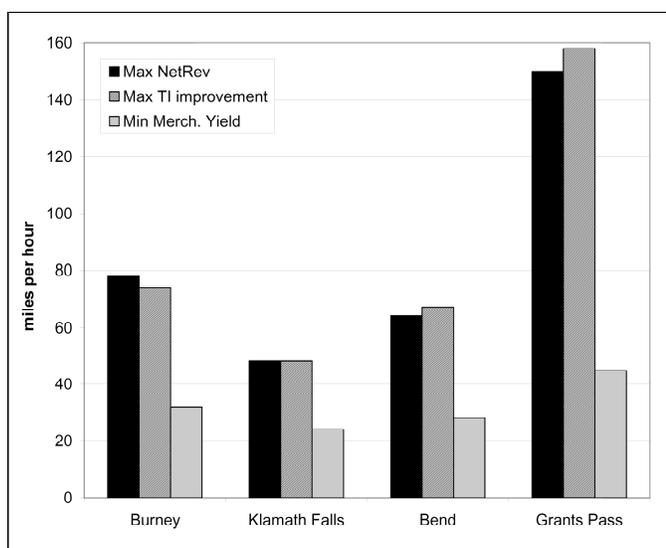
Figure 4—Average improvement in FFE-predicted crowing index, by proposed processing site to which recovered material would be hauled, by scenario for scenarios 1, 2 and 3.

Table 5—Aggregate yield, net revenue, and improvement in crown fire potential (from a pre-treatment mean CI of 22 and TI of 7) for the four ecoregion study area for four fuel treatment policy scenarios, when all effectively treatable acres are treated.

Scenario	Biomass (millions of tons)	Merchantable volume (millions of ft^3)	Net revenue (millions of dollars)	Mean change in CI (miles per hour)	Mean change in TI (miles per hour)
1. Max. net rev.	79	9,527	2,639	63	96
2. Max Δ TI	94	8,620	922	83	98
3. Min Merch. Vol.	75	3,574	-2,566	23	35
4. Max Δ CI	93	9,765	1,817	80	114

DISCUSSION

There is plenty of biomass to supply four 50 MW power plants for decades under the most aggressive scenarios (for example, scenario 2), but supply under the most conservative scenarios (for example, 3A) would be far more limited. Another alternative that we have not yet analyzed would be to operate several smaller or less heavily capitalized power plants for a shorter period of time in order to reduce haul costs and make treatment feasible over a greater area.

By any basis of calculation, most of the material removed in these treatments is merchantable and would fetch higher prices than the $18 per green ton currently paid for biomass-sized material by power plant operators in northern California. For scenario 1, 75 percent of the total tonnage of wood removed is merchantable, with the remaining 25 percent in biomass-sized material composed of trees less than 7 inches and the tops and limbs of larger trees. And of the biomass-sized material, only 20 percent is in trees less than 7 inches (i.e., only 5 percent of the total wood tonnage removed). On a value basis, merchantable wood recovered accounts for 90 percent of the total value recovered. This helps explain why prescriptions that do not maximize net revenue or that reduce the quantity of merchantable-sized material recovered fare so poorly on a net revenue basis.

Both harvest costs and haul costs are considerable, averaging $1634 and $560 per acre, respectively, under scenario 1, with the haul costs for biomass alone averaging $127 per acre. And with the configuration of four processing sites we specified, haul costs alone averaged $8.53 per green ton, nearly half the $18 per green ton that biomass was assumed to fetch upon delivery, suggesting strongly that biomass rarely pays its own way out of the woods, given that harvest costs averaged $22 per ton over all size classes of material, and are surely greater for biomass-sized material.

The average net revenue per acre under scenario 1 was $493, though on some acres, the net revenue is much greater, and on others, it is negative, sometimes considerably so. For some plots, if none of the biomass-sized material was hauled to processing sites but was instead left at the landing, the net revenue per acre would be greater, but in all likelihood, *in situ* disposal costs for this material, for example by burning, would likely drive net revenue to zero or below. Leaving the biomass-sized material in the woods would reduce harvest costs and increase net revenue, but make the estimated fire risk reduction benefits more dubious.

While it is possible to focus on acres where net revenue is positive, for example, under scenario 1A, this results in a 51 percent reduction in the area treated relative to the area that could be treated effectively, and calls into question whether the fuels reduction achieved would be effective at a landscape scale. Furthermore, some caveats must be taken into account in interpreting this analysis that could even reduce the estimate of 2.2 million acres that could be treated effectively and generate positive net revenue. At almost every decision point requiring an assumption, we assumed maximum land availability, minimum cost and maximum revenue. For example, we assumed that all non-reserved acres would be allocated to a fuels-reduction treatment. In fact, some private landowners might well choose other prescriptions that generate more net revenue and achieve less or no fuel reduction benefit, while others would be unwilling to consider any treatment. And, much of the National Forest land in the study area may be in late successional reserves, riparian reserves, or other designated uses that could be considered incompatible with the fuel reduction treatments we've considered. Nor did we include the costs of planning, administration, site clean-up, environmental assessments, or litigation. In estimating accessibility, we assumed that any road on the map actually exists on the ground and would be passable by the equipment needed to transport equipment to the site and material from the site to a processing facility. In haul cost calculations, the nature of the grid-based cost accumulation carries the implicit assumption that any 250 m cell containing a road contains a road heading in the direction of the processing site. Furthermore, the price used for biomass-sized material derives from a competitive market price paid by a large-capacity biomass-fired power plant; yet in this analysis, we dispersed biomass conversion facilities to assure a source of supply sufficient to provide feedstocks for a number of years, but this geographic separation also makes them unlikely to compete with one another. So the cost and value calculations and the area availability calculations embedded in this analysis *represent best-case conditions and are optimistic.* We also assumed that all treatable lands were treated immediately; however, this would be unrealistic and even if spread out over a few years, would still generate wood at a rate so much greater than current harvest patterns, that wood product prices would likely be substantially depressed, reducing net revenue even below the estimates reported here.

Other caveats are that we did not consider existing processing capacity, either for biomass or merchantable material, so our results are not a justification for adding new capacity, particularly in places like Shasta County that already have substantial capacity. Nor did we factor in the

capital costs of building any processing capacity. Adding biomass processing facilities at additional sites (beyond the four modeled in this analysis) would reduce the haul costs for many acres, thereby increasing net revenue. However, the plants would need to have smaller capacity, and economies of scale, and the assumed biomass price, could be compromised.

Key strengths of the BioSum analytic framework are: 1) it is based on a statistically representative sample of the entire landscape, 2) it is connected to detailed ground observations that permit an extremely high level of resolution in characterizing outcomes (for example, knowing the species and size distribution of the material recovered, and being able to model the improvement in crown fire potential), 3) the raster-based haul cost module enables a level of spatial detail not previously attempted without imposing enormous costs for first building an error-free vector based road network, and 4) the approach is adaptable to any place in the United States, by virtue of its reliance on FIA data (available nationwide as part of a National Program), publicly available models (for example, FVS and STHARVEST), and even topologically inferior GIS road coverages.

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