

1        **JOINTLY OPTIMIZING SELECTION OF FUEL TREATMENTS**  
2                    **AND SITING OF FOREST BIOMASS-BASED ENERGY**  
3        **PRODUCTION FACILITIES FOR LANDSCAPE-SCALE FIRE**  
4                    **HAZARD REDUCTION**

5                    **P. J. DAUGHERTY**

6        Environmental Analysis and Research Team, Forest Inventory and Analysis Program,  
7                    USDA Forest Service, PNW Research Station, Portland, OR 97208

8                    **JEREMY S. FRIED**

9        Environmental Analysis and Research Team, Forest Inventory and Analysis Program,  
10                    USDA Forest Service, PNW Research Station, Portland, OR 97208

11                    **ABSTRACT**

12        Landscape-scale fuel treatments for forest fire hazard reduction potentially produce large  
13        quantities of material suitable for biomass energy production. The analytic framework FIA  
14        BioSum addresses this situation by developing detailed data on forest conditions and production  
15        under alternative fuel treatment prescriptions, and computes haul costs to alternative sites at which  
16        forest biomass-based energy production facilities could be constructed. This research presents a  
17        joint-optimization approach that simultaneously selects acres to be treated by fuel treatment  
18        prescription and assigns bioenergy production facility locations and capacities. Effects of  
19        alternative fuel treatment policies on fuel treatment effectiveness, economic feasibility, material  
20        produced, generating capacity supported, and the location and capacity of assigned facilities are  
21        evaluated. We applied this framework to a 28-million-acre, four-ecosystem landscape in central  
22        Oregon and northern California. Using a maximum net revenue objective function while varying

1 acres treated and effectiveness benchmarks, we found the study area capable of producing  
2 estimated net revenue of 5.9 to 9.0 billion US\$, treatment of 2.8 to 8.1 million acres, biomass yield  
3 of 61 million to 124 million green tons, and bioenergy capacity of 496 to 1009 MW over a 10-year  
4 period. Results also suggest that unless small-capacity (< 15 MW) facilities achieve efficiencies  
5 over 90 percent of what large-capacity facilities can achieve, they do not represent a viable  
6 alternative, given the large amount of biomass removed. Analysis of a range of facility capacities  
7 revealed robustness in the optimal spatial distribution of forest bioenergy production facilities.

8 **Keywords:** joint optimization, spatially explicit facility siting, forest biomass energy.

## 9 INTRODUCTION

10 Historical practices starting with European settlers (e.g., overgrazing in the late 1800s,  
11 selective timber harvests, and fire suppression) have transformed vast areas of forest  
12 ecosystems in the western United States to the point that they have significantly departed  
13 from the historical range. Significant changes in structure and function of ponderosa pine  
14 and dry mixed-conifer forests have resulted in increased fire severity and size (Covington  
15 and Moore 1994a, 1994b, Covington et al. 1997). Currently, 43 percent of the conifer  
16 forests with high-frequency low-severity fire regimes are at high risk of losing key  
17 ecosystem components; an additional 53 percent are at moderate risk (Schmidt et al.  
18 2002). The resulting increase in large, stand-replacing fires has intensified interest in  
19 assessing the feasibility of landscape-scale fuel treatment. Doubts have grown about the  
20 feasibility of widespread use of prescribed fire owing to concerns about air quality,  
21 liability, narrow windows of opportunity to implement treatments, and potentially  
22 undesirable fire effects (Winter and Fried 2000, Cleaves et al. 2000). For most forestry  
23 professionals and most of the public, fuel treatment has become virtually synonymous  
24 with thinning of the forests to reduce fire severity and the likelihood of stand-replacing

1 fire, especially since the advent and passage of the Healthy Forests Restoration Act of  
2 2003.

3 Conventional wisdom suggests that effective treatments require the removal of large  
4 numbers of small stems, at considerable cost, and that this harvested material would have  
5 little or no value. One approach to this challenge that also serves to promote renewable  
6 energy and increase employment opportunities in rural areas involves development of  
7 forest bioenergy production facilities to convert biomass into electrical energy. Although  
8 biomass energy plays a significant role in some countries, e.g., in 2001, bioenergy  
9 contributed 98 TWh or 20 percent of Sweden's energy (SVEBIO 2003), bioenergy  
10 facilities require sizable, up-front investment. Private investors are understandably  
11 concerned about the prospects of a reliable supply of competitively priced feedstock over  
12 the life of such facilities, and are unlikely to take on this risk without guarantees,  
13 contracts, or assurances sufficient to build their confidence in the viability of the  
14 enterprise.

15 Fire and forest planners and managers, rural community economic development staff, and  
16 potential investors in forest bioenergy production capacity could benefit from knowledge  
17 regarding location of potential woody biomass supply and the type and quantity of wood  
18 that could flow from landscape-scale fuel treatments. This paper presents the  
19 development and application of an analytical system, FIA BioSum (Forest Inventory and  
20 Analysis Biomass Summarization), designed to provide this type of information. The  
21 system compares a variety of fuel treatment prescriptions, assesses their economic  
22 feasibility by providing a complete analysis of harvest and haul costs, and offers a model-  
23 based characterization of fire hazard reduction.

1 This paper focuses on the optimization component of FIA BioSum, which jointly  
2 optimizes the selection of fuel treatments for landscape-scale fire hazard reduction and  
3 assignment of locations and capacities for forest bioenergy production facilities. We  
4 briefly describe the FIA BioSum analytical framework, and detail the formulation  
5 approach taken in the optimization component. We describe the assumptions and  
6 parameters used to apply this framework to a 28-million-acre, four-ecosystem landscape  
7 in central and southern Oregon and northern California. We present results on the spatial  
8 distribution of facilities and their assigned capacity as compared to a potential biomass  
9 accumulation gradient and the high-speed road network. We develop two groups of  
10 scenarios that analyze the effects of different minimum facility capacities and the effects  
11 of different assumptions regarding acres treated and required level of treatment  
12 effectiveness in reducing fire hazard. We present the results of these scenarios in terms  
13 of consistency in facility location and capacity, net revenue generated, merchantable  
14 volume and biomass produced, area treated by treatment effectiveness level, and  
15 aggregate bioenergy capacity.

## 16 **THE ANALYTICAL SYSTEM, FIA BIOSUM**

17 FIA BioSum integrates data and simulation programs by using linked spatial and  
18 relational databases (Fried, et al. 2005, Fried and Christensen 2004, Fried, et al. 2003,  
19 Fried 2003). It creates a geographically analytic framework for assessing and  
20 summarizing biomass production that would result from a landscape-scale fuel treatment  
21 program. We used publicly available data, including forest inventory plot measurements  
22 and derived variables (e.g., biomass, volume), along with geographic information system

1 (GIS) layers that represent roads, existing wood processing facilities, and landowner  
2 class. We used publicly available computer simulators for growth and yield, fire and fuel  
3 effects, and fuel treatment costs. The system requires assumptions, silvicultural  
4 prescriptions designed to achieve fuel treatment, and decision rules developed in  
5 consultation with local fire, fuels, silviculture, and logging experts. Reliance on off-the-  
6 shelf data and models combined with local expertise for developing parameters facilitates  
7 system portability to any fire-prone forest ecosystem. The necessary FIA inventory data  
8 is publicly available. Although plot coordinates are “fuzzed” to comply with landowner  
9 confidentiality requirements, we do not believe that this will materially affect BioSum  
10 results.

## 11 **Database Components**

12 Two linked databases store inventory and spatial data and output from simulation models  
13 and other data processing utilities. These databases ultimately determine the variables,  
14 dimensions, and coefficients for the optimization model. The relational (MS Access) and  
15 spatial (ArcGIS) databases are linked by inventory plot and potential forest bioenergy  
16 production facility locations. Tree-level forest inventory data drives the system by  
17 providing input for the simulation of fuel reduction treatments. Outcomes of simulated  
18 fuel treatments (yield, cost, revenue, effectiveness) are also stored in the database for  
19 each plot-prescription combination.

20 Basic spatial data used to assess haul costs consist of locations of inventory plots and  
21 potential biomass processing sites, a spatially complete coverage of broad landowner  
22 class (e.g., private, national forest, other public), and a comprehensive coverage of the

1 transportation system that includes unit costs of transport over each link. We tessellate  
2 the vector transportation cost coverage into 250-m grid cells, with each cell's value set to  
3 the cost per ton-mile of traversing the cell on the least-cost transportation link in that cell  
4 (cells containing no roads are assigned infinite haul cost). After experimenting with a  
5 range of grid cell sizes, we chose 250 meters because it performed well in bridging  
6 artifact gaps in the road network without undue underestimation of haul cost due to  
7 spurious connections (e.g., roads running along opposite sides of a river). The resulting  
8 impedance surface forms the basis of haul-cost calculations. For each potential forest  
9 bioenergy facility location, we use the haul-cost surface to generate a cost accumulation  
10 grid, and perform an overlay on plot locations to arrive at haul cost to that facility from  
11 every plot in a study area. This 250-m impedance surface was used only to estimate haul  
12 cost parameters; it was not integrated into the simulation or optimization models.

### 13 **Simulation Components**

14 We use the Forest Vegetation Simulator (FVS) (Stage 1973, Wykoff et al. 1982) to  
15 simulate fuel treatment prescriptions and, via the integrated Fire and Fuels Extension  
16 (FFE) (Reinhardt and Crookston 2003), assess the likely change in fire hazard these  
17 treatments would produce. Fifteen FVS variants are available for the western United  
18 States, making the system applicable to all forest regions in this area. The fuel treatment  
19 prescriptions applied in FVS generate harvested tree lists for each plot. Postprocessing  
20 programs compute plot and tree attributes used at later stages in the analysis (e.g., slope,  
21 number of stems harvested, average stem size harvested, and volume and biomass by  
22 species and size class). The FFE models calculate fire-related stand attributes, including  
23 indices of crown fire potential for each plot, specifically, torching index (TI) and

1 crowning index (CI). The TI represents the wind speed at which fire could be expected  
2 to move from surface fuels into crown fuels and is highly influenced by vertical stand  
3 structure (ladder fuels) and height to crown base. The CI is the wind speed at which a  
4 crown fire could be expected to be sustained and is heavily influenced by crown bulk  
5 density. The system uses increases in CI or TI as measures of treatment effectiveness in  
6 regard to fire hazard reduction (i.e., higher wind speed thresholds imply *lower* hazard  
7 because high winds occur less frequently).

8 A small-tree harvest cost model, STHARVEST (Fight et al. 2003), processes FVS output  
9 data, calculating logging costs via regressions and look-up tables derived from empirical  
10 data on small-diameter-timber sales. STHARVEST requires specification of logging  
11 system, range of tree diameters to be included, volume per acre, and disposition of  
12 residue. For each plot and prescription, STHARVEST provides an estimated on-site cost  
13 of implementing the prescription. Harvested materials brought to the loading area are  
14 categorized into (1) merchantable, consisting of stems of trees of merchantable species  
15 greater than a specified diameter, and (2) biomass, consisting of trees below a  
16 merchantable threshold diameter, the limbs and tops of merchantable trees, and all  
17 harvested nonmerchantable trees. FIA BioSum also accounts for miscellaneous costs  
18 (e.g., brush cutting, and erosion-inhibiting measures), where warranted.

19 The spatially modeled haul costs are combined with the outputs from FVS, FFE, and  
20 STHARVEST to form a database containing simulation outcomes for each plot-  
21 prescription combination and for each potential facility location. These outcome data  
22 include biomass and merchantable yields, harvest and haul costs, gross and net revenues,  
23 and change in TI and CI. The database information on the plot-prescription combinations

1 and potential facility locations determine most of the decision variables and the size of  
2 the optimization model; the associated data provide technical coefficients used in the  
3 model.

#### 4 **THE OPTIMIZATION MODEL**

5 We developed a mixed-integer optimization model that simultaneously selects the best  
6 fuel treatment to implement on each acre (as represented by plot points and expansion  
7 factors) and the best locations and capacities for forest bioenergy production facilities.  
8 Relative to other decision support systems designed to guide location decisions and  
9 capacity choices for forest bioenergy production facilities (e.g., Noon and Daly 1996,  
10 Graham et al. 2000), FIA BioSum is most similar to the approach taken by Freppaz and  
11 others (2004). Both models determine the optimal facility size and quantity and location  
12 of biomass to be collected, and calculate transportation cost based on accessibility and  
13 distance. The models differ in the optimization approach and level of detail. Freppaz  
14 and others (2004) use fixed facility numbers and location and treat biomass supply as an  
15 annual amount that could be collected from a given parcel. We include a near-continuous  
16 spatial-choice set for potential facility locations. We also use a mixed-integer pricing  
17 structure to address the scale efficiency of larger capacity facilities. The mixed-integer,  
18 joint-optimization approach allows for the simultaneous assessment of policy on fire  
19 hazard reduction and forest bioenergy facility assignment. The ability to change facility  
20 assignments in response to policy-induced changes in fuel treatments should provide a  
21 more accurate assessment of policy impacts on forest conditions, given that the  
22 assumption of fixed facility locations imposes tighter constraints on the decision space.

1 We also include more internal specification of the forest production process, defining  
2 multiple treatment options and tracking multiple outputs in addition to biomass (e.g.,  
3 merchantable volume, fire hazard reduction – see application to case study section of this  
4 paper for details on implementation of model).

## 5 **Objective Functions**

6 The model is formulated with a set of alternative objective functions, one of which is  
7 selected for solving any given scenario. The primary objective function maximizes net  
8 revenue, calculated as the revenue from delivered merchantable wood and biomass less  
9 treatment and haul costs, aggregated over all acres that receive treatment within the  
10 analysis region. We also formulate objective functions that maximize area-weighted  
11 torching (or crowning) index improvement, biomass production, and acres treated.

## 12 **Harvest Decision and Accounting Variables**

13 The model uses a single-period harvest selection formulation, where each harvest  
14 decision variable represents the assignment of acres to a plot-prescription combination,  
15 where *plots* are conceptually analogous to stand or land type in the optimization literature  
16 on forest planning. Restriction on available land base (area constraints) takes the  
17 standard form:

$$18 \quad \sum_{j=1}^J x_{lj} = A_l \quad \forall l, l = 1, \dots, L \quad (1)$$

19 where  $x_{lj}$  equals acres of plot  $l$ ,  $l = 1, \dots, L$ , assigned to fuel treatment prescription  $j$ ,  $j = 1,$   
20  $\dots, J$ ;  $A_l$  equals total area (acres) represented by plot  $l$ ,  $l = 1, \dots, L$ ; and  $J$  and  $L$  equal the  
21 number of treatments and plots, respectively.

1 The model defines a number of accounting variables for the model. They take the form:

$$2 \sum_{l=1}^L \sum_{j=1}^J c_{lj} x_{lj} - \text{var} = 0 \quad (2)$$

3 The coefficient,  $c_{lj}$ , equals the per acre contribution of the plot-treatment variable to the  
4 output being tracked. Production accounting variables (var) include net revenue,  
5 merchantable volume, delivered biomass, change in area-weighted torching and crowning  
6 indices, and area treated. We also generate accounting variables that define groups of the  
7 plot-treatment variables that meet a certain criterion; in these cases the coefficient,  $c_{lj}$ ,  
8 equals 0 or 1. These variables allow constraining by groups of plot-treatment variables,  
9 and include groups defined by treatment effectiveness, ownership class, and treatment  
10 diameter limits.

## 11 **Forest Bioenergy Production Facility Formulation**

12 The selection of facility location and capacity uses a mixed-integer approach, with binary  
13 facility selection variables for location and binary pricing variables to account for  
14 increased efficiency of larger facilities. The key components of this portion of the  
15 formulation include: biomass transfer (from plot to biomass facility), biomass feedstock  
16 accumulation, biomass facility selection, and biomass pricing equations.

### 17 *Biomass transfer and forest bioenergy production facility accumulation equations*

18 The following equations model the biomass transportation network, and ensure that  
19 nonmerchantable woody biomass generated by fuel treatments either becomes feedstock  
20 for a forest bioenergy production facility or is disposed of via an air-curtain destructor.

$$1 \quad \sum_{j=1}^J b_{lj}x_{lj} - \sum_k B_{lk} - AD_l = 0 \quad \forall l, l = 1, \dots, L; \forall k \in \{k \mid h_{lk} \leq HL\} \quad (3)$$

$$2 \quad \sum_{l=1}^L B_{lk} - P_k = 0 \quad \forall k, k = 1, \dots, K \quad (4)$$

3 Equation 3 states that sum of the biomass produced by all treatments for a given plot  
4 must be shipped to a facility or burned on site by using an air-curtain destructor. The  
5 coefficient  $b_{lj}$  equals the per acre biomass produced by a plot-treatment decision, and the  
6 expression,  $\sum b_{lj}x_{lj}$ , represents the total biomass produced on a given plot. This quantity  
7 must equal the sum of the amounts in the biomass transfers variables,  $B_{lk}$ , and the air-  
8 curtain destructor variable,  $AD_l$ . The biomass transfer variables,  $B_{lk}$ , track biomass  
9 shipped from plot  $l$  to facility  $k$ , and are necessary for assigning haul costs, which are plot  
10 to facility specific. Each plot can only deliver to a subset of facilities,  $k \in \{k \mid h_{lk} \leq HL\}$ ,  
11 defined by an upper limit on the haul cost, where haul cost from plot  $l$  to facility  $k$ ,  $h_{lk}$ , is  
12 less than the specified limit,  $HL$ . Equation 4 requires that the amount shipped from all  
13 plots to facility  $k$ ,  $\sum B_{lk}$ , equals the facility's received biomass feedstock,  $P_k$ .

#### 14 *Forest bioenergy facility selections equations*

15 We model the forest bioenergy facility selection as a decision to build a facility if there is  
16 sufficient biomass supply for an assumed life at a minimum electrical generating  
17 capacity. If a potential facility location reaches the minimum supply threshold, the site is  
18 selected, and the facility can take on any capacity above the minimum and below a  
19 specified maximum. The facility selection uses a standard dichotomous (either-or)  
20 choice formulation (Dantzig 1963).

$$1 \quad P_k - (\text{PL})IP_k \geq 0 \quad \forall k, k = 1, \dots, K; IP_k \in \{0,1\} \quad (5)$$

$$2 \quad P_k - (\text{PU})IP_k \leq 0 \quad \forall k, k = 1, \dots, K; IP_k \in \{0,1\} \quad (6)$$

3 Where  $P_k$  equals biomass delivered to facility  $k$ ,  $IP_k$  is a binary variable (0,1 integer)  
4 indicating if a facility  $k$  receives sufficient biomass to be built ( $IP_k$  equals 1 if delivered  
5 weight exceeds lower supply threshold, PL), and PU equals the upper limit for facility  $k$ .  
6 If the binary variable equals 0, equations 5 and 6 ensure that the delivered biomass equals  
7 zero (i.e., reduces to  $0 \geq P_k \geq 0$ ). Equation 5 allows the binary variable to equal 1 only if  
8 delivered biomass exceeds the lower threshold. Together, the equations force delivered  
9 biomass to equal zero or to fall between the lower and upper capacity limits.

#### 10 *Biomass pricing equations*

11 Because we do not model the internal details of energy production in forest bioenergy  
12 facilities, we address scale efficiencies through prices for delivered biomass. Increased  
13 efficiency in larger facilities allows those facilities to pay a higher per-unit delivered  
14 price. This situation differs from standard demand function situations, because in this  
15 case, when a facility exceeds a given capacity threshold, the price paid for all (not the  
16 marginal) delivered material changes. Because facility capacity is an endogenous  
17 variable, we use a variation on the conditional constraint technique to change the per-unit  
18 delivered price based on facility capacity.

$$19 \quad P_k - (\text{PB}_1)INI_k \geq 0 \quad \forall k, k = 1, \dots, K; INI_k \in \{0,1\} \quad (7)$$

$$20 \quad P_k - (\text{M})INI_k \leq (\text{PB}_1) \quad \forall k, k = 1, \dots, K; INI_k \in \{0,1\} \quad (8)$$

$$21 \quad P_k - (\text{M})INI_k - PWI_k \leq 0 \quad \forall k, k = 1, \dots, K; INI_k \in \{0,1\} \quad (9)$$

1  $c_0 P_k - c_1 PWI_k - VAL_k = 0 \quad \forall k, k = 1, \dots, K$  (10)

2 Equations 7 and 8 set the value of the binary variable,  $INI_k$ , to 1 if the delivered biomass  
3 exceeds  $PB_1$ , the price-break level, and 0 otherwise, in a manner analogous to the site  
4 selection equations.  $M$  is an arbitrarily large constant relative to possible values of  $P_k$ .  
5 Equation 9 sets a penalty variable,  $PWI_k$ , equal to the delivered biomass weight when the  
6 delivered weight is less than the price-break level; if biomass exceeds the price break, the  
7 large value  $(M)INI_k$  allows the penalty variable to equal zero. Equation 10 uses this  
8 penalty variable to lower the total value of biomass  $VAL_k$ , by assessing a per-unit price  
9 penalty,  $c_1$ , against the full per-unit price,  $c_0$ . This approach accommodates additional  
10 breaks by adding, for each price break, another set of equations 7, 8, and 9, with the new  
11 price break, binary variable, and penalty variable, and by adding a corresponding penalty  
12 variable term to equation 10.

13 **APPLICATION TO A CASE STUDY**

14 We applied the FIA BioSum framework to a 28-million-acre, four-ecosection study area  
15 in central Oregon and northern California (figure 1). We selected these ecosections  
16 (Klamath, Modoc Plateau, southern Cascades, and eastern Cascades) because current fire  
17 regime condition class maps of the United States (Schmidt et al. 2002) classify  
18 substantial area in these ecosections as significantly departed from historical fire regimes.  
19 These areas likely have high fuel loading and stand conditions that make them a high  
20 priority for fuel treatment.

## 1 **Model Implementation**

### 2 *Inventory data*

3 A total of 6200 field plots representing 25.0 million acres of potentially forested land fell  
4 within the study area boundary (Hiserote and Waddell 2004). Plots came from six  
5 different inventories, each of which constitutes a statistically representative sample of a  
6 portion of the total landscape and includes measurements of tree attributes such as  
7 diameter, height, crown ratio, and species. This plot set was culled to remove plots that  
8 were observed on the ground to be nonforest or were located in designated wilderness,  
9 natural areas, parks, preserves, monuments, national recreation areas, national wildlife  
10 refuges, or inventoried roadless areas. We also omitted plots on steep (> 40 percent)  
11 slopes that were too far from transportation networks for technically feasible harvest  
12 systems. Finally, we omitted plots containing no trees over 5 inches in diameter. These  
13 reductions resulted in a set of 4686 plots that represents about 14.8 million acres of  
14 treatable forest land – 9.4 million in public and 5.4 million in private ownership. We did  
15 not account for special use areas with harvesting restrictions such as riparian buffers or  
16 late successional reserves designated under the Northwest Forest Plan. Nor did we  
17 account for the Healthy Forests Restoration Act of 2003 direction that 50 percent of  
18 treatment occurs within a fixed distance of communities.

### 19 *Simulation Parameters and Assumption*

20 We used two FVS/FFE variants, south-central Oregon and northeastern California (Dixon  
21 2002) and east Cascades (Smith-Mateja 2004), to simulate fuel treatments. Nine fuel  
22 treatment prescriptions (table 1) representing two treatment approaches were developed

1 in consultation with fire and fuel specialists and applied to all plots for which they were  
2 valid. Five of the treatments focused on density reduction to thwart propagation of crown  
3 fires, and involved thinning proportionately across all diameter classes to a target residual  
4 basal area, with 70 percent of the harvested basal area removed from trees 5.5 to 14.5  
5 inches in diameter at a height of 4.5 feet (dbh). The other four focused on ladder fuels  
6 reduction to reduce risk of crown fire initiation, and involved thinning from below (trees  
7 > 5.5 inches dbh) to a target residual basal area. These four treatments had a range of  
8 residual basal area targets (60 to 125 ft<sup>2</sup>/ac) and maximum acceptable diameters for cut  
9 trees (10 in. to no limit). If the maximum diameter limit was reached before the target  
10 residual basal area, then the latter was not achieved. Because the most aggressive  
11 treatment had a residual basal area of 60 ft<sup>2</sup>/ac, plots with less basal area would be  
12 ineligible for treatment and were excluded from the analysis. In addition, plot treatment  
13 combinations that generated less than 300 ft<sup>3</sup>/ac of total volume (biomass and  
14 merchantable combined) were deemed unrealistic and discarded; for some plots, no  
15 treatment cleared this hurdle and these plots were excluded.

16 We assumed whole-tree logging systems for slopes ≤ 40 percent and cable systems on  
17 slopes > 40 percent. We defined merchantable material as stems of softwood trees > 7.0  
18 in. dbh to a 5 in. top, and biomass as trees brought to the loading area that were 3.5 to 7.0  
19 in. dbh, the limbs and tops of merchantable trees, and all harvested hardwoods. Trees  
20 less than 3.5 in. were assumed to be cut and scattered, and trees 3.5 to 5.5 in. dbh were  
21 cut and scattered on slopes > 40 percent and cut and brought to the loading area on slopes  
22 < 40 percent.

1 Because this analysis targets fuel treatments that reduce the stand-replacing fire hazard,  
2 we only included treatments that effectively achieved this goal. Increasing either the  
3 torching index (TI), the wind speed to initiate torching, or the crowning index (CI), the  
4 wind speed that sustains crown spread, will reduce fire hazard. We defined a treatment as  
5 effective with respect to TI (TI effective) or CI (CI effective) if it matched one of the  
6 following four sets of conditions:

- 7 1. Pretreatment index  $\leq 25$ , posttreatment index  $\geq 25$ , and index change  $\geq 10$  mph,
- 8 2. Pretreatment index  $\leq 25$  and index change  $\geq 20$  mph,
- 9 3. Pretreatment index between 25 and 50, and index change  $\geq 15$  mph, or
- 10 4. Pretreatment index  $\geq 50$  and index change  $\geq 20$  mph.

11 Because the basal area reduction treatments that reduce crown fire hazard (as represented  
12 by increasing CI) often increase torching hazard (as represented by decreasing TI), we  
13 defined two levels of overall treatment effectiveness. We defined treatments as highly  
14 effective if either:

- 15 1. Treatment is TI effective, CI does not decrease by more than 10 mph, and  
16 posttreatment CI exceeds 25 mph, or
- 17 2. Treatment is CI effective, TI does not decrease by more than 10 mph, and  
18 posttreatment TI exceeds 25 mph.

19 We defined moderately effective treatments by relaxing the second set of conditions to:  
20 treatment is CI effective and TI does not decrease by more than 10 mph. After discarding  
21 plots with no moderately or highly effective treatments, 2396 plots remained,  
22 representing 8.1 million acres that could be treated with moderate effectiveness; 4.1  
23 million of these acres were amenable to highly effective treatments.

1 *Potential forest bioenergy facility locations and haul cost*

2 We systematically located 221 potential forest bioenergy production facility sites on a  
3 20x20-km grid, with minor offsets to ensure that all sites were on private land. We  
4 combined, edge-matched, and cleaned GIS road layers from various government agencies  
5 to produce a study-area-wide GIS road coverage with each road segment assigned a rated  
6 travel speed. Speeds were converted to unit costs (i.e., cost per mile per ton of material  
7 hauled) by using current cost data for operating logging and chip trucks and travel times  
8 per road segment. For each potential site, a cost accumulation grid was generated in  
9 Arc/Info, and spatially joined (via overlay) to the plot grid to provide haul cost to that site  
10 from every plot in the study area. We assumed that merchantable material would be  
11 delivered to the 86 existing wood processing facilities in the study area, and unit haul  
12 costs for merchantable material were exogenously assigned for each plot as the average  
13 haul cost to the three facilities with the lowest haul cost.

14 *Optimization model specifications*

15 We included all plot-treatment combinations that achieved moderately effective fire  
16 hazard reduction, resulting in 11,627 plot-treatment decision variables. Haul-cost limits  
17 were set at 36 US\$/green ton (gton) to allow for relatively large biomass supply areas.  
18 Each of the 221 potential sites could collect biomass from an average of 2163 plots.  
19 Each of the 2396 plots could deliver to an average of 205 potential sites. This approach  
20 resulted in 490,970 biomass transfer columns, the largest component of the optimization  
21 model. We based facilities' biomass requirements on conventional stoker/steam turbine  
22 systems (Badger 2002). We calculated the minimum biomass supply needed to select a

1 potential facility site based on a 10-year operating life and a standard operating level of  
2 300 days per year (e.g., a 20 MW facility requires 2,457,000 green tons of biomass). We  
3 effectively set no upper limit on facility capacity, by setting the upper limit in the site-  
4 selection equation (eq. 6) to an arbitrarily high constant. To reflect efficiency differences  
5 by facility capacity (Badger 2002), we specified three price levels defined by price breaks  
6 at 7.5 and 15 MW. Prices were set at 9, 13, and 18 US\$/gton for facilities capable of  
7 producing  $\leq 7.5$  MW, between 7.5 and 15 MW, and  $\geq 15$  MW, respectively. The pricing  
8 structure is used to explore the tradeoff between less efficient facilities and lower  
9 transportation cost achieved by locating a greater number of smaller facilities closer to  
10 the biomass. We based the pricing structure on current delivered prices in California  
11 (Guth 2004).

12 The resulting mixed-integer model contained 662 binary variables, approximately 7000  
13 rows, and 500,000 columns. The matrix was very sparse, with approximately 0.4 percent  
14 nonzero coefficients. We generated the matrix by using Perl (Wall et al. 2000) scripts to  
15 process data into standard MPS format. The use of Perl scripts creates a size-independent  
16 matrix generator, because the data tables are processed line by line and the size of the  
17 matrix is determined by the size of table. We generated the model on a standard desktop  
18 computer, and solved the problem by using Cplex (Bixby 2002) on a Sun Fire 240 Unix  
19 workstation. Solution times on this dual-processor platform averaged 15 to 20 hours of  
20 computing time.

1 *Scenarios simulated with the optimization mode*

2 We first examined facility assignment to potential sites under the smallest minimum  
3 facility capacity constraint (5 MW); this scenario maximized net revenue and placed no  
4 restrictions on plot-treatment combinations that could be selected. We compared the  
5 solution to a potential biomass accumulation gradient and high-speed road network to  
6 confirm the logic of facility assignments. We also used this model as the starting point  
7 for sensitivity analysis on the price structure for delivered biomass. We then developed  
8 two groups of scenarios to assess robustness of facility assignments and to evaluate  
9 potential for net revenue, merchantable and biomass production, acres treated by  
10 effectiveness level, and total bioenergy capacity. Each scenario's solution represents the  
11 optimal solution for a unique set of constraints.

12 In the first group of scenarios, we varied the minimum-capacity constraint, requiring a  
13 minimum biomass supply for 15, 20, 40, and 60 MW capacities before a facility could be  
14 assigned to a potential site (scenarios 15MWMin, 20MWMin, 40MWMin, and  
15 60MWMin). These four scenarios produced information on consistency of facility  
16 assignment and sensitivity of outputs (e.g., net revenue, production, and acres treated) to  
17 changes in minimum capacity. In the second group, we examined the impacts of  
18 alternative policies with respect to treatment effectiveness and whether or not treatment is  
19 required on all treatable acres without regard to cost. We generated these scenarios by  
20 combining two sets of policies: the first set allowed any acres to be treated vs. requiring  
21 all acres to be treated; the second allowed selection of moderately or highly effective  
22 treatments vs. only highly effective treatments. The resulting four scenarios: any-mod+,

1 all-mod+, any-high, and all-high enabled analysis of effects on outputs (e.g., net revenue)  
2 and provided additional information on the consistency of facility assignments.

### 3 **Results**

#### 4 *Initial solution and price sensitivity analysis*

5 The initial model maximized net revenue with a 5 MW minimum capacity constraint, and  
6 no restriction on which plot-treatment combinations could be selected. Figure 2 shows a  
7 side-by-side comparison of (1) the assigned facility locations and capacities and high-  
8 speed road network, and (2) a potential biomass accumulation gradient. The  
9 accumulation gradient represents, at each point, the potential amount of biomass that  
10 could be collected to that point given a specified haul-cost limit. Facility assignments are  
11 consistent with the accumulation gradient and density of high-speed (low haul cost)  
12 roads. Assigned facilities are concentrated in areas with higher biomass accumulation  
13 potentials, with high-capacity facilities assigned in areas with only one high-speed road  
14 and low-capacity facilities more numerous in areas with high densities of high-speed  
15 roads.

16 Of the 41 selected sites, 21 were assigned facilities with a capacity of 15 MW, and only 6  
17 were assigned facilities with capacity  $\geq 20$  MW, with the largest at 33 MW. The 15 MW  
18 capacity corresponds to the second price-break threshold, indicating that the price penalty  
19 for lower efficiency made the selection of small capacity ( $< 15$  MW) financially unsound.  
20 Additional simulations with alternative integer pricing structures revealed that low-  
21 capacity facilities are only assigned when the price breaks are set at 15, 17, and 18  
22 US\$/gton for facilities  $\leq 7.5$  MW, between 7.5 and 15 MW, and  $\geq 15$  MW, respectively.

1 In this case, only 6 facilities out of 46 were selected at the 7.5 MW size. Facilities less  
2 than 7.5 MW were only selected when there was no price difference between capacities  
3 of 5 and 15 MW (i.e., a single price break at 15MW with a price of 17 US\$/gton for less  
4 efficient facilities). This result suggests that unless smaller capacity facilities achieve 94  
5 percent of the efficiency of larger capacity facilities, they do not represent a viable  
6 alternative.

### 7 *Minimum facility capacity scenarios*

8 We evaluated consistency in facility locations by simulating minimum capacity  
9 constraints of 15, 20, 40, and 60 MW (scenarios 15MWMin, 20MWMin, 40MWMin, and  
10 60MWMin in figure 3). All scenarios maximized net revenues and had no restrictions on  
11 plot-treatment combinations that could be selected. Note that the 15MWMin scenario's  
12 solution matches the initial model owing to the effects of pricing structure discussed  
13 above. Across the first three scenarios, increases in the minimum capacity decreased the  
14 number of facilities (from 41 to 31 to 17) with little change in the spatial pattern of  
15 facility assignments: 84 percent of facility assignments in scenario 20MWMin and 94  
16 percent of the facility assignments in scenario 40MWMin were also assigned facilities in  
17 the 15MWMin scenario. Facility assignment patterns also remained consistent between  
18 the second and third scenarios: 71 percent of the 40MWMin locations were also assigned  
19 in the 20MWMin scenario. Comparing the 15MWMin and 20MWMin scenarios, only  
20 two of the five new sites in scenario 20MWMin represented significant relocations (#39  
21 and #98). Comparing scenario 20MWMin to 40MWMin, only one of the five new sites  
22 showed a significant shift (#109). The fourth scenario, (60MWMin), showed greater  
23 shifts in facility assignments. Whereas 80 percent of this scenario's facility site

1 assignments were also assigned in scenario 15MWMin, only 50 and 20 percent were  
2 assigned in scenarios 20MWMin and 40MWMin, respectively. Some facilities in the  
3 60MW scenario were assigned quite different capacities and locations. For example, the  
4 78MW facility at site 68 represents a large shift in location and an increase in capacity  
5 relative to the other scenarios.

6 In all four minimum-capacity scenarios, the solutions assigned the majority of facilities to  
7 minimum capacity. The 15, 20, 40 and 60MWMin scenarios assigned 66, 74, 94, and 80  
8 percent of selected sites to minimum capacity, respectively. These results indicate that,  
9 for the majority of the study area, haul costs limit the area of biomass collection. In other  
10 places, biomass concentration influences the delineation of collection areas, as indicated  
11 by the elimination of sites along the eastern boundary of the study area as the required  
12 minimum capacity was increased. This area has the lowest concentration of available  
13 biomass, and can only support smaller capacity facilities.

14 Production, treatment area, and net revenue varied little across the minimum-capacity  
15 scenarios (table 2). In all scenarios, the majority of net revenue derives from the sale of  
16 merchantable wood (reported in the table as merchantable net revenue). The change in  
17 minimum capacity had little effect on merchantable volume and merchantable net  
18 revenue, accounting for the small variation in net revenue. As the minimum-capacity  
19 constraint was increased, net revenue from biomass decreased. Comparing the lowest  
20 minimum capacity scenario (15MWMin) to the highest (60MWMin), biomass net  
21 revenue decreased by 22 percent, accounting for the 2 percent drop in overall net  
22 revenue. Although biomass revenues decreased by 22 percent, delivered biomass only  
23 decreased by 4 percent, resulting in a 5-percent decrease in bioenergy capacity. The

1 uniformity in delivered biomass across all four scenarios occurred, in part, because an  
2 increase in minimum facility capacity increased the optimal level of biomass to be  
3 processed (and produced) in sub-areas. For example, in the northern part of the study  
4 area (see figure 3), the 15MWMin and 20MWMin scenarios assigned four and three  
5 facilities with an overall bioenergy capacity of 69 and 64 MW. The 40MWMin and  
6 60MWMin scenarios assigned two and one facilities, with the overall capacity of 80 and  
7 85 MW. This result supports the concept that the joint-optimization provides a more  
8 accurate representation of constraint effects. As minimum facility capacity increased,  
9 choices of plot-treatment combinations were changed to maintain the highest net revenue  
10 by redefining optimal biomass collection areas. All four scenarios delivered all harvested  
11 biomass to forest bioenergy production facilities; none was eliminated by air-curtain  
12 destruction.

### 13 *Policy scenarios*

14 We developed four scenarios (any-mod+, all-mod+, any-high, all-high) to assess the  
15 impacts of alternative policies with respect to treatment effectiveness (moderate or high  
16 versus high effectiveness) and to whether or not all treatable acres are treated without  
17 regard to cost (any versus all acres treated). These scenarios also maximized net revenue,  
18 and used a 20 MW minimum-capacity constraint (using other minimum-capacity  
19 constraints produced similar results). The any-mod+ scenario represented the least  
20 constrained model in terms of treated acres and prescription choices, and achieved the  
21 highest net revenue (table 3). A policy requiring the treatment of all acres (scenario all-  
22 mod+) reduced net revenue by 26 percent (from 8.94 to 6.65 billion US\$). This decline  
23 occurred because acres that have only negatively valued plot-treatment choices were

1 forced into solution (i.e., some acres can only be treated at a cost). The requirement to  
2 treat all acres caused merchantable volume to increase by 14 percent, but merchantable  
3 net revenue decreased by 39 percent (because all harvest costs are deducted from the  
4 merchantable gross revenue). Delivered biomass increased by 49 percent (83.21 to  
5 123.87 million green tons). Additional facilities were assigned to process the biomass  
6 (all harvested biomass was used by facilities), but this utilization only partially offset the  
7 costs. The policy required treatment of 8.12 million acres, with 3.21 million receiving  
8 highly effective treatments. The policy also provided the largest bioenergy capacity,  
9 1009 MW.

10 A policy restricting harvest to highly effective treatments and not requiring the treatment  
11 of all treatable acres (scenario any-high) significantly reduced the acres treated. Only  
12 2.84 of the 4.05 million acres that have one or more highly effective prescriptions, were  
13 selected for treatment. Net revenue declined by 20 percent (8.94 to 7.15 billion US\$),  
14 primarily owing to decreases in merchantable harvest relative to the any-mod+ scenario.  
15 Delivered biomass decreased by 27 percent, resulting in a 25 percent decrease in  
16 bioenergy capacity (661 to 496 MW). Scenario all-high, which required highly effective  
17 treatment of all acres that had at least one highly effective treatment, achieved the lowest  
18 net revenue, owing to reductions in merchantable volume and the inclusion of acres  
19 where costs exceed revenues. However, this policy resulted in approximately the same  
20 amount of treated acres, delivered biomass, and bioenergy capacity as in the least  
21 constrained model. The policy also resulted in the greatest area allocated to highly  
22 effective treatments, 4.05 million acres.

1 The effect of these policy scenarios on the consistency of facility assignments (number,  
2 location, and capacity) was analogous to the effects found in the minimum-capacity  
3 scenarios. As in the capacity scenarios, three of the policy scenarios (any-mod+, all-  
4 mod+, any-high) assigned the majority of facilities, approximately 70 percent, to  
5 minimum capacity. The all-high scenario assigned only 57 percent of facilities to  
6 minimum capacity. This scenario was the most constrained in terms of treated acres and  
7 prescription choices, with many acres (21 percent) having only one highly effective  
8 treatment option. This scenario eliminated some of the flexibility in the joint-  
9 optimization approach; for part of the study area, the decision space was reduced to the  
10 optimization of facility assignments given a fixed amount of biomass. In the policy  
11 scenarios, the number of facilities changed with acres treated, rather than with minimum  
12 capacity. As acres treated decreased, the number of facilities decreased, with little  
13 change in their spatial distribution. When compared to the policy scenario with the most  
14 facilities (all-mod+), 63 to 83 percent of facilities assigned in the other policy scenarios  
15 were also assigned in the all-mod+ scenario. In addition, the distribution of facilities was  
16 consistent across policy and minimum-capacity scenarios. For example, of the 41 facility  
17 assignments in the 15MWmin capacity scenario and the 47 facility assignments in the all-  
18 mod+ policy scenario, 34 sites were common to both.

## 19 **Discussion**

20 The application of FIA BioSum to the four-ecosection study area in central Oregon and  
21 northern California indicates that landscape-scale treatments can provide sufficient  
22 biomass to support significant capacity in bioenergy facilities. If built, forest bioenergy  
23 production facilities could be part of the solution to the large quantity of small-diameter

1 material generated by these treatments. Given our model assumptions, the facilities are  
2 financially viable, and payments for delivered biomass could provide a small offset for  
3 treatment costs. More importantly, biomass utilization would avoid onsite burning and  
4 provide other social benefits (e.g., jobs, renewable energy capacity, improving air quality,  
5 and reducing greenhouse gas emissions). With current pollution technology, forest  
6 bioenergy production facilities meet current California air-quality standards, as indicated  
7 by the 37 biomass power plants located throughout California. From a strictly financial  
8 perspective, all simulated scenarios generated positive net revenue, which bodes well for  
9 the viability of landscape-scale fuel treatment in this region. Even requiring treatment on  
10 all 8.12 million acres for which moderately effective hazard reduction can be achieved  
11 resulted in positive net revenue. This scenario could produce 124 million green tons of  
12 biomass, with a bioenergy capacity to serve approximately 100,000 homes (1009 MW)  
13 for ten years.

14 These results are optimistic in that we assume all acres represented in the model can, in  
15 fact, be treated via the prescriptions specified in this model. Three million of these eight  
16 million acres are privately owned forest. The net revenue results represent social net  
17 revenue, without considering the distribution of costs and benefits. Feasibility largely  
18 depends on the aggregate value of the merchantable wood recovered in these treatments  
19 offsetting the aggregate treatment costs. The latter are modeled for the treatment as a  
20 whole rather than modeling merchantable and biomass costs separately. In practice,  
21 private owners may not choose to harvest and deliver biomass-size material (which rarely  
22 pays its own way to the loading area, let alone to the processing facility), without  
23 compensation for the additional costs. Cost for treating the nonmerchantable material

1 would still occur, e.g., in the form of on-site burning, but could well be lower than the  
2 extraction costs accounted for by FIA BioSum. If transaction costs were negligible,  
3 offsetting these extraction costs on private lands is theoretically addressable, given the  
4 overall positive social net revenue anticipated with reducing fire hazard. The practicality  
5 of addressing the problem depends on the transaction costs of setting up a subsidy  
6 mechanism to favor the social optimum over the private optimum. With public lands, the  
7 charging of all treatment costs to the merchantable harvest is not problematic, as moving  
8 nonmerchantable material to a loading area has been an accepted practice on public lands  
9 for many years, and contractors are accustomed to incorporating this activity into their  
10 bid prices.

11 In addition, even the “any” policy scenarios selected some plot-treatment combinations  
12 for which per acre net revenues are negative (i.e., merchantable and biomass revenue do  
13 not cover treatment and haul costs). These acres, representing about five percent of the  
14 treatment area, receive treatment because the resulting biomass production from those  
15 acres justifies construction of an additional forest bioenergy production facility. The  
16 additional facility lowers the haul cost for biomass delivered to that site (and possibly to  
17 other facilities), making the marginal contribution to aggregate net revenue positive for  
18 these negatively valued plot-treatments. This situation is analogous to the selection of  
19 below-cost timber sales to offset harvest flow constraints in harvest scheduling models.  
20 The selection of the negatively valued plot-treatments presents greater difficulty in  
21 designing appropriate subsidies, given that the benefits accrue to the operators of the  
22 forest bioenergy facilities and not to the landowners.

1 The model assumes a 10-year payback period for forest bioenergy production facilities,  
2 material requirements of conventional stoker/steam turbine systems, and single-entry fuel  
3 reduction treatments. We modeled the 10-year payback period by requiring a 10-year  
4 supply of biomass before a facility could be assigned to a site. Changing that assumption  
5 to a 20-year payback period would result in the same changes that occurred when moving  
6 from a 20 to a 40 MW minimum facility capacity (i.e., changing to a 20-year supply  
7 would double the supply requirements; we could simply label the 40 MW results as 20  
8 MW with 20-year supply). Modeling the material requirements on conventional  
9 technologies represents a relatively neutral assumption. Although conventional systems  
10 use more biomass per MW than does gasification technology, they have lower capital  
11 cost and are a proven technology. The assumption of a single-entry fuel reduction  
12 treatment underestimates the longer-term supply of biomass from the area. After 10 to 20  
13 years of growth, much of the area would require a second treatment to keep fire hazard  
14 low. The second-entry treatments would likely contain a lower ratio of merchantable to  
15 biomass yield (Hollenstein et al. 2001), and the effect on facility locations requires  
16 further study.

17 We set unit prices for delivered biomass and unit haul costs exogenously, relying on  
18 current market prices for delivered biomass and prevailing haul costs. An increase in  
19 energy prices would tend to increase the value of delivered biomass, and assuming  
20 competitive markets, increase the price paid by forest bioenergy production facilities.  
21 However, an increase in energy prices would also, via diesel fuel prices, increase unit  
22 haul costs, and indirectly affect harvest costs. Rather than trying to model the  
23 complexities of such countervailing trends, we've assumed that the effects would be

1 largely neutral regarding the model’s recommendations regarding treatments and plant  
2 locations. Experimentation with a wide range of biomass prices in an earlier version of  
3 the BioSum model that relied on heuristics rather than optimization produced only  
4 modest variation in treatment selection and products generated.

5 The consistency in the spatial distribution of facility assignments across scenarios  
6 suggests robustness in our finding that utilization of biomass produced in landscape-scale  
7 fuel treatments can be economically viable. In general, scenarios that treated more acres  
8 assigned additional facilities to new locations rather than relocating facilities that were  
9 selected in scenarios that treated fewer acres. The stability of model-selected locations  
10 across all scenarios indicates key attractor locations for forest bioenergy production  
11 facilities. This consistency also offsets concerns raised by other assumptions, and  
12 suggests the possibility of identifying key sites for initiating pilot projects (e.g., sites in  
13 areas dominated by public lands and consistently in solution across scenarios).

## 14 **CONCLUSIONS**

15 The FIA BioSum framework provides a statistically representative, data-based foundation  
16 for assessing the opportunities that fuel treatments can provide for expanding bioenergy  
17 generation capacity. The joint-optimization approach allows for simultaneous  
18 consideration of policy effects on forest outputs (e.g., net revenue) and facility  
19 assignments (location and capacity). Using FIA BioSum, we estimated that the  
20 application study area was capable of producing net revenue of 5.9 to 9.0 billion US\$,  
21 treatment of 2.8 to 8.1 million acres, biomass yield of 61 million to 124 million green  
22 tons, and bioenergy capacity of 496 to 1009 MW over a 10-year period. The FIA

1 BioSum scenarios also provided information on the production potential for merchantable  
2 wood products derivable from landscape-scale fuel treatments (8.4 to 12.4 billion cubic  
3 feet).

4 Analysis with a range of forest bioenergy-facility capacities revealed robustness in the  
5 optimal spatial distribution of bioenergy facilities. This robustness depends on the extent  
6 of the transportation network relative to the sources of woody biomass and on the ability  
7 to change plot-treatment combinations to define different biomass collection areas.

8 In the four-ecosection region in Oregon and California, the pricing structure analyses  
9 indicate that facilities with capacities below 15 MW are not competitive unless they can  
10 achieve conversion levels that are 94 percent as efficient as those achieved by larger  
11 facilities. The distribution of biomass production and extensive road network allows  
12 larger capacity facility assignment sufficiently closely spaced such that the savings in  
13 haul costs achievable via smaller and more ubiquitous facilities are negligible relative to  
14 the sacrifice in conversion efficiency.

15 Results of these optimizations do not form the basis of an optimal fuel treatment  
16 program. Those responsible for decisions leading to a treatment program will need to  
17 factor in the nonmarket benefits and costs of hazard reduction, the differences among  
18 landowners and land management agencies with respect to resource goals unrelated to  
19 fuel management, and the reluctance of investors to commit capital to constructing forest  
20 bioenergy production facilities without a reasonable expectation of sufficient supply. FIA  
21 BioSum does provide a starting point for land management agencies to address the latter,  
22 and a tool for further analysis.

1 **ACKNOWLEDGEMENTS**

2 We gratefully acknowledge the data collection efforts of the PNW-FIA data collection  
3 team; John Szymoniak and John Gerritsma for guidance on prescriptions; Roger Fight,  
4 Guy Pinjuv, Bruce Hartsough, and Glenn Murphy for assistance with STHARVEST and  
5 the harvest cost assumptions; Glenn Christensen, Nick Crookston and Don  
6 Vandendriesche for assistance with FVS; Dale Weyermann for assistance in modeling  
7 haul costs; and Jamie Barbour for fundraising and guidance. We appreciate those who  
8 provided critical funding support: Roger Condit of the Western Forest Leadership  
9 Coalition, David Cleaves of the National Fire Plan, and the USDA Forest Service PNW  
10 Research Station’s Forest Inventory and Analysis, Human and Natural Resources  
11 Interactions, and Focused Science Delivery Programs. We thank Tara Barrett, Susan  
12 Willits, and Lynn Starr for early review and suggestions; and David Martell and two  
13 anonymous referees for comments that improved the quality of the paper.

14 **REFERENCES**

15 Badger, P.C. 2002. Processing cost analysis for biomass feed stocks. Oak Ridge National  
16 Laboratory. ORLN/TM-2002/199. 52 p.

17 Bixby, R.E. 2002. Solving real-world linear programs: a decade and more of progress.  
18 Operations Research 50(1):3-15.

19 Cleaves, D.A., J. Martinez, and T.K. Haines. 2000. Influences on prescribed burning  
20 activity and costs in the national forest system. Gen. Tech. Rep. SRS-37. Asheville,  
21 NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 34

1 p.

2 Covington, W.W., and M.M. Moore. 1994a. Postsettlement changes in natural fire  
3 regimes: ecological restoration of old-growth ponderosa pine forests. *Journal of*  
4 *Sustainable Forestry* 2:153-181.

5 Covington, W.W., and M.M. Moore. 1994b. Southwestern ponderosa forest structure and  
6 resource conditions: changes since Euro-American settlement. *Forestry* 92(1):39-  
7 47.

8 Covington, W.W., P.Z. Fule, M.M. Moore, S.C. Hart, T.E. Kolb, J.N. Mast, S.S. Sackett,  
9 and M.R. Wagner. 1997. Restoring ecosystem health in ponderosa pine forests of  
10 the Southwest. *Journal of Forestry* 95(4):23-29.

11 Dantzig, G.B. 1963. *Linear Programming and Extensions*. Princeton University Press.  
12 New Jersey.

13 Dixon, G.E. 2002. South central Oregon/northeastern California prognosis geographic  
14 variant (SORNEC). Fort Collins, CO: U.S. Department of Agriculture, Forest  
15 Service, WO-Forest Management Service Center. 40 p.

16 Fight, R.D., X. Zhang, and B.R. Hartsough. 2003. Users guide for STHARVEST: software  
17 to estimate the cost of harvesting small timber. Gen. Tech. Rep. PNW-582.  
18 Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest  
19 Research Station. 12 p.

20 Freppaz, D., M. Riccardo, M. Robba, M. Rovattia, R. Sacilea, and A. Taramassoa. 2004.

- 1           Optimizing forest biomass exploitation for energy supply at a regional level.  
2           Biomass and Bioenergy 26:15-25.
- 3   Fried, J.S., G. Christensen, D. Weyermann, R.J. Barbour, R. Fight, B. Hiserote, and  
4           G. Pinjuv. 2005. Modeling opportunities and feasibility of siting wood-  
5           fired electrical generating facilities to facilitate landscape-scale fuel  
6           treatment with FIA BioSum. In: Bevers, M., T.M. Barrett, comps. Systems  
7           Analysis in Forest Resources: Proceedings of the 2003 Symposium;  
8           October 7-9, Stevenson, WA. Proceedings PNW-GTR-656. Portland, OR.  
9           U.S. Department of Agriculture, Forest Service, Pacific Northwest  
10          Research Station, pp. 195-204.
- 11   Fried, J.S. and G. Christensen. 2004. FIA BioSum: A tool to evaluate financial costs,  
12          opportunities, and effectiveness of fuel treatments. Western Forester 49(5):12-13.
- 13   Fried, J.S., J. Barbour and R. Fight. 2003. FIA BioSum: Applying a multi-scale evaluation  
14          tool in Southwest Oregon. Journal of Forestry 101(2):8.
- 15   Fried, J.S. 2003. Evaluating landscape-scale fuel treatment policies with FIA data.  
16          Western Forester 48(1):6-7.
- 17   Graham, R.L., B.C. English, and C.E. Noon. 2000. A geographic information  
18          system-based modeling system for evaluating the cost of delivered energy  
19          crop feedstock. Biomass and Bioenergy 18:309-329.

- 1 Guth, T. 2004. Biomass and renewable energy development potential. Biomass and  
2 Bioenergy 18:309-329. In: CIBO Corporate Energy Security and Sustainability  
3 Conference. Technical Seminar - Selected Papers. February 2004. Council of  
4 Industrial Boiler Owners. [Http://www.cibo.org/corpenergy/mainframe.htm](http://www.cibo.org/corpenergy/mainframe.htm). Last  
5 accessed 26 June 2006.
- 6 Hiserote, B., and K.L. Waddell. 2004. The PNW-FIA Integrated Database [database on  
7 CD]. Version 1.4.1. <http://www.fs.fed.us/pnw/fia/publications/data/data.shtml>. Last  
8 accessed 10 March 2005.
- 9 Hollenstein, K., R.L. Graham, and W.D. Shepperd. 2001. Biomass flow in western forests:  
10 simulating the effects of fuel reduction and presettlement restoration treatments.  
11 Journal of Forestry 99(10):12–19.
- 12 Noon C.E., and M.J. Daly 1996. GIS-based resource assessment with BRAVO. Biomass  
13 and Bioenergy 10(2-3):101-109.
- 14 PUBLIC LAW 108-148-DEC. 3, 2003. 117 STAT. 1887. 108th Congress. Healthy  
15 Forests Restoration Act of 2003.
- 16 Reinhardt, E. and N.L. Crookston (Technical Editors). 2003. The fire and fuels extension  
17 to the forest vegetation simulator. Gen. Tech. Rep. RMRS-116. Ogden, UT: U.S.  
18 Department of Agriculture, Forest Service, Rocky Mountain Research Station. 209  
19 p.
- 20 Schmidt, K.M., J.P. Menakis, C.C. Hardy, W.J. Hann, and D.L. Bunnell. 2002.  
21 Development of coarse-scale spatial data for wildland fire and fuel management.

- 1 Gen. Tech. Rep. RMRS-87. Ogden, UT: U.S. Department of Agriculture, Forest  
2 Service, Rocky Mountain Research Station. 41p.
- 3 Smith-Mateja, E. 2004. East Cascades variant of the forest vegetation simulator. Fort  
4 Collins, CO: U.S. Department of Agriculture, Forest Service, WO-Forest  
5 Management Service Center. 32 p.
- 6 SVEBIO. 2003. Focus Bioenergy – A Review. No.1. Available at  
7 [http://www.svebio.se/English/Focus%20Bioenergy/Fokus\\_Bioenergi\\_1eng.pdf](http://www.svebio.se/English/Focus%20Bioenergy/Fokus_Bioenergi_1eng.pdf).  
8 Last accessed 10 March 2005.
- 9 Stage, A.R. 1973. Prognosis model for stand development. Res. Pap. INT-137. Ogden,  
10 UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and  
11 Range Experiment Station. 14 p.
- 12 Wall, L., T. Christiansen, and J. Orwant. 2000. Programming Perl (3rd Edition). O'Reilly  
13 and Associates, Inc. Cambridge, MA.
- 14 Winter, G.J., and J.S. Fried. 2000. Homeowner perspectives on fire hazard, responsibility,  
15 and management strategies at the wildland-urban interface. *Society and Natural*  
16 *Resources* 13: 33-49.
- 17 Wykoff, W.R., N.L. Crookston, and A.R. Stage. 1982. User's guide to the stand Prognosis  
18 model. Gen. Tech. Rep. INT-133. Ogden, UT: U.S. Department of Agriculture,  
19 Forest Service, Intermountain Forest and Range Experiment Station. 112 p.

1 Table 1. Fuel treatment prescriptions, representing two treatment approaches

Prescription	Density Reduction					Fuel Reduction			
	A	B	C	D	E	F	G	H	J
Target residual basal area (ft <sup>2</sup> )	125	125	90	90	90	80	60	60	60
Maximum allowed dbh for harvest trees (in)	21	none	21	16	none	21	none	21	10

- 1 Table 2. Results of minimum facility capacity scenarios for net revenue, merchantable  
 2 and biomass production, acres treated by effectiveness, and forest bioenergy capacity

	Scenario label			
	15MWMin	20MWMin	40MWMin	60MWMin
Minimum capacity (MW)	15	20	40	60
Net revenue (US\$*10 <sup>9</sup> )	8.97	8.94	8.82	8.73
Merchantable net rev (US\$*10 <sup>9</sup> ) <sup>1</sup>	7.68	7.71	7.66	7.73
Biomass net revenue (US\$*10 <sup>9</sup> ) <sup>1</sup>	1.29	1.23	1.16	1.00
Merchantable volume (10 <sup>9</sup> *ft <sup>3</sup> )	10.96	10.93	10.95	10.89
Delivered biomass (10 <sup>6</sup> *gton)	83.23	81.21	83.93	79.60
Acres treated (10 <sup>6</sup> )	4.50	4.49	4.51	4.40
Highly effective acres (10 <sup>6</sup> )	2.55	2.53	2.54	2.51
Number of facilities	41	31	17	10
Bioenergy capacity (MW)	678	661	683	643

- 3 <sup>1</sup> Treatment costs are only deducted from merchantable gross revenue. Biomass net revenue equals  
 4 delivered value minus haul costs.

1 Table 3. Result of policy scenarios for net revenue, merchantable and biomass  
 2 production, acres treated by effectiveness, and forest bioenergy capacity (with 20 MW  
 3 minimum capacity constraint)

	Scenario label			
	any-mod+	all-mod+	any-high	all-high
Constraint on acres treated <sup>1</sup>	Any	All	Any	All
Constraint on effectiveness <sup>2</sup>	mod/high	mod/high	high	high
Net revenue (US\$*10 <sup>9</sup> )	8.94	6.65	7.15	5.88
Merchantable net rev (US\$*10 <sup>9</sup> ) <sup>3</sup>	7.71	4.74	6.24	4.61
Biomass net revenue (US\$*10 <sup>9</sup> ) <sup>3</sup>	1.23	1.92	0.91	1.27
Merchantable volume (10 <sup>9</sup> *ft <sup>3</sup> )	10.93	12.41	8.35	9.22
Delivered biomass (10 <sup>6</sup> *gton)	81.21	123.87	60.92	84.40
Acres treated (10 <sup>6</sup> )	4.49	8.12	2.84	4.05
Highly effective acres (10 <sup>6</sup> )	2.53	3.21	2.84	4.05
Number of facilities	31	47	23	30
Bioenergy capacity (MW)	661	1009	496	688

4 <sup>1</sup>“Any” allows the model to select optimal number of acres to treat; “all” requires treatment of all acres that  
 5 meet effectiveness constraint.

6 <sup>2</sup>Effectiveness refers to the CI/TI criteria, and limits acres considered in analysis; with high constraint, only  
 7 highly effective acres are available for harvest.

8 <sup>3</sup>Treatment costs are only deducted from merchantable gross revenue. Biomass net revenue equals  
 9 delivered value minus haul costs.

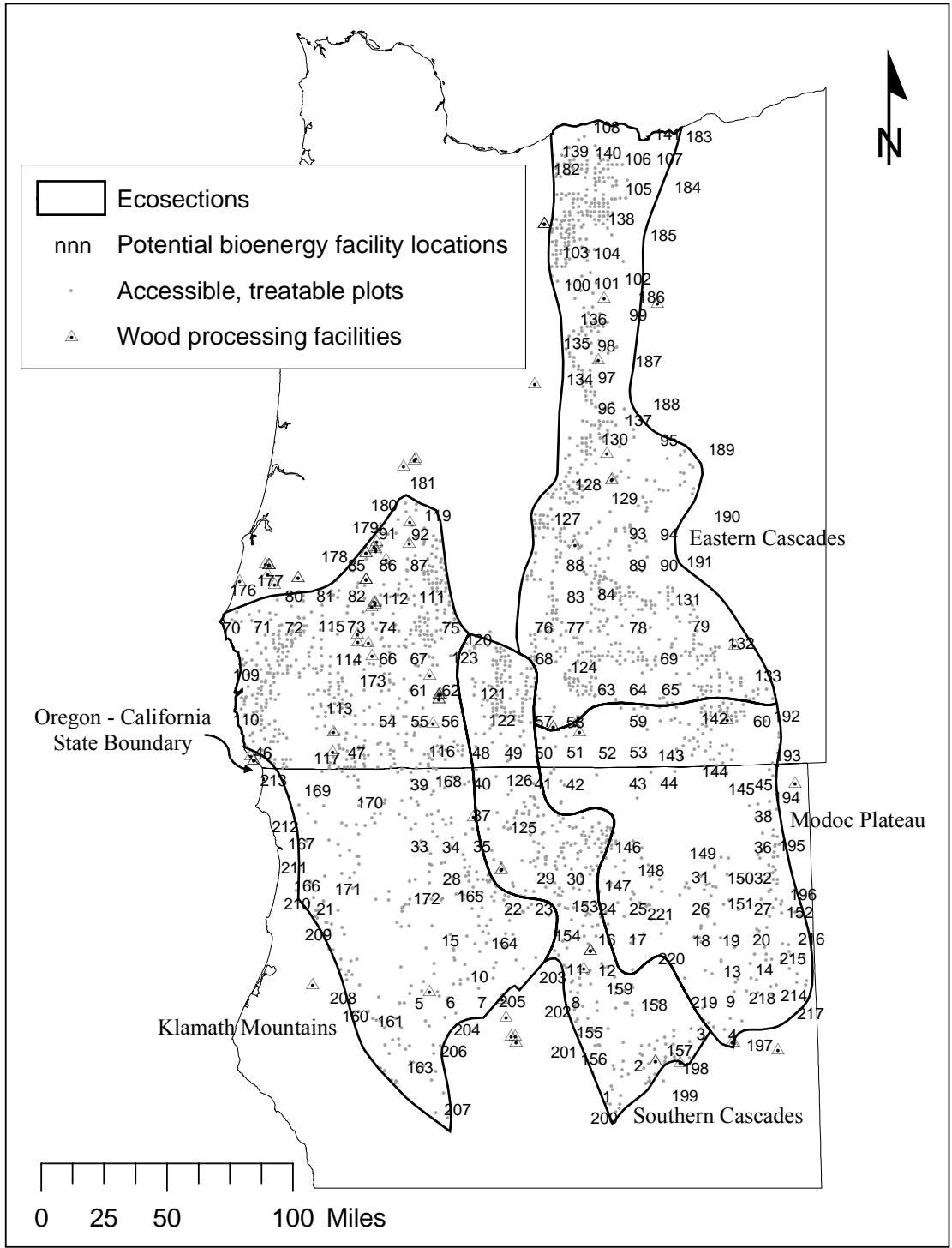


Figure 1.

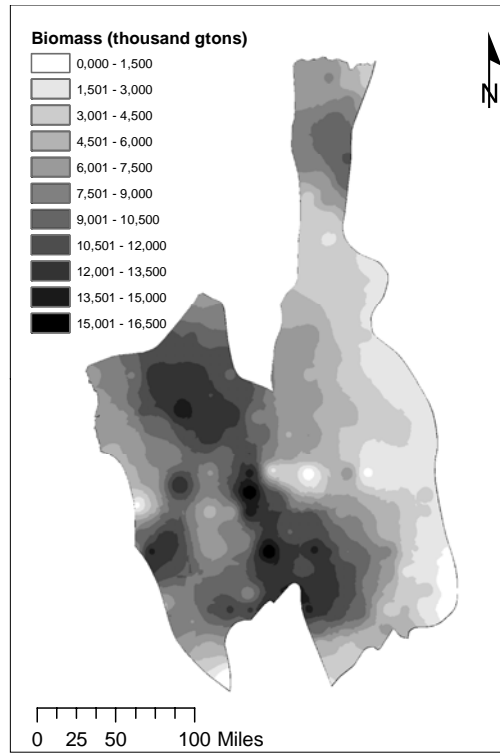
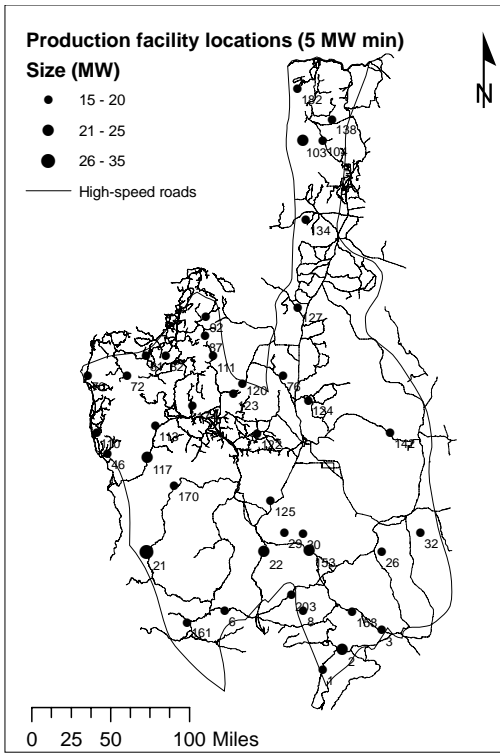


Figure 2.

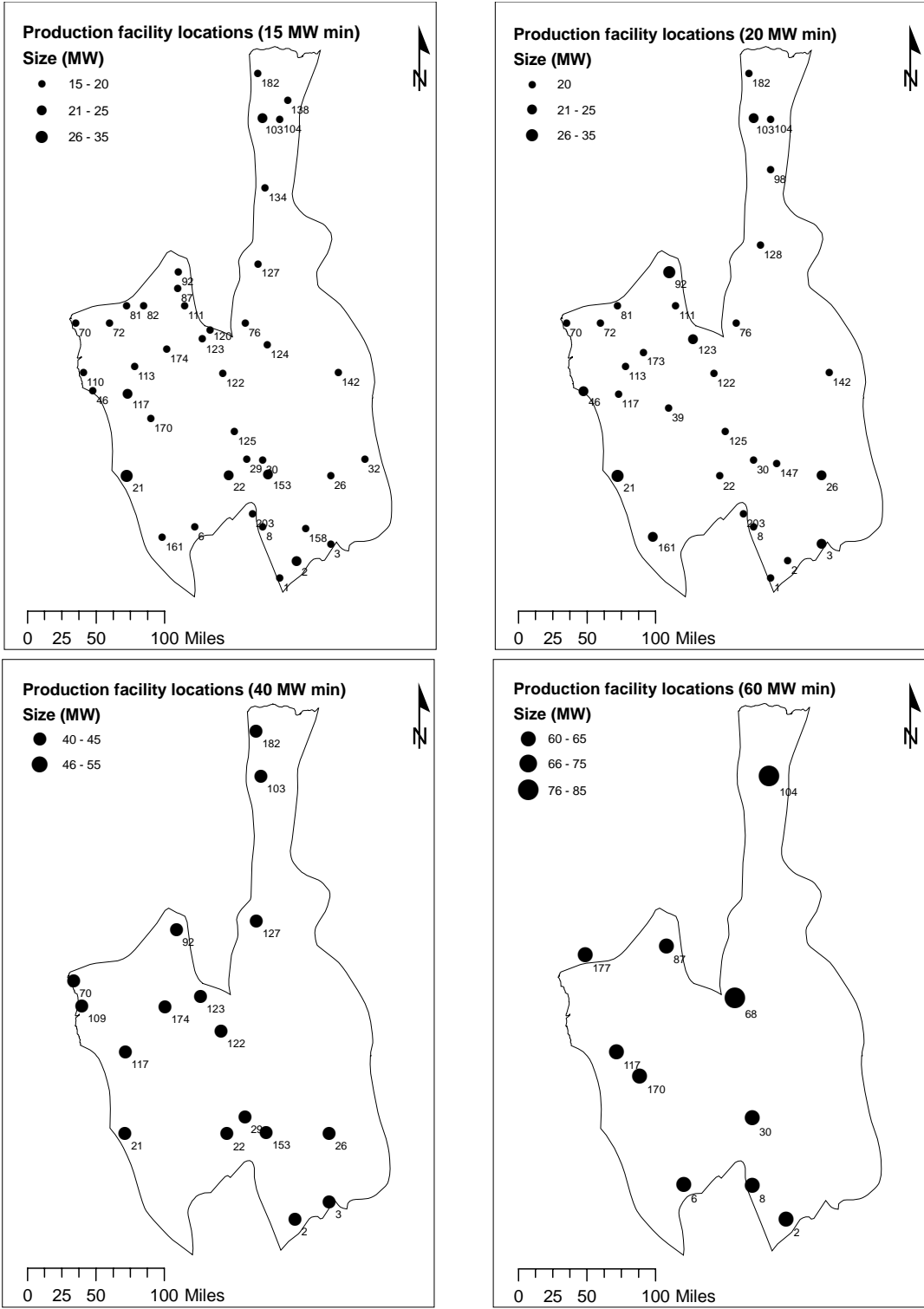


Figure 3.

1 *Figure captions*

2

3 Figure 1. The four ecosection study area, with potential forest bioenergy production  
4 facility sites, accessible plots, and existing wood processing facilities considered in this  
5 analysis

6

7 Figure 2. a) Assigned forest bioenergy production facility locations (for 5MW minimum  
8 capacity) and high-speed road network; b) potential biomass accumulation gradient

9

10 Figure 3. Assigned forest bioenergy production facility locations and capacity for  
11 minimum capacity constraints of 15, 20, 40, and 60 MW