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

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ABSTRACT

Landscape-scale fuel treatments for forest fire hazard reduction potentially produce large quantities of material suitable for biomass energy production. The analytic framework FIA BioSum addresses this situation by developing detailed data on forest conditions and production under alternative fuel treatment prescriptions, and computes haul costs to alternative sites at which forest biomass-based energy production facilities could be constructed. This research presents a joint-optimization approach that simultaneously selects acres to be treated by fuel treatment prescription and assigns bioenergy production facility locations and capacities. Effects of alternative fuel treatment policies on fuel treatment effectiveness, economic feasibility, material produced, generating capacity supported, and the location and capacity of assigned facilities are evaluated. We applied this framework to a 28-million-acre, four-ecosystem landscape in central Oregon and northern California. Using a maximum net revenue objective function while varying acres treated and effectiveness benchmarks, we found the study area capable of producing estimated net revenue of 5.9 to 9.0 billion US$, treatment of 2.8 to 8.1 million acres, biomass yield of 61 million to 124 million green tons, and bioenergy capacity of 496 to 1009 MW over a 10-year period. Results also suggest that unless small-capacity (< 15 MW) facilities achieve efficiencies over 90 percent of what large-capacity facilities can achieve, they do not represent a viable alternative, given the large amount of biomass removed. Analysis of a range of facility capacities revealed robustness in the optimal spatial distribution of forest bioenergy production facilities.

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

INTRODUCTION

Historical practices starting with European settlers (e.g., overgrazing in the late 1800s, selective timber harvests, and fire suppression) have transformed vast areas of forest ecosystems in the western United States to the point that they have significantly departed from the historical range. Significant changes in structure and function of ponderosa pine and dry mixed-conifer forests have resulted in increased fire severity and size (Covington and Moore 1994a, 1994b, Covington et al. 1997). Currently, 43 percent of the conifer forests with high-frequency low-severity fire regimes are at high risk of losing key ecosystem components; an additional 53 percent are at moderate risk (Schmidt et al. 2002). The resulting increase in large, stand-replacing fires has intensified interest in assessing the feasibility of landscape-scale fuel treatment. Doubts have grown about the feasibility of widespread use of prescribed fire owing to concerns about air quality, liability, narrow windows of opportunity to implement treatments, and potentially undesirable fire effects (Winter and Fried 2000, Cleaves et al. 2000). For most forestry professionals and most of the public, fuel treatment has become virtually synonymous with thinning of the forests to reduce fire severity and the likelihood of stand-replacing fire, especially since the advent and passage of the Healthy Forests Restoration Act of 2003.

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

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

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

THE ANALYTICAL SYSTEM, FIA BIOSUM

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

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

Database Components

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

Basic spatial data used to assess haul costs consist of locations of inventory plots and potential biomass processing sites, a spatially complete coverage of broad landowner class (e.g., private, national forest, other public), and a comprehensive coverage of the transportation system that includes unit costs of transport over each link. We tessellate the vector transportation cost coverage into 250-m grid cells, with each cell's value set to the cost per ton-mile of traversing the cell on the least-cost transportation link in that cell (cells containing no roads are assigned infinite haul cost). After experimenting with a range of grid cell sizes, we chose 250 meters because it performed well in bridging artifact gaps in the road network without undue underestimation of haul cost due to spurious connections (e.g., roads running along opposite sides of a river). The resulting impedance surface forms the basis of haul-cost calculations. For each potential forest bioenergy facility location, we use the haul-cost surface to generate a cost accumulation grid, and perform an overlay on plot locations to arrive at haul cost to that facility from every plot in a study area. This 250-m impedance surface was used only to estimate haul cost parameters; it was not integrated into the simulation or optimization models.

Simulation Components

We use the Forest Vegetation Simulator (FVS) (Stage 1973, Wykoff et al. 1982) to simulate fuel treatment prescriptions and, via the integrated Fire and Fuels Extension (FFE) (Reinhardt and Crookston 2003), assess the likely change in fire hazard these treatments would produce. Fifteen FVS variants are available for the western United States, making the system applicable to all forest regions in this area. The fuel treatment prescriptions applied in FVS generate harvested tree lists for each plot. Postprocessing programs compute plot and tree attributes used at later stages in the analysis (e.g., slope, number of stems harvested, average stem size harvested, and volume and biomass by species and size class). The FFE models calculate fire-related stand attributes, including indices of crown fire potential for each plot, specifically, torching index (TI) and crowning index (CI). The 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. The CI is the wind speed at which a crown fire could be expected to be sustained and is heavily influenced by crown bulk density. The system uses increases in CI or TI as measures of treatment effectiveness in regard to fire hazard reduction (i.e., higher wind speed thresholds imply *lower* hazard because high winds occur less frequently).

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

The spatially modeled haul costs are combined with the outputs from FVS, FFE, and STHARVEST to form a database containing simulation outcomes for each plot-prescription combination and for each potential facility location. These outcome data include biomass and merchantable yields, harvest and haul costs, gross and net revenues, and change in TI and CI. The database information on the plot-prescription combinations and potential facility locations determine most of the decision variables and the size of the optimization model; the associated data provide technical coefficients used in the model.

THE OPTIMIZATION MODEL

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

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

Objective Functions

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

Harvest Decision and Accounting Variables

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

$$\sum_{j=1}^{J} x_{lj} = A_l \qquad \forall l, l = 1, \cdots, L \tag{1}$$

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

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

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

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

Forest Bioenergy Production Facility Formulation

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

Biomass transfer and forest bioenergy production facility accumulation equations

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

$$\sum_{j=1}^{J} b_{lj} x_{lj} - \sum_{k} B_{lk} - AD_l = 0 \qquad \forall l, l = 1,...,L; \forall k \in \{k \mid h_{lk} \le HL\} \tag{3}$$

$$\sum_{l=1}^{L} B_{lk} - P_k = 0 \qquad \forall k, k = 1,...,K \tag{4}$$

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

Forest bioenergy facility selections equations

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

$$P_k - (\mathrm{PL})\,IP_k \geq 0 \qquad \forall k, k = 1, \cdots, K;\ IP_k \in \{0,1\} \tag{5}$$

$$P_k - (\mathrm{PU})\,IP_k \leq 0 \qquad \forall k, k = 1, \cdots, K;\ IP_k \in \{0,1\} \tag{6}$$

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

Biomass pricing equations

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

$$P_k - (\mathrm{PB}_1)\,IN1_k \geq 0 \qquad \forall k, k = 1, \cdots, K;\ IN1_k \in \{0,1\} \tag{7}$$

$$P_k - (\mathrm{M})\,IN1_k \leq (\mathrm{PB}_1) \qquad \forall k, k = 1, \cdots, K;\ IN1_k \in \{0,1\} \tag{8}$$

$$P_k - (\mathrm{M})\,IN1_k - PW1_k \leq 0 \qquad \forall k, k = 1, \cdots, K; IN1_k \in \{0,1\} \tag{9}$$

$$c_0 P_k - c_1 PW1_k - VAL_k = 0 \qquad \forall k, k = 1, \cdots, K \tag{10}$$

Equations 7 and 8 set the value of the binary variable, $IN1_k$, to 1 if the delivered biomass exceeds PB_1, the price-break level, and 0 otherwise, in a manner analogous to the site selection equations. M is an arbitrarily large constant relative to possible values of P_k. Equation 9 sets a penalty variable, $PW1_k$, equal to the delivered biomass weight when the delivered weight is less than the price-break level; if biomass exceeds the price break, the large value (M)$IN1_k$ allows the penalty variable to equal zero. Equation 10 uses this penalty variable to lower the total value of biomass VAL_k, by assessing a per-unit price penalty, c_1, against the full per-unit price, c_0. This approach accommodates additional breaks by adding, for each price break, another set of equations 7, 8, and 9, with the new price break, binary variable, and penalty variable, and by adding a corresponding penalty variable term to equation 10.

APPLICATION TO A CASE STUDY

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

Model Implementation

Inventory data

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

Simulation Parameters and Assumption

We used two FVS/FFE variants, south-central Oregon and northeastern California (Dixon 2002) and east Cascades (Smith-Mateja 2004), to simulate fuel treatments. Nine fuel treatment prescriptions (table 1) representing two treatment approaches were developed in consultation with fire and fuel specialists and applied to all plots for which they were valid. Five of the treatments focused on density reduction to thwart propagation of crown fires, and involved thinning proportionately across all diameter classes to a target residual basal area, with 70 percent of the harvested basal area removed from trees 5.5 to 14.5 inches in diameter at a height of 4.5 feet (dbh). The other four focused on ladder fuels reduction to reduce risk of crown fire initiation, and involved thinning from below (trees > 5.5 inches dbh) to a target residual basal area. These four treatments had a range of residual basal area targets (60 to 125 ft^2/ac) and maximum acceptable diameters for cut trees (10 in. to no limit). If the maximum diameter limit was reached before the target residual basal area, then the latter was not achieved. Because the most aggressive treatment had a residual basal area of 60 ft^2/ac, plots with less basal area would be ineligible for treatment and were excluded from the analysis. In addition, 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.

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

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

1. Pretreatment index ≤ 25, posttreatment index ≥ 25, and index change ≥ 10 mph,
2. Pretreatment index ≤ 25 and index change ≥ 20 mph,
3. Pretreatment index between 25 and 50, and index change ≥ 15 mph, or
4. Pretreatment index ≥ 50 and index change ≥ 20 mph.

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

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

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

Potential forest bioenergy facility locations and haul cost

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

Optimization model specifications

We included all plot-treatment combinations that achieved moderately effective fire hazard reduction, resulting in 11,627 plot-treatment decision variables. Haul-cost limits were set at 36 US$/green ton (gton) to allow for relatively large biomass supply areas. Each of the 221 potential sites could collect biomass from an average of 2163 plots. Each of the 2396 plots could deliver to an average of 205 potential sites. This approach resulted in 490,970 biomass transfer columns, the largest component of the optimization model. We based facilities' biomass requirements on conventional stoker/steam turbine systems (Badger 2002). We calculated the minimum biomass supply needed to select a potential facility site based on a 10-year operating life and a standard operating level of 300 days per year (e.g., a 20 MW facility requires 2,457,000 green tons of biomass). We effectively set no upper limit on facility capacity, by setting the upper limit in the site-selection equation (eq. 6) to an arbitrarily high constant. To reflect efficiency differences by facility capacity (Badger 2002), we specified three price levels defined by price breaks at 7.5 and 15 MW. Prices were set at 9, 13, and 18 US$/gton for facilities capable of producing ≤ 7.5MW, between 7.5 and 15 MW, and ≥ 15 MW, respectively. The pricing structure is used to explore the tradeoff between less efficient facilities and lower transportation cost achieved by locating a greater number of smaller facilities closer to the biomass. We based the pricing structure on current delivered prices in California (Guth 2004).

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

Scenarios simulated with the optimization mode

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

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

Results

Initial solution and price sensitivity analysis

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

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

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

Minimum facility capacity scenarios

We evaluated consistency in facility locations by simulating minimum capacity constraints of 15, 20, 40, and 60 MW (scenarios 15MWMin, 20MWMin, 40MWMin, and 60MWMin in figure 3). All scenarios maximized net revenues and had no restrictions on plot-treatment combinations that could be selected. Note that the 15MWMin scenario's solution matches the initial model owing to the effects of pricing structure discussed above. Across the first three scenarios, increases in the minimum capacity decreased the number of facilities (from 41 to 31 to 17) with little change in the spatial pattern of facility assignments: 84 percent of facility assignments in scenario 20MWMin and 94 percent of the facility assignments in scenario 40MWMin were also assigned facilities in the 15MWMin scenario. Facility assignment patterns also remained consistent between the second and third scenarios: 71 percent of the 40MWMin locations were also assigned in the 20MWMin scenario. Comparing the 15MWMin and 20MWMin scenarios, only two of the five new sites in scenario 20MWMin represented significant relocations (#39 and #98). Comparing scenario 20MWMin to 40MWMin, only one of the five new sites showed a significant shift (#109). The fourth scenario, (60MWMin), showed greater shifts in facility assignments. Whereas 80 percent of this scenario's facility site assignments were also assigned in scenario 15MWMin, only 50 and 20 percent were assigned in scenarios 20MWMin and 40MWMin, respectively. Some facilities in the 60MW scenario were assigned quite different capacities and locations. For example, the 78MW facility at site 68 represents a large shift in location and an increase in capacity relative to the other scenarios.

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

Production, treatment area, and net revenue varied little across the minimum-capacity scenarios (table 2). In all scenarios, the majority of net revenue derives from the sale of merchantable wood (reported in the table as merchantable net revenue). The change in minimum capacity had little effect on merchantable volume and merchantable net revenue, accounting for the small variation in net revenue. As the minimum-capacity constraint was increased, net revenue from biomass decreased. Comparing the lowest minimum capacity scenario (15MWMin) to the highest (60MWMin), biomass net revenue decreased by 22 percent, accounting for the 2 percent drop in overall net revenue. Although biomass revenues decreased by 22 percent, delivered biomass only decreased by 4 percent, resulting in a 5-percent decrease in bioenergy capacity. The uniformity in delivered biomass across all four scenarios occurred, in part, because an increase in minimum facility capacity increased the optimal level of biomass to be processed (and produced) in sub-areas. For example, in the northern part of the study area (see figure 3), the 15MWMin and 20MWMin scenarios assigned four and three facilities with an overall bioenergy capacity of 69 and 64 MW. The 40MWMin and 60MWMin scenarios assigned two and one facilities, with the overall capacity of 80 and 85 MW. This result supports the concept that the joint-optimization provides a more accurate representation of constraint effects. As minimum facility capacity increased, choices of plot-treatment combinations were changed to maintain the highest net revenue by redefining optimal biomass collection areas. All four scenarios delivered all harvested biomass to forest bioenergy production facilities; none was eliminated by air-curtain destruction.

Policy scenarios

We developed four scenarios (any-mod+, all-mod+, any-high, all-high) to assess the impacts of alternative policies with respect to treatment effectiveness (moderate or high versus high effectiveness) and to whether or not all treatable acres are treated without regard to cost (any versus all acres treated). These scenarios also maximized net revenue, and used a 20 MW minimum-capacity constraint (using other minimum-capacity constraints produced similar results). The any-mod+ scenario represented the least constrained model in terms of treated acres and prescription choices, and achieved the highest net revenue (table 3). A policy requiring the treatment of all acres (scenario all-mod+) reduced net revenue by 26 percent (from 8.94 to 6.65 billion US$). This decline occurred because acres that have only negatively valued plot-treatment choices were forced into solution (i.e., some acres can only be treated at a cost). The requirement to treat all acres caused merchantable volume to increase by 14 percent, but merchantable net revenue decreased by 39 percent (because all harvest costs are deducted from the merchantable gross revenue). Delivered biomass increased by 49 percent (83.21 to 123.87 million green tons). Additional facilities were assigned to process the biomass (all harvested biomass was used by facilities), but this utilization only partially offset the costs. The policy required treatment of 8.12 million acres, with 3.21 million receiving highly effective treatments. The policy also provided the largest bioenergy capacity, 1009 MW.

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

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

Discussion

The application of FIA BioSum to the four-ecosection study area in central Oregon and northern California indicates that landscape-scale treatments can provide sufficient biomass to support significant capacity in bioenergy facilities. If built, forest bioenergy production facilities could be part of the solution to the large quantity of small-diameter material generated by these treatments. Given our model assumptions, the facilities are financially viable, and payments for delivered biomass could provide a small offset for treatment costs. More importantly, biomass utilization would avoid onsite burning and provide other social benefits (e.g., jobs, renewable energy capacity, improving air quality, and reducing greenhouse gas emissions). With current pollution technology, forest bioenergy production facilities meet current California air-quality standards, as indicated by the 37 biomass power plants located throughout California. From a strictly financial perspective, all simulated scenarios generated positive net revenue, which bodes well for the viability of landscape-scale fuel treatment in this region. Even requiring treatment on all 8.12 million acres for which moderately effective hazard reduction can be achieved resulted in positive net revenue. This scenario could produce 124 million green tons of biomass, with a bioenergy capacity to serve approximately 100,000 homes (1009 MW) for ten years.

These results are optimistic in that we assume all acres represented in the model can, in fact, be treated via the prescriptions specified in this model. Three million of these eight million acres are privately owned forest. The net revenue results represent social net revenue, without considering the distribution of costs and benefits. Feasibility largely depends on the aggregate value of the merchantable wood recovered in these treatments offsetting the aggregate treatment costs. The latter are modeled for the treatment as a whole rather than modeling merchantable and biomass costs separately. In practice, private owners may not choose to harvest and deliver biomass-size material (which rarely pays its own way to the loading area, let alone to the processing facility), without compensation for the additional costs. Cost for treating the nonmerchantable material would still occur, e.g., in the form of on-site burning, but could well be lower than the extraction costs accounted for by FIA BioSum. If transaction costs were negligible, offsetting these extraction costs on private lands is theoretically addressable, given the overall positive social net revenue anticipated with reducing fire hazard. The practicality of addressing the problem depends on the transaction costs of setting up a subsidy mechanism to favor the social optimum over the private optimum. With public lands, the charging of all treatment costs to the merchantable harvest is not problematic, as moving nonmerchantable material to a loading area has been an accepted practice on public lands for many years, and contractors are accustomed to incorporating this activity into their bid prices.

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

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

We set unit prices for delivered biomass and unit haul costs exogenously, relying on current market prices for delivered biomass and prevailing haul costs. An increase in energy prices would tend to increase the value of delivered biomass, and assuming competitive markets, increase the price paid by forest bioenergy production facilities. However, an increase in energy prices would also, via diesel fuel prices, increase unit haul costs, and indirectly affect harvest costs. Rather than trying to model the complexities of such countervailing trends, we've assumed that the effects would be largely neutral regarding the model's recommendations regarding treatments and plant locations. Experimentation with a wide range of biomass prices in an earlier version of the BioSum model that relied on heuristics rather than optimization produced only modest variation in treatment selection and products generated.

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

CONCLUSIONS

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

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

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

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

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

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Table 1. Fuel treatment prescriptions, representing two treatment approaches

	Density Reduction					Fuel Reduction			
Prescription	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 allowed dbh for harvest trees (in)	21	none	21	16	none	21	none	21	10

Table 2. Results of minimum facility capacity scenarios for net revenue, merchantable 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$*$10^9$)	8.97	8.94	8.82	8.73
Merchantable net rev (US$*$10^9$)[1]	7.68	7.71	7.66	7.73
Biomass net revenue (US$*$10^9$)[1]	1.29	1.23	1.16	1.00
Merchantable volume (10^9*ft^3)	10.96	10.93	10.95	10.89
Delivered biomass (10^6*gton)	83.23	81.21	83.93	79.60
Acres treated (10^6)	4.50	4.49	4.51	4.40
Highly effective acres (10^6)	2.55	2.53	2.54	2.51
Number of facilities	41	31	17	10
Bioenergy capacity (MW)	678	661	683	643

[1] Treatment costs are only deducted from merchantable gross revenue. Biomass net revenue equals delivered value minus haul costs.

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

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

[1] "Any" allows the model to select optimal number of acres to treat; "all" requires treatment of all acres that meet effectiveness constraint.

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

[3] Treatment costs are only deducted from merchantable gross revenue. Biomass net revenue equals delivered value minus haul costs.

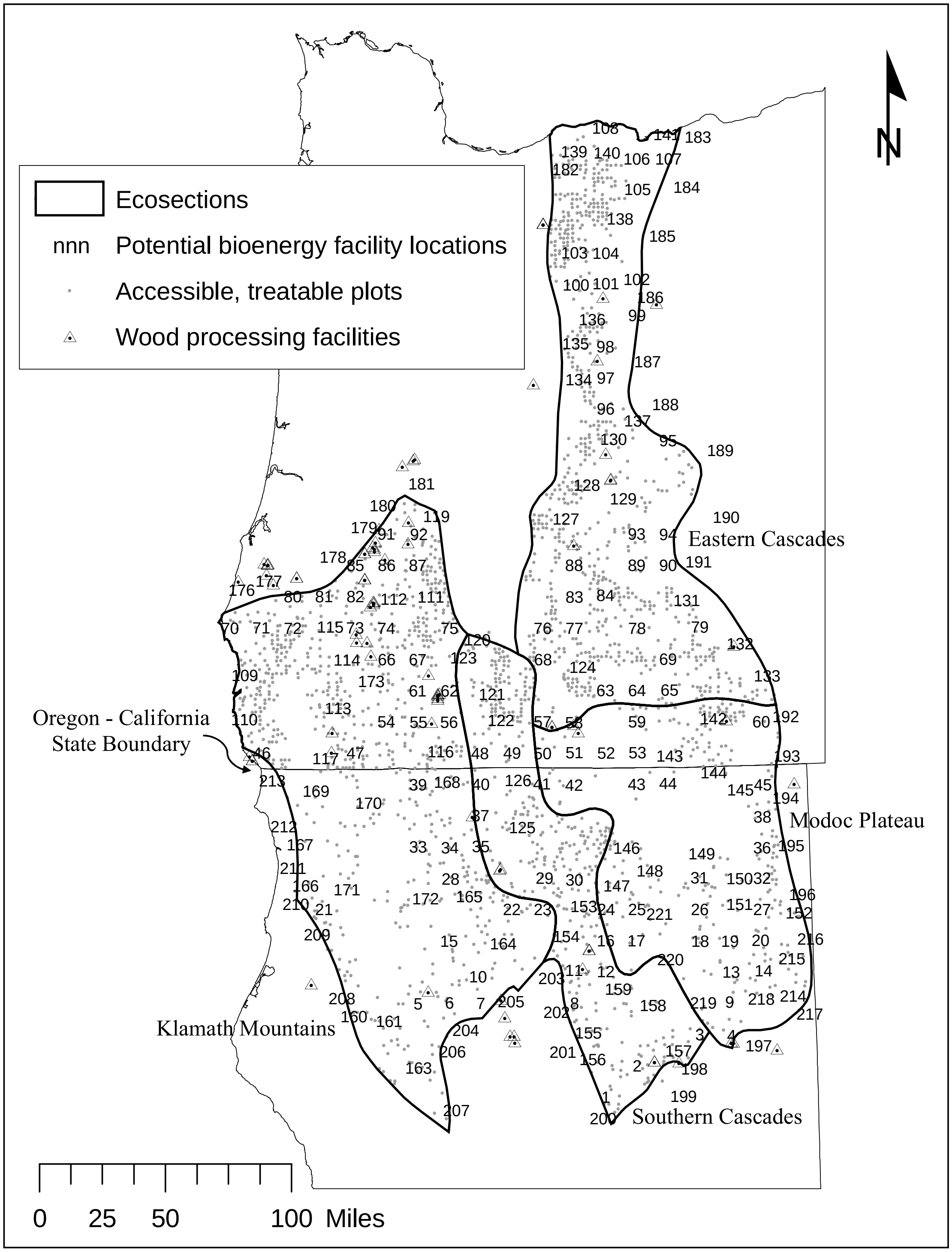
Ecosections
nnn Potential bioenergy facility locations
Accessible, treatable plots
Wood processing facilities
N
Eastern Cascades
Modoc Plateau
Klamath Mountains
Southern Cascades
Oregon - California
State Boundary
0 25 50 100 Miles

Figure 1.

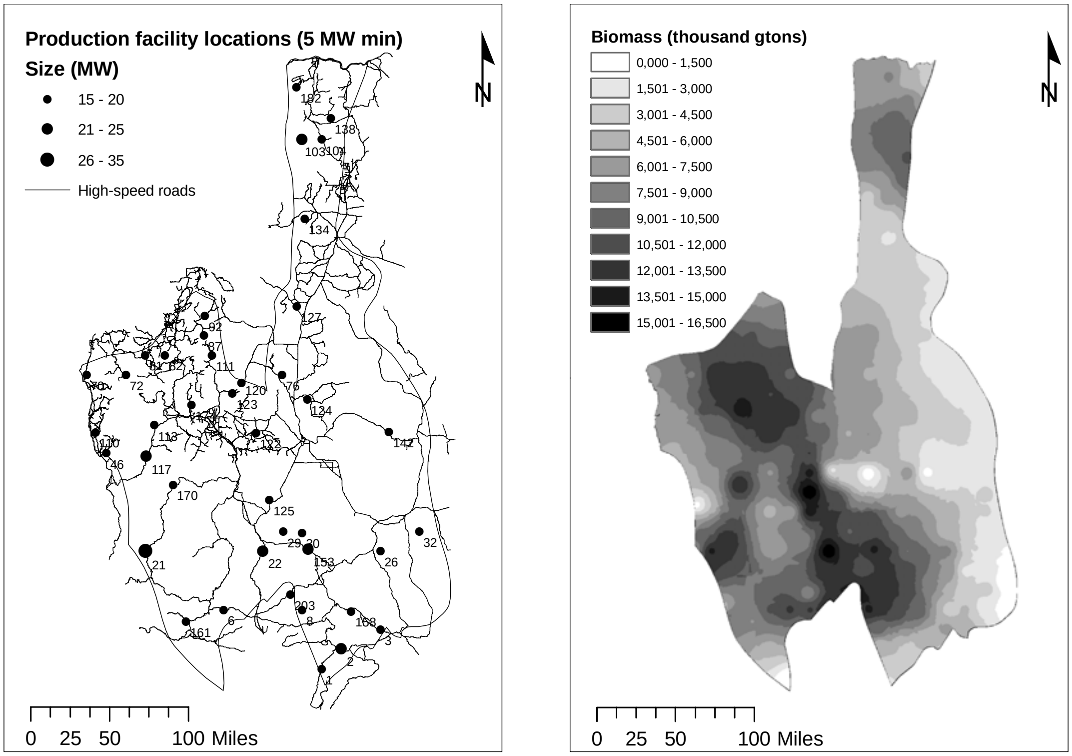
Production facility locations (5 MW min)
Size (MW)
15 - 20
21 - 25
26 - 35
High-speed roads
0 25 50 100 Miles
Biomass (thousand gtons)
0,000 - 1,500
1,501 - 3,000
3,001 - 4,500
4,501 - 6,000
6,001 - 7,500
7,501 - 9,000
9,001 - 10,500
10,501 - 12,000
12,001 - 13,500
13,501 - 15,000
15,001 - 16,500
0 25 50 100 Miles

Figure 2.

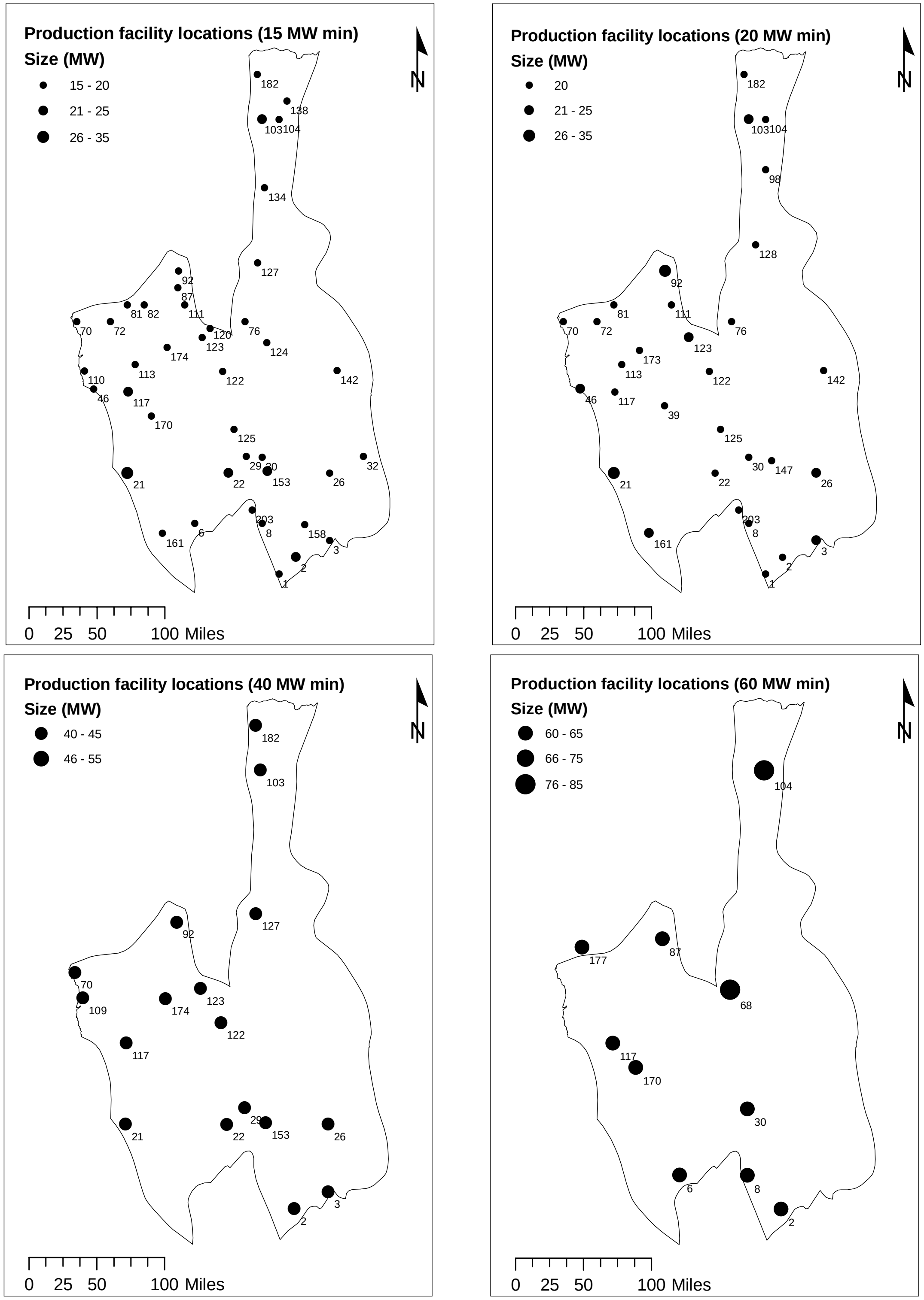
Production facility locations (15 MW min)
Size (MW)
15 - 20
21 - 25
26 - 35
N
182 138 103 104 134 127 92 87 81 82 111 70 72 120 123 76 124 174 113 122 142 110 46 117 170 125 29 30 153 32 21 22 26 203 8 6 161 158 3 2 1
0 25 50 100 Miles
Production facility locations (20 MW min)
Size (MW)
20
21 - 25
26 - 35
N
182 103 104 98 128 92 81 111 70 72 76 123 173 113 122 142 46 117 39 125 30 147 21 22 26 203 8 161 3 2 1
0 25 50 100 Miles
Production facility locations (40 MW min)
Size (MW)
40 - 45
46 - 55
N
182 103 127 92 70 109 174 123 122 117 29 21 22 153 26 3 2
0 25 50 100 Miles
Production facility locations (60 MW min)
Size (MW)
60 - 65
66 - 75
76 - 85
N
104 177 87 68 117 170 30 6 8 2
0 25 50 100 Miles

Figure 3.

Figure captions

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

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

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