Journal of Forestry, 2019, 1–17
doi:10.1093/jofore/fvz033
Research Article - fire & fuels management
Received December 17, 2018; Accepted April 29, 2019
Advance Access publication June 5, 2019

OXFORD

Research Article - fire & fuels management

Estimating Biomass Availability and Cost When Implementing Forest Restoration with Tethered Harvest Systems

Joshua H. Petitmermet, Jeremy S. Fried, and John Sessions

Joshua H. Petitmermet (joshuapetitmermet@gmail.com), Mendocino Redwood Company, LLC, 850 Kunzler Ranch Road, PO Box 996, Ukiah, CA 95482. Jeremy S. Fried (jeremy.s.fried@usda.gov), USDA Forest Service, PNW Research Station, Forest Inventory and Analysis Program, 620 Southwest Main Street, Portland, OR 97205. John Sessions (john.sessions@oregonstate.edu), College of Forestry, Oregon State University, Corvallis, OR 97331.

Abstract

Using an adaptation of Forest Inventory and Analysis's BioSum framework, which models prospective management of forested landscapes using forest inventory data, we tested several fire-resistance-promoting restoration treatments, implemented with tethered cut-to-length harvest systems, for effectiveness and economic feasibility in the dry national forests of southern Oregon and northern California. Treatments elevated fire resistance on most forested area, primarily via increases in the separation of canopy and surface fuels and among tree crowns, and the most effective treatments could more than cover treatment cost with sales of wood in most stands. If, instead of disposal by burning at the landing, small-diameter wood was delivered to a biochar facility capable of paying US$50 per bone dry ton, this would increase the share of forest area on which treatment could break even from 61 percent to 67 percent, slightly more than the 66 achievable with a treatment subsidy of US$100 ac^{-1}. Potential treatment area appears to be currently constrained by institutional capacity, not treatment effectiveness, economics, opportunity, or need. Even with the currently modest scale of management activity, sufficient biochar feedstock is available in the upper Klamath Basin to supply at least one large-scale biochar facility over the next 20 years.

Keywords: fire resistance, fuel treatment feasibility, BioSum, Forest Inventory and Analysis, Forest Vegetation Simulator

Nearly two decades of frequent, extreme fires in the western United States have elevated awareness of fire hazard in federal forests (Stephens and Ruth 2005). This has led to acceptance of the potential for active forest management to reduce the incidence of stand-replacing crown fire and its many adverse effects while promoting forest resilience (Stephens et al. 2009, Safford et al. 2012, Toman et al. 2014). These adverse effects include greenhouse gas emissions, unhealthful air quality, soil loss, invasion by exotic plants, timber and habitat loss, and damage to infrastructure. Owing to their current structure and composition, 80 percent of dry mixed conifer forests in the western United States are rated as hazardous with respect to crown fire potential (Jain et al. 2012), with a third (nearly 10.9 million acres) on slopes exceeding 40 percent. Restoration on federal forest lands in the western United States typically focuses on changing fuel structure rather than maximizing wood volume or value extracted. Unlike traditional timber harvest operations, many of the trees removed in restoration treatments are small, have little to no market value, and incur a greater cost per unit

Management and Policy Implications

With tethered, mechanized harvest systems and prescriptions designed to significantly reduce stand density while retaining large trees and multistory characteristics, if present, most stands had one or more treatments that would be both effective in enhancing fire resistance and implementable at a cost lower than the revenues from sales of removed wood. Maintaining multistory structure as a goal results in more harvest of merchantable-sized trees, greater economic feasibility, and increased area that can be treated without subsidy. Even with a market for biochar, sales of biochar feedstock would be a tiny share of revenues, but would modestly expand the area over which self-paying treatment is possible. Even at current management return intervals of 100 years, sufficient feedstock would be available for a biochar facility to be viable; however, such long return intervals may preclude treatment effectiveness at landscape scale. At a return interval of 25 years, restoration treatments in the upper Klamath Basin could return 587 million present value dollars at a real 3 percent discount rate over 20 years and treat all the stands for which treatment would enhance resistance without any external subsidy. Future work is needed to better understand the impacts of logging residue from the cut-to-length operations modeled here, and the extent to which these might require additional, expense-incurring treatment.

volume. Although ambitious efforts to restore federal forests on gentle terrain have begun (e.g., the 1.2 million acres covered by northern Arizona's Four Forest Restoration Initiative, 4FRI 2018), the near absence of markets for small logs (<6 in. small-end diameter) presents formidable challenges in Arizona and much of the West. The continuing decline in sawmilling infrastructure and absence of chip-using industries have meant there is little to no demand for small logs and chips (Barbour et al. 1998, Wagner et al. 1998, Monserud et al. 2004, Stewart et al. 2004, UOW 2013). Although low-value wood can be disposed of in situ via burning, this can be costly and emits carbon. Restoration costs can be significantly higher on steep terrain, with cable harvesting costing two to three times as much as mechanized harvest on flat terrain (Fight and Barbour 2005, Arriagada et al. 2008).

Opportunities to reduce restoration costs are beginning to emerge. Tethered, ground-based mechanized harvest systems may reduce costs compared to manual chainsaw felling and cable yarding (Amishev 2016). Stampfer (2016) suggested that for thinning in central Europe, the harvest cost per cubic meter for a harvester and forwarder was one-half the cost of chainsaw felling, cable yarding, and processing at the landing. In addition, biochar, a long-lived carbon product produced through pyrolysis, offers a potential use for logs that are not merchantable because of the small size or noncommercial species. Biochar is useful in water filtration and as a soil amendment for commercial agriculture and home garden applications (Lehmann 2007, Biederman and Harpole 2013, Trippe et al. 2015). At a sufficiently low price, large quantities could be used in commercial agriculture, offering a possible pathway to longer C sequestration than on-site combustion (Campbell et al. 2018a). However, the seller's reservation price depends on biochar production costs (including feedstock). This reservation price depends on operational scale, which in turn depends on local feedstock availability and cost (Sessions et al. 2018). In this paper, we concentrate on biochar production. Campbell et al. (2018b) investigated several biochar use pathways, including biochar/biofuel, and concluded that the joint biochar/biofuel option required a significantly higher breakeven biochar product price than the biochar only pathway. Could a landscape like the Upper Klamath Basin in southern Oregon and northern California, which currently lacks markets for small-diameter wood, produce enough to supply a biochar facility, and if so, at what cost?

This paper evaluates multiple scenarios with respect to the biophysical potential for and economic feasibility of using active restoration management to reduce stand-replacing crown fire on approximately 1.9 million ac. of national forests in the upper Klamath Basin (Figure 1). The primary objective for each forested acre was to maximize crown fire resistance over a two-decade time horizon. A separate evaluation (Sessions et al. 2018) assessed the feasibility of siting a sizable biochar facility within this landscape (at Worden, OR) and relied on supply and marginal cost curves developed in this study to predict the quantity of biochar feedstock that could be supplied to such a facility.

Methods

Overview

Data from the USDA Forest Service's Forest Inventory and Analysis (FIA) Program offer a large, highly

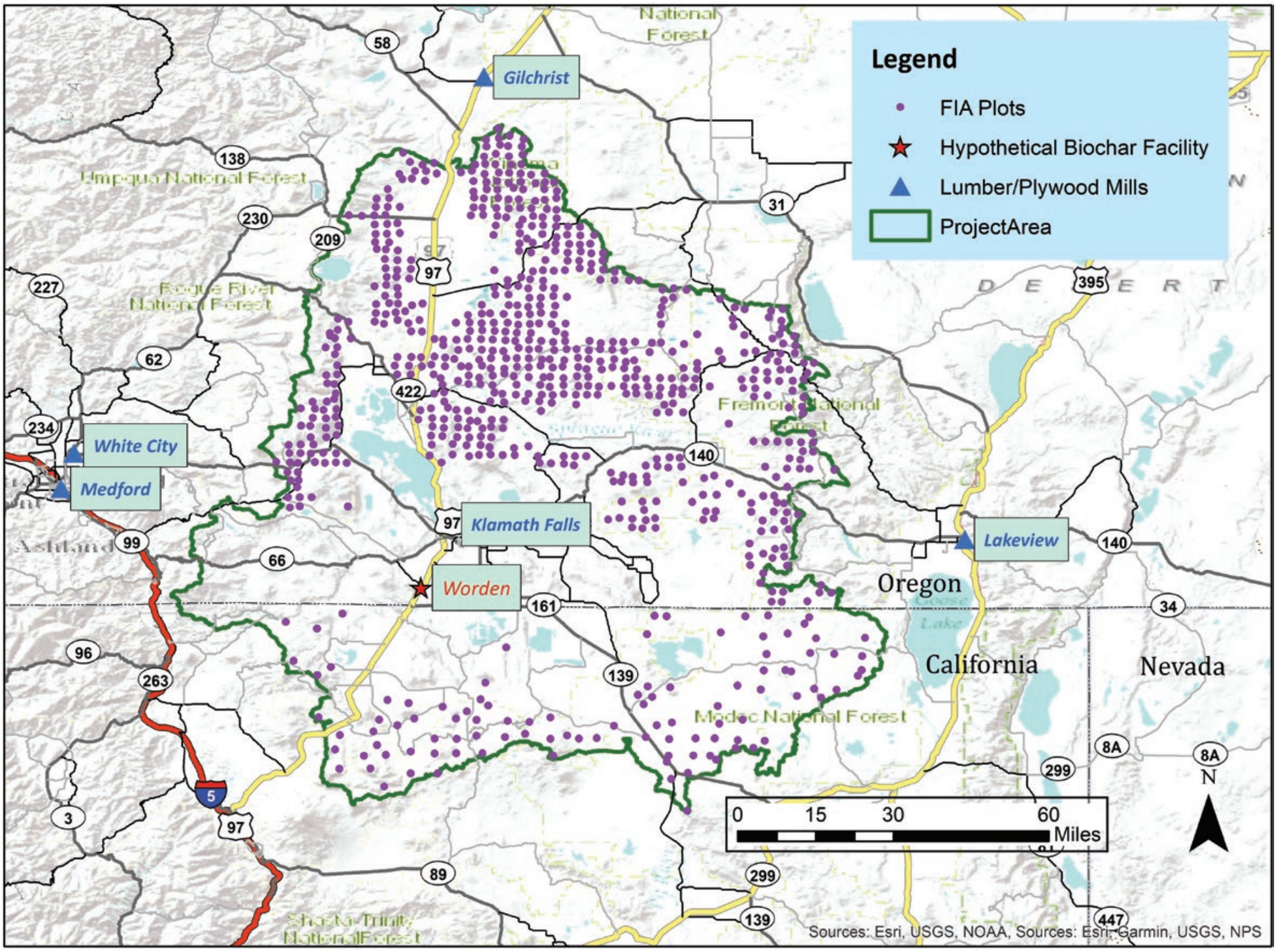

Figure 1. Upper Klamath Basin study area boundary, straddling the California–Oregon border, and locations of forested, unreserved FIA plots on national forest lands within the study area, lumber and plywood mills in the vicinity and of a prospective biochar facility at Worden, OR.

detailed representative sample of all forests (McRoberts et al. 2005) suitable for exploring these questions and assessing treatment benefits, costs, and the value of harvested material. The FIA Bioregional Inventory Originated Simulation Under Management (BioSum[1]) framework has been successful in assessing facility siting (Daugherty and Fried 2007) and in evaluating the effectiveness and feasibility of silvicultural operations, including fuel treatments, on multimillion-acre forested landscapes (Fried et al. 2017a).

We applied BioSum to the FIA forest inventory plot data within the upper Klamath Basin. FIA plots may straddle >1 condition when, for example, part of a plot is nonforest or there is more than one owner class. We considered only forested conditions on national forest land, in some cases relying on "partial plot" data. In BioSum, these full and partial plots become "stands," each representing up to 6,000 acres, depending on FIA stratification protocols, to be modeled and projected in the Forest Vegetation Simulator (FVS; Crookston and Dixon 2005). We projected these stands with and without forest restoration treatments and, following Fried et al. (2017b), characterized treatment effectiveness as the difference between composite resistance scores (CRSs, described below) computed for treated and untreated stand trajectories. For each stand, the treatment that produced the greatest cumulative improvement in CRS over the 20-year analysis horizon was deemed best so as to maximize mean fire resistance and to implicitly incorporate treatment longevity in the decision rules governing treatment selection. To characterize treatment costs, we relied on cost models for a slope-threshold switchable tethered/untethered harvesting system developed empirically for a treatment operation in the upper Klamath Basin (Petitmermet 2018), and developed haul cost estimates (Petitmermet 2018) following logic described for earlier BioSum analyses (Fried et al. 2005). This analysis extended beyond the "standard" BioSum workflow in two significant respects: (1) trees selected for harvest under these restoration treatments were merchandised via a bucking algorithm that optimized log value, with material priced by species and log size, rather than by tree size, thus enabling more accurate valuation and clear delineation between biochar feedstock and merchantable wood volume; and (2) we built a mixed integer programming model to solve the landscape optimization problem that considers and constrains treatment activity over time (even flow) while maximizing treatment effectiveness for the landscape. These considerations and constraints include biochar feedstock price assumptions, the economic feasibility of forest restoration treatments, and treatment capacity limits. These extensions are implemented as documented and publicly available Python scripts (Petitmermet 2019) to facilitate replication of this analysis, and extension to other areas and questions.

Data and Analysis Framework

A full cycle of 10 panels of the USDA Forest Service's FIA program's data for California and Oregon, collected between 2005 and 2015 (see Bansal et al. 2017 or Christensen et al. 2016 for details on data), were downloaded[2] and clipped by GIS overlay with the upper Klamath Basin boundary to select an inventory sample. After dropping full or partial plots that were (1) not forested, (2) not in national forest ownership, or (3) smaller than one-fourth of a full plot (unlikely to contain enough trees to provide a robust representation of stand characteristics), a total of 730 full or partial plots, representing 1.9 million forested acres,[3] remained available for analysis. Once loaded into the BioSum software, these became "stands" for the duration of the analysis. Each stand contained stand and tree attributes, and an expansion factor for landscape representation, providing a "test bed" on which silvicultural prescriptions could be defined and simulated.

BioSum provides modules for estimating the operational costs of restoration treatments and the cost of transporting harvested material to wood-processing facilities (Figure 2). BioSum's heuristic optimization module rates treatment effectiveness and selects which treatments are best for each stand; however, for this analysis, we instead built custom scripts, described below, for merchandising the wood derived from harvested trees and scheduling treatment operations.

Restoration Prescriptions

We crafted six treatments (Table 1), patterned on silviculture already occurring on federal forests, that achieve immediate and sustained enhancements in fire resistance via retention of large trees and favoring retention of more resilient tree species, while also achieving nonfuels objectives like maintaining existing multistory forest structure. Each prescription could be applied in the first year of any of the four 5-year periods of the 20-year analysis planning horizon. Re-treatment was not allowed. Grounded in our understanding of how forest managers in this region restore fire-resistant forest structures, these prescriptions were designed toward four goals: (1) enhance fire resistance; (2) economic feasibility; (3) match silvicultural system to initial stand structure by applying thin-from-below to single story, Q-factor to multistory, and pseudoclearcut/type conversion to fire-intolerant species dominated stands; and (4) span a range of removal intensity with respect to target residual basal area and diameter caps. Species preferences in all six prescriptions favored retention of fire-tolerant species and removal of fire intolerant ones. All 24 prescription/timing combinations (with six treatments available for implementation in each of the four periods), and a 20-year grow-only prescription (to serve as a basis for comparison), were coded as FVS Keyword Control Programs and implemented via the southern Oregon variant of FVS (version 1778) using Suppose 2.06. A basal area trigger (minimum) served to restrict treatments to well-stocked and overstocked stands, determining whether a stand-treatment combination was eligible for consideration.

Treatment and Transportation Cost and Value of Delivered Wood

The contribution of each prescription to net value was calculated from harvesting costs (cutting, processing, forwarding to the landing, and loading), haul costs, log values, and an assumed biochar feedstock price. Models from a study of tethered and untethered operation of harvesters and forwarders in the upper Klamath Basin (Petitmermet et al. 2019) were applied to obtain harvest costs as a function of machine distance traveled, slope, and the weight of material handled. A "NEAR" geoprocessing operation was applied to "fuzzed" stand locations, and the USGS National Transportation Datasets for California and Oregon[4] determined the closest road points and provided estimates of forwarding distance. Haul costs were estimated from the closest road points to nearby

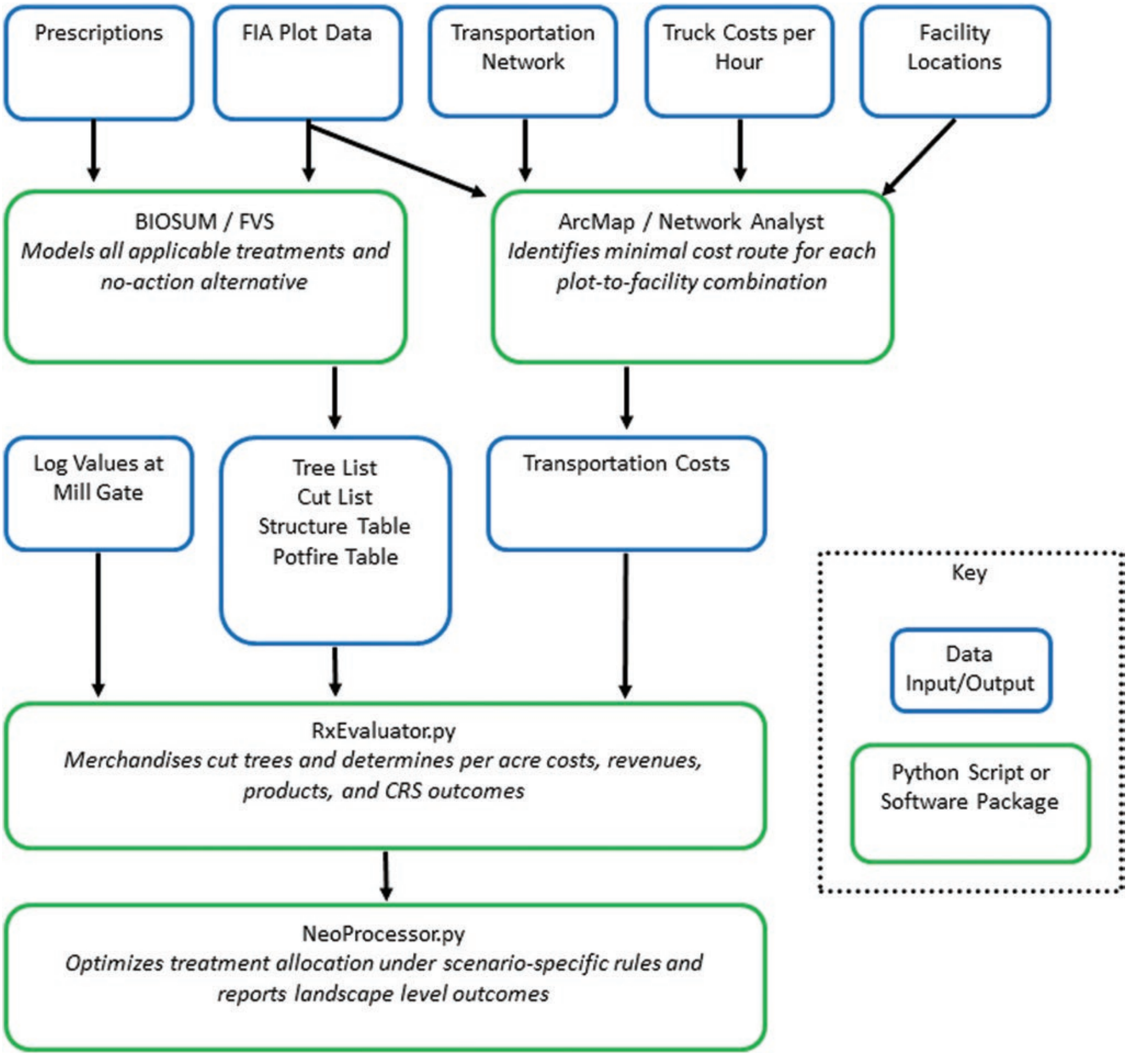

Figure 2. Simplified project workflow. A full description of Biosum, FVS, and ArcMap methods used can be found online at biosum.info. Python scripts used and associated process documentation available at github.com/JPetitmermet/Neo-Processor.

veneer, lumber, and plywood mills—Klamath Falls, Yreka, White City, Lakeview, and Weed—and to a hypothetical biochar production facility at Worden, OR. Unit cost–distance along the road network depended on road standard and surface.

All trees selected for harvest under a prescription were modeled as processed at the stump so as to maximize merchantable value with all logs having a small end diameter >4 in. forwarded to the road point. A dynamic programming, forward-reaching algorithm (Denardo 2017) identified the best combination of extractable logs per tree, subject to a minimum top inside diameter of 6 in. and regional mill-gate values. Logs of noncommercial species and tops with small ends of 4–6 in. were allocated to biochar feedstock. We assumed that smaller tops and limbs would be dropped on forwarder trails to mitigate ground disturbance by equipment and be sufficiently rearranged and mixed with soil to negligibly affect surface fuel loading. Net log revenues were calculated as the sum of merchantable log revenues and biochar feedstock value less operations and haul cost.

Evaluating Fire Resistance and Treatment Effectiveness

Each stand-treatment combination, including for the grow-only case, was evaluated for fire resistance at each 5-year time step of the FVS simulation using the CRS metric (Jain et al., unpublished, Fried et al. 2017b). Designed in consultation with fire and fuels managers, the metric evaluates treatment effectiveness from the perspective of reducing crown fire extent (e.g., percent of crowns burned or scorched) and tree mortality when flame lengths are moderate (6–8 ft.).

Table 1. Summary of prescription parameters for species, strata count, basal area trigger, residual basal area target, and diameter at breast height "cap," above which no trees are cut.

Treatment style	Treatment number	Dominant species*	Strata count†	Minimum basal area (ft² per acre)	Residual basal area target (ft² per acre)	Diameter at breast height "cap" (in.)
Thin from below	1	Any or none	1	150	100	10
	2	Any or none	1	150	100	16
	3	Any or none	1	120	75	21
Q-factor‡	4	Any or none	≥2	125	75	20
	5	Any or none	≥2	110	50	24
Pseudoclearcut§	6	PICO¶	Any	80	N/A**	N/A
		JUOC‖	Any	35	N/A**	N/A

* A species is considered dominant when it comprises 70 percent or more of the basal area for the stand.
† Strata count taken from Forest Vegetation Simulator STRCLASS output tables.
‡ Q-factors were determined by dominant species (one that accounts for at least 70 percent of stand basal area) and were set at 1.15 for ponderosa pine, 1.25 for incense cedar, 1.35 for any one or multiple true fir species, 1.4 for Douglas-fir, and 1.3 when no species was dominant.
§ Only permitted for stands where lodgepole pine (*Pinus contorta* Douglas ex Loudon) or western juniper (*Juniperus occidentalis* Hook.) comprised 70 percent or more of the basal area, and a basal area target was met; the end result was that in overstocked lodgepole and juniper stands, all lodgepole and juniper were removed, and any trees of other species were retained.
¶ Lodgepole pine (*Pinus contorta* Douglas ex Loudon).
‖ Western juniper (*Juniperus occidentalis* Hook.).
** Type six (pseudoclearcut) treatments remove all trees of the dominant species and leave all others.

CRS is the sum of subscores derived from four components: canopy bulk density (from the FVS Potential Fire Report table), fuel strata gap (canopy base height in single-stratum stands and the distance separating the top of the lowest stratum from the base of the next stratum in multistrata stands), resistant species (proportion of basal area in resistant species), and survival volume (percentage of stand volume predicted to survive a moderate fire). Component subscores of 0, 1, 2, or 3 are assigned based on thresholds from the literature or reflecting practical considerations relating to what resistance means (Table 2). CRS ranges from zero (no resistance) to 12 (very high resistance). Canopy bulk density and fuel strata gap account for resistance achieved by reducing crown fire probability, whereas resistant species and survival volume reflect fire effects under any kind of fire. As implemented in analyses to date (Fried et al. 2017b, Jain et al., unpublished), any improvement in CRS compared to a no management alternative is considered effective and desirable, whereas any reduction in CRS is viewed as counterproductive to achieving fire resistance.

Species considered resistant (Agee 1993, Jain et al. 2012) were ponderosa (*Pinus ponderosa* Laws.), Jeffrey (*Pinus jeffreyi* Ralf.), and sugar (*Pinus lambertaina* Doug.) pine, Douglas-fir (*Psuedotsuga menziesii* [Mirb.] Franco), and red (*Abies magnifica* A. Murray bis) and Shasta (*Abies shastensis* Lemmon) fir. Volume survival is 100 minus the percentage of live tree volume expected to die in a fire with 6–8-ft. flame lengths, estimated using species and diameter at breast height (dbh)-specific coefficients from the First Order Fire Effects Model (FOFEM; USDA FS 2018; see Petitmermet (2018) for coefficients). Subscores are assigned (Table 2) and summed to produce CRS for each of 5 years of interest for each stand-prescription combination: the four treatment years (1, 6, 11, and 16) and the last year in the 20-year planning horizon.

Landscape Optimization

Building on these stand-prescription combination outcomes, we sought to maximize mean CRS in the upper Klamath basin for each 5-year period, subject to limitations in each period on area treated, variation in area treated per year, and total revenue (≥0, allowing areas with a positive net revenue to subsidize those without). The FIA expansion factors (of up to 6,000 ac) associated with each stand were decomposed into stand "subunits," each 100 ac or less[5], to allow acres represented by a plot to be treated via different prescriptions and in different years. Only one prescription (including "no treatment") could be assigned per subunit.

The mathematical problem to be solved is

Table 2. Fire-resistance components used to evaluate effectiveness.

Component score	Canopy bulk density (kg m^{-3})	Fuel strata gap (ft)	Resistant species (percent)	Survival (percent)
0	>0.15	≤7	≤25	≤2
1	0.11–0.15	7–20	25–50	2–30
2	0.051–0.10	20–30	50–75	30–75
3	≤0.05	>30	75–100	>75

Note: Every site is assigned a value for each of the four components with a maximum score of 12.

$$\text{Max} \sum_i \sum_t \sum_p \text{CRS}_{itp} \cdot X_{itp} \cdot A_i \qquad i = 1 \text{ to } N; \quad p = 1 \text{ to } 4; \quad t \in T^i \tag{1}$$

Subject to:

$$\sum_t \sum_p X_{itp} = 1 \qquad i = 1 \text{ to } N; \quad p = 1 \text{ to } 4; \quad t \in T^i \tag{2}$$

$$\sum_i \sum_t A_i \cdot X_{itp} \le \text{TRT}_p \qquad i = 1 \text{ to } N; \quad p = 1 \text{ to } 4; \quad t \in T^i \tag{3}$$

$$0.8 \cdot \text{TRT}_{\text{ave}} \le \sum_i \sum_t A_i \cdot X_{itp} \le 1.2 \cdot \text{TRT}_{\text{ave}} \qquad i = 1 \text{ to } N; \quad p = 1 \text{ to } 4; \quad t \in T^i \tag{4}$$

$$\sum_i \sum_t \text{CT}_{itp} \cdot X_{itp} \le \sum_i \sum_t \text{RT}_{itp} \cdot X_{itp} \qquad i = 1 \text{ to } N; \quad p = 1 \text{ to } 4; \quad t \in T^i \tag{5}$$

$$X_{itp} \in \{0, 1\} \tag{6}$$

where: X_{itp} is a binary variable equaling 1 when subunit i is treated with treatment t in period p; T^i denotes eligible treatments for group i, where T^i varied from 1 to 4, depending on forest type; CRS_{itp} is the composite resistance score of subunit i, treatment t, period p; A_i is the area of group i; TRT_p is the upper limit of area treated in period p; TRT_{ave} is the mean area treated per period; CT_{itp} is the cost of treatment t, subunit i, in period p; and RT_{itp} is the revenue from treatment t, subunit i, period p

Equation 1 maximizes area-weighted CRS across the landscape. Equation 2 enforces the limit of one treatment per subunit. Equation 3 requires that the total area treated in each period be less than or equal to an upper limit on area treated for the period. Equation 4 enforces an even flow constraint, requiring the area treated in any period to deviate from the mean for all periods by no more than 20 percent. Twenty percent was chosen as a reasonable estimate of variability considering business cycles in the primary timber market. Equation 5 requires the revenue generated in each period to be equal to or greater than the cost of implementing all treatments in that period, transporting merchantable material to an appropriate facility, and (in some scenarios) disposal of nonmerchantable material. Equation 6 requires that the subunit be treated or assigned to grow-only.

This landscape contained 9,287 operable subunits (those with at least one potential fuel-reduction treatment during the planning horizon). With two to five prescriptions per operable subunit and up to four different time periods in which to implement a treatment, the simulation generated approximately 63,000 binary variables per run. The problem was solved using a variation of the Great Deluge algorithm (Dueck 1993) with the addition of several rules to escape local minima (Petitmermet 2018). The Great Deluge has been shown to be competitive to other popular heuristics (Bettinger et al. 2002). In a typical run, about 10 million trial moves were made, or about 1,080 moves per subunit, where one move is defined as changing the prescription or timing of the treatment, on one operable subunit.

Analytical Scenarios

To explore a range of possible future outcomes we prepared eight analytical scenarios. For three levels of treatment capacity represented as a management return interval (MRI), calculated as total forest area divided by area treated per year, we modeled two feedstock outcomes, (1) burned at landing (BAL) because of absence of a market and (2) used as biochar (UAB)—in other words, delivered to Worden and receiving US$50 per bone dry ton (BDT) (Table 3). This hypothetical delivered price, from an empirical study in the Klamath Basin (Petitmermet 2018) that assessed a facility's feedstock requirements and mean estimated transport costs, serves as a proxy price for a currently nonexistent market. BAL scenarios approximate current reality, in which the absence of a biochar feedstock market results in the material being piled at the landing as part of the harvesting operation, and eventually burned at a cost equal to US$5.40 ac^{-1} (P. Cheng, pers. commun., 2017). We also modeled an unconstrained (UNC) scenario with

Table 3. Feedstock disposition, annual area treated, and management return interval for the grow-only, BAL, UAB, and UNC scenarios.

Scenario label	Feedstock disposition	Annual area treated (acres)	Management return interval (years)
G-O	NA—grow-only	0	NA—grow-only
MRI-100 BAL	BAL	19,000	100
MRI-100 UAB	UAB	19,000	100
MRI-50 BAL	BAL	38,000	50
MRI-50 UAB	UAB	38,000	50
MRI-25 BAL	BAL	76,000	25
MRI-25 UAB	UAB	76,000	25
UNC	UAB	No limit	NA

Note: BAL, burned at landing; MRI, management return interval; UAB, used as biochar; UNC, unconstrained.

no limits on either area treated or feedstock use and a grow-only (G-O) scenario without treatment. Excepting G-O, area-weighted CRS was maximized for all periods, with any eligible stand-treatment combination entering the solution if it enhanced that objective. Each scenario was modeled 30 times. We report scenario means and standard deviations (a useful index of relative reliability, given the model's stochastic elements).

Since some forest industry landowners in California have authorized their foresters to invest as much as US$200 per acre to subsidize forest operations that deliver a fuel treatment or fire-hazard-reduction benefit (W. Stewart, pers. commun. 2018), we also evaluated the potential for subsidies of US$100 or US$200 ac^{-1} to move stands from a debt-incurring status (net revenue below zero) to break even or better status.

Results

Area Eligible for Treatment and Treatment Outcome

About one million acres of federal forest land in the upper Klamath Basin (54 percent of the total) had sufficient stocking to be eligible for one or more treatments during the 20-year simulation. One to three thin-from-below (TFB) prescriptions were simulated on 56 percent of the eligible area, one or two q-factor (q-f) prescriptions on 21 percent, and a pseudoclearcut (pCC) prescription on 30 percent[6]. All treatments were effective in achieving an immediate improvement in CRS above the grow-only value on most of the eligible area. Most of the TFB and q-f improvements occurred in the fuel strata gap and Canopy Bulk Density (CBD) scores (Table 4). TFB treatments implemented in later planning periods delivered progressively less gain in mean CRS, likely owing primarily to increases in fuel strata gap that occur as stands age and become taller; and the other kinds of treatments led to progressively greater gain in CRS. No treatment elevated CRS on every eligible acre (Table 5), and some resulted in no increase in CRS on up to 14 percent of eligible acres. Given that the objective function in the optimization maximizes CRS improvement, these stand-treatment combinations would likely not be part of any solution. Table 5 reports eligible area and distribution by CRS outcome for the fourth planning period; in earlier periods, fewer acres were eligible because of fewer stands meeting the basal area requirements for treatment, but the distribution of area by CRS sign change (increase, decrease or neither) was comparable.

Effects of Biochar Feedstock Price and Treatment Subsidy on Stand-Level Treatment Feasibility

Of the treatment-eligible acres, 74 percent had at least one self-paying treatment, even if biochar feedstock was piled and burned at the landing (the BAL scenario), and this increased to 77 percent when this feedstock was instead delivered to a biochar facility (the UAB scenario). The effect of use on break-even status was greatest for prescriptions that generated higher proportions of small-diameter material, such as TFB 1, which harvests no large trees, and pCC 6, which produces mainly low-value and noncommercial wood (Table 6).

Both levels of treatment subsidy proved effective at moving some forest area with negative net revenue to break-even status. On average, subsidy shifted some treatment-eligible acres with a negative net revenue to break even or better status—3 and 8 percent at US$100 and US$200 ac^{-1} for the UAB (Figure 3a) and 5 and 10 percent for the BAL (Figure 3b) scenarios. Notably, these shifts were greatest for prescriptions TFB 3 and pCC 6. Most multistory acres treated with q-f 4 and 5 already achieved break-even, and the low-diameter cap in TFB 1 precluded break-even on most acres

Table 4. Immediate change in subscores and CRSs achieved by three TFB, two q-f, and one pCC treatment relative to grow-only when implemented at year 1 (i.e., directly on field collected data with no prior stand projection).

	Mean score change				
	Subscore				Composite resistance score
Treatment	Fuel strata gap	Canopy bulk density	Resistant species	Survival	
TFB 1	1.15	0.91	0.17	0.30	2.53
TFB 2	1.04	1.18	0.34	0.43	2.98
TFB 3	0.87	1.19	0.39	0.38	2.83
q-f 4	0.66	1.42	0.25	0.25	2.57
q-f 5	0.70	1.26	0.36	0.24	2.56
pCC 6	0.34	0.73	2.49	1.24	4.81

Note: CRS, composite resistance score; pCC, pseudoclearcut; q-f, q-factor; TFB, thin-from-below.

Table 5. Area eligible for treatment (thousand acres) and percent of area for which each treatment produces an increase, no change or a decrease in CRSs if implemented in year 16, the beginning of the fourth planning period.

Treatment	Area eligible for treatment	Percentage where CRS increased	Percentage with no change in CRS	Percentage where CRS decreased
TFB 1	129.0	91	9	0
TFB 2	260.1	94	5	1
TFB 3	509.4	91	9	0
q-f 4	177.7	86	14	0
q-f 5	193.4	93	7	0
pCC 6	284.5	98	1	1

Note: CRS, composite resistance score; pCC, pseudoclearcut; q-f, q-factor; TFB, thin-from-below.

even under UAB and high subsidy. Without such payments, TFB 1 achieves break-even on only 10 percent of eligible acres.

Landscape Management Scenario Results

Annual treatment capacity, derived from MRI for this landscape, was a binding constraint for the 100-year and 50-year MRI scenarios, such that the area treated for both scenarios—BAL and UAB—for each MRI was identical to the annual treatment area capacity for that MRI for each time point (Table 7). Scenarios with a 25-year MRI treatment capacity resulted, on average, in 44,000 ac treated annually, which was 58 percent of the allowed capacity under that MRI, and differences between the BAL and UAB scenarios at each time point were <0.2 percent. In the unconstrained scenario, which specified no annual treatment area limit or even-flow constraints, more than half the eligible area was treated in the first 5 years. Other stands were treated in subsequent periods as their basal area grew to exceed one or more prescriptions' eligibility thresholds. Approximately 91 percent of treatment-eligible acres were treated under this unconstrained scenario.

The grow-only (G-O) prescription resulted in a CRS sum of 34.6 out of a potential 60 (five time points with a maximum possible CRS of 12 at each point). The unconstrained scenario (UNC) produced a CRS sum of 50.8, establishing an effective maximum possible resistance achievable on this landscape with these prescriptions. CRSs were identical for scenarios with a common MRI (Table 8). The most binding capacity constraint (MRI-100) produced the smallest CRS sum for this landscape—only 15 percent greater than G-O—whereas MRI-25 resulted in a 35 percent gain and achieved a score that was 78 percent of the maximum possible score.

Net revenue was positive for all scenarios and differed by both treatment capacity and feedstock outcome, with net revenue increasing with treatment capacity and when biochar feedstock was used, rather

Table 6. Total area eligible for treatment and percent of eligible area exceeding break-even (net revenue ≥ US$0) by the end of the fourth 5-year cycle for each prescription and feedstock outcome (thousand acres).

Treatment	Area eligible for treatment	Percentage of eligible area exceeding break-even	
		BAL*	UAB†
TFB 1	129.0	15	20
TFB 2	264.1	58	63
TFB 3	509.4	67	69
q-f 4	177.7	74	80
q-f 5	193.4	86	89
pCC 6	288.0	38	42

Note: BAL, burned at landing; pCC, pseudoclearcut; q-f, q-factor; TFB, thin-from-below; UAB, used as biochar.
* Feedstock is burned at the landing at a cost of US$5.40 ac^{-1}.
† Feedstock is delivered to Worden processing facility generating US$50 per bone dry ton in gross revenue.

than burned (Table 9). UAB scenarios returned 9–13 percent more present net revenue for a 20-year program of treatments implemented at a consistent rate over time than BAL scenarios for the same MRI. The unconstrained action scenario generated positive net revenue over the 20-year simulation, but generated little revenue after the initial 5-year period, thanks to an unconstrained objective function that sought to maximize CRS sum over two decades. This drove assignment of the most intensive prescriptions as early as possible. The only stands that remained available for treatment in later periods were those just growing above the basal area trigger for the first time.

As with the annual area treated and CRS sums, sawlog production was essentially identical for all scenarios with the same MRI, generating an annual mean of approximately 295, 478 and 541,000 BDT for the 100-, 50-, and 25-year MRI scenarios, respectively (Table 10). Biochar feedstock production was also identical for all scenarios with the same MRI, generating an annual mean of approximately 91, 184, and 201,000 BDT for the 100-, 50-, and 25-year MRI scenarios, respectively (Table 10). The unconstrained scenario generated a mean sawlog production of 515,000 BDT $year^{-1}$. As with net revenue, most sawlog material produced (71 percent) was delivered in period 1, and total production was less than for the 25-year MRI because of the sharp reduction in growing stock by the end of the first period.

Predicting BioChar Feedstock Supply and Facility Viability

Separate supply curves reflecting the incremental costs of delivering biochar feedstock already at the landing (i.e., for *L*oading onto trucks and *H*auling to Worden [LH]) (Figure 4a–c) and the total costs of delivery from the stump (i.e., also including *F*orwarding costs [FLH]) (Figure 4d) were prepared for the UAB scenarios for each MRI and for the UNC scenario[7]. For each scenario and 5-year period, these curves trace the mean marginal cost, in dollars BDT^{-1} of feedstock produced for each production quantity, over all simulations for the scenario. The FLH curves represent our best estimates of the full variable cost associated with producing and delivering feedstock, whereas the "LH" curves offer a basis for comparing the cost of delivering feedstock to Worden to current (BAL) practice.

Marginal costs for the first 250,000 BDT per period (50,000 BDT $year^{-1}$) ranged from US$46 to US$52 BDT^{-1} on the FLH curves and US$20 to US$29 BDT^{-1} on the LH curves. As expected, the short (25-year) MRI shifts the supply curve dramatically to the right (Figure 4c versus a), and including forwarding costs shifts it substantially upwards (Figure 4d versus c). The unconstrained supply curve (Figure 4b) suggests sufficient feedstock for many biochar facilities in the first period, with a subsequent, dramatic reduction to levels similar to the 100-year MRI in subsequent periods, i.e., sufficient for only one or two facilities. Marginal cost was slightly greater with the lower-capacity (100-year MRI) scenario owing to the effectiveness-driven optimization choosing acres and prescriptions that maximize the effect on CRS rather than those that might deliver feedstock at lower cost. The mean cost for the first 250,000 BDT per period ranged from US$42 to US$56 BDT^{-1} on the FLH curves and US$20 to US$26 BDT^{-1} on the LH curves (Table 11). As with the marginal costs, the mean unit cost increased as treatment capacity decreased.

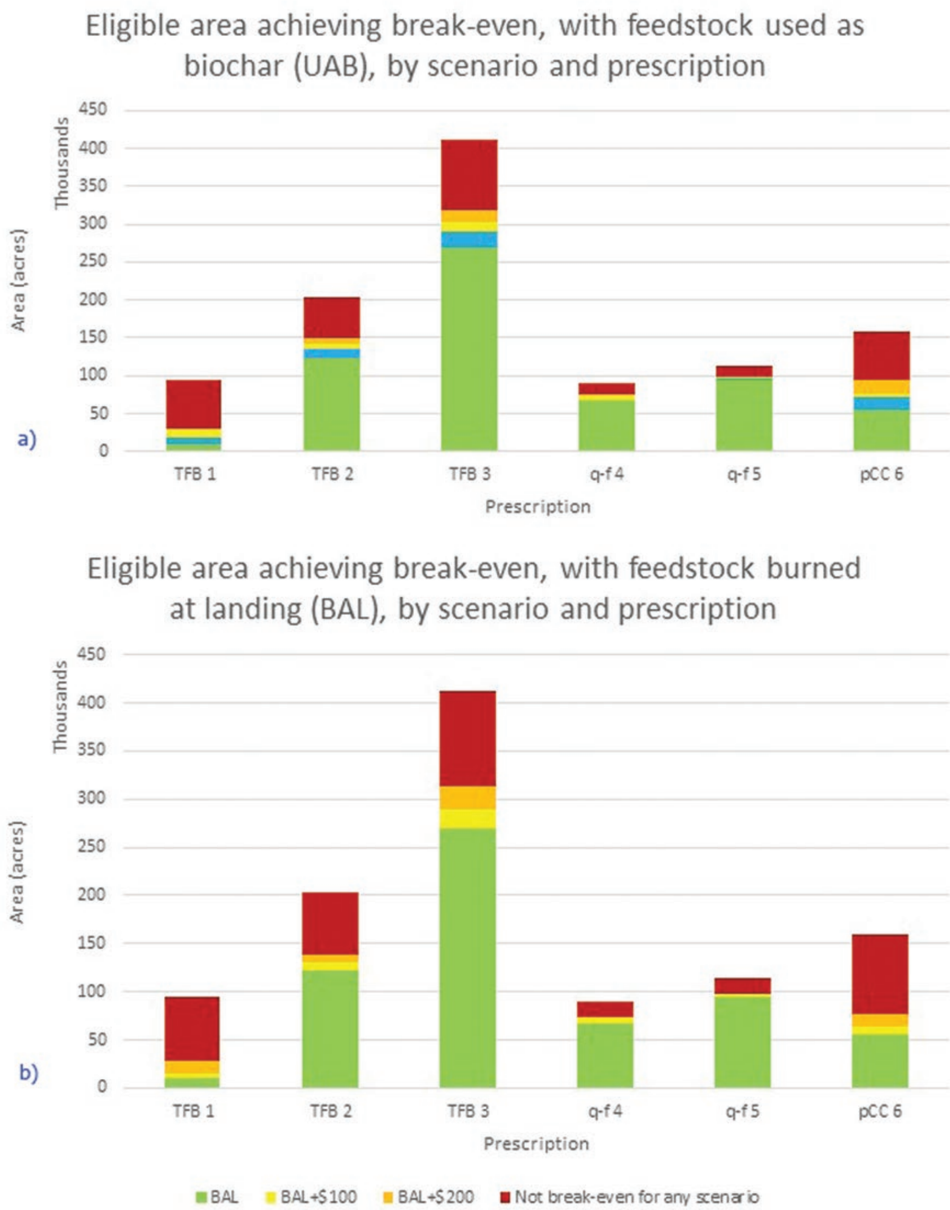

Figure 3. (a) Area for which each treatment was implementable (total bar height), incrementally partitioned by capacity to achieve break-even or better with (1) burning all biochar feedstock at the landing, incorporating a cost of US$5.40 ac^{-1} (green), (2) delivering biomass to a facility at Worden, OR, for a payment of US$50 per bone dry ton (green + blue), (3) delivery at US$50 per bone dry ton and collection of a US$100 ac^{-1} treatment subsidy (green + blue + yellow), (4) delivery at US$50 per bone dry ton and collection of a US$200 ac^{-1} subsidy (green + blue + yellow + orange), and (5) not capable of achieving break-even for any scenario (red). (b) Area for which each treatment was implementable (total bar height), incrementally partitioned by capacity to achieve break-even or better with (1) disposal of what would otherwise be biochar feedstock by burning at the landing, (2) burning at the landing and collection of a US$100 ac^{-1} treatment subsidy (green + yellow), (3) burning at the landing and collection of a US$200 ac^{-1} subsidy (green + yellow + orange), and (4) not capable of achieving break-even for any scenario (red).

Discussion and Conclusion

Somewhat surprisingly, given that the prescriptions tested applied species selection pressure to favor fire-resistant species, improved resistance was mainly attributable to improvements in the canopy metrics fuel strata gap and CBD, not in the resistant species abundance or survival scores. This suggests that only so much progress is possible in stands dominated by fire-intolerant tree species. Although fire mortality models such as FOFEM predict greater resistance/lower mortality probabilities for large trees, designing

Table 7. Mean annual treatment area (thousand acres), by 5-year period, over 30 simulations per scenario, and total area treated, averaged by management return interval across the burned at landing and used as biochar scenarios (which generated identical results for MRI-100 and MRI-50 and nearly identical results for MRI-25), and for the unconstrained scenario.

Scenario	Period 1	Period 2	Period 3	Period 4	Total
MRI-100	19	19	19	19	380
MRI-50	38	38	38	38	760
MRI-25	43	50	43	42	886
Unconstrained scenario	109	38	21	14	912

Note: MRI, management return interval.

Table 8. Mean composite resistance score, by year, sum of scores for these five representative years, and sum of scores expressed as a percentage of the maximum possible score, over 30 simulations per scenario and the grow-only scenario.

Scenario	Year 1	Year 6	Year 11	Year 16	Year 20	Sum of scores	Percentage of maximum
Grow-only	6.84	6.91	6.98	6.98	7.00	34.64	58
MRI-100	7.15	7.60	8.03	8.52	8.54	39.83	66
MRI-50	7.45	8.47	9.38	10.19	10.21	45.69	76
MRI-25	7.55	8.78	9.61	10.34	10.36	46.65	78
Unconstrained	9.06	10.02	10.41	10.66	10.67	50.82	85

Note: The burned-at-landing and used-as-biochar scenarios produced identical results for a given capacity constraint so only one set of results is reported per MRI. MRI, management return interval.

Table 9. Mean annual net revenue (million dollars) from sales of wood, less treatment and haul costs, by scenario and 5-year period, and total present net value over 20-year simulation at discount rate of 3 percent, over 30 simulations.

Scenario	Period 1	Period 2	Period 3	Period 4	20-year present net value
Grow-only	0	0	0	0	0
MRI-100 BAL	30.9	21.9	18.1	17.6	351.7
MRI-100 UAB	33.1	23.6	20.3	19.7	383.1
MRI-50 BAL	41.5	21.8	24.3	32.1	466.9
MRI-50 UAB	45.6	25.7	28.4	35.9	528.1
MRI-25 BAL	47.6	22.8	27.8	34.8	520.2
MRI-25 UAB	52.2	27.9	31.6	38.7	587.8
Unconstrained	86.9	3.0	0.6	3.9	436.0

Note: BAL, burned at landing; MRI, management return interval; UAB, used as biochar.

treatments that cut no large trees presents some challenges, especially when the threshold for "large" is as small as 10–21 in., as it was for the thinning prescriptions we crafted for single-story stands. We allowed treatments to go forward only if residual stand density could achieve a proportional removal target—something that can be impossible when diameter caps become binding—rendering a large area of the forest untreatable. Although we could have allowed treatment that respected the caps, but produced stands that exceeded density targets, in some cases this would have amounted to removal of so few trees as to be both economically infeasible and ineffective at promoting resistance.

Even at a feedstock price of US$50 BDT^{-1}, which is greater than the highest prices paid by biomass power generators when feedstock demand was at a peak, a biochar market would produce, at best, a very modest increase in break-even treatable area compared to the BAL scenario. The Northwest Advanced Renewables Alliance Project (NARA[8]) proposed a somewhat greater marginal cost of US$70 BDT^{-1} for lower-quality forest

Table 10. Mean, based on 30 simulations, of annual sawlog and biochar feedstock production, in thousand bone dry tons, for biochar use (used as biochar) scenarios, by MRI and 5-year planning period and implied, two-decade total yield.

Scenario	Period 1	Period 2	Period 3	Period 4	20-year yield
Sawlogs					
MRI-100	334	287	273	286	5,897
MRI-50	522	410	450	530	9,562
MRI-25	583	498	506	576	10,820
UNC	1465	284	160	148	10,291
Biochar feedstock					
MRI-100	76	91	91	104	1,810
MRI-50	165	198	188	185	3,687
MRI-25	188	244	186	187	4,025
UNC	538	161	57	43	3,992

Note: MRI, management return interval; UNC, unconstrained.

residues, but that project presupposed an investment of US$342 million for a green field facility (Martinkus et al. 2017). Moreover, even with tethered systems, extraction of merchantable material may not always be a net positive source of revenue as it was here. Treatment subsidies per unit area can reduce effective net costs of extracting merchantable wood, biochar feedstock, or both, and, at the levels modeled here, appear to be at least equally effective at bringing forest area into break-even status. Notably, the q-factor treatments less frequently required subsidy to achieve break-even, owing to a greater share of removals in merchantable size classes, even accounting for the effect of diameter caps.

At present, biochar feedstock supply appears to be constrained by the social, political, and federal budget and staffing factors driving treatment capacity, not by treatment opportunity, need, or biophysical capacity of the forest. On the 2.3 million acre Fremont-Winema National Forest, approximately 10,000 acres year^{-1} were harvested, precommercially thinned, and/or influenced by a prescribed fire between 2007 and 2016 (P. Cheng, pers. commun., 2017). Assuming that half the area treated with prescribed fire also receives mechanical treatment, there would be management activity occurring on 25,000 acres year^{-1}, implying an MRI of approximately 100 years. This study demonstrates that over the two decades projected, treatments can be quite effective, achieving a mean CRS as high as 50 out of the possible 60 over those 20 years. If conducted at scale, and implemented, more realistically, over time rather than all at once, they could still achieve 78 percent of the maximum resistance score. The grow-only results demonstrate that leaving the forest unmanaged will not lead to any overall improvement in fire resistance. Although fuel strata gap scores may improve somewhat as stands grow, resistant species scores will not, and CBD scores inevitably decline without management.

While the impact of the UAB scenario on area that could be treated at break-even or better was modest (a 6 percent increase), the effect on net revenue (a 9–13 percent increase) is more pronounced because feedstock use increases the net revenue on all acres, not just those that could not break even without use. Prices higher than US$50 BDT^{-1} would lead to further increases in net revenue and area that can be treated at break-even or better, and further reduce both the incidence of smoke produced from burn piles and immediate emissions of greenhouse gases associated with fuel-treatment operations.

The biochar production facility contemplated for construction at Worden, Oregon would need an assured supply of 50,000 BDT year^{-1} over at least two decades to be economically viable, should a robust market for biochar emerge (Sessions et al. 2018). Even with the current, modest levels of treatment activity represented here by the 100-year MRI, the national forests on this landscape appear to be capable of generating such nonmerchantable woody biomass quantities at a mean cost of US$23 BDT^{-1} if the forwarding cost is considered to be chargeable against, for example, revenues from merchantable wood generated by these treatments, since the removal of both merchantable wood and biochar feedstock is integral to the effectiveness of these treatments. If the biochar feedstock must carry the full cost of FLH, this mean rises to US$47 BDT^{-1}.

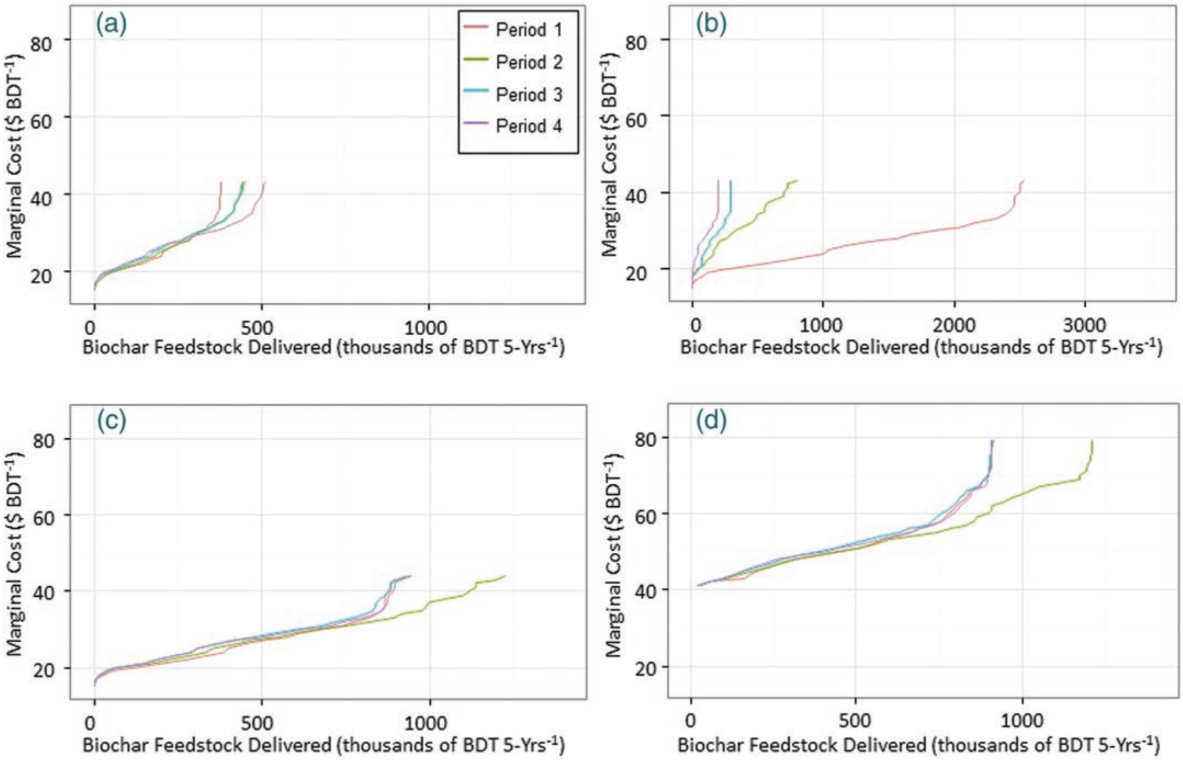

Figure 4. Marginal cost at Worden, during each 5-year period, as a function of biochar feedstock produced from the upper Klamath, under four used-as-biochar scenarios: (a) treatment capacity associated with a management return interval of 100 years, with only loading and hauling costs considered; (b) unconstrained with only loading and hauling costs considered; (c) treatment capacity associated with a management return interval of 25 years, with only loading and hauling costs considered; and (d) treatment capacity associated with a management return interval of 25 years, inclusive of forwarding, loading, and hauling costs.

Our best approximation of a forest-restoration program commensurate with current operational capacity suggests the possibility of up to double the 50,000 BDT year^{-1} viability threshold (Figure 4), with a clear potential to generate greater quantities of feedstock when treatment capacity can be expanded to the point that stand-level treatments actually become effective in changing the frequency of large, high-intensity fire on national forest lands. However, this assumes all forests can be managed and that forest restoration is always a key objective. Even outside reserved areas, objectives are sometimes incompatible with mechanical treatment. Because future land allocations and policies are dynamic and unknowable, we presented estimates that are best interpreted as a biophysical potential consistent with active, landscape-restoration-focused, not production-maximizing, management—in essence, an upper bound on supply from national forest lands that would almost certainly be reduced, to some extent, by social, legal, and policy considerations.

Contrary to our initial assumptions and widely held conventional wisdom, revenue from sales of logs and biochar feedstock proved sufficient to cover costs in every scenario analyzed. However, this finding comes with four caveats. First, cost estimates are for tether-equipped cut-to-length equipment, which is not yet deployed at the scale required to perform all the desired treatments, so other ground and/or cable-based systems with higher harvest costs might be used on steep ground, in practice; however, much less than 10 percent of upper Klamath forests are steep as sampled at the scale of an inventory plot. Second, revenues estimated here depend on social acceptance of treatments that leave a lower basal area and cut somewhat larger trees. The type 1 (TFB) treatment that cuts no trees larger than 10 in. dbh rarely achieved break-even and was infrequently the most effective treatment available. Third, we did not explicitly account for the cost of removing trees incapable of producing at least one 8-ft sawlog or 8-ft log of biochar feedstock material; where large shares of the felling workload is in very small stems (less than 6 in. dbh), this analysis may understate costs. Fourth, it is likely that a follow-on management

Table 11. Mean cost (US$ per bone dry ton), accounting for loading and hauling, and forwarding, loading and hauling for the first 250,000 bone dry ton[9] of biochar feedstock delivered to a contemplated facility at Worden, Oregon, per 5-year period, by management return interval.

	Loading and hauling mean cost				Forwarding, loading, and hauling mean cost			
	Period				Period			
Management return interval (years)	1	2	3	4	1	2	3	4
100	22.49	23.24	23.59	23.92	45.99	46.49	46.66	47.02
50	21.02	21.51	21.58	21.68	43.68	44.66	44.63	44.56
25	20.56	21.23	21.56	21.64	43.69	44.07	44.55	44.46
UNC	20.04	23.56	25.93	28.80	42.32	47.82	51.16	55.96

activity will be needed following cut-to-length treatments in some stands to reduce surface fuel loading, and re-treatment of some kind, at least to address resurging ladder fuels, will be needed in no more than 20–30 years for treatment effects to persist (Jain et al., unpublished). Cut-to-length systems generally operate on "brush mats" created by collecting and piling onto trails where equipment operates, the branches and stem segments of submerchantable size, for which there are no markets. Driving equipment over these mats may reduce soil impacts and rearrange and masticate the material to some extent, but does not reduce total wood mass per unit area. Treatment costs will be higher where managers determine that a prescribed fire or pile and burn operation is required to reduce the fuels in these brush mats.

Modeled stump to facility costs were modestly below the preliminary US$50 BDT^{-1} biochar price used to parameterize the UAB scenario, with mean price decreasing as treatment capacity increased owing to the objective function's focus on maximizing CRS, driving the optimization toward favoring high-cost stands with a large impact on CRS over stands with lower cost and lower impact. Increases in area treated resulted in more low-cost, low-impact stands being included in the solution.

The best strategies for a sustainable fuels treatment program have yet to be formulated and may vary by place and time. Candidates could include periodic mechanical entry at intervals similar to the historical mean fire return interval, periodic entry at intervals significantly longer than the historical mean fire return interval to reduce cumulative impacts of forest operations, or even a single "corrective" entry followed by prescribed fire at regular intervals. Each could plausibly prove ideal for reducing fire hazard while meeting other social, economic, and ecological objectives; they also have different implications for an industry that seeks to use the small-diameter material produced by mechanical treatments.

Acknowledgments

The authors acknowledge funding provided by Oregon State University's Institute for Working Forest Landscapes, and technical assistance and advice provided by Paul Cheng at the Fremont-Winema National Forest, Sara Loreno at Ecotrust, and John Bailey and Jerry Mohr of Oregon State University. We are grateful for the comments of three anonymous reviewers that significantly improved this paper.

Endnotes

1. BioSum software is downloadable from www.biosum.info.
2. Available online at https://apps.fs.usda.gov/fia/datamart/datamart.html.
3. Note that the area represented by the partial plots dropped because of reason 3 was redistributed among the plots and partial plots retained in the analysis.
4. https://viewer.nationalmap.gov/basic/.
5. For example, a stand with a 5,250-ac expansion becomes 5,250 div 100 = fifty-two 100-ac subunits and one 5,250 mod 100 = 50-ac subunits.
6. Some of the area eligible for pseudoclearcuts was also eligible for the other treatment types, so the sum is >100 percent.
7. BAL scenarios, under which no biochar feedstock is delivered (because this material is burned at the landing), have no supply curves.
8. https://nararenewables.org/.
9. For the unconstrained scenario (UNC) in period 4, the mean cost estimates are for the first 215,000 BDT, because this scenario does not deliver the full feedstock requirement of 250,000 BDT in period 4.

Literature Cited

4FRI. 2018. *What is the four forest restoration initiative?* Available online at www.4fri.org; last accessed April 6, 2019.

Agee, J. 1993. *Fire ecology of Pacific northwest forests*. Island Press, Washington, DC. 493 p.

Amishev, D. 2016. *Winch-assist technologies available to Western Canada*. Technical Report 37. FPInovations, Vancouver, BC, Canada. 48 p.

Arriagada, R., F. Cubbage, K. Abt, and R. Huggett Jr. 2008. Estimating harvest costs for fuel treatments in the West. *Forest Prod. J.* 58(7/8):24–30.

Bansal, S., L. Brodie, S. Stanton, K. Waddell, M. Palmer, G. Christensen, O. Kuegler, et al. 2017. *Oregon's forest resources, 2001–2010: Ten-year forest inventory and analysis report.* USDA Forest Service Gen. Tech. Rep. PNW-GTR-958, Pacific Northwest Research Station, Portland, OR. 130 p.

Barbour, R., C. Keegan, and D. Van Hooser. 1998. Changing timber quality in the Western United States. P. 126–138 in *Proceedings of Forest management into the next century: What will make it work? Publ. 7276*. Forest Products Society, Madison, WI.

Bettinger, P., D. Graetz, K. Boston, J. Sessions, and W. Chung. 2002. Eight heuristic planning techniques applied to three increasingly difficult wildlife planning problems. *Silva Fennica* 36(2):561–584.

Biederman, L., and W. Harpole. 2013. Biochar and its effects on plant productivity and nutrient cycling: A meta-analysis. *GCB Bioenergy* 5(2013):202–214. Available online at https://doi.org/10.1111/gcbb.12037; last accessed April 6, 2019.

Campbell, J., J. Sessions, D. Smith, and K. Trippe. 2018a. Potential carbon storage in biochar made from logging residue: Basic principles and southern Oregon case studies. *PLoS One* 13(9):e0203475. Available online at https://doi.org/10.1371/journal.pone.0203475; last accessed April 6, 2019.

Campbell, R.M., N.M. Anderson, D.E. Daugaard, and H.T. Naughton. 2018b. Financial viability of biofuel and biochar production from forest biomass in the face of market price volatility and uncertainty. *Appl. Energ.* 230:330–343.

Christensen, G.A., K.L. Waddell, S.M. Stanton, and O. Kuegler. 2016. *California's forest resources: Forest inventory and analysis, 2001–2010*. USDA Forest Service Resour. Bull. PNW-RB-268, Pacific Northwest Research Station, Portland, OR. 24 p.

Crookston, N., and G. Dixon 2005. The forest vegetation simulator: A review of its structure, content, and applications. *Comput. Electron. Agr.* 49(2005):60–80.

Daugherty, P., and J. Fried. 2007. Jointly optimizing selection of fuel treatments and siting of forest biomass-based energy production facilities for landscape-scale fire hazard reduction. *INFOR: Inform. Syst. Oper. Res.* 45(1):17–30.

Denardo, E. 2017. *Dynamic programming: Models and applications*. Dover Publications, Mineola, NY. 227 p.

Dueck, G. 1993. New optimization heuristics: The great deluge algorithm and the record-to-record travel. *J. Comput. Phys.* 104.1(1993):86–92.

Fight, R.D., and J. Barbour. 2005. *Financial analysis of fuel treatments*. USDA Forest Service Gen. Tech. Rep. PNW-662, Pacific Northwest Research Station, Portland, OR. 20 p.

Fried, J.S., G. Christensen, D. Weyermann, R.J. Barbour, R. Fight, B. Hiserote, and G. Pinjuv. 2005. Modeling opportunities and feasibility of siting wood-fired electrical generating facilities to facilitate landscape-scale fuel treatment with FIA BioSum. P. 195–204 in *Proceedings of the 2003 Symposium on Systems Analysis in Forest Resources*, Bevers, M., and T.M. Barrett (comps.). USDA Forest Service PNW-GTR-656, Pacific Northwest Research Station, Portland, OR.

Fried, J., L. Potts, S. Loreno, G. Christensen, and R. Barbour. 2017a. Inventory based landscape-scale simulation of management effectiveness and economic feasibility with BioSum. *J. For.* 115:249–257.

Fried, J.S., T.B. Jain, S. Loreno, R.F. Keefe, and C.K. Bell. 2017b. A framework for evaluating forest restoration alternatives and their outcomes, over time, to inform monitoring: Bioregional inventory originated simulation under management. P. 40–50 in *Proceedings of the 2017 Forest Vegetation Simulator (FVS) Virtual e-Conference*, Keyser, C.E., and T.L. Keyser (eds.). USDA Forest Service E-Gen. Tech. Rep. SRS-224, Southern Research Station, Asheville, NC.

Jain, T., M. Battaglia, H.-S. Han, R. Graham, T. Russell, C. Keyes, J. Fried, and J. Sandquist. 2012. *A comprehensive guide to fuel management practices for dry mixed conifer forests in the northwestern United States: Chapter 11*. USDA Forest Service Gen. Tech. Rep. RMRS-GTR-292, Rocky Mountain Research Station, Fort Collins, CO. 331 p.

Jain, T.B., J.S. Fried, and S.M. Loreno. In review. Evaluating the effectiveness of multipurpose fuel treatments in enhancing fire resistance in dry mixed conifer forests of the western U.S. *For. Sci.*

Lehmann, J. 2007. A handful of carbon. *Nature* 447:143–144.

Martinkus, N., G. Latta, T. Morgan, and M. Wolcott. 2017. A comparison of methodologies for estimating delivered forest residue volume and cost to a wood-based biorefinery. *Biomass Bioenerg* 106:83–94.

McRoberts, R.E., W.A. Bechtold, P.L. Patterson, C.T. Scott, and G.A. Reams. 2005. The enhanced forest inventory and analysis program of the USDA Forest Service: Historical perspective and announcement of statistical documentation. *J. For.* 103(6):304–308.

Monserud, R., E. Lowell, C. Eini, D. Becker, S. Hummel, E. Donoghue, R. Barbour, et al. 2004. *Contemporary wood utilization research needs in the Western United States*. USDA Forest Service Gen. Tech. Rep. PNW-GTR-616, Pacific Northwest Research Station, Portland, OR. 49 p.

Petitmermet, J.H. 2018. *Tethering and Biochar: Two emergent technologies with implications for fuels treatments* *on federal forest lands*. M.Sc. thesis, Oregon State University, Corvallis, OR. 194 p. Available online at https://ir.library.oregonstate.edu/concern/graduate_thesis_or_dissertations/0g354m150; last accessed April 6, 2019.

Petitmermet, J.H. 2019. *Neoprocessor Github site*. Available online at https://github.com/JPetitmermet/Neo-Processor; last accessed April 6, 2019.

Petitmermet, J.H., J. Sessions, J. Bailey, and R. Zamora-Cristales. 2019. Cost and productivity of tethered cut-to-length systems in a dry forest fuel reduction treatment, a case study. *For. Sci*. doi:10.1093/forsci/fxz010.

Safford, H.D., J.T. Stevens, K. Merriam, M.S. Meyer, and A.M. Latimer. 2012. Fuel treatment effectiveness in California yellow pine and mixed conifer forests. *For. Ecol. Manage*. 274:17–28.

Sessions, J., D. Smith, K. Trippe, J. Fried, J. Bailey, J. Petitmermet, W. Hollamon, C. Phillips, and J. Campbell. 2018. Can Biochar link forest restoration with commercial agriculture? *Biomass Bioenerg*. 123:175–185.

Stephens, S.L., and L.W. Ruth. 2005. Federal forest-fire policy in the United States. *Ecol. Appl.* 15:532–542.

Stampfer, K. 2016. *Harvester and forwarder on steep slopes—The European perspective. Council on Forest Engineering Demo International 2016 Conference*. Available online at https://www.cif-ifc.org/wp-content/uploads/2016/10/Stampfer.pdf; last accessed April 6, 2019.

Stephens, S.L., J.J. Moghaddas, C. Edminster, C.E. Fiedler, S. Haase, M. Harrington, J.E. Keeley, et al. 2009. Fire treatment effects on vegetation structure, fuels, and potential fire severity in western U.S. forests. *Ecol. Appl.* 19:305–320.

Stewart, H.G., K.A. Blatner, F.G. Wagner, and C.E. Keegan. 2004. Risk and economic feasibility of processing small-diameter material in the U.S. West. Part I: Structural lumber. *Forest Prod. J.* 54(12):97–103.

Toman, E., B. Shindler, S. McCaffrey, and J. Bennett. 2014. Public acceptance of wildland fire and fuel management: Panel responses in seven locations. *Environ. Manage*. 54(3):557–570.

Trippe, K., S. Griffith, G. Banowetz, and G. Whittaker. 2015. Changes in soil chemistry following wood and grass biochar amendments to an acidic agricultural production soil. *Agron. J.* 107:1440–1446.

UOW. 2013. *Washington forest biomass assessment report*. Prepared for the Washington Department of Natural Resources. Available online at http://wabiomass.cfr.washington.edu/docs/WashingtonForestBiomassSupplyAssessment.pdf; last accessed April 6, 2019.

USDA FS. 2018. *First order fire effects model (FOFEM)*. Available online at https://www.firelab.org/document/fofem-files; last accessed April 6, 2019.

Wagner, F., C. Keegan, R. Fight, and S. Willits. 1998. Potential for small diameter sawtimber utilization by the current sawmill industry in western North America. *Forest Prod. J.* 48(9):30–34.