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Inventory-Based Landscape-Scale Simulation of Management Effectiveness and Economic Feasibility with BioSum

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The Forest Inventory and Analysis (FIA)-based BioSum (Bioregional Inventory Originated Simulation Under Management) is a free policy analysis framework and workflow management software solution. It addresses complex management questions concerning forest health and vulnerability for large, multimillion acre, multiowner landscapes using FIA plot data as the initial stand conditions to conduct statistically representative analyses and simulations. The system now includes extensive data consistency and integrity checks for analytical quality assurance, access to any measured or calculated stand attribute for defining effective management, and the capacity to project stands forward while allowing multiple, sequential management interventions, with stand metrics calculated at each time step, all available to drive the choice of what is best for each stand. One example of a policy-relevant finding based on this empirical analytic framework is that fire hazard reduction is both more effective and can occur without subsidy in most southern Oregon and northern California forests, provided that some medium-sized trees are removed; another is that harvest residues recovered for energy contribute only modestly to treatment feasibility.

Keywords: restoration, feasibility, fuel treatment

Foresters understand that management decisions have implications at scales ranging from single trees to forested landscapes and that predicting effects at a broad scale is overwhelmingly complex without the application of assumptions so simplistic that they undermine the viability of a prediction. Yet facing this complexity is unavoidable, given that these decisions can profoundly influence the health of our forested ecosystems and their capacity to deliver the societal benefits on which we rely. How can we evaluate the cumulative effects of myriad stand-level treatments undertaken by landowners and forest managers, operating with different priorities, while also accounting for the interactions with forest products markets, to arrive at likely outcomes for the larger forested landscape in terms of future resiliency? Although formal modeling of management over large forested landscapes for practical learning about options and potential outcomes has yet to be adopted as a standard operating procedure, foresters have come to understand that ecosystem management all but requires whole-landscape analysis to evaluate management strategies and to inform the individual projects that comprise those strategies.

Although initially developed as a tool for landscape-scale simulation of the management and economics of fire-prone forests of the western United States, BioSum (Bioregional Inventory Originated Simulation Under Management[1]) can be used to analyze any kind of potential management opportunities and outcomes over very large (>1 million acres) forested landscapes. At this scale, tradeoffs between spatial specificity and the accuracy of the key data needed to conduct the analysis are unavoidable. For the purposes for which BioSum is best applied, the accuracy and representativeness of tree list data are very important, whereas the precise locations of every tree and stand are less so. Over the last two decades, as geographic information systems and various kinds and sources of remotely sensed data

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rapidly evolved and were deployed into forest management organizations, analysts have focused on the precision of location (e.g., of streams, roads, and stand boundaries), potentially at the expense of accuracy and precision regarding forest structure and composition. As a consequence, many forest information systems are spatially focused, but, given the complexity of key questions and their dependence on attributes not easily captured by conventional remote sensing approaches, they are not always adroit at accurately answering questions such as "how many acres of forest are at risk from one or more threats," "how many of those acres could be restored to within a historical hazard range," "how much would it cost to do so," and "how much wood and of what types could be produced" and assessing the relative effectiveness and economic efficiencies of alternative treatment regimes, implemented over multiple decades.

Data collected on the Forest Inventory and Analysis (FIA) plot network sacrifice some spatial specificity but enable a highly accurate, tree list-informed understanding of stand structure and composition that can address these questions for a representative sample of the entire forested landscape. The data have the potential for the development of management scenarios specifying trajectories of management interventions that address complex sets of objectives that are sensitive to differences in landowner emphasis (e.g., by owner class or land allocation), operability, local wood processing infrastructure, and prices offered for harvested wood products. Because they are generated from a statistically representative, field-based sample, the FIA data have a unique advantage in that each plot can be regarded as representing a known fraction of the forested landscape. This feature enables strong inferences from analysis results to the likely biophysical (forest stand attributes) and economic outcomes (costs, revenues, and production) of management in the forest at large.

For large, multimillion-acre, multiowner landscapes, we devised the semiautomated, user interface-driven BioSum analysis framework with supporting analysis software and workflow protocols over the past decade to conduct such statistically representative analyses. Using the FIA plot data as the initial stand conditions, we apply silvicultural prescriptions designed to achieve forest restoration goals such as reducing stand density to promote forest health, restoring species composition, and lowering crown fire potential.

This framework builds on earlier work on biomass summarization, predating completion of the BioSum software, that relied on the Forest Vegetation Simulator (FVS) primarily as a "prescription engine" (e.g., Fight et al. 2004) to apply fuel reduction treatments to "stand" data derived from inventory plot data from a systematic sample of forested land, the Fuel Reduction Cost Simulator (FRCS) (Fight et al. 2006) to estimate the costs of implementing those treatments, a travel time algorithm to estimate costs of hauling harvested material from the forest to mills and bioenergy facilities, and various logic models for selecting the best treatments based on improvements in torching and crowning indices—both thought to be related to crown fire potential (Fried et al. 2005). The framework, which was used to evaluate multiple scenarios in a 21-million acre forested region of northern California and Southern Oregon, showed the following: that most (67–79%) of the biomass that could be removed in effective treatments would be contained in merchantable logs destined for conversion into comparatively long-lived wood products (Barbour et al. 2008); that the region could, depending on assumptions and objectives, annually produce up to $590 million in net revenue, yield 6–12 million green tons of biomass and 0.8–1.2 billion cubic feet of merchantable wood over the course of a decade while reducing the fire hazard on 2.8-8.1 million acres and providing bioenergy capacity of 496–1,009 MW (Daugherty and Fried 2007); and that landing-based, 1,000-kW BioMax plants could be an economically viable solution for converting nonmerchantable trees and the tops and limbs of merchantable trees into electricity, contingent on access to the electrical grid (Bilek et al. 2005).

In every BioSum analysis, assumptions must be made as to which acres are open to potential management and which kinds of silvicultural prescriptions, logging systems, and surface fuels management approaches to explore. We typically assume that reserved and designated roadless areas on public lands are off-limits to management, but that any other forested acre could *potentially* be managed. Of course many ostensibly unreserved acres have special considerations for habitat, recreation, visual constraints, riparian protection, and other concerns that make them unavailable for management, de facto, so the statistics generated from the representative FIA sample on which BioSum relies should be considered the upper limits on what is biophysically possible, given realistic economic constraints and the absence

Management and Policy Implications

The representative sample of the forested landscape provided by Forest Inventory and Analysis (FIA) data is widely acknowledged as both an analytic resource treasure and a challenging data set to use. We developed the BioSum (Bioregional Inventory Originated Simulation Under Management) tool to make the data and the analyses it can enable more accessible to analysts and policymakers. BioSum leverages FIA data to assess the biophysical and economic outcomes, over time and for broad spatial extents, of management alternatives aimed to, for example, reduce fire hazard, by integrating the data with off-the-shelf and custom models and tools. This approach facilitates documented "what-if" reanalysis and exploration through formal scenario building. BioSum integrates the Forest Vegetation Simulator (FVS) stand projection model, a treatment cost estimation model, contemporary and local pricing and merchandising data, and a spatially explicit haul cost accounting system to compare the economic feasibility and efficacy of candidate sequences of silvicultural treatments. It can be used to evaluate whether treatments accomplish forest restoration goals such as reducing stand density to promote forest health, achieving a different species composition, and reducing both surface fuel loading and the ladder fuels that can lead to stand-replacing fires. The system provides broad analytical capacity to address myriad issues, such as the following: although simulated treatments of all forests in Arizona and New Mexico generated positive net revenue in only a small fraction of high hazard forests, BioSum results suggest that with the right treatments, sufficient positive net revenue on some acres could be generated to offset losses on other acres within the same landownership, providing the potential to expand treatments to more than half of the forest area rated hazardous, without additional subsidy; and BioSum quantified the substantial carbon sequestration and substitution potential of fuel treatments in the short to moderate fire-return interval forests common to much of the western United States.

of socially determined constraints, not necessarily as achievable targets or likely outcomes.

The newly released (in 2015) modeling software, BioSum 5, extends the previously reported framework primarily by the following:

1. Fully integrating, with workflow management software and innumerable data consistency and integrity checks, the disparate models and analysis steps into a seamless workflow that enables an FVS- and Microsoft Access-capable analyst to build a simulation model of any kind of forest management at the landscape scale and for policy analysts and decisionmakers to iteratively explore outcomes, in terms of management effectiveness and economic feasibility, over entire landscapes under a range of current and potential future assumptions and scenarios.
2. Facilitating the tracking and use as effectiveness criteria of any stand attribute collected on or calculated from FIA plot data (such as volume and value of merchantable and energy wood) and a rich suite of stand metrics that can be generated in FVS or other tree list processing models, concerning, for example, stand structure, species composition, deadwood, carbon dynamics, and potential fire behavior.
3. Projecting stands forward for as many as four 5- or 10-year cycles, with the potential for multiple manipulations per stand of overstory, surface vegetation, and fuel structures, with stand metrics calculated at each time step, and usable in the treatment selection logic that drives the choice of the best management package for each plot over the entire time horizon, if desired.

This overview of the modeling system offers highlights of lessons learned from conducting a variety of BioSum analyses focused on the treatment of forest fuels, a condensed summary of how the model operates, and some examples of questions, as yet unexplored, for which BioSum is well-suited.

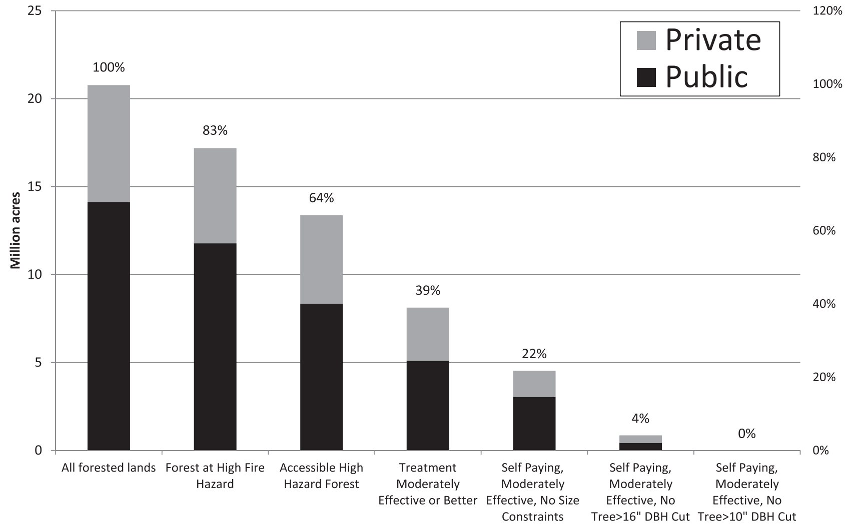

Figure 1. Area, within the Klamath, Modoc Plateau, southern Cascades, and eastern Cascades ecoregions, of (1) forestland, (2) forestland rated hazardous, based on estimates from FIA data processed via FFE-FVS, (3) roaded and nonreserved hazardous forest, (4) no. 3 that is treatable with moderate effectiveness, (5) no. 3 that is treatable with moderate effectiveness and positive net revenue generation, (6) no. 3 that is treatable with moderate effectiveness and positive net revenue generation and a 16 in. cap on size of trees that can be removed, (7) no. 3 that is treatable with high effectiveness, positive net revenue generation, and a 16 in. limit on size of trees that can be removed, and (8) no. 3 that is treatable with moderate effectiveness and positive net revenue generation and a 10-in limit on size of trees that can be removed.

Lessons from BioSum Simulation of Fuel Treatments

Effective Treatments Remove Medium-Sized Trees, Not Just Small Trees

For the Oregon-California Analysis, 10 silvicultural prescriptions were simulated for 7,532 stands derived from 6,168 FIA plots (some plots have >1 stand type, in FVS parlance) representing 21 million forested acres in the Klamath, Southern Oregon, Modoc, and East Cascades FVS variant regions straddling southern Oregon and northern California. Prescriptions were split between thin-from-below (ladder fuel reduction) and thin-across-diameter classes (crown spacing enhancement) approaches and varied in their residual basal area targets and maximum tree size eligible for harvest. Whole-tree and cut-to-length logging systems were simulated on gentle (<40%) slopes where ground-based equipment can operate and manual felling/bucking on steep slopes. Trees of all noncommercial species larger than 3 in. dbh (5 in. on steep slopes) and tops and limbs of commercial species of merchantable size trees whole-tree harvested on gentle slopes were collected to the landing and chipped for energy wood. Bolewood was priced by species and size class according to recent pricing data, and energy wood was assumed to be valued at $18/green ton delivered to an electrical generating facility.

Even with the availability of a multitude of fire hazard-relevant metrics computed by the Fire and Fuels Extension (FVS-FFE) (Rebain 2010), deciding on logical and meaningful criteria for what constitutes effective treatment, even from the single-objective perspective of reducing crown fire potential, is surprisingly challenging. The effectiveness could depend on the level of pre- and posttreatment metrics relative to a standard or goal. It could also depend on the magnitude of the change achieved by the treatment and how one deals with cases where treatment shifts one metric toward the goal while shifting another metric away from the goal. For this analysis, we considered a treatment effective based on two indices, the torching index (TI) and the crowning index (CI), which are the wind speed, in mph, that the model predicts would be required before a surface fire would transition to torching individual trees (TI) or become a crown fire (CI). Higher index values (wind speeds in mph) correspond to greater resistance to crown fire (lower hazard). After consulting with fuels managers and seeking to balance the different aspects that are important in determining treatment effectiveness, we assumed four pathways to effectiveness for each index:

1. Stand has a pretreatment index value of <25 mph and a posttreatment value of ≥25 mph, and treatment achieves a change of ≥10 mph.

Table 1. Net revenue from treatments, area treated, energy and merchantable wood mass produced, energy wood value, and ratio of merchantable wood value to energy wood value for eight treatment-only scenarios (no posttreatment projection) simulated for a 21-million acre forested region in southern Oregon and Northern California encompassing the Klamath, Modoc Plateau, southern Cascades, and eastern Cascades ecoregions.

Scenario no.	Scenario description	Net revenue (billion $)	Acres (million)	Energy wood (million green tons)	Merchantable wood (million green tons)	Energy wood value (billion $)	Ratio of merchantable to energy wood value
1	Max NR ModEff	8.9	4.5	83	309	1.5	11
2	Max NR HighEff	7.1	2.8	61	235	1.1	12
3	Max NR ModEff ALL	5.6	8.1	138	350	2.5	7
4	Max TI improvement HighEff	4.7	3.9	85	241	1.5	8
5	Max NR ModEff 21″ limit	2.8	3.2	70	142	1.3	5
6	Max NR ModEff 16″ limit	0.3	0.9	20	27	0.4	3
7	Max NR ModEff 16″ limit ALL	−2.5	4.8	71	51	1.3	1
8	Max NR ModEff 10″ limit ALL	−2.8	3.4	33	0	0.6	0

Scenarios were driven by sets of decision rules that selected from among treatments for each forested plot that applied one of eight rules: select the treatment for each stand that is (1) Max NR ModEff (at least moderately effective and maximizes net revenue [stands where net revenue is less than zero will not be treated]), (2) Max NR HighEff (highly effective and maximizes net revenue), (3) Max NR ModEff ALL (at least moderately effective and maximizes net revenue and treats all treatable stands, even when net revenue is negative), (4) Max TI ModEff ALL (highly effective and maximizes the improvement in TI), (5) Max NR ModEff 21″ limit (at least moderately effective and maximizes net revenue but cuts no trees larger than 21 in. dbh), (6) Max NR ModEff 16″ limit (at least moderately effective and maximizes net revenue but cuts no trees larger than 16 in. dbh), (7) Max NR ModEff 16″ limit ALL (at least moderately effective and maximizes net revenue but cuts no trees larger than 16 in. dbh and treats all treatable stands, even when net revenue is negative), and (8) Max NR ModEff 10″ limit ALL (at least moderately effective and maximizes net revenue but cuts no trees larger than 10 in. dbh and treats all treatable stands, even when net revenue is negative).

Table 2. Net revenue from treatments, area treated, merchantable volume, and energy wood mass produced for six treatment-only (no projection) scenarios modeled for all forested areas of Arizona and New Mexico with a broad spectrum of forest type-specific treatment alternatives.

Scenario no.	Scenario description	Net revenue (billion $)	Acres (millions)	Merchantable volume (billion ft^3)	Energy wood (million green tons)
1	Max NR All	−1.6	11.2	4.4	80
2	Max NR NR + only	+1.0	1.6	2.2	17
3	Max NR Subsidize	0	7.7	3.3	48
4	Min Merchantable Volume All	−2.3	11.2	3.1	73
5	Min Merchantable Volume NR + only	+0.7	1.6	1.9	15
6	Min Merchantable Volume Subsidize	0	4.9	1.4	22

Scenarios were driven by heuristics that selected, for each stand, among treatments deemed effective, the one that (1) Max NR All (maximized net revenue and treated all treatable stands), (2) Max NR NR + only (maximized net revenue and treated only stands where net revenue was greater than zero), (3) Max NR Subsidize (expanded the area treated in scenario 2 toward scenario 1 to include as many acres as possible by subsidizing money-losing ones with net revenue earned on other acres by the same landowner, for public lands only), (4) Min Merchantable Volume All (minimized harvest of merchantable wood and treated all treatable stands), (5) Min Merchantable Volume NR + only (minimized harvest of merchantable wood and treated only stands where net revenue was greater than zero), and (6) Min Merchantable Volume Subsidize (expanded the area treated in scenario 5 toward scenario 4 to include as many acres as possible by subsidizing money-losing ones with net revenue earned on other acres by the same landowner, for public lands only).

2. Stand has a pretreatment index of <25 mph, fails to reach a posttreatment value of ≥ 25 mph, but does achieve a change of ≥ 20 mph.
3. Stand has a pretreatment index value between 25 and 50 mph, and treatment achieves an improvement of ≥ 15 mph.
4. Stand has a pretreatment index value of >50 mph. and treatment achieves a change of ≥ 20 mph.

These four expressions are evaluated, for both indices, to determine whether a treatment is TI effective and whether it is CI effective. Then, the overall level of effectiveness, considering accomplishments with respect to both indices, is defined as follows:

A. Highly effective treatments achieve at least one of two criteria:
   TI effective, $\Delta CI > -10$, posttreatment $CI > 25$
   CI effective, $\Delta TI > -10$, posttreatment $TI > 25$
B. Moderately effective treatments achieve:
   CI effective, $\Delta TI > -10$

Both levels of effectiveness allow for some "back-sliding" in one index (by up to 10 mph) if the treatment is effective with respect to the other index.

Our analysis revealed that most forests in this region rate as hazardous, when a 20-mph hazard threshold for TI and CI was applied and that most of the hazardous forest area is amenable to effective treatment by our definitions (Figure 1); however, requiring treatments to generate revenue sufficient to offset all costs reduces the treatable area substantially and when treatment choices are constrained to preclude harvest of merchantable-sized wood, treatment area drops dramatically to $<5\%$ of the entire forest with a diameter cap of 16 in. and to 0% with a diameter cap of 10 in.

Once a BioSum analysis database has been assembled, it is easy to explore a broad range of potential scenarios and policy alternatives simply by applying alternative criteria for determining the effectiveness and alternative heuristics (sets of decision rules) for selecting the best treatment when more than one treatment rates as effective. Explorations of the Oregon-California BioSum database revealed profound differences, depending on assumptions (Table 1). For example, the level of effectiveness required makes a big difference in area treated and wood and revenue generated (scenario 1 versus 2) and assuming that all acres that can be effectively treated are included (ALL), rather than just those that generate positive net revenue, produces even greater differences in these attributes (e.g., scenarios 1 versus 3 and 6 versus 7). Diameter caps also have a profound influence on the ratio of merchantable value produced to value of harvest residues used as energy wood (scenarios 1 versus 5 versus 6 versus 8). The broad range of potential outcomes represented in Table 1 highlights the importance of clearly communicating the assumptions inherent in a BioSum analysis or any analysis of potential wood availability associated with a landscape-wide change in management.

An encouraging finding was that even under a policy requiring that treatment costs be covered by sales of harvested wood, more than half of the acres for which one or more treatments are effective would be eligible, in part because effective treatments tend to harvest both submerchantable trees, to reduce ladder fuels, and merchantable-sized trees, to further raise canopy base height and reduce crown density. However, when treatment options are eliminated by the imposition of diameter limits, the fraction of the forested landscape where effective, cost-covering treatment is possible is dramatically reduced. Although there has long been speculation that utilizing small diameter trees and harvest residues as energy wood would enhance the economic feasibility of fuel treatments, these numbers tell a different story. For any scenario in which overall net revenue is positive (treatment-derived product revenues exceed costs), merchantable wood flows exceed energy wood yield, typically by a large margin; on a value basis, the contributions of energy wood utilization to economic feasibility, relative to sales of merchantable wood, are even more modest.

A similar BioSum analysis was undertaken for the entire forested area of Arizona and New Mexico, with a different set of silvicultural prescriptions and operability and effectiveness assumptions (e.g., specific prescriptions were targeted for each forest type, treatment operations were limited to slopes of <40%, and a single level of treatment effectiveness was specified), for the purpose of evaluating potential locations for bioenergy production facilities and the appropriate facility scale. BioSum was extended to estimate transportation costs over rail and road networks, and the results showed that rail transportation significantly extended the area over which wood could be collected, supporting the case for building wood utilization facilities scaled to greater capacity.

The economic feasibility proved quite different than for Oregon and California. Unlike Oregon/California scenario 3, in which forcing treatment of all treatable acres (including those that lose money) still generated 5.6 billion dollars of net revenue, in Arizona and New Mexico, treating all 11.2 million acres that could be effectively treated implies a negative net revenue: −1.6 billion dollars (Table 2). Only 1.6 million acres could be treated if costs must be covered by revenue. As most Southwest forestlands are

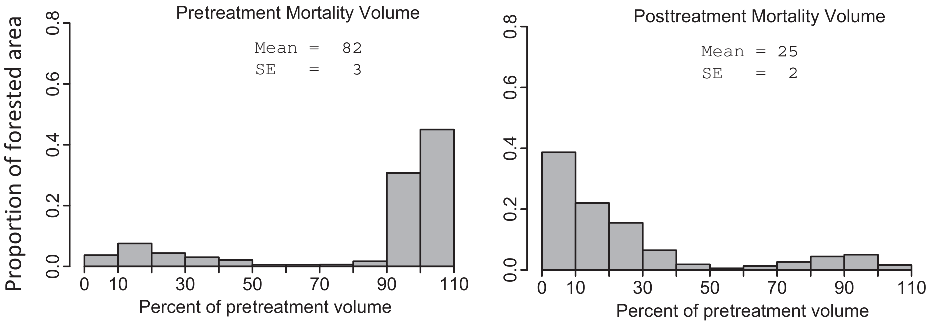

Figure 2. Predicted tree mortality, expressed as a proportion of pretreatment live tree volume, before treatment and after the treatment that most reduced the hazard score for 1.027 million acres in Douglas-fir and true fir forests in the inland Northwest.

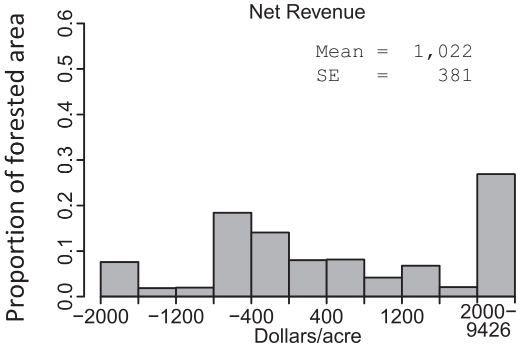

Figure 3. Histogram of predicted net revenue per acre for Douglas-fir and true fir forests in Northern California and the Klamath Mountains region if the most effective treatment is applied to every stand in the 368,000 acres in these forest types in this region currently rated hazardous.

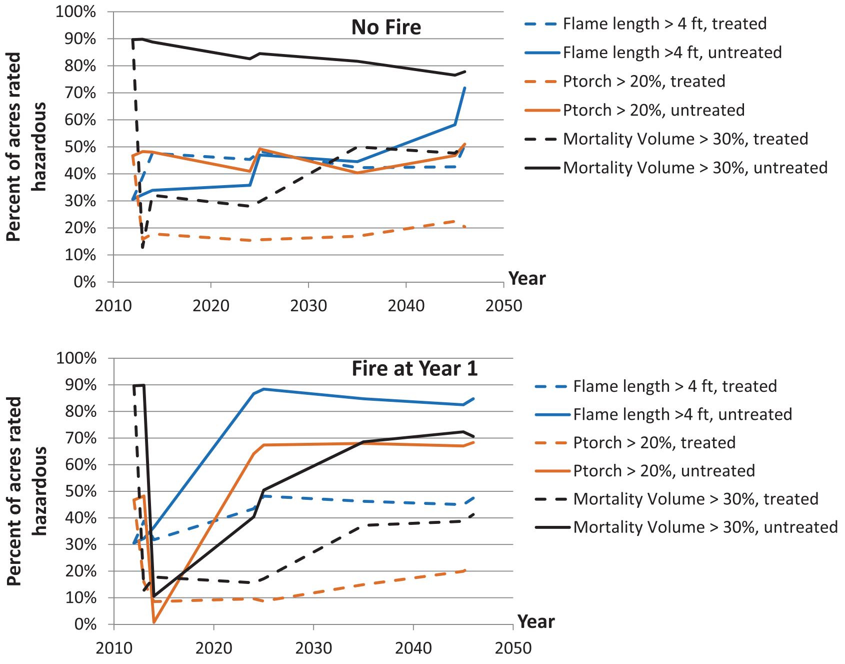

Figure 4. Percentage of forested area rated hazardous with respect to firefighter safety (surface flame length), crown fire potential (probability of torching [PTorch]), and stand resilience (percentage of live tree volume killed by a simulated fire under severe weather), with the best available treatment and no treatment over 33 years when no fire was simulated after treatment and when a fire was simulated 1 year after treatment.

in public ownership, we explored the concept of allowing acres that generate revenues in excess of costs to subsidize treatment of other acres on the same public landownership (private lands were excluded). Choosing the prescription that maximizes net revenue on every treatable acre, which in all cases meant cutting some merchantable trees, and allowing subsidy within an ownership, treatable area was increased from 1.6 to 7.7 million acres.

Illustrating Hazard for All Unreserved Forests Offers Context for Stand-Level Challenges/Opportunities

As part of a recently completed synthesis guide to fuels management in the dry mixed conifer forests of 8 western states (Idaho, Montana, Utah, Oregon, Wyoming, Nevada, Washington, and California), we simulated 12 fuel treatments using cut-to-length and whole-tree harvest systems on 5,174 mixed conifer forest inventory plots (approximately 30 million acres) to evaluate effectiveness and economic feasibility (Jain et al. 2012). That study relied on three different thinning styles: crown thinning to achieve greater spacing between crowns; ladder fuel reduction focused on removal of smaller trees that connect surface fuels with canopy layers; and restoration focused on retaining early seral species, such as ponderosa pine (*Pinus ponderosa*) and removing late seral species, such as grand fir (*Abies grandis*). In that analysis, we devised a hazard score that accounted for whether or not a stand was hazardous with respect to crown fire potential (based on FVS-FFE metrics TI and the probability of torching), firefighter safety (based on surface flame length), and resilience (based on FVS-FFE predicted percentage of tree volume that would be killed by fire). Hazard thresholds were established for each of the four metrics, and, for each, a stand "earned" a point for exceeding the threshold; these points were summed to obtain a composite hazard score between 0 and 4. Treatment success was defined as any reduction in this composite hazard score, and treatments that achieved the greatest reductions in hazard score were deemed the most effective.

The synthesis guide includes BioSum simulation results, summarized as means and totals by region and forest type, including the frequency with which each treatment performed best, the average treatment accomplishment for each component metric in the hazard score, the volumes and value of

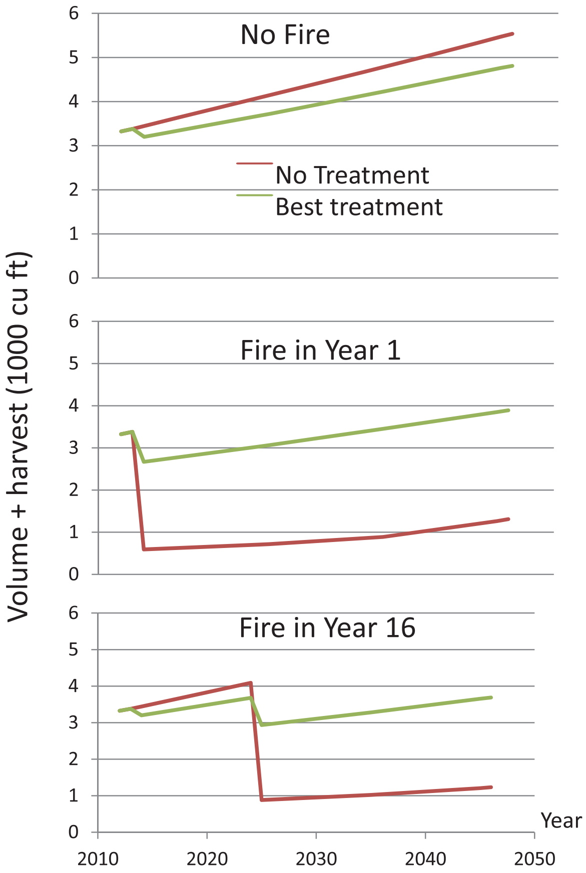

Figure 5. Mean, FVS-modeled merchantable wood volume density (thousands of cubic feet per acre) in live trees plus the live tree volume equivalent in harvested product effects (from carbon stores in long-lived products and climate benefits via substitution) with no treatment and with the best available treatment for cases of no fire, fire 1 year posttreatment, and fire 16 years posttreatment.

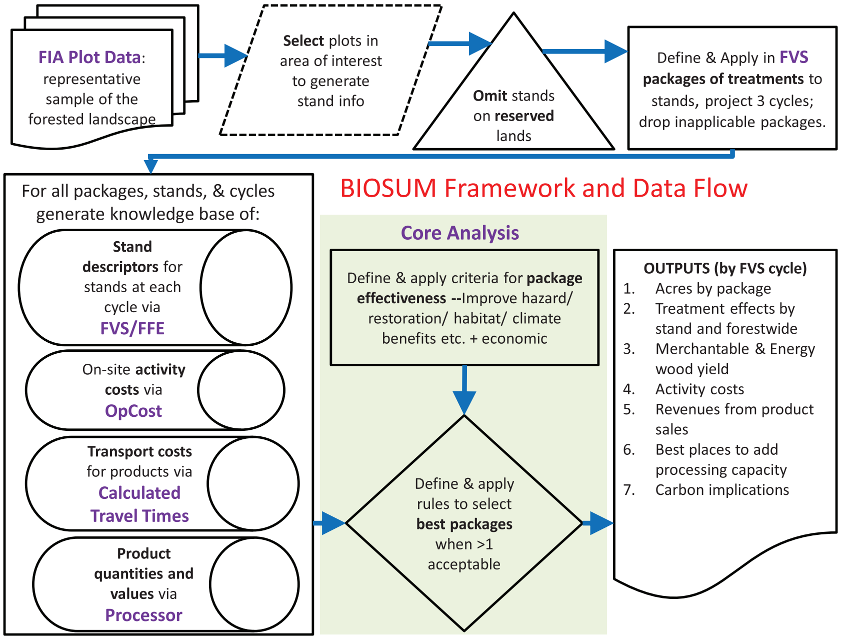

Figure 6. Flow chart of a BioSum analysis indicating key analysis steps, model elements, and workflow management software modules.

harvested wood derived from the best treatments, and onsite and transportation costs associated with the treatments. An extensive appendix presents histograms by region and forest type. For example, Figure 2 shows how predicted tree mortality, expressed as a proportion of pretreatment live tree volume, drops dramatically with treatment in Douglas-fir (*Pseudotsuga menziesii*) and true fir forests in the inland Northwest. Pretreatment, most stands would experience 90–100% volumetric mortality; posttreatment, <20% is typical, at least for the 1,027,000 acres where treatment was predicted to be effective for reducing the composite hazard score. Such summaries inform managers about the prospects for achieving significant change in specific hazard components. Histograms of the economic consequences (e.g., net revenue) of applying the best treatment to every stand convey the considerable variability among stands, forest types, and regions and the proportion of stands for which treatment is possible without subsidy (Figure 3).

Carbon Implications of Fuel Treatments in Western Forests

Based on learning from the analysis for the fuels synthesis, we expanded the list of fuel treatments by five, ultimately doubling the forest area that modeling suggested could be effectively treated. To understand how forest carbon stocks change due to growth and fire-induced mortality and the implications for greenhouse gas emissions of fuel treatments carried out over time, we simulated all 11 treatments in every stand in year 1, and then projected four alternative FVS scenarios: with no fire, with fire at year 1, with fire at year 16, and with fire at year 32. This allowed us to assess the impact of implementing the most effective treatment (the one that most reduced hazard score) on total climate benefits, inside and outside of the forest. Considering again the same three dimensions of hazard—crown fire potential, firefighter safety, and resilience—we looked at the percentage of the forested acres that would rate as hazardous by each of these criteria, over time, for each scenario. With no fire, FVS predicted that application of the best available treatment would result in sustained decreases in the area rated hazardous with respect to crown fire potential and resilience, whereas improvements to firefighter safety were shorter-lived (Figure 4). When fire was modeled as occurring at year 1, the hazardous area fraction, as measured

How BioSum Works—In a Nutshell

The BioSum software, now at version 5, consists of several components, including a Microsoft Windows computer program that manages the workflow of a BioSum analysis (Figure 6). The first step after identifying an area of interest is to import FIA data in FIADB format, which can be downloaded from the national FIA website (at fia.fs.fed.us). BioSum stores these data in a project directory where all information for an analysis is stored and processed. Silvicultural prescriptions to model are described by the user, and labels are assigned within BioSum; the keywords and parameters for implementing the prescriptions in FVS are developed separately within the FVS software environment. The user can specify an unlimited number of management packages, each containing a prescription or no action choice for each of four growth cycles of 5 to 10 years each. Harvesting systems can be selected separately for each prescription, if desired, or selected later when wood processing scenarios to model are developed. BioSum writes FVS-readable ASCII text files to pass the inputs to the FVS environment; for example, they can be imported with the FVS utility PREDISPOSE.

All BioSum analyses completed to date were accomplished by a team covering multiple knowledge domains, including geographic information science, silviculture, fire and fuels management, economics, and perhaps most critically, the FVS model. An experienced FVS analyst can devise and implement appropriate simulations that account for all prescription elements in each package, including surface fuel treatment; fuel managers and silviculturists provide "yard loss" parameters to account for differences in logging slash left behind by whole-tree harvest systems versus those that leave tops and limbs where trees are felled and regeneration parameters, for example, those generated by running a REPUTE analysis (Vandendriesche 2010). In analyses currently underway, treatments are triggered by stand conditions (such as basal area) each decade, and analyses of up to 130 alternative treatment "packages" (sequences of treatments), applied to stand data drawn from several thousand inventory plots, have been modeled. The workflow in a BioSum analysis progresses as FVS output is imported into the BioSum project, and BioSum calculates volume and biomass using the standard, species and region-specific FIA equation systems for every tree in the FVS CUTLIST tables containing records of trees harvested by the prescriptions applied in each package at each growth/treatment cycle.

BioSum's PROCESSOR module accomplishes two essential tasks to characterize wood processing output for each stand-package combination for each growth/treatment cycle: computing per acre volume and weight of harvested wood by user-specified species group and tree diameter class; and estimating per acre treatment costs, including harvest operations and any related activities such as treatment of surface fuels and erosion control. The system relies on the FVS/OpCost module, developed in the open source R development environment, with logic similar to the that of the FRCS (Dykstra et al. 2009) which OpCost replaced, and also includes findings from more recent cost studies and additional harvest system options (Bell and Keefe 2014). The user can specify multiple alternative PROCESSOR scenarios to reflect, for example, different logging systems, different grouping parameters (e.g., for species and diameter classes), and different merchantability standards and product prices. Any of these PROCESSOR scenarios can be selected later when the user is running BioSum's CORE ANALYSIS module to select the "best" treatment packages to fulfill any set of objectives.

Calculating travel times is a parallel process in the workflow that can be completed in a geographic information system (GIS) environment such as ArcGIS. It can be undertaken at any point after importation of FIADB formatted data, but before CORE ANALYSIS, to generate a table of round-trip truck travel times between the publicly available, approximate locations of each FIA plot and a user-supplied list of existing and potential processing facilities that accept merchantable and/or energy wood (chipped residues from harvest of merchantable trees and other trees removed as part of the prescription that are of noncommercial size or species). Inputs to this process are publicly available GIS layers representing road networks and travel speeds and geographic coordinates of the wood processing facilities; a set of scripts and instructions are available to guide the analyst through this process using ArcGIS, and these could be modified to allow processing in other GIS environments.

by every dimension, would be reduced regardless of treatment. In the no treatment case, conditions quickly returned to and in some cases exceeded prefire levels. They remained substantially reduced in cases where the best available treatment was applied to every stand.

It is widely recognized that forests have the potential to produce climate benefits, via both in-forest carbon stores and out-of-forest use of harvested forest products (Cooper 1983, Marland 2003, Pacala and Socolow 2004, Nabuurs et al. 2007 as cited by Smyth et al. 2014), although quantifying this potential unequivocally remains challenging (Smyth et al. 2014) and there remains significant debate among scientists on how best to do so (McKinley et al. 2011). Out-of-forest benefits can be generated through both sequestration in long-lived products and via substitution, for example, the use of wood in lieu of fossil energy-intensive building materials and production of wood-based bioenergy in lieu of fossil fuel-generated energy (Malmsheimer et al. 2011). These out-of-forest benefits are recognized by the Intergovernmental Panel on Climate Change in that they are ultimately accounted for by national greenhouse gas reporting systems as reduced emissions in nonforestry sectors of the economy, for example, reduced production of steel, concrete, and fossil fueled energy—the commodities replaced by substitution of wood. However, they have not yet been included in forest-centered offset accounting systems such as the one operated by the California Air Resources Board. Where harvested wood is converted mainly to building products and wood energy, Smyth et al. (2014) estimated significant net mitigation benefits from active forest management in similar forest types in Canada. A regional study in the fire-prone forests of California, where harvested wood is used in these ways, found that, for the average tree, the estimated climate benefits are at least as great as leaving that tree's volume in the forest as live tree wood (Stewart and Nakamura 2012).

Except in the case of no fire or other disturbance events, FVS projections in Douglas-fir-dominated western mixed conifer forests indicated that total climate benefits, when considering both in-forest live-tree carbon storage and out-of-forest benefits of harvested wood (including full substitution benefits), were greater when the best mechanical fuel treatment was applied, whether fire was assumed to occur at 1, 16, or 32 years after treatment (Figure 5). Considering fire frequency, the results suggest that, at least in these forests, climate benefits will be greater with treatment when fire-return intervals are shorter than about 100 years, harvest residues are used for energy, and substitution benefits are included. Alternative scenarios for wood product utilization rates, or substitution rates can be readily applied to the BioSum model projections to estimate potential climate benefits to reflect cases when not all of these out-of-forest benefits can be delivered. For example, if harvested wood is used for paper rather than long-lived building products and harvest residues are burned or left in the woods to decay, the climate benefits of fuel treatment could be greatly reduced, even with short fire-return intervals (Smyth et al. 2014).

Continued

All of the aforementioned processing steps feed into CORE ANALYSIS, BioSum's policy analysis engine, where analysts can interactively specify effectiveness criteria based on any of the FIA or FVS attributes at growth/treatment cycle 1, select which PROCESSOR scenario to apply, choose which processing facilities to enable, and choose optimization parameters such as "pick the treatment package that" "minimizes crown fire potential," "maximizes net revenue (or minimizes costs)," or "retains the most large trees or canopy cover." Including attribute values from growth/treatment cycles 2–4 in the decision criteria can be accomplished via database queries. Every CORE ANALYSIS simulation generates a suite of sizable (multigigabyte) scenario output databases, containing treatment area and per acre costs (both on site and for wood transportation), revenue from product sales, product quantities, and stand attribute outcomes of all packages for all cycles which can be easily aggregated, using database queries, by, for example, owner class, product species group, product tree diameter class, forest type, stand density class, treatment style, or cycle. Aggregation of outputs is also possible by wood processing facility, and sampling errors could be computed if desired.

The scenario output database can be mined to reveal the many dimensions of what alternative management approaches may accomplish in a forested landscape and how feasibility is driven by the choices about which possibilities to explore. It is easy to repeat and then compare and contrast scenario output databases generated from different constraint sets (e.g., imposing diameter caps, requiring treatments to pay for themselves, and treatment longevity criteria) to learn which policy drivers are most influential in achieving management objectives. The databases could also be used by a manager interested in how different sequences of silvicultural activity might play out at the stand level in terms of stand composition and structure, economics, and production. After querying BioSum plot tables to identify plots similar to those of a stand of interest, the corresponding BioSum intermediate output (from PROCESSOR) that serves as input to CORE ANALYSIS could also provide insights on the likely outcomes of multiple silvicultural sequences on that stand.

Analyses in Progress

Several analysis projects using BioSum 5 are underway, and some of them are relying on the enhanced analysis enabled by this software. One such project, sponsored by the California Energy Commission, centers on estimating multidecade availability of woody biomass and merchantable wood in California under alternative future management scenarios compatible with a restoration focus on public lands and business-as-usual versus climate-aware management approaches on private lands. Another, sponsored by the Joint Fire Sciences Program, focuses on evaluating fuel treatment cost effectiveness in western mixed conifer forests for a broad range of treatment approaches, harvesting systems, and surface fuels management strategies. The multitemporal modeling enabled in this version of the software encourages explicit consideration of treatment longevity in effectiveness criteria and poses interesting challenges in defining a framework for representing tradeoffs among product yields, revenue and cost streams, and forest resilience over time.

Future Work

BioSum can be productively deployed to address a much broader range of questions than biomass availability and the feasibility of fuel hazard reduction. For example, the system could be used to evaluate some aspects of habitat suitability under alternative management approaches, if those can be represented as silvicultural prescription packages and if habitat descriptors can be computed from tree lists. It could also be used to explore alternative pathways toward forest restoration, where treatment success might be judged on conformance, at some point in time, to desired future conditions specified as stand metrics. BioSum could also be used to sift through stands that are probably vulnerable to climate change impacts and explore the efficacy and feasibility of alternative approaches to reducing that vulnerability while enhancing resiliency at the forest scale.

The BioSum software and documentation are now freely available[1] for anyone to use. This extensively tested and fully functioning landscape-scale analysis system feeds on standard inventory data and offers promise for many kinds of forest-based analyses. A high priority for improvement to this tool in a future version is an enhanced CORE ANALYSIS that enables an interface-driven, multicycle effectiveness evaluation. Inclusion of enhanced reporting options, such as production of charts to summarize output from the CORE ANALYSIS, PROCESSOR, and FVS modules, would facilitate interpretation of model outputs for some users. This tool extends our capacity for interpreting FIA's "snapshot" representative sample of the forest both in terms of information depth and, via FVS, projections of alternative futures. We hope that managers, policymakers, and interested public groups find it valuable as they respond to ongoing challenges to the health and successful management of our forests.

Endnote

1. For more information, see www.biosum.info.

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