Landscape Analysis with FVS and Optimization Techniques: Efficient Management Planning for the Gotchen Late Successional Reserve

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Abstract—We combine simulation and optimization techniques to test hypotheses about variable-intensity management in a 15,000-acre forest reserve. The Forest Vegetation Simulator (FVS) and integer optimization techniques together help identify tradeoffs between two landscape resource goals: maintaining late successional forest and reducing the threat of wildfire. The FVS model allows us to evaluate the contribution of stand-level treatments to each landscape goal, whereas optimization identifies efficient solutions that allow us to test for complementary or competitive relations between the two goals over time and space. The methods we discuss in this paper are adaptable to forested areas of various sizes and with different resource goals. To illustrate the value and innovation of our approach, an example demonstrates how uncertainty in FVS simulations might affect landscape solutions. This example is the pilot application of a new FVS bootstrap model. Our preliminary results indicate that we should change the definition of late-successional forest used for our final analysis.

Concern about the persistence of species associated with old forests of the U.S. Pacific Northwest led to the creation of a regional forest reserve network in 1994 (Northwest Forest Plan: USDA/USDI 1994). These reserves—called late-successional reserves or LSRs—cover over 5 million acres of Federal land throughout the range of the northern spotted owl (*Strix occidentalis caurina*) in Washington, Oregon, and California. The standards and guidelines for management of LSRs are designed to protect late-successional forest ecosystems from "loss to large-scale fire, insect and disease epidemics, and major human impacts" (USDA/USDI 1994).

Coincident with establishment of the LSR network, aerial detection surveys mapped a western spruce budworm (*Choristoneura occidentalis*) outbreak in the eastern Washington Cascades. The area of the outbreak included the Gotchen LSR, where budworm defoliation was mapped over several thousand acres throughout the 1990s. By 2000, ongoing defoliation and subsequent tree mortality created conditions that caused forest managers and neighboring private and tribal landowners to worry about wildfire. However, forest structures that support elevated budworm populations also contribute to desirable owl habitat, and this apparent paradox raises questions about the role of active management in the LSR.

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Study Objectives

The Gotchen LSR study was designed to test hypotheses about differences in passive versus active management in the 15,000-acre LSR landscape over time and space (Hummel and others 2001). As part of the study, we are using both the Forest Vegetation Simulator (FVS) and integer optimization techniques to characterize relations between the two potentially competing landscape goals of maintaining late successional forest (LSF) and reducing the threat of fire. The FVS model allows us to evaluate the contribution of stand-level treatments to each landscape goal, whereas optimization allows us to identify what different combinations of stand treatments might best meet LSR objectives over time. We are also interested in exploring the potential effects of within-stand variation on landscape-level results and are therefore using a new bootstrap model that assesses uncertainty in FVS projections caused by variation in input data. This paper documents our methods and their potential utility to landscape analysis and planning.

Methods

Combining Simulation and Optimization

By integrating FVS with an optimization algorithm we can derive benefits from both simulation and optimization techniques. Simulations permit detailed analyses of relatively few outcomes while optimization techniques explore a multitude of solutions at the expense of detail. Together, these techniques enable us to generate and evaluate multiple combinations of treated and untreated stands in relation to landscape objectives, to identify efficient landscape solutions, and to calculate net revenues associated with these solutions. By "efficient" we mean that there are no other solutions that increase the level of one resource goal (in other words, LSF) without a corresponding decrease in the other resource goal (in this case, fire threat reduction). A

"solution" is a set of selected treatment schedules. These schedules represent the type and timing of treatments for each stand within the LSR. Our objective is to identify a set of solutions that maintain a specific amount of late-successional forest in the Gotchen LSR subject to a constraint of minimizing a spatially explicit landscape fire threat index. A "production possibility frontier" results from graphing the efficient solutions, and this frontier can inform land managers, policymakers, and interested citizens about potentially complementary or competitive relations among landscape goals over time. The shape of the frontier is particularly informative when relative resource values are unknown, as in the Gotchen LSR.

Characterizing Stands in the Landscape

We began by characterizing current vegetation conditions in the Gotchen LSR using photo-interpretation methods developed for the Interior Columbia Basin Ecosystem Management Project (ICBEMP) and 1995 aerial photos (1:12,000) (Hessburg and others 1999). This step resulted in 159 polygons, which we stratified into 15 "stand types" by structure class and potential vegetation (Hummel and others 2001). We then summarized the existing inventory and stand exam data for each stand type; data collected before 1999 were discarded. Stand types that were originally under sampled or unsampled were selected for sampling in 2001 using a randomized design with probability proportional to size. All data were collected using the USDA Forest Service Region 6 timber stand exam protocol and formatted as FVS tree lists.

Creating Projection Units from Polygons

The size of some of the original polygons concerned us because of both ecological and operational issues. We consider it vital that vegetation patterns be able to change over time in our analysis and not be constrained by current landscape geometry. For example, the large polygons in the southern part of the Gotchen LSR, which resulted from fire exclusion and selective logging, tend to be bigger than would be expected from studies of regional disturbance ecology (for example, see Edmonds and others 2000). We introduced the ability for new patterns to emerge by substratifying the original polygons into smaller "projection units." We created 330 projection units (units) by considering biophysical, administrative, and operational factors provided by the Mt. Adams Ranger District of the Gifford Pinchot National Forest. These units represent the smallest area to which a treatment in FVS is applied. FVS tree lists were randomly assigned to unsampled units within the same stand type.

Developing an FVS Analysis Framework

We next created a four-level decision tree (tree) for our FVS analyses. The criteria used for decisions within the tree came from the photo-interpreted data, from consultation with staff of the Gifford Pinchot National Forest and the U.S. Fish and Wildlife Service, and from published information. On the first level, all units were sorted into "dry," "moist," or "cold" forest types, based on strata developed in the ICBEMP process. On the second level, each forest type was further sorted according to definitions for "late-successional forest"(LSF), "nesting habitat" (NH) or "non-late-successional forest" (NonLSF). For our definition of LSF, we used the "grand fir quantitative description of desired conditions" from the Gifford Pinchot National Forest Late Successional Reserve Assessment (Forest LSRA) (USDA 1997). This definition includes a mean tree diameter of 18.6 inches diameter at breast height (d.b.h.) and a minimum of 240 ft^2 of basal area per acre. Nesting habitat, which is more restrictive than LSF, was defined by local USDA Forest Service and USDI Fish and Wildlife Service biologists, with reference to Thomas and others (1990) and Buchanan and others (1995). It requires, for example, that 25 percent of the basal area requirement for LSF be in trees larger than 25 inches d.b.h.. Any unit not classified as either LSF or NH is, by process of elimination, classed as NonLSF. On the third level, these NonLSF units were further refined by key structural characteristics, to segregate into potential treatment categories. There are various reasons a unit may not meet the definition for LSF, which, in turn, influences the logic of treatments designed to develop or perpetuate late-successional forest conditions. For example, a mixed-species, multistoried unit may not have sufficient basal area or canopy closure, whereas a single-species, single-storied stand would lack sufficient structural and compositional variety.

Applying Treatments in FVS and Summarizing Results

In the first three levels of the decision tree, we grouped units in ways relevant to the Gotchen LSR landscape goals. In the fourth level, these groups are variously eligible for different treatments. Units qualifying as nesting habitat or cold forest types are automatically assigned the passive (no action) treatment alternative. All other units are eligible for treatment alternatives that are designed to (1) protect LSF, (2) restore landscape patterns, or (3) reduce fire threat. The optimization techniques we use require that each possible treatment alternative be applied to each eligible unit. The East Cascades variant of FVS simulates effects associated with these alternatives and a no-action alternative over five time intervals, each of which is a decade in length. If three alternatives were available in each interval, there would be a total of 1024 (4^5) schedules per unit. We reduce this number of schedules by using rules to evaluate whether to apply a treatment to a given unit in a given interval. The number of feasible alternatives varies by unit. We expect that some units will qualify for very few (less than 10) alternative schedules while some units will qualify for many (up to 100).

We evaluate the outcome of every treatment applied in each unit in each interval. First we use FVS compute statements (Crookston 1990) and the Fire and Fuels Extension to FVS (FFE-FVS) (Beukema and others 2000) to calculate values for structure class (definition in Hummel and others 2001), flame length, and torching and crown fire spread. We then use these values to evaluate the status of each unit compared to our LSF and fire threat definitions. The latter definition incorporates adjacency criteria similar to that described in Wilson and Baker (1998), adapted for the Gotchen LSR study by Dr. J.K.

Agee, Fire Ecologist at the University of Washington. We calculate the fire threat to any unit "d" as a weighted combination of five factors: flame length, torching, and crown fire spread in "d," plus torching and crown fire spread in upwind units "u." In the Gotchen LSR, upwind units are those to the east, as the conditions under which severe fire weather occurs are mostly from low humidity, east winds. Our weighting of the five factors considers unit characteristics more heavily than adjacent units in calculating overall points; the weighting is not meant to be a linear function of fire risk. Rating groups are summarized as low threat (1 to 3 points, fair survival of residual stand, control likely), moderate threat (3.3 to 6 points, some ponderosa pine [*Pinus ponderosa*] or Douglas-fir [*Pseudotsuga menziesii*] residuals survive, control problematical), and high threat (6+ points, stand replacement fire likely, control unlikely). We next run the cut tree lists from FVS through the Financial Evaluation of Ecosystem Management Activities (FEEMA) software (Fight and Chmelik 1998) to evaluate the net revenues (dollars/acre) associated with a treatment. These steps produce a text file with "resource values" for LSF, fire threat, and net revenue for each unit and each treatment schedule over the planning horizon.

Evaluating FVS Output using Optimization

The resource values become input to an optimization algorithm that identifies the schedule for each unit that best achieves landscape goals, when evaluated together with all other units in each interval. We initially considered using the Parallel Processing Extension (PPE) of FVS (Crookston and Stage 1991), which allows the comparison of alternative management policies on a collection of stands. The PPE has limitations, however, that affect its usefulness. The spatial array of management activities in the Gotchen LSR is important because management actions affect not only the immediate stand, but also influence conditions, and thus management decisions in neighboring stands. Spatial analysis of all possible treatment combinations requires techniques not available in the PPE. We explore this enormous solution space using integer optimization techniques known as heuristics (Reeves 1993).

For this paper, we did an exploratory optimization analysis using a simplified problem specification and FVS results from a diameter-limit treatment. To select a diameter limit, we first developed a regression equation from over 500 grand fir (*Abies grandis*) trees measured in the Gotchen LSR. Our equation relates d.b.h. to age as follows: d.b.h.= -0.212 + 0.194*AGE, when the standard errors of the estimates are 0.44 and 0.01, respectively ($P<0.0001$, $R^2=0.66$). Our treatment removed all grand fir trees under 12 inches d.b.h. in eligible units; each unit could be treated only once or have no treatments scheduled in the 50-year planning horizon. We ran FVS simulations for each potential schedule on all eligible units for 50 years.

Considering the Effects of Uncertainty

The FVS user can estimate variation attributable to stochastic events over time by making multiple projections of the same initial tree list, by using site appropriate insect, pathogen, and fire model extensions, and by invoking different random numbers. We use the western root disease (Frankel 1998) and fire models (Beukema and others 2000) to incorporate stochastic events in FVS. These techniques result in different realizations of stand development for the same initial tree list. Simple summary statistics (mean, standard deviation) can then be calculated for model results.

Another source of uncertainty in FVS outcomes comes from sampling. A new bootstrap program (Gregg and Hummel, this proceedings) now makes it easy to estimate variation associated with sampling. This is important because the data used to create a FVS tree list come from a sample of stand conditions. Information on the variation between sample plots within a tree list enables the user to provide additional information about the precision of FVS projections. It also offers a useful way to evaluate the design of the original stand stratification and sampling system.

Output from the bootstrap program includes prediction intervals, which are intervals around a set of FVS predictions about a population. These intervals are based on different components of variation. For example, one interval available as program output is based on variation from the stochastic elements in the FVS model. This interval, which we refer to as the FVS prediction interval (FVSPI), is based on the original FVS tree list, rerun as many times as the user specifies, each time with a new random number seed. The FVSPI mean is, therefore, the mean predicted value of the total number of FVS runs made with the original tree list and new random number seeds.

Another prediction interval available for the bootstrap program is based on variation from sampling error. This interval, which we refer to as the sampling error prediction interval (SEPI), is based on resamples of the original tree list, bootstrapped as many times as the user specifies. These bootstrapped samples are generated by repeatedly sampling the original tree list with replacement (Efron and Tibshirani 1993). The SEPI mean is the mean predicted value of the total number of FVS runs made with bootstrapped samples of the original tree list. Except in rare cases, the SEPI interval also includes the random elements from the FVS model. This is because in FVS the sequence of random numbers changes with very small changes in the tree list. Bootstrap resampling methods imply changes in the tree list sufficient to generate new random number seeds in FVS over multiple time intervals.

When using the bootstrap program, we change the random number and resample the original tree list. This ensures that the SEPI interval is consistently computed, even in the rare cases when it might be theoretically possible to separate sampling error from random events. All bootstrapped prediction intervals assume that the model is the correct form. If this assumption is not met, then associated bias will be included in the intervals.

The SEPI intervals help us consider how different results might be if we consider variation from sampling error in addition to that from stochastic events. In the Gotchen LSR study, such information is essential to test whether differences in the predicted area of LSF associated with various treatment combinations are indeed significant. It also helps place within-stand variation in a landscape context. In this pilot application of the bootstrap model, we ran it for 50 years on each untreated tree list in the Gotchen LSR.

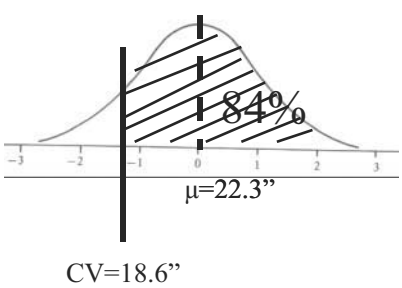
Results

Implications of the Diameter-Limit Treatment

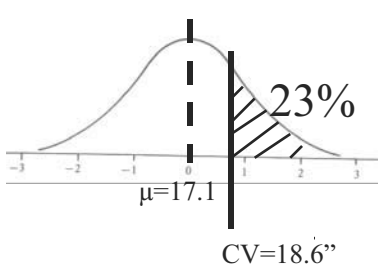
The diameter-limit treatment resulted in many of the units being categorized as LSF over time. Scheduling the treatment on some units increases the amount of LSF up to some point, which means that the relationship between treatment and LSF is complementary. We used a simple optimization algorithm to characterize this relationship between harvest level and LSF. The amount of LSF in the no-action alternative starts at 1,320 acres in the current time period and grows to 3,350 acres in year 40 (the sum of LSF for each of the five periods is 10,300 acres). The sum of maximum acres of LSF obtained over the five planning periods was approximately 40,020 and is achieved by harvesting (harvest levels of 15.8, 14.0, 4.4, 7.6, and 4.2 million board feet in year 0, 10, 20, 30, and 40). Between the no-action alternative and the maximum LSF alternative there are relative tradeoffs associated with timber harvest and LSF. Cutting trees under 12 inches d.b.h. increases QMD and thus often immediately created more LSF based on the Forest LSRA definition. These results are inconsistent with scientific literature on spotted owl habitat requirements, which indicates some basal area in smaller diameter classes is essential (see for example, Thomas and others 1990). These results raise questions about the sensitivity of a QMD-based LSF definition, and we therefore did not evaluate the financial implications of this example.

Implications of Uncertainty

Our bootstrap analysis underscores the importance of considering different sources of variation when evaluating FVS model output. We compared FVS output against the Forest LSRA requirement of 18.6 inches mean tree diameter (QMD) for two units within the Gotchen LSR. In unit 102, the QMD after 10 years was estimated by the east Cascades variant of FVS to be 22.3 inches d.b.h. Because the "critical value" of 18.6 inches d.b.h. is smaller than this estimated value, the unit would qualify as LSF, based on the Forest LSRA definition. The empirical distribution generated by the FVS bootstrapping program reveals that, indeed, 84 percent of the observations exceed the critical value (fig. 1a). Confidence in the projected outcome is thus quite high. In contrast, in unit 1111 the mean QMD after 40 years was projected to be 17.1 inches d.b.h.. Because this outcome is smaller than the 18.6 inches d.b.h. critical value, unit 1111 would not qualify as LSF based on the Forest LSRA definition. The bootstrapped distribution reveals, however, that 23 percent of the observations exceed the critical value (fig. 1b). This means that almost a quarter of the time the unit could qualify as LSF. Evaluations based purely on the REPI predicted mean would not recognize this possible outcome.



a. Unit 102: the QMD critical value (CV=18.6 inches d.b.h.) is less than the projected SEPI mean value for QMD (μ=22.3 inches d.b.h.). As indicated by the shaded area to the right of the CV, the unit qualifies as LSF in 84 percent of the FVS projections.



b.Unit 1111: the QMD critical value (CV=18.6 inches d.b.h.) is greater than the projected SEPI mean value for QMD (μ=17.1 inches d.b.h.). As indicated by the shaded area to the right of the CV, the unit qualifies as LSF in 23 percent of the FVS projections.

Figure 1—Identifying late successional forest (LSF) in FVS: implications of uncertainty.

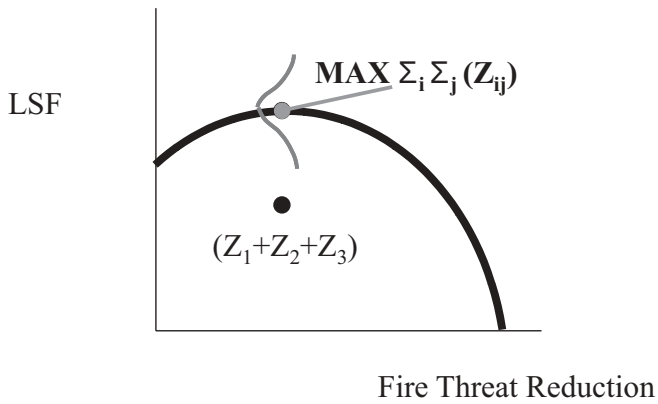


Figure 2—Hypothetical tradeoff between two landscape resource goals: late-successional forest (LSF) and fire threat reduction.

In a landscape context, the potential implications of such variation relate to the area of the units involved. For example, unit 102 includes just 50 acres. Thus, we have high confidence in our prediction over a limited area. In contrast, unit 1111 covers almost 800 acres. By failing to display a range of outcomes associated with a simulated mean projection, we would underestimate the likelihood for this area to contribute to landscape goals for LSF over time.

Our bootstrap analysis also suggested that the amount of LSF appears highly sensitive to variation in FVS projections. The area of predicted LSF could as much as double if values one standard deviation from the SEPI mean were used rather than the mean value itself. This variation associated with FVS projections increased over time. Together with results from our preliminary optimization analysis, the bootstrap results also support changing the QMD-based definition of LSF.

Conclusions

We will use the results from this preliminary analysis to modify the definitions and treatments we use in our landscape analysis. Our hypothesis is that reducing fire threat and maintaining LSF may be complementary, or at least nonconflicting, at low levels of threat reduction. In contrast, we expect that a high level of fire threat reduction would directly conflict with maintaining LSF. Figure 2 is a generalized production possibility frontier and represents our hypothesized relationship between acres of LSF and fire threat reduction. The uncertainty associated with FVS simulation is illustrated by the interval around the frontier, whereas inefficient solutions lie within it. The frontier identifies how stand-level treatments aggregate to affect the landscape objective, and portrays the relative tradeoffs associated with two landscape goals. Perhaps of even more value to managers needing to set priorities with limited resources, it also reveals if stand level treatments have a measurable impact on landscape objectives.

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