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Abstract

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The Forest Vegetation Simulator (FVS) is a computer program that projects the development of forest stands in the United States and British Columbia, Canada. The proceedings of the second FVS conference, held in Fort Collins, CO, includes 34 papers dealing with applications of FVS that range from the stand-level through full-scale landscape analyses. Forecasts ranging from wildlife habitat indicators through economic returns on investments take into account the effects of insects, pathogens, and fire. Also presented are recent advances in computer visualization technology, the analysis of model prediction uncertainty, model development techniques, software support tools, and the reconstruction of historical stand conditions.

Keywords: forest management, forest planning, landscape dynamics, vegetation dynamics, prognosis model, visualization, growth and yield, forest health, habitat modeling

The Compilers

Nicholas L. Crookston is an Operations Research Analyst with the USDA Forest Service, Rocky Mountain Research Station in Moscow, ID. He has spent his career working on the base FVS system and its extensions. His first contribution to FVS, in the late 1970s, involved creating the first extension — one that represented mountain pine beetle population dynamics in lodgepole pine. Work on the development of the Douglas-fir tussock moth and western spruce budworm extensions followed. These extensions formed a template on which all FVS extensions have been based. Mr. Crookston conceived and built the Event Monitor and, in a collaborative effort with Al Stage, built the Parallel Processing Extension to FVS. His more recent efforts include designing and building the Suppose user interface and leading the effort to build the Fire and Fuels extension.

Robert N. Havis is an Information Technology Specialist with the USDA Forest Service, Forest Management Service Center (FMSC) in Fort Collins, CO. A civil and environmental engineer by training, Mr. Havis has been involved in software support for FVS base code and model extensions since 1998. He maintains the FVS base variants and implements new developments in FVS software. The FMSC is the technology transfer center for the FVS model system, and the keepers of the FVS base code and the Fuels and Fire Effects extensions. The FMSC distributes the FVS to the public, provides user training and hotline support, and develops new geographic variants and enhancements to existing variants.

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Second Forest Vegetation Simulator Conference

Fort Collins, CO
February 12–14, 2002

Compilers:

Nicholas L. Crookston
Robert N. Havis

Conference Endorsements

- The Society of American Foresters (SAF)
- The International Union of Forestry Research Organizations (IUFRO) Groups:
  - 4.11 Statistical Methods, Mathematics and Computer
  - 4.01 Mensuration Growth and Yield
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Collaborative Technology Development and Transfer: Keynote at the Second Forest Vegetation Simulator Conference

Bov B. Eav, Ph.D.
Associate Deputy Chief for Research and Development
USDA Forest Service

Good morning!

I am delighted to have this opportunity to be with you at this conference. And thank you for asking me to speak to a topic that is of special interest to me, so special that my career in the Forest Service began in this arena and continued for 9 years. In addition, the opportunity to visit with former colleagues and friends is just as strong as my interest in this subject. I worked side by side with many of you at this conference to develop and incorporate insect and disease models into the Prognosis Model, the original Forest Vegetation Simulator (FVS). It's good to see you all again.

Why FVS?

Today, more than ever, I am convinced that simulation modeling is one of the most effective means of supporting science-based decisions. Here are some of the compelling reasons for FVS and other simulation models.

1. Simulation models *inform decisionmakers*. Decisions are only as good as the quality of the predicted effects of carrying out the decisions. If the consequences of decisions are not known at all, then any decision is as good as any other. The best tool to predict the consequences of land management decisions is a simulation model such as FVS. While models such as FVS cannot predict the effects of decisions with certainty, they do provide good indications of what to expect when decisions are carried out. With recent advances in the realistic display of model outputs, effects of decisions can be displayed in a way that decisionmakers and everyone interested in the decisions can appreciate and understand. This is of great value to the Forest Service and other land management agencies as community participation in decisionmaking is a rule in our society.

2. Models and decision support tools can be used to *document the scientific basis for land management decisions*. More and more, decisions made with respect to policies affecting livelihoods and communities across the country are being challenged and questioned on the grounds that they are not science based. A well-documented simulation model gives decision makers the confidence that their decisions are grounded in peer-reviewed scientific principles and findings.

3. Simulation models are an excellent way to *synthesize knowledge* relevant to decisionmaking process in a form that is integrated with other analytical tools used by land managers. There is no single tool in the scientific world that carries more potential than FVS in helping natural resource managers take a peek into the future. FVS, with its extensions, allows us to synthesize what is known about the development of forest vegetation through time and its response to management actions and natural disturbances. Because of the exponential increase in the amount of information that resource analysts and decisionmakers must consider in formulating their decisions, no single person or even team could do the synthesis in their own heads. Tools such as simulation models and decision support systems must be developed as analytical aids to analysts and decisionmakers.

4. During model development, scientists have an opportunity to *discover knowledge gaps* about how forest ecosystems work, which then leads to pathways for research.

The fact that the Forest Service and other land management organizations use FVS to develop forest and project plans in all regions of the country and some parts of Canada is a strong validation of its usefulness. The successful use of FVS and other decision support tools that many of you in this room participated in were clearly demonstrated in resource management decisions at the large area plans such as the Columbia River Basin Assessment and to many Forest plans and numerous project level Environmental Impact Statements.

These are four important reasons for continuing and sustaining your work in FVS. When dollars are getting scarce for R&D, it is incumbent upon us to find new ways of getting the job done. I am convinced more than ever before that FVS is one of the most important ways to bring science to bear on informed decisionmaking.

Collaborative Research, Technology Development, and Transfer

Working on models is a great way to promote collaboration among researchers, academics, students, and practitioners as demonstrated by the kind of people present at this gathering.

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Collaboration works best when all participants have something to gain. The researchers want to see their research results put into practice and perhaps get a few additional publications; academicians are interested in having a good teaching tool and having funds to support graduate students; the students need a problem to write their theses on and a set of data that are either readily available or a sponsor ready to pay for its collection; and the practitioners want the best available knowledge and information to use as a basis for sound decisions.

Collaboration promotes ownership and pride in the product. In 1987, I presented to the Director of Forest Health Protection what I thought was a compelling case why Forest Health Protection should invest in the development and care and feeding of insect and disease models along with a plan to accomplish the tasks. I was given the go-ahead and strong encouragement to proceed with the plan. The catch is that I was not given the requested dollars to get it done. I remember thinking to myself, "Thanks for nothing, Mr. Director. Now what?" Looking back, it's probably just as well that it happened that way because what it forced me to do was to build partnerships and coalitions with researchers, Regional Offices, and Forest staffs to go after the dollars and jointly managed resources. If the Director gave me all the required resources, the models developed would have been Methods Application Group models, with inputs from others. They would not have had the ownership from National Forests, Regions, and Research and Development that they enjoyed. And their acceptance all throughout the Forest Service may not have been as strong.

I believe the collaborative spirit displayed by all of you in this room is an outstanding example of "what can be accomplished if we do not worry about who is getting the credit," to quote one of our former presidents.

I wish you a successful conference. And I thank you for providing me with this opportunity to be with you and for your attention.

Session 1. Tools

FVS Lessons on the Web: A Resource for Users and Instructors

John D. Shaw
James N. Long

Abstract—A Web site (http://www.cnr.usu.edu/online/simulation) has been developed to provide users of the Forest Vegetation Simulator, Stand Visualization System, and Suppose an opportunity for self-instruction. Instructors may use the Web site as a source of lessons and data that can be used in a variety of classroom situations. Future expansion of the site includes a section highlighting cover types and silvicultural systems from across North America, and development of distance-delivered courses.

The Forest Vegetation Simulator (FVS), and the related programs Suppose and the Stand Visualization System (SVS), have been widely adopted as the standard programs for projecting forest growth on USDA Forest Service land. These programs have received relatively little attention as teaching tools in silviculture classes and other college courses in which growth projections are used. In this paper we describe our adoption of FVS, SVS, and Suppose as teaching tools, and announce the availability of Web-based resources available to users and instructors.

Using FVS in the Classroom

We started using FVS in the classroom in 1995 in a senior-level silviculture class (FR4250). Early in the semester, students collected stand inventory data during field trips to Utah State University's T.W. Daniel Experimental Forest. After a few weeks of class, the students were introduced to FVS during a laboratory session. Data collected in the field were pooled and used to create a tree list file for one Engelmann spruce-subalpine fir stand. This stand served as the example that was used to illustrate the effects of thinning, uneven-aged management, and other silvicultural practices.

The use of class time was not too efficient in the first 2 years, for several reasons. We could not expect all students in the class to be on par in computer skills. Few students were familiar with the concept of writing scripts or program code, so teaching them how to construct an FVS keyword file required more effort than merely familiarizing them with a text editor. A significant portion of the class time allotted to learning FVS was used getting the students' first simulations to run. However, students quickly learned to build subsequent keyword files on their first working version, and encountered fewer errors when adding new keywords to their simulations. Hardware and software architecture in the teaching laboratory was also problematic. Students did not have personal disk space on the system, so they were forced to direct FVS output to the floppy drive. This arrangement imposed limitations on output speed and volume. We also used the DOS version of SVS, which required command-line modification of the video mode on the computers. This, coupled with the need to run a conversion program to convert FVS output files to SVS input files, added more teaching overhead to the simulation lessons.

Despite the overhead time required to deal with technical issues (in other words, everything not related to silviculture), FVS and SVS proved to be effective tools in the effort to illustrate stand dynamics and the consequences (intended and unintended) of silvicultural manipulation. We found that, when given a verbal description of a silvicultural prescription later in the semester (table 1), students were generally able to deal with the technical issues effectively and concentrate on silviculture.

Encouraged by 2 years of success and refinement, in 1997 we allocated 2 weeks of lecture and lab time (12 instruction hours) to FVS, SVS, and the newly released Suppose interface. Our teaching lab had been upgraded with new computers and personal user space for each student, eliminating many technical obstacles. The goal was to increase the students' proficiency with the programs, and increase the number and complexity of silvicultural simulations to which they were exposed. Advances in development of the programs, including the advent of Suppose and the Windows version of SVS, not only required us to make changes in the lesson plan, but also reduced the overhead requirement. We were able to eliminate lecture time spent on all program control keywords (for example, STATS, TREEDATA, PROCESS) and some keywords associated with stand data (for example, STDINFO, DESIGN), although we continued to briefly describe how keyword files were generated by Suppose. Most of the time previously spent on technical issues was reallocated to learning the Suppose interface. With the elimination of the hardware and data conversion issues surrounding SVS, our time allocated to running SVS decreased dramatically. Because SVS has an easy-to-use interface and something of a gaming element (for example, perspective modification, tree design, timber marking), students need only a brief introduction and tend to explore the capabilities of the program on their own.

In early 2000, the Dean's Office of the College of Natural Resources released a request for proposals for development of "inquiry-based learning" projects. Although the

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Table 1—Example of verbal silvicultural prescription converted into FVS simulation by students in a lab exercise.

Shelterwood and Retention System Project	
Objectives:	1. Additional experience with practical applications of FVS, SVS, and Suppose. 2. Development of a "base case" shelterwood system for ponderosa pine on the Black Hills National Forest 3. Explore implications of reserves
2000	Seedcut – thin from below; 4 to 999 inches; leave 20 TPA
	Regeneration – natural regen; PP 700 TPA, 70% survival after 10 years
2030	Final removal – thin from above, 999 to 3 inches, leave 0 TPA
	PCT – thin from below, 0 to 10 inches, leave 300 TPA
2120	CT – thin from below when SDI approx. 270, leave 130 TPA, i.e., SDI ca. 125 if Dq ca. 10 inches)
2160	End of Rotation
	Report: 1. yield table 2. SVS images for: a) current stand, b) 2040 (i.e., 10-yrs after removal), c) EOR
	Extra credit: Modify the removal to leave different numbers of reserves: a) 0 TPA (you have already done this), b) 5 TPA, c) 10 TPA, d) 20 TPA
	What are the implications of the reserves in terms of: 1. total yield of next rotation (i.e., must subtract out initial volume of reserves)? 2. yield of "understory"? 3. growth and yield "costs" of reserves (if any)?

concept of inquiry-based learning appeared to be broadly defined (similar to ecosystem management in its formative years), most of the existing examples involved the independent exploration of topics on the worldwide Web as a complement to some in-class exercise. We felt that the FVS module in FR4250 was an ideal candidate for adaptation to this learning process, so we proposed and were awarded start-up funds for Web-authoring software and development time.

We deployed the Web site (fig. 1; http://www.cnr.usu.edu/online/simulation) in fall of 2000 for use in FR4250. We assigned introductory modules on each of the three programs as a pre-lab reading assignment, and students were given a take-home quiz with a few questions on each module. In addition, students were instructed to read about, and attempt to create on their own user accounts, the Suppose directory structure and Windows desktop shortcuts to Suppose and SVS. By this time, a required course on computer applications in natural resources had been added to the undergraduate curriculum, so we expected that the students would have a higher computer aptitude and better capacity for self-instruction.

Use of Web-based lessons had a substantial effect on the progress made during the 2-week simulation module in FR4250. Most students met our expectations of coming to the first class of the module with a basic understanding of the programs and their user accounts prepared for use. The students who did not complete all the tasks required relatively little coaching, from us or their classmates, to catch up with the rest of the class on the first day. The cumulative effect of having students with better computer aptitude and self-instruction modules available was being able to cover the same amount of material in 1 or 2 fewer days. To date, we have used the extra time for review, discussion of advanced topics, and completion of a trial (that is, no-grade) assignment similar to the ones they are assigned during the remainder of the semester.

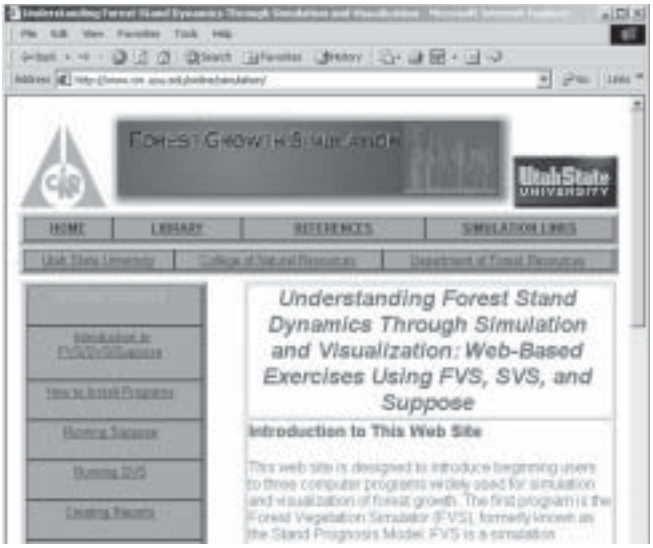

Figure 1—Simulation and visualization home page.

Following the initial deployment of the Web site, we considered possible additions to the site that would improve its utility in other courses and for FVS users in general. We considered two types of additions: those involving adaptation of existing materials, and those involving development of new material. In both cases we would have the opportunity to take advantages of the unique qualities of the Web.

Expanding the Web Presence

During development of the silviculture module, it became apparent that Web-based modules could be useful in other classes or for any FVS users. We focused the next phase of development on modules with general applicability. The obvious candidate for inclusion was the FVS keyword reference manual.

We obtained the most current revision of the keyword reference manual (Van Dyck 2000) from the Forest Management Service Center, converted the text to Web pages, and added extensive hyperlinks throughout (fig. 2). The online manual is more convenient to use than the hard copy version, because users can quickly navigate among keyword entries and create bookmarks using their Web browser. In the future, the keyword manual may be integrated into the Suppose interface.

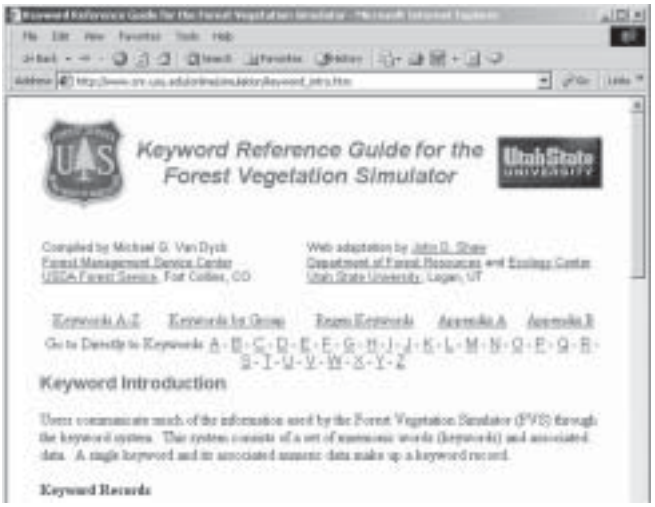

Figure 2—Introduction to FVS keyword reference guide.

The Forest Management Service Center also maintains a training guide (Van Dyck 2001) that covers a wide range of FVS keywords and operations in Suppose. Although our classroom modules do not require the depth provided by the training guide, we anticipated that we or other instructors might require some of the lessons in the future. We converted the training guide to a hyper-linked document, similar in format to the keyword manual.

Integrating the keyword and training manuals into the Web site provided two important benefits: we saved time on lesson development, and we were able to hyperlink our existing Web pages to relevant entries in the two manuals. Although a significant number of labor hours were required to convert the manuals to a format consistent with the rest of the Web site, we anticipate that future updates of the documents will require relatively little effort.

One important distinction between the Forest Service exercise guide and the modules we developed for class is that the Forest Service manual focuses primarily on developing technical competence with the software (that is, it is a "how-to" manual), whereas we focus more on teaching silvicultural methods and only include the technical understanding of the software that is necessary to accomplish the lesson. As a result, the lessons we develop and the ones in the Forest Service exercise guide are complementary.

The third area of expansion, which may prove to be of most interest to instructors in general, is a section on cover types from across North America (those areas covered by FVS variants). This section was inspired by an article in the November 2000 issue of the Journal of Forestry (McNab and Ritter 2000) describing the 100–year history of the Old Orchard plantation on the Biltmore Estate in North Carolina. We obtained data on the Old Orchard plots from the authors and created two sets of FVS tree files. The first set includes data from the 100–year inventory of the plots done in 1999. We constructed the second data set using the site data from the plots and descriptions of the stand when it was planted in 1899. We also provide the user with a table of treatments applied to the stands over the past 100 years. The user has the opportunity to manage the 1899 stand for 100 years using FVS and compare results to inventory conditions. We provide several questions that the user may use as starting points for exploring the stands, but there are many other approaches that instructors might use.

We hope to build the cover types section into a resource that can be used by instructors everywhere. We hope to obtain a wide range of data from local sources for inclusion. We will not only provide data, but we will also provide some background information about the stand or a detailed history such as the one that has been recorded for the Old Orchard plantation. To date we have compiled data for several cover types, including aspen, Douglas-fir, lodgepole pine, longleaf pine, Engelmann spruce-subalpine fir, and red spruce-eastern white pine. Visitors to the Web site who wish to contribute data may contact the senior author.

Conclusion

We have developed a Web resource that can be used by instructors wishing to incorporate FVS into their lesson plan, or by other FVS users who want to improve their expertise or have easy access to reference material. The evolution of the Web site will be based on instructors' current and future needs, and future development of FVS, SVS, and Suppose. We anticipate that we will use the Web site as a component of distance-delivery courses in the near future. We hope to continue development as FVS becomes a more popular management tool and demand for education in its use increases.

Acknowledgments

We thank the Dean's Office of the Utah State University College of Natural Resources for providing the incentive to develop the simulation Web site. We also thank M. Van Dyck, USDA Forest Service, Forest Management Service Center, for providing the source documents for the FVS keyword and exercise manuals, and W.H. McNab, B.A. Ritter, and R. Seymour for providing data for the cover type examples section.

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Creating Visual Simulations of Fuel Conditions Predicted by the Fire and Fuels Extension to the Forest Vegetation Simulator

Robert J. McGaughey

Abstract—The Fire and Fuels Extension (FFE) to the Forest Vegetation Simulator (FVS) can help managers assess the risk, behavior, and impact of fire in forest ecosystems. The FFE reports surface fuel characteristics including the weight of woody material in various size classes. Visualization software currently linked to FVS can help managers better understand and communicate stand structure and changes in stand structure resulting from growth, mortality, and management activities. However, such visual simulations do not currently include surface fuels. This paper describes the development of calibrated log models: models of individual pieces of coarse woody debris that represent specific weights of fuels in various sizes. Such models are used to represent surface fuels in visual simulations. The paper presents motivations for the study along with a description of the procedures used to measure and photograph logs and an overview of the process for creating the calibrated log models. An example log model is presented along with visual simulations that depict fuel conditions.

Users of the Forest Vegetation Simulator (FVS) (Wykoff and others 1982, Teck and others 1996) have been using visual simulations produced by the Stand Visualization System (SVS) (McGaughey 1997; http://www.fs.fed.us/pnw/svs) to better understand and communicate the results of their FVS projections. The Fire and Fuels Extension (FFE) to FVS links changes in forest vegetation due to growth, natural or fire-caused mortality, and management activities to changes in expected fire severity and behavior (Beukema and others 2000). Given the recognition of fire as an important component of forested ecosystems and the realization that decades of fire suppression activities have resulted in an increase in the amount of forest lands at risk of catastrophic fires, it makes sense to incorporate the results from FFE into visual simulations designed to portray stand conditions.

This paper describes the development of calibrated log models: models of individual pieces of coarse woody debris that represent specific weights of fuels in various sizes. The paper discusses motivations for the study along with a description of the procedures used to measure and photograph logs and an overview of the process use to create calibrated log models. An example log model is presented along with visual simulations of fuel conditions produced using EnVision (McGaughey, in press; http://www.fs.fed.us/pnw/envision), a program that has several of the capabilities of SVS.

The primary objective of this study is to build a set of models that represent individual pieces of coarse woody debris. These models, called calibrated log models in this paper, represent the physical dimensions of a log and use photographs to characterize the log ends, surface (bark), and branches. Models provide sufficient detail to represent specific fuel weights in various size classes. EnVision uses the models to produce visual simulations that depict standing live and dead trees reported by FVS along with downed fuels reported by FFE.

Motivations for this Study

This study was motivated by a desire to represent fuel conditions and fire effects predicted by FFE in visual simulations commonly produced by FVS users. Previous efforts to represent fuel conditions have focused on two methods: photo series and visual modeling of individual fuel components.

The most common method used to illustrate fuel conditions relies on a library of images, called a photo series, to depict conditions within various stand and grassland ecotypes. For a specific ecotype, a photo series includes images that illustrate a range of fuel conditions along with quantitative data describing fuels. Photo series have great appeal because users can directly compare their site conditions to photographs included in the series and select the image that best matches the conditions they observe. They can then use the quantitative information associated with the image to estimate fuel loads for their site. The Fire and Environmental Research Applications (FERA) Team within the USDA Forest Service, Pacific Northwest Research Station, has produced a comprehensive photo series that includes single photos and stereo pairs for the United States. For an example from this series, see Ottmar and others 1998.

Fuel specialists successfully apply the photo series approach to a variety of forest and grassland ecotypes. Users typically relate well to photographs that depict actual sites. However, their ability to correctly match conditions illustrated in a photograph to their specific site and fuel conditions remains untested. In addition, because a photo series

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includes a limited number of images, users may not find images that adequately represent the conditions they observe. An approach that produces images based on the quantitative descriptions of fuel and stand conditions produced by FVS-FFE may be more appropriate for model users.

Previous work by this author created visual models of fuel conditions for stands in eastern Oregon being treated as part of the Limber Jim Fuels Reduction Project using SVS (McGaughey 1997). For that project, fuels were inventoried using standard line transect methods. Computer programs used the fuel data to create a population of plant and log models to represent fuel conditions. Figure 1 shows example images that depict pretreatment and posttreatment stand conditions. This effort, while it produced images that were useful for public orientation prior to site visits, did not produce images that compared well with the typical photo series. Limitations of the rendering system (SVS) made it difficult to accurately represent fuels smaller than 3 inches in diameter. The inability to represent fine fuels did not greatly affect the visual simulations because most of the downed logs were actually full-length tree stems with few intact branches. In addition, the standard SVS viewpoint (viewer located some distance from the stand and the image contains most, if not all, of the 1 acre stand representation) used for most images made it impossible to discern individual branches on downed trees.

The methods used in SVS do not adequately represent fuel properties. First, SVS uses simple tree models that are not detailed enough to represent individual branches or branch patterns. The tree models used in SVS are abstract representations of trees that are recognizable as trees but do not realistically model tree characteristics and do not generally compare well to images of actual trees. The lack of adequate branch representations makes it impossible to model a known quantity of fine fuels because most of the fine fuels are contained in tree branches. A second problem with tree models used in SVS is that they all look "perfect." That is, all trees have straight stems and well-shaped crowns. These models produce stand visualizations that communicate overall stand characteristics but do not represent the variety of tree forms and condition classes needed to produce images that compare favorably with on-site impressions. The third problem with the process used for the Limber Jim project was the algorithm used to place downed material. The current algorithm included with SVS (TBL2SVS utility) does not accurately model the interaction of downed pieces. The result is that many of the downed logs appear to be floating above the ground surface with no visible means of support. This anomaly did not necessarily create problems for the Limber Jim project because viewpoints were located to provide overviews of the 1 acre stand; therefore, viewers simply could not see the problem. When rendering the same data in EnVision using a viewpoint that approximates the view from the ground within the stand (fig. 2), the problem is more apparent.

Existing methods used to represent fuel conditions are adequate only in select situations. Photo series do not include images that represent all conditions present within an ecotype. In addition, users match images to site conditions and then use the corresponding fuel descriptions for analysis and planning. A more desirable approach is to have the FFE results directly influence the image because it is unlikely that a photo series image will represent fuel quantities that exactly match the FFE results. Previous work with SVS indicates that its rendering methods cannot sufficiently represent fuel properties for pieces less than 3 inches in diameter.

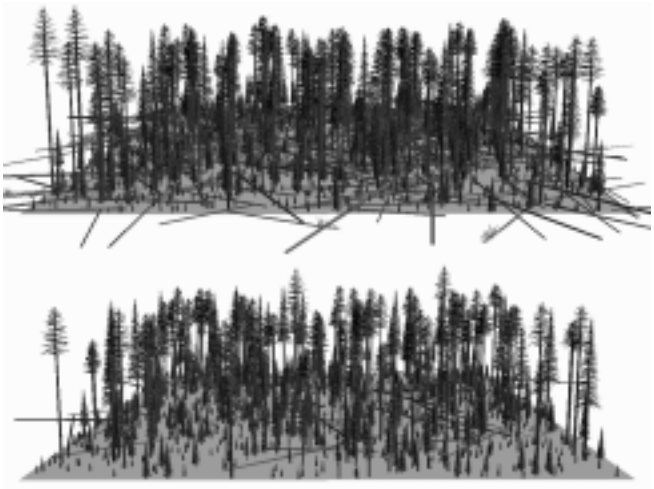

Figure 1—Visual simulations of pretreatment (top) and posttreatment (bottom) conditions in a mixed conifer stand in eastern Oregon. Pretreatment fuel load for material 3 inches in diameter and greater is 54 tons per acre, and posttreatment fuel load is 10 tons per acre.

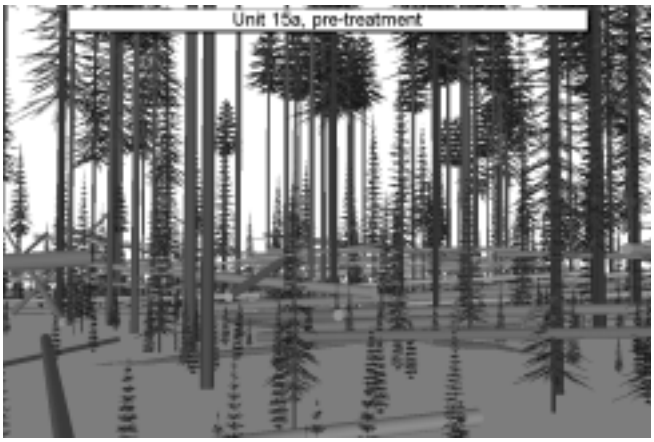

Figure 2—Data from the Limber Jim project rendered in EnVision using a near-ground viewpoint.

Creating Calibrated Log Models

Calibrated log models are created using field measurements and photographs of actual pieces of woody debris. The

intent of the log models is to provide accurate, visually realistic representations of downed fuels in various size classes. The models do not represent highly detailed log form or individual branch locations or orientations.

Collecting Field Measurements and Photos

Field measurements and photographs capture an adequate description of individual logs without collecting more information than needed to produce visually realistic models. Field measurements characterized the size and general shape of the bole, branching patterns, and bole and branch weights. Field measurements were divided into three procedures: log characterization, branch inventory, and photography.

Log characterization—Log characterization procedures capture the log size and geometry. The overall procedure for log measurement involved suspending the log from two tripods rigged with a block-and-tackle for lifting the log and a spring scale for weighing the log. After the log was suspended, field personnel recorded the weight from each scale and visually divided the log into sections for measurement and photography. Section breaks were located at major bends in the log or were placed to keep sections shorter than 5 feet. Section markers (string and nails) were left in place for photography. Orientation guides (2-foot diameter tempered hardboard discs with attachment points for reference lines) were attached to each end of the log. Reference lines (strings), used to measure the shape of the log, were attached to the orientation guides.

The length, large and small end diameters (outside bark), and the weight were measured for each log. Weight was recorded with and without branches. For each log section the following attributes were measured: length of section, large and small end diameters (outside bark), and the distance from the reference line to the actual log center at the small end of the section. (Note: large end diameter was measured for only the first section; for subsequent sections, the large end diameter was the same as the previous section's small end diameter.) Section attributes were measured twice. The second set of measurements was taken after the log had been rotated 90 degrees clockwise. This produced two diameter measurements that were averaged to compute the small end diameter of the section and two deviations from centerline that were used to calculate the rotations needed to properly orient the log section in the final log model.

Branch inventory—The branch inventory was designed to quantify the weight of small fuels present on the log. The inventory was done for each log section to facilitate the construction of new logs (different from those measured) by stacking several sections and adding the fuel weights. The branch inventory was a 100 percent sample. All branches were removed from the logs and clipped at size break points using a go/no-go gauge with openings for 0.25-, 1-, and 3-inch sizes. As branches were clipped, they were placed in separate buckets to be weighed at the completion of each section. A sample was collected from all branches on the log in each size class to determine moisture content.

Photography—Three types of photographs were taken: log section photos, branch photos, and log end photos. Log section photos captured the surface (bark) of the bole and some branches that were cropped from the final image. The log section photos were digitally merged to create a texture map for the conic frustum used to represent a particular log section. Branch photos were taken with the entire log section positioned at the bottom of the frame. Images were framed to include all branches that originated on the log section. Extensive overlap between branch images on adjacent sections was expected. The goal of branch images was to capture all branches on the upper surface of the log and the portion of the log section above its centerline. Four sets of images were taken for each log section. Each set captured the view of the log as it was rotated in 90-degree increments. Log end photographs were taken to be used as texture maps for the disk that closes the large and small end of the log.

Photographs were taken with a digital camera using a resolution of 2048 by 1536 and 24-bit color. Images were stored on the camera's 64Mb storage cards (about 83 images per card). Section markers were visible in both log and branch images to assist when editing the images. A total of two to four overview images, two log end images, and eight images per log section (four log section images and four branch images) were captured for each log.

Branch photographs were taken using a blue backdrop held on a rigid frame (to minimize wrinkles) and positioned behind the section being photographed. The consistent background color facilitated image editing.

Building the Log Models

Logs models are created using the solid modeling capabilities in EnVision. Logs models consist of a series of tapered cylinders stacked end-to-end with spherical joints to hide gaps between sections. A disc closes the ends of the first and last sections. Branch planes are added using "wings" that project from the log center. Figure 3 shows the EnVision model file for a single log section (the large end section of the log model shown in fig. 4). Figure 4 shows the geometric primitives used to model a simple log containing three sections.

Figure 5 shows an example log model with all texture images applied.

Branch Representation

The method illustrated in figure 4 uses branch images mapped onto flat plates. This approach produces a model that appears correct when viewed from the side. However, when viewed from the end, branches are not visible because the "wings" have no thickness. The net result when rendering sets of log models to depict fuel conditions is that viewers will not be able to see all of the branch material. One solution to this problem is to twist the branch plates. Figure 6 shows end views of the log shown in figure 5 with flat branch plates and twisted branch plates. The viewpoint used in figure 6 is raised slightly above the log end so branches mapped onto the flat plates are visible. When viewed from the same elevation as the log end, you cannot see the branch plates.

```
EPO
1.0
Log 001-section 1
; do rotation for section
rotate -1.4 y
rotate -.24 x
pushmatrix
      ; draw log end
      settextureimage "001_large_end.bmp" 0 0 0
      disk 0 2.3 18 1 1
      ; draw log
      rotate 90 z
      settextureimage "001_stem_sect1.bmp" 0 1 1
      cylinder 2.3 2.29 47.0541 18 1 1
      ; draw joint
      translate 0 0 47.0541
      sphere 2.29 9 9 1
popmatrix
; branches
pushmatrix
      settextureimage "001_branches_sect1alt.bmp" 1 0 0
      spiral 33 33 47.0541 0 12 1 .75 0 .25 1
      rotate 90 z
      spiral 36 36 47.0541 0 12 1 .5 0 .25 1
      rotate 90 z
      spiral 12 12 47.0541 0 12 1 .25 0 .25 1
      rotate 90 z
      spiral 12 12 47.0541 0 12 1 0 0 .25 1
popmatrix
```

Figure 3—Sample EnVision model file for a single log section.

Using the twisted plates also affects the appearance of the log when viewed from the side. The branches appear slightly shorter but the appearance is still satisfactory.

When placing the log models and subsequently rendering them, only half of the branches will be visible because most logs will lay on the ground surface and half of the branches will project below ground. In reality, when a tree falls down, the branches on the portion of the stem closest to the ground either break or bend. Few branches are driven into the ground. Modeling the bending or breakage of branches would be difficult given that the log models do not represent individual branches, only collections of branches. However, there needs to be some adjustment to account for the broken or bent branches in a rendered image. One solution is to simply double the number of branch plates on each log model. For logs resting on the ground, this should result in a viewer "seeing" the correct amount of branches. For logs that are partially elevated, too many branches would be visible. It is unclear just how many of the additional branches would be visible since other logs would either partially or completely screen these branches from view. Further experimentation will be needed to assess various branch representation options.

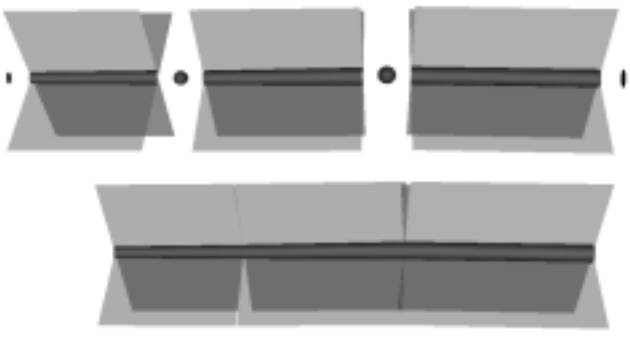

Figure 4—Log models consist of a series of geometric primitives. The upper image shows the individual components and the lower image shows primitives combined to form a log model.

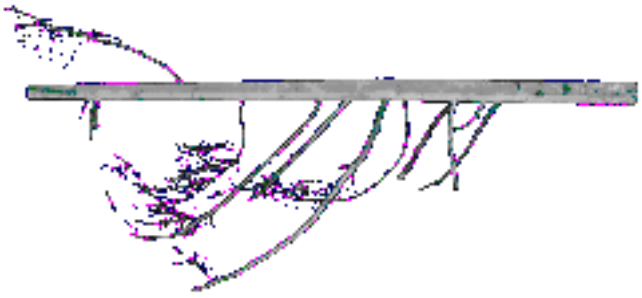

Figure 5—Log model rendered in EnVision.

Figure 6—End views of the log model shown in figure 5 with flat branch plates (left) and twisted branch plates (right).

Simulating Fuel Conditions

The final step in producing visual simulations to represent fuel properties is the creation of a population of log models that represents the specific fuel conditions reported by FFE. This part of the project was not complete at the time of this writing so the discussion that follows is subject to change.

The fuel bed simulation program will accomplish two tasks. First, it will sample from the collection of log models to build a population of models that represents specific fuel conditions. Second, it will distribute the models throughout the stand and calculate an appropriate orientation for each model.

The first step of the sampling algorithm is to select an appropriate subset of log models based on characteristics of standing trees such as the species mix and size distribution. After selecting a subset, the algorithm assembles a collection of models that matches the fuel characteristics reported by FFE. The initial prototype of the fuel bed simulation program will attempt to match the fuel weights in larger size classes only. Experimentation with the program will likely indicate the need for more complex logic. Most likely, the algorithm will use a heuristic approach that looks at the weight of material already added to the fuel bed and selects a model with an appropriate mix of material weights in each of the fuel size classes. It may be possible to fine-tune the fuel weights by adding or subtracting branches from individual log models or by assembling new log models using sections from measured logs.

After creating an acceptable collection of log models, the spatial positioning algorithm needs to distribute models over the stand plot. There are two major issues to be resolved when calculating the spatial distribution and orientation of individual log models: log models should be placed so they do not collide with standing trees, and models should be oriented so all logs appear to be stacked correctly. Solving the first issue is relatively straightforward. The algorithm can evaluate the position and size of the standing trees and place log models so logs do not pass through standing trees. In dense stands, placement could be difficult especially if the log models are long. The stacking problem is more difficult to solve. The new algorithm will need to look at how all logs interact to determine a realistic stacking orientation.

A simple example illustrates the potential for representing fuel conditions using the log models. Figure 7 shows a sample fuel bed created using a single log model. This fuel bed represents 3 tons per acre of material less than 3 inches in diameter and 20 tons per acre of material 3 inches and larger. Figure 8 shows the simulated fuel bed along with standing trees.

Conclusions

The ability to produce visual simulations that depict fuel properties as well as stand conditions will help FVS-FFE users communicate changes in stand structure and fire risk that result from natural processes, management activities, and fire. Preliminary experiments with the use of the calibrated log models described in this paper look promising. The resulting visual simulations depict fuels in small size classes represented by fine branches and larger fuels represented by large branches and boles. Remaining work in this project includes measurement of many more logs and branches, both burned and unburned, and subsequent construction of log models for use in the fuel bed simulation program. Field crews will collect measurements during spring 2002 and model building should be complete by late

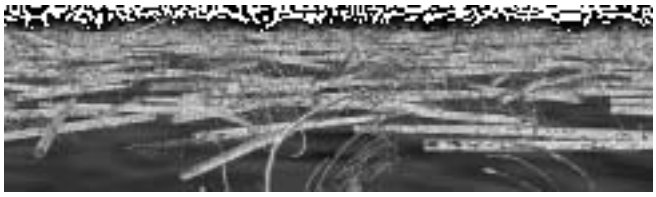

Figure 7—Visual simulation of surface fuel layer representing 3 tons per acre of material less than 3 inches in diameter and 20 tons per acre of material 3 inches and larger.

Figure 8—Visual simulation that combines the surface fuel layer shown in figure 7 with standing tree information.

2002. Work on the fuel bed simulation program is progressing and a prototype should be ready by mid-2002. Visual simulations will be compared to photographs of areas where fuel conditions have been measured. This will include comparison with images from the photo series produced by the Fire and Environmental Research Applications Team of the PNW Research Station. The results of these comparisons will dictate further work on the fuel bed simulation program.

Acknowledgments

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Southern Pine Beetle Keyword Component Addfile for Use with FVS

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James (Rusty) Rhea

Abstract—The Southern Pine Beetle Keyword Component Addfile is a keyword set used within the Forest Vegetation Simulator (FVS) to simulate the effects of southern pine beetles (SPB) (*Dendroctonus frontalis*), Zimmermann (*Coleoptera: Scolytidae*). Individual stands are evaluated with a hazard rating system to determine their susceptibility to SPB depredation. SPB-induced mortality is determined, in part, by the stand's hazard rating. This is a strategic model that demonstrates potential pine timber and habitat loss due to SPB. The user can proactively reduce the stand's hazard level by scheduling appropriate management actions within FVS. Once preset conditions are met and a SPB outbreak is scheduled, losses due to SPB will be estimated.

Modeling the effects of insects and pathogens within FVS is conventionally achieved through the use of pest-specific FVS Variant Extensions, which are supported by the staffs of the USDA Forest Service Forest Health Technology Enterprise Team (FHTET) and the USDA Forest Service Forest Management Service Center. These extensions represent the state of the art in pest modeling and have been developed for use exclusively with the Western variants of FVS. These extensions require substantial investment of time and money to build and maintain.

In 2000, the director of Forest Health Protection in USDA Forest Service Southern Region requested assistance from FHTET with FVS-Pest Model solutions for the South addressing southern pine beetle, oak decline, and littleleaf disease. Due to the immediate need and budgetary constraints, it was decided to simulate pest impacts in the South using FVS keyword sets, rather than develop fully integrated pest extensions. These keyword sets can then be bundled into stand-alone **K**eyword **C**om**P**onent Addfiles (*.kcp* files) to be included in FVS simulations as appropriate. One of the advantages of developing pest models with FVS keywords is that the code is stand alone; modifications can be made to the FVS base model without requiring changes to the pest specific .kcp files. Occasionally, traditional pest extensions might require immediate and extensive coding changes if the base FVS code is altered in fundamental ways. Another advantage is the ability of the developer/user to quickly make changes in a single file that drastically streamlines the testing and development phase. The FVS Event Monitor feature allows for the creation and evaluation of user-defined variables that describe stand conditions. These variables can then be used to schedule management actions or growth/mortality functions with the "IF…THEN…ENDIF" FVS keyword.

At its simplest level, the SPB keyword set "kills" a percentage of targeted pine species in a simulated stand by the use of the FVS keyword "FIXMORT" if a drawn random number is less than, or equal to, the estimated probability of a SPB outbreak occurring in that multiyear FVS cycle. The SPB keyword set comprised three geographically specific FVS addfiles that cover the Coastal (*SPB_Coas.kcp*), Piedmont (*SPB_Pied.kcp*), and Mountain (*SPB_Mtn.kcp*) subregions in Region 8 (table 1). The Coastal and Piedmont SPB keyword files may be used with the Southern (SN) and Southeast (SE) FVS variants. The Mountain SPB keyword file may be used with the SN, SE, and Northeast (NE) variants. Coastal and Piedmont hazard ratings are determined in accordance with USDA-Forest Service guidelines (Hess and others 1997). The Mountain hazard rating was developed through the Mountain Risk formula (Heddon 1983). The estimated effects of SPB, as well as probability of outbreak occurrence contained in these three addfiles, represent the best professional judgment of entomologists in Forest Health Protection Region 8 (FHP R8), USDA Forest Service.

Table 1—Targeted species by subregion

Subregion	Pine species	FVS code	Scientific name
Coastal	Loblolly	LP	*Pinus taeda*
	Shortleaf	SP	*Pinus echinata*
	Slash	SA	*Pinus elliottii*
	Longleaf	LL	*Pinus palustris*
Piedmont	Loblolly	LP	*Pinus taeda*
	Shortleaf	SP	*Pinus echinata*
	Virginia	VP	*Pinus virginiana*
Mountain	Shortleaf	SP	*Pinus echinata*
	Virginia	VP	*Pinus virginiana*
	Pitch	PP	*Pinus rigida*
	Eastern white	WP	*Pinus strobus*

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Methods

Assumptions

The SPB keyword sets are based on the following assumptions as theorized by FHP R8 entomologists:

- Seven to eight SPB outbreaks in 120 years
- One catastrophic outbreak in 100 years
- SPB prefer sawtimber to poletimber
- SPB prefer poletimber to saplings
- SPB-induced mortality does not affect pine species less than 1.0 inch d.b.h.
- A catastrophic outbreak applies heavy mortality to diameter classes greater than or equal to 1.0 inch d.b.h.
- SPB-induced mortality is not treated as a release

In response to the current ongoing infestation in upland stands, and upon request from FHP R8 entomologists, eastern white pine (*Pinus strobus*) (WP) was added to the Mountain Keyword set. Because the effects of SPB on WP are not well documented, it was decided that the SPB impact on WP should be estimated as half that of the impact of SPB on other target species. That is, if the mortality leveled against shortleaf pine (*Pinus echinata*) is calculated to be 45 percent, then SPB-induced mortality on WP will be half that, or 22.5 percent.

SPB Hazard

Potential SPB mortality, or percent of basal area loss (PBALOSS), is determined by the SPB event monitor variable HAZARD. A stand's hazard classification, or rating, is defined by current stand conditions and determines the levels of mortality applied to target pine sawtimber, if an outbreak occurs. There are three SPB hazard classifications, low (1), medium (2) and high (3), which are based on the stand's overall susceptibility to SPB depredation. Potential PBALOSS of sawtimber for target pine species is shown in table 2.

Actual PBALOSS is calculated as follows:

$$PBALOSS = A + (B - A)\ Random2$$

Where A equals the lower range limit
B equals the upper range limit
Random2 equals a pseudorandom number between zero and one, or
$(0 < Random2 < 1)$

For example, PBALOSS for a high hazard stand (table 2) would be calculated as follows:

$$PBALOSS = .4 + [(.8 - .4) \times Random2]$$

Calculating Hazard Near the Coast

SPB hazard in *SPB_Coas.kcp* is calculated by combining the basal area of targeted pine species within the loblolly/shortleaf and slash/longleaf pine communities, compared to the stand mean top height. Low hazard (1) is the default condition unless the stand meets any of the conditions included in tables 3 and 4. A high hazard (3) classification for the shortest tree range in the loblolly and shortleaf pine community was added to the original R8 classification.

Table 2—PBALOSS (sawtimber) by hazard class

Hazard rating	Percent basal area loss
1 - Low	0 to 10
2 - Moderate	20 to 40
3 - High	40 to 80

Table 3—Hazard ratings for coastal loblolly and shortleaf pine communities.

[a]Mean stand top height (ft)	Loblolly and shortleaf pine combined basal area greater than or equal to 50% stand total				
	Pine basal area (ft^2)				
	< 70	70 to 80	80 to 90	90 to 100	> 100
106+	1	2	2	2	3
76 to 105	1	2	2	3	3
66 to 75	1	1	2	3	3
56 to 65	1	1	2[b]	2[b]	3[b]
0 to 55	1	1	1	1	1

1 = Low hazard
2 = Medium hazard
3 = High hazard
[a]Mean stand top height(ft) as calculated from the 40 largest trees by d.b.h.
[b]Indicates change from original hazard classification parameters (Hess and others 1997).

Table 4—Hazard ratings for coastal slash and longleaf pine communities.

[a]Mean stand top height (ft)	Slash and longleaf pine combined basal area greater than or equal to 70% stand total Pine basal area (ft^2)				
	< 70	70 to 80	80 to 90	90 to 100	> 100
106+	1	1	1	1	2
76 to 105	1	1	1	2	2
66 to 75	1	1	2	2	2
0 to 65	1	1	1	1	1

1 = Low hazard
2 = Medium hazard
3 = High hazard
[a]Mean stand top height(ft) as calculated from the 40 largest trees by d.b.h.

Calculating Hazard on the Piedmont

SPB hazard in *SPB_Pied.kcp* is calculated by combining the basal area of targeted pine species within the loblolly and shortleaf/Virginia pine communities, compared to the stand mean top height. Low hazard (1) is the default condition unless the stand meets any of the conditions included in tables 5 and 6. Virginia pine was added to the shortleaf pine community for a combined basal area with a more comprehensive determination of hazard risk in the Piedmont. We added a high hazard (3) classification for the shortest tree classification range in the loblolly community.

Calculating Hazard in the Mountains

SPB hazard in *SPB_Mtn.kcp* is calculated using the Mountain Risk formula (Hedden 1983), incorporating 5-year radial growth (RG) of targeted pines and the percentage of targeted pine basal area (PER_PINE) relative to total stand basal area. The 5-year radial growth of targeted pine species is estimated using the FVS Event Monitor function, SPMCDBH. SPMCDBH can be configured to return average diameter growth, excluding bark. Diameter growth is then divided by two to generate an approximation of radial growth in the multiyear cycle. Average radial growth (avgRG) is then calculated using a weighted mean average for all targeted species. AvgRG is then divided by the Time Interval (TI) and multiplied by 5 to generate a 5-year radial growth (RG) variable, as per: RG = (avgRG / TI)

The variable STAT is then calculated by taking the natural log of the product of RG and 25.4, as per: STAT = ALOG(RG• 25.4)

The Mountain Risk Score is then calculated as per:

SCORE = –1.90 –(3.97• PER_PINE)+(2.14• STAT)

The resulting SCORE is then used to determine the stand's hazard classification (table 7).

The Hazard Regulator

Because SPB-induced mortality is not treated as a Release, logic was built into the SPB keyword sets that assures a stand's hazard rating either stays the same or gets worse over time, based on current stand conditions. Management actions cause the hazard rating to be recalculated based on current stand conditions. This logic was added after it was observed that hazard went down after sizable SPB mortality was applied in a preliminary SPB keyword simulation. According to FHP R8 entomologists, this downturn contradicts what has been observed in the field. In nature, the unaffected portion of the stand that had been attacked by

Table 5—Hazard ratings for coastal loblolly and pine communities.

[a]Mean stand top height (ft)	Loblolly pine combined basal area greater than or equal to 50% stand total Pine basal area (ft^2)				
	< 70	70 to 79	80 to 89	90 to 100	> 100
106+	1	2	2	2	3
76 to 105	1	2	2	2	3
61 to 75	1	1	2	3	3
50 to 60	1	1	2[b]	2[b]	3[b]
0 to 49	1	1	1	1	1

1 = Low hazard
2 = Medium hazard
3 = High hazard
[a]Mean stand top height(ft) as calculated from the 40 largest trees by d.b.h.
[b]Indicates change from original hazard classification parameters (Hess and others 1997).

Table 6—Hazard ratings for piedmont shortleaf and Virginia[b] pine communities.

[a]Mean stand top height (ft)	Shortleaf and Virginia[b] pine combined basal area greater than or equal to 50% stand total				
	Pine basal area (ft^2)				
	< 70	70 to 80	80 to 90	90 to 100	> 100
106+	1	2	2	2	3
76 to 105	1	2	2	3	3
56 to 75	1	2	3	3	3
45 to 55	1	2[b]	2[b]	2[b]	3[b]
0 to 44	1	1	1	1	1

1 = Low hazard
2 = Medium hazard
3 = High hazard
[a]Mean stand top height(ft) as calculated from the 40 largest trees by d.b.h.
[b]Indicates change from original hazard classification parameters (Hess and others 1997).

Table 7—Mountain risk score.

Score comparison	Hazard classification
Score > 0.40	1
0.40 ≥ Score ≥ –0.56	2
Score < –0.56	3

SPB would be as susceptible to a subsequent SPB outbreak as it was to the previous infestation.

SPB Outbreak

The SPB Event Monitor variable "Outbreak" determines if a SPB infestation will occur, and if so, how severe its consequences will be. Outbreak is an integer variable between zero and four, and represents the range of potential outcomes for each FVS multiyear cycle (table 8).

No SPB-induced mortality is leveled against targeted pine species in the simulated stand in a cycle where the variable outbreak = 0 (no outbreak). As determined by the stand's hazard rating (table 9), SPB-induced mortality is differentially applied to various diameter classes in light (1) and moderate (2) outbreaks.

For the purposes of the SPB Event Monitor, the diameter classes are defined with lower d.b.h. breakpoints as sawtimber (10 inch), poletimber (3 inch), and saplings (1 inch). The SPB Event Monitor does not affect pine species smaller than 1 inch.

SPB mortality will be evenly applied to sawtimber, poletimber, and saplings during a heavy outbreak (3) condition. Regardless of hazard classification, extreme SPB mortality will be applied to all diameter classes in catastrophic outbreak (4) condition. Catastrophic mortality will range between 80 and 100 percent of basal area loss.

Yearly Probability of Outbreak Occurrence

Nonzero outbreak values are assigned if a drawn pseudo-random number between zero and one is less than or equal to the estimated probability of that type of outbreak occurring in the multiyear FVS cycle. Yearly probabilities of SPB outbreak occurrence are based on two assumptions: first, R8 entomologists expect a stand to endure seven to eight SPB infestations over a 120-year period, and second, there will be at least one catastrophic event during a 100-year period.

The probability that a catastrophic outbreak will occur is set at 1 percent per year (one outbreak per 100 years). The probability that an outbreak will occur at all (7.5 outbreaks per 120 Years = 0.0625 or 6.25 percent) is the upper probability limit for a light outbreak in a single year. Likewise, moderate and heavy outbreaks have been assigned a yearly probability of occurrence of 5.0 and 2.5 percent, respectively.

Discounting Probability Logic

The Southern Pine Beetle keyword set uses discounting logic to scale the probability of each outbreak event to the length of the multiyear cycle. In this manner, the probability

Table 8—SPB outbreak variable values.

Outbreak severity	Outbreak values
No outbreak	0
Light	1
Moderate	2
Heavy	3
Catastrophic	4

Table 9— Percentage basal area mortality by outbreak severity class. Relative percentage of mortality applied.

Size class	Catastrophic outbreak (4)	Heavy outbreak (3)	Moderate outbreak (2)	Light outbreak (1)
Saplings	80 to 100	100	50	25
Poletimber	80 to 100	100	75	50
Sawtimber	80 to 100	100	100	100

of outbreak occurrence can never exceed 100 percent regardless of the length of the user-defined cycle. This is achieved by raising the probability of the nonevent to the power of the number of years in a cycle, Time Interval (TI). Therefore, the probability of a light outbreak in a cycle is defined as:

$$\text{ProbLightOutbreak} = 1 - (\text{ProbNoLightOutbreak})^{TI}$$

By default, FVS operates in 5-year cycles in the Southern Variant (TI = 5).

For example, if probNoLightOutbreak = 0.9375, the probability that a light outbreak will occur in a 5-year cycle is:

$$\text{ProbLightOutbreak5Yr} = 1 - (.9375)^5$$
$$\text{ProbLightOutbreak5Yr} = 27.6 \text{ percent.}$$

In each multiyear cycle, a pseudorandom number between zero and one is compared to the calculated probability values of each type of outbreak event — light, moderate, heavy, and catastrophic. Determination of an outbreak event and its associated outbreak severity is illustrated in table 10, in which a drawn pseudorandom number between zero and one is compared to the probability of the various nonevents, raised to the power of the Time Interval (TI). Thus, a single pseudorandom number (rN) can determine outbreak occurrence *and* outbreak severity (table 10). A (rN) with a value of 0.223 in a particular FVS cycle will trigger a moderate outbreak of SPB-induced mortality on targeted pine species. A (rN) with a value of 0.333 in a subsequent cycle will represent a No Outbreak scenario, and simulated trees will continue to grow affected only with FVS calculated background mortality and competition effects.

Use of Random Numbers

The SPB keyword set is designed to run deterministically based on the default FVS pseudorandom number seed (55329). However, the user can easily edit the *.kcp* file in any text-editing program to run the SPB keyword set stochastically. To do this the user must remove the comment character "!" from the line of code that reads

```
!RANNSEED  0
```

This establishes "0" as the replacement value for the pseudorandom number seed. Using "0" will cause the results to vary among multiple runs of the same simulation file.

Table 10—Random number comparison assigning outbreak severity in a 5-year cycle.

Outbreak severity	Pseudorandom number (rN) comparison	Probability of outbreak in a 5-year cycle (percent)
No outbreak	1.0 ≥ rN > 0.275	72.5
Light	0.275 ≥ rN > 0.226	4.9
Moderate	0.226 ≥ rN > 0.119	10.7
Heavy	0.119 ≥ rN > 0.049	7.0
Catastrophic	0.049 ≥ rN ≥ 0.0	4.9

Also, the user can set his/her own pseudorandom number seed by replacing the zero with any odd integer (Van Dyck 2002).

Applying Mortality

SPB mortality is leveled against targeted species in the stand by use of the FVS keyword "FIXMORT." In the following example taken directly from the code, targeted pine species are attacked in a moderate outbreak (2) using the Mountain SPB keyword set (table 11). Stand hazard is high (3), and PBALOSS is assigned at 60 percent. Poletimber PBALOSS (POLELOSS) is then calculated at 45 percent, and sapling PBALOSS (SAPLOSS) would be 30 percent. White pine mortality in the same diameter classes is calculated at half that of the other targeted pine species. WPBALOSS, WPPOLE, and WPSAP represent mortality on white pine sawtimber, poletimber, and saplings, respectively.

The FIXMORT keywords are embedded within an event monitor IF-THEN block and will execute only if an outbreak is scheduled. The variable COUNT is used to assure sequential processing of the various code blocks within the SPB keyword set.

The use of zero (0) in FIXMORT field 6 replaces calculated FVS background mortality for targeted species, whereas the use of one (1) in FIXMORT field 7 indicates mortality levels will be applied on a point basis. This simulates SPB taking discrete portions of the stand, thereby reducing release effects among targeted pine species.

Output

The standard FVS output file contains a wealth of information about the simulation the user has created and run.

Table 11—Applying SPB mortality in *SPB_Mtn.kcp*

```
!Test for an outbreak event and differentially
!apply mortality based upon the severity of the
!Outbreak

IF
OUTBREAK NE 0 AND COUNT EQ 10
THEN

! Apply mortality to saplings
FIXMORT 0 PARMS (SP,SAPLOSS,1,3.0,0,1)
FIXMORT 0 PARMS (PP,SAPLOSS,1,3.0,0,1)
FIXMORT 0 PARMS (VP,SAPLOSS,1,3.0,0,1)
FIXMORT 0 PARMS (WP,WPSAP,1,3.0,0,1)

! Apply mortality to poletimber
FIXMORT 0 PARMS (SP,POLELOSS,3,10.0,0,1)
FIXMORT 0 PARMS (PP,POLELOSS,3,10.0,0,1)
FIXMORT 0 PARMS (VP,POLELOSS,3,10.0,0,1)
FIXMORT 0 PARMS (WP,WPPOLE,3,10.0,0,1)

! Apply mortality to sawtimber
FIXMORT 0 PARMS (SP,PBALOSS,10,999,0,1)
FIXMORT 0 PARMS (PP,PBALOSS,10,999,0,1)
FIXMORT 0 PARMS (VP,PBALOSS,10,999,0,1)
FIXMORT 0 PARMS (WP,WPBALOSS,10,999,0,1)

ENDIF
```

The user is urged to pay particular attention to the sections "Stand Composition," "Activity Summary," and "Summary Statistics" of the standard FVS output. The user can gain direct insight into the inner workings of the SPB keyword set with the two postprocessors that directly report all SPB event monitor variables:

- Compute1—Table of Compute Variables (with headers)—good for general assessment and examination of overall trends within the stand.
- Compute2—Table of Concatenated Compute Variables (comma delimited)—presents the same data in comma-delimited format, which can be imported into spreadsheet programs such as Microsoft Excel® or FVS-EMAP (see these proceedings). SPB event monitor variables of particular interest are HAZARD, OUTBREAK, PER_PINE, STAND_BA, and PINEBA. Analysis of event monitor results within the spreadsheet environment is helpful; the user can sort by one or more variables (such as FVS-cycle year). It is relatively easy to copy values from each cycle to individual worksheets and calculate sum totals and/or averages.

Conclusion

The SPB keyword sets are three geographically specific FVS Addfiles that emulate the effects of SPB upon a simulated stand over time. Current stand conditions are evaluated to calculate a SPB hazard rating for that stand in a given cycle. If a drawn pseudorandom number is less than or equal to the probability of an outbreak event, SPB mortality is levied against targeted pine species in the stand, based on the SPB hazard rating and/or the type of SPB outbreak scheduled for the stand in that cycle. SPB-induced mortality is not intended to act as a release for surviving trees. Therefore, unless management actions are scheduled by the user, the stand's hazard rating can only remain the same, or get worse over time. Appropriate management actions, as portrayed by FVS keywords, can reduce a stand's SPB hazard rating and potentially reduce loss of pine basal area due to simulated SPB mortality.

The three SPB keyword sets and User's Guide are available at:

http://www.fs.fed.us/foresthealth/technology/products.htm
or by contacting:

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Pre-Suppose: Preprocessor to Suppose

Don Vandendriesche

Abstract—The Pre-Suppose program is designed to help analysts organize inventory data for management planning. Pre-Suppose rapidly generates preliminary statistics on a proposed data group. This provides the ability to quickly evaluate the homogeneity of selected forest strata. Plot attributes can be chosen from a variety of code and range keys to designate a data group. Rapid processing of plot summary values renders important statistical information relevant to the keyed items. Once the user is satisfied with the selected criteria and resultant output, support files can be created that link directly to the Suppose interface for the Forest Vegetation Simulator. Pre-Suppose has been programmed to work dynamically with forest inventory data stored in a Microsoft Access database. A case example using Forest Inventory Analysis data from the Black Hills National Forest in South Dakota is presented to demonstrate program capabilities.

The Suppose (Crookston 1997) interface presupposes that inventory data are available in the proper format for the Forest Vegetation Simulator (FVS) (Dixon 2001). Several computer programs have been written to translate data from stand examination and permanent plot inventories into file formats needed for FVS. However, most translation programs lack the ability to scrutinize data elements prior to export. Users are frequently perplexed regarding how to assemble inventory data items into comprehensive strata needed for further analysis. The Pre-Suppose program addresses data attribute querying in the context of strategic planning for large-scale forest ownerships.

Pre-Suppose was written for the Microsoft Windows operating system using the Visual Basic programming language. "Any application that requires the user to perform a series of steps to arrive at a predetermined result can benefit from a Wizard" (Eidahl 1998). Pre-Suppose adheres to this programming tenet. Like most computer programs, Pre-Suppose has input and output components. The input components are addressed through three steps within the Pre-Suppose Wizard. Once the user chooses the input elements, the proper output reports are generated. Following a brief discussion of relevant forest planning aspects, associated functionality of the Pre-Suppose Wizard will be presented.

In: Crookston, Nicholas L.; Havis, Robert N., comps. 2002. Second Forest Vegetation Simulator Conference; 2002 February 12–14; Fort Collins, CO. Proc. RMRS-P-25. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

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Planning Framework

Quite often, forest planning efforts require developing estimates of conditions and outcomes by *stand type*. A stand type is an aggregation of the physical, vegetative, and developmental characteristics used to identify homogeneous forest strata (Davis and Johnson 1987). Physical attributes describe the site aspects of the forest, such as topography, soils, and habitat type. Vegetative attributes characterize the flora aspects of the forest, such as cover type species, size, and density. Developmental attributes portray the human-use aspects of the forest, such as roads, building, and administrative boundaries. Stand types, by definition, are nonspatial but comprise many geographically identifiable forest stands.

Physical and developmental characteristics are initially addressed by following a land classification scheme. For example, *suitable lands*, according the USDA Forest Service protocols, constitute the land base for determining the allowable sale quantity and the vegetation management practices associated with timber production. Suitable lands must be available, capable, and technically favorable under current management techniques.

Once the land has been classified, *management prescriptions* are formulated. Management prescriptions provide an activity schedule that describes the conditions by which vegetation will be treated to obtain desired outcomes. For example, no treatment is a popular contemporary management option. Similar vegetation types often respond in a predictable manner. Thus, vegetative characteristics are defined by common overstory tree species, of similar size and density. Understory components are increasingly important and add the dimension of plant association or community type. Typically, major forest cover types are derived from life zones, plant biomes, or ecological geography (for example, ecoregions, Bailey 1995). They depict the base vegetation layer.

The Pre-Suppose program can be used to query the physical, vegetative, and developmental attributes within a forest inventory data set. Layout of a schematic flow chart can be easily accomplished by following the intuitive steps of the Pre-Suppose Wizard. The Forest Inventory Analysis (FIA) data set from the Black Hills National Forest in South Dakota will serve as an example.

Forestland Classification

Winnowing the land base constitutes the initial step in the development of stand types to be used in a forest scheduling model. The derivation of the potential timber base is extremely important insofar as it defines the basic units, the building blocks for the analysis. Once the land base is classified and incorporated into a scheduling model, it is extremely difficult to alter. A change in the land

classification scheme could essentially mean starting from the beginning and redoing the analysis.

The 1986 and 1999 measurements of the Forest Inventory Analysis plot grids will be used as the empirical basis for the Black Hills National Forest, Phase II Amendment of its 1997 Revised Land and Resource Management Plan. The FIA plot locations will represent the various stand types within the land classification scheme. This diagram will serve as a flow chart for assigning stand types and associated acreages and plot counts.

Candidate Lands in Timber Base

There are many possible ways to partition a forested area into land classes that form the timber base. Experience has shown that four major breaks need to be described: (1) Administrative Availability – lands that are withdrawn by statutes, regulations, or policies (that is, wilderness areas, cultural, and special-use sites) are identified at the first level of the land class hierarchy; (2) Physical Capability – lands that are physically limited in their ability to sustain commercial stands of timber (for example, extremely dry or wet sites, inadequate growth rate) are separated at the second level of the land class hierarchy; (3) Ecological Suitability – lands that are designated for resource values other than timber production (that is, critical wildlife, watershed protection, visual corridors) compose the third level of the land class hierarchy; and (4) Technical Favorability – lands that are unable to be treated by current technology or restricted by special treatment needs (that is, inaccessible areas, steep terrain, insect, disease, fire areas) are excluded to form the fourth level of the land class hierarchy. Figure 1 provides a delineation of the forestland classification for the Black Hills National Forest. Associated acreages and FIA plot counts are presented for each stand type. Area and inventory estimates are not given for nonsampled strata.

Stand Types Within the Timber Base

Stand types comprise forest land units that have the same combination of physical, vegetative, and developmental

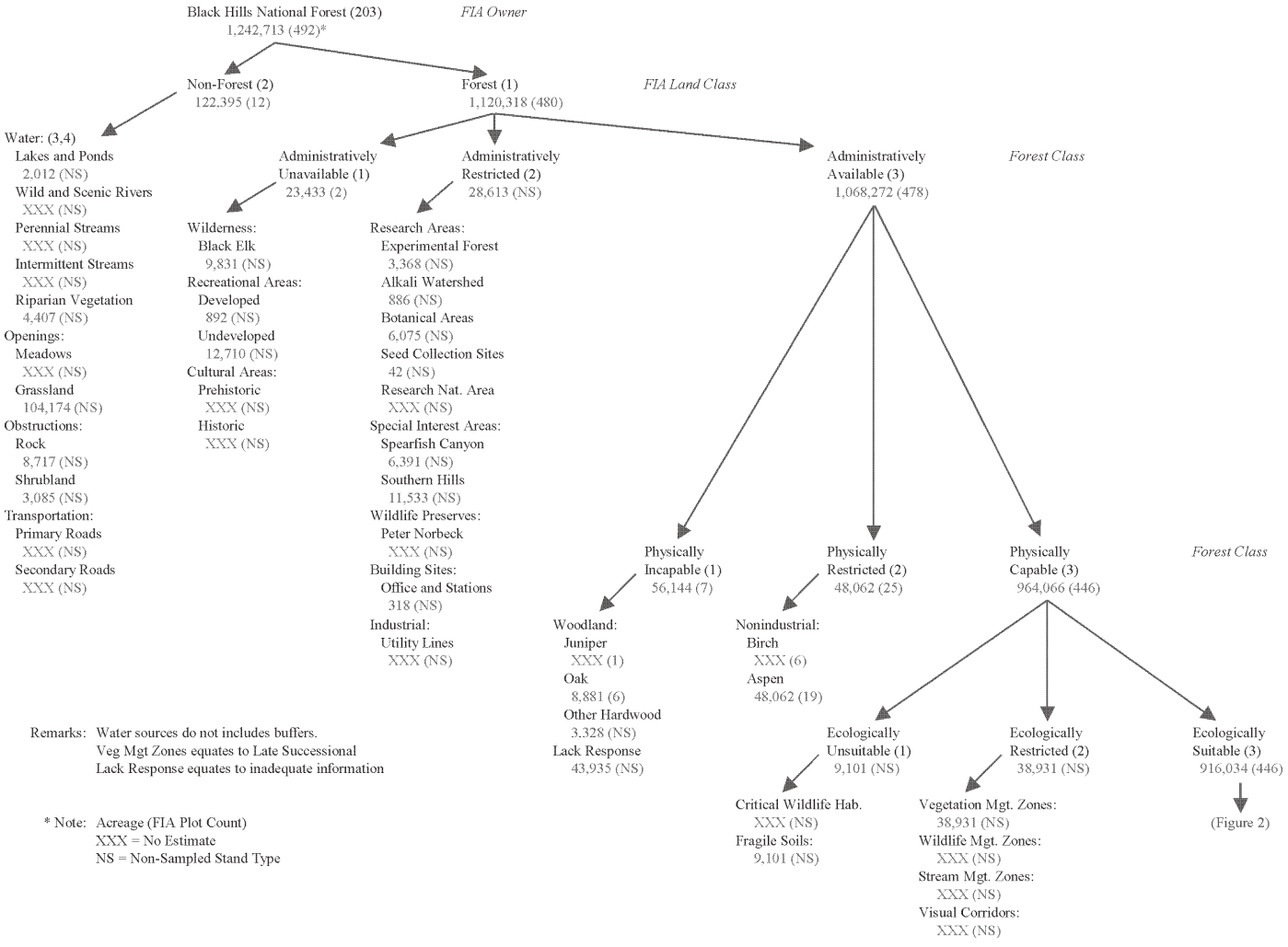

Figure 1—Forestland classification template.

characteristics to stratify as homogenous entities. Developmental and physical attributes have been addressed in defining the resultant "Available – Capable – Suitable – Favorable" forestland base. The vegetative characteristics (type, size, density) can be described by the predominant overstory forest canopy. Figure 2 provides a depiction of the tentatively suitable forest land base for the Black Hills National Forest. Acreage values were derived using Geographic Information System (GIS) software resident at the Black Hills Supervisors Office. The Pre-Suppose program was used to query the FIA data sets to assemble plot counts for the various stand types.

Pre-Suppose Application

Pre-Suppose was developed to assist forest analysts in developing stand types for management planning. The program leads users through a series of three input forms (parameter, plot, and key screens). Upon conclusion, a statistical report is presented to aid evaluation of a proposed data group. A brief description of the processing sequence used by Pre-Suppose follows.

Once the Pre-Suppose program has been invoked, a splash screen is displayed, followed directly by an *open* database dialog window. Pre-Suppose processes information stored in Microsoft Access database files. A listing of internal data tables will be presented during step 1 of the Pre-Suppose Wizard.

The user can choose between any one of several locations or time periods or both. For example, FIA data for the Black Hills National Forest has been assembled in database format from the 1986 and 1999 measurements. During the later, two complementary grids were installed. The primary grid was monumented in accordance with a 5,000 m design. The secondary grid was based on a centroid-hexagon layout. Over time, the hexagon grid will become the principal sampling design. Pre-Suppose easily accommodates the varying data sources as depicted in figure 3. Checkboxes within the listbox window provide the option of selecting the preferred data sets.

Pre-Suppose allows an expanded search beyond the boundaries of a given ownership. Lets say that FIA plot sample size is sparse in a specified locale as is true with many Eastern National Forests. There are numerous cover types represented over the landscape. Plot intensity per cover type is limited. Users could expand their search to FIA plots located in proximity to the National Forest. So long as the treatment and development histories are similar, these plots could be

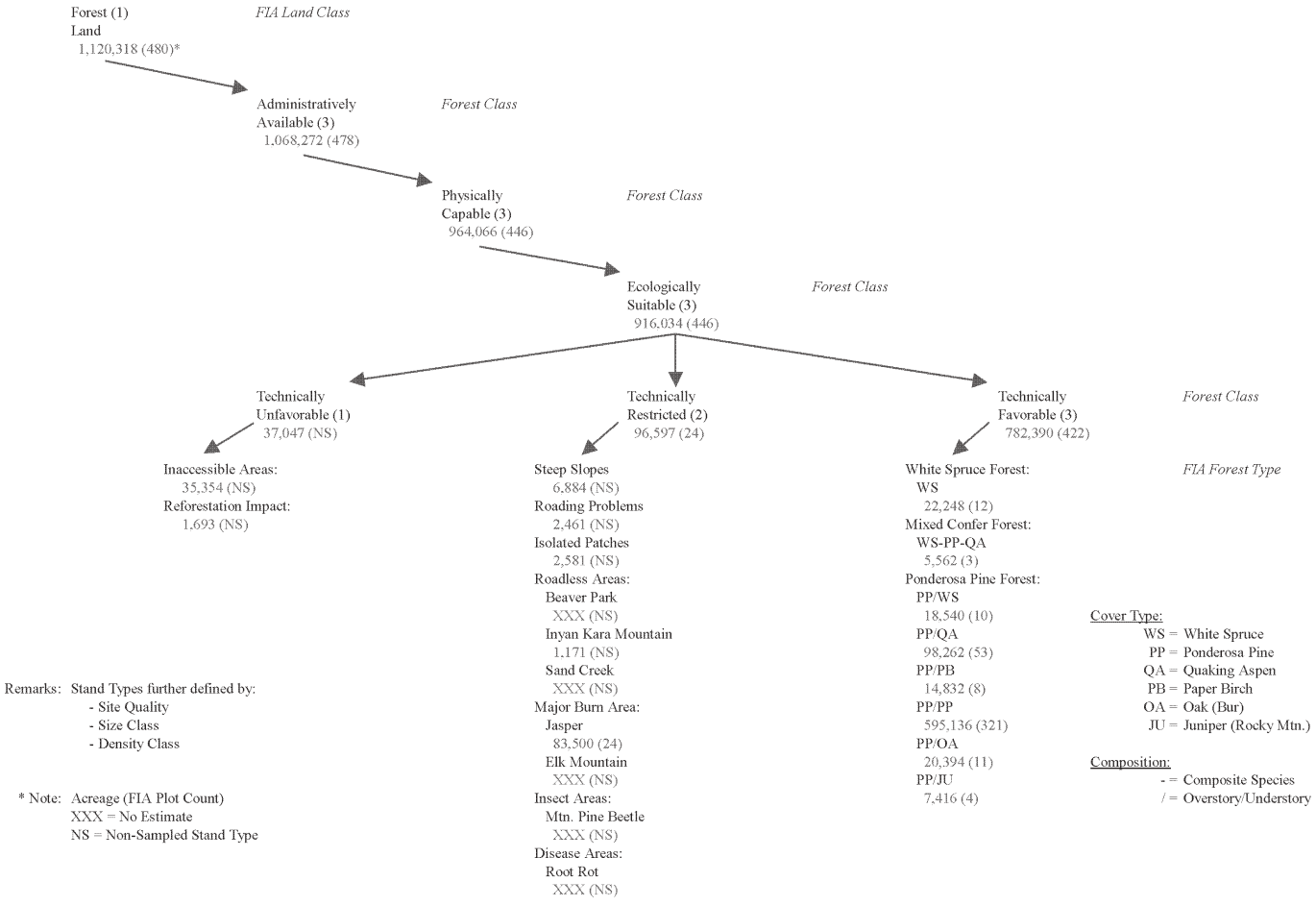

Figure 2—Stand type delineation.

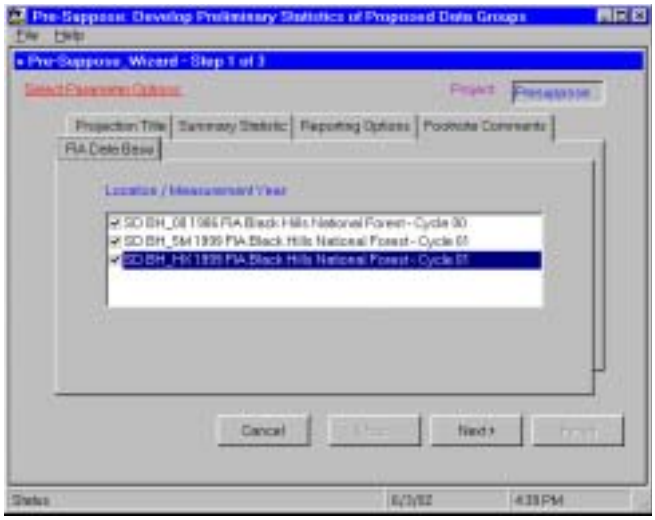

Figure 3—Parameter selection screen.

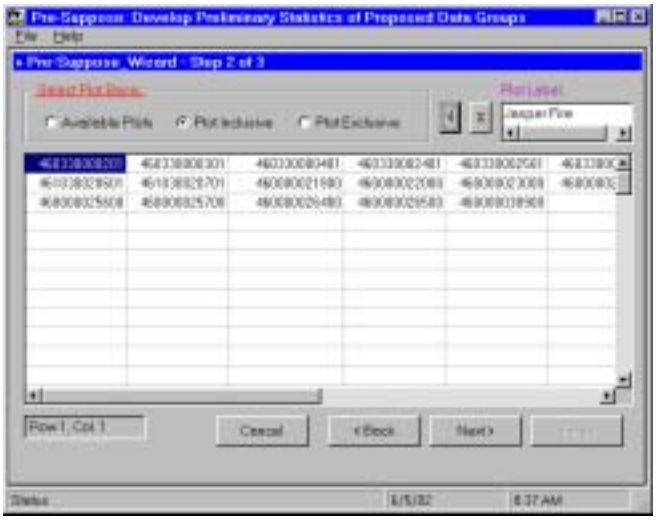

Figure 4—Plot selection screen.

used as *condition class* samples to strengthen the inferences related to the vegetation stand type. All that is needed is for the FIA data to be loaded into the proper database for Pre-Suppose to access.

Step 1 of the Pre-Suppose Wizard is commonly referred to as the *parameter* screen. Input parameters are gathered that inform Pre-Suppose which database tables to use, how to title and footnote the output reports, and which statistical summaries to produce. Plot summary values can be generated for a variety of tree classes (such as live, harvest, mortality trees). Parameter values are retained as defaults for subsequent runs of Pre-Suppose. Thus, following initial set up of the individual tabs, additional runs only require proceeding by mouse clicking the *Next* command button.

Step 2 of the Pre-Suppose Wizard is commonly referred to as the *plot* screen. Plots are specified for inclusion or exclusion from further processing. By default, all "Available Plots" are used in the statistical analysis. However, there are times when noncoded events affect the FIA data set. For example, a recent catastrophic wildfire (Jasper Fire) burned over 80,000 acres of the Black Hills National Forest. The FIA plots within the fire perimeter were identified using GIS software. A text file was generated that could be imported into Pre-Suppose to populate the plot screen. Refer to figure 4. A label can be included for additional identification of the plot set.

Plot counts input through step 2 of the Pre-Suppose Wizard can be used to directly populate the forestland classification diagram. Note that the Jasper Fire was identified as a subclass beneath the *Available – Capable – Suitable – Technically Restricted* forest class. By including only these plots, Pre-Suppose can produce a plot summary statistical report relative to prefire conditions. Pre-Suppose can also provide a direct link of these plots to the Suppose interface. In contrast, in order to properly sort the *Technically Unfavorable* and *Technically Favorable* forest classes, the Jasper Fire plots would need to be excluded from those data run. Pre-Suppose readily handles this task. Mouse clicking the *Next* command button will prompt Pre-Suppose to continue.

Step 3 of the Pre-Suppose Wizard is commonly referred to as the *key* screen. Any data item collected during the field measurement or any value calculated during the office processing can be accessed by the user to form forest strata or stand types. Data items are assigned as either code or range keys. Coded items are generally discrete or qualitative variables. For example, ownership, land class, or forest type are representative of coded data. Range items are generally continuous or quantitative variables. For example, elevation, stand age, or site index are representative of range data.

Keyed data items entered through step 3 of the Pre-Suppose Wizard eases the effort to built stand types as designated in a forestland classification chart. For the Black Hills example, to identify those FIA plots composed of the *Available – Capable – Suitable – Favorable* forest class that are *Ponderosa pine* overstory with *White spruce* understory, the following steps would be used:

Pre-Suppose_Wizard – Step 3 of 3:

1. Add Code Key: Land Class 1 = Forest Land
2. Add Code Key: Forest Class 3333 = Available – Capable – Suitable – Favorable
3. Add Code Key: Forest Type 211 = Ponderosa pine
4. Add Range Key: Forest Sub-Class 3 = White spruce

Figure 5 provides a graphic depiction of the process used to enter the Ponderosa pine overstory code key. The *Data Index* window operates in a similar fashion as the treeview folder pane within the Windows Explorer program. The *Plot Record* branch nodes are derived from the FIA plot record. The Plot Record is further defined as either *Classification Data* or *Summary Data*. Classification data are coded stand measurements. Summary data are computed per acre stand values. The *Tree Record* branch nodes are derived from the FIA tree record. The Tree Record is further defined as either *Measurement Data* or *Calculated Data*. Measurement data are field measured tree attributes. Calculated data are computed per tree values. Mouse clicking the Classification Data branch under the Plot Record node will expand a list of

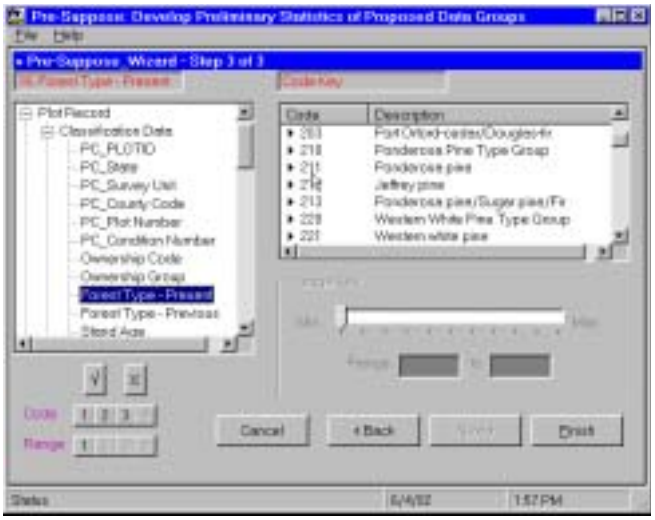

Figure 5—Key selection screen.

available data items. Selecting the *Forest Type – Present* sub-branch will awaken the listview window in the upper right corner of the step 3 window displaying available code items. Mouse clicking the "211" code will designate ponderosa pine as the overstory forest type to be entered into the selection process. The check symbol located in the lower left corner of step 3 will record the query attribute. Clicking the *Finish* command button will prompt Pre-Suppose to continue.

After gathering input through the three steps of the Wizard, Pre-Suppose is ready to generate the output reports. Three text files are produced by Pre-Suppose. The first report, *Plot Summary Statistical Analysis* (PSSA), contains an abbreviated statistical analysis of the specified strata. Figure 6 displays the PSSA output report for the ponderosa pine/white spruce stand type residing within the tentatively suitable forest land base on the Black Hills.

The top of the PSSA report provides identification information such as the database tables used, the plot basis, and

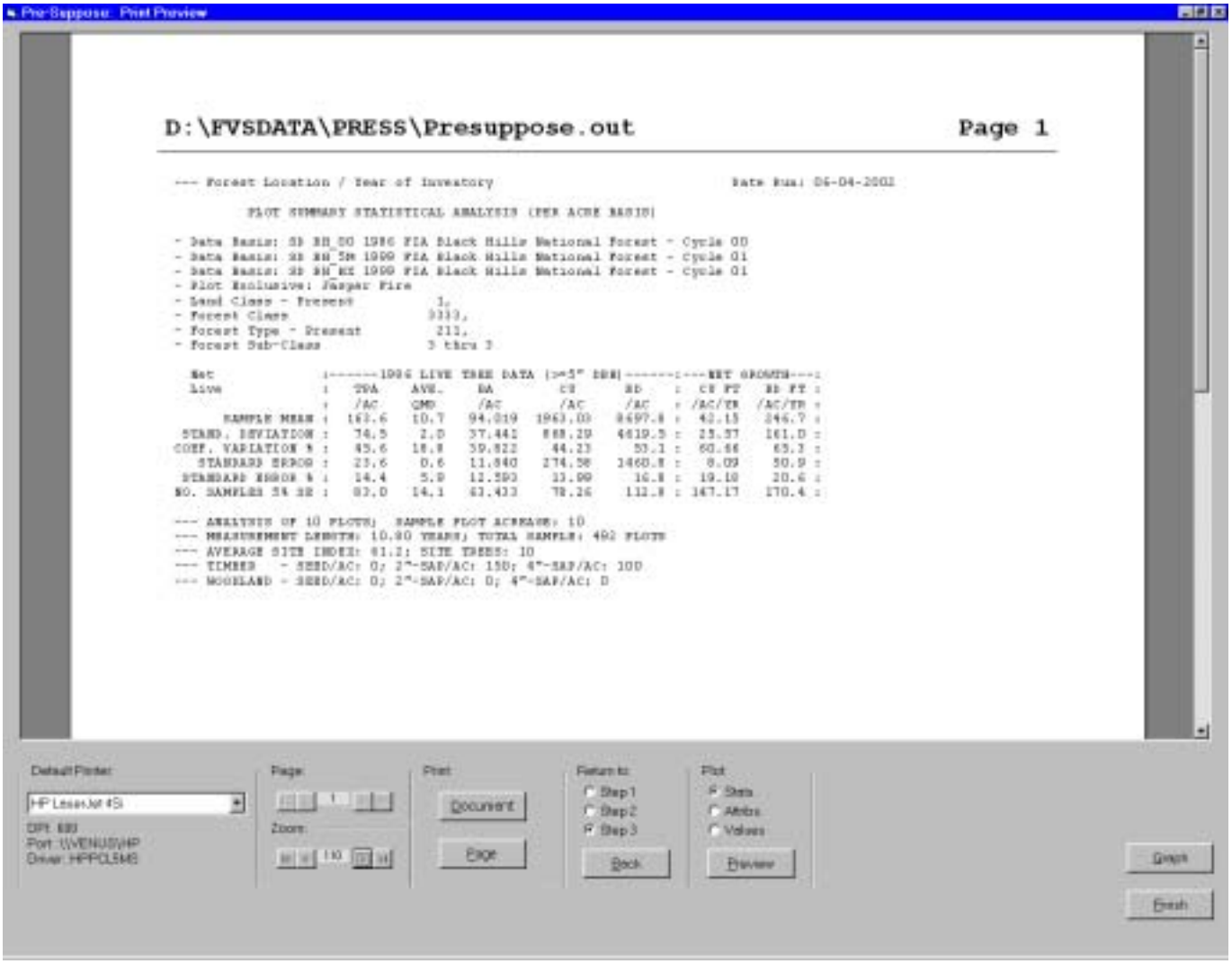

Figure 6—Plot summary statistical analysis report.

the sort key prescribed. The middle section of the report provides a table that lists classical statistical measures for trees per acre, average quadratic mean diameter, basal area per acre, and cubic and board foot volumes per acre. Statistical inferences for volume growth are also displayed. Values appearing in the statistics table are for trees 5 inches and greater in diameter. The bottom of the PSSA report includes information on the number of sample plots rendered by the sort criteria, growth measurement length, average site index for the strata, and a seedling/sapling count distribution.

The second text file produced by Pre-Suppose is called the *Listing of Plot Attributes*. As the name implies, this report sequentially lists plot records that comprise the requested strata. This listing can be used as a permanent record of the plots that compose the data sort. It can also be used to examine data relationships. For example, using the Black Hills data set, there was a need to partition the dominant ponderosa pine overstory by understory tree species components (that is, juniper, oak, birch, aspen, spruce seedling–sapling counts). Using Pre-Suppose to query the database by understory species, a relationship between aspect and elevation was noted. Given that ponderosa pine seedlings and saplings occur on all aspects and all elevations, analysis showed that juniper and aspen composed the understory on southerly aspects. Juniper resided at lower elevations while aspen occurred much higher. On northerly aspects, a progression from low/dry to high/moist was observed. Juniper understory gave way to oak, oak to birch, birch to aspen, and aspen to spruce. Much of this relationship was revealed by close examination of the Listing of Plot Attributes report.

The third text file produced by Pre-Suppose is entitled the *Listing of Plot Values*. A complete listing of plot summary values (trees, quadratic mean diameter, basal area, cubic foot, board foot) is presented on a per acre basis. Values are listed for each plot that met the sort criteria. Annual cubic and board foot volume growth is also included as well as seedling and sapling stem counts. Understories values are listed separately by timber and woodland species.

For visual interpretation of the output, a graphing option is available. Users can pick any set of continuous variables for the data group and produce a scatter plot diagram. Sometimes, visual inspection of the data set can reveal suspicious outliers. Data points can be selected on the graph to identify associated plot numbers. Figure 7 provides an example of this handy feature. Step 2, the plot exclusion feature of Pre-Suppose, can be used to eliminate suspect data points.

The value of the Pre-Suppose program for building stand types is tremendous. As a result of its rapid processing of plot summary records, resultant data group can be quickly generated. Output from trial runs can be evaluated based upon statistical merits to determine if an adequate plot count has been obtained with the input criteria. Building a defendable forestland classification scheme for a strategic forest planning project is a snap with Pre-Suppose.

Additional Features

Suppose Linkage

The ultimate goal of Pre-Suppose is to develop forest strata to relay to the Suppose interface. Pre-Suppose prompts the user to enter titles for the *Suppose.loc* file and for the *Stand List File*. These two files reside in the background to assist Suppose in its operation. For strata that contain many plots, the caption on the Print Preview windows (fig. 6) will indicate which plot Pre-Suppose is currently processing. This aids in determining that Pre-Suppose is still working on the selected strata. Once the data group is available to Suppose, using the "File/Open Locations File" menu option will facilitate locating the newly created Suppose.loc file. The "Select Simulation Stands" window within Suppose will appear. By picking the "Location Title" and "Group Code" as designated in Pre-Suppose, the associated plots will be displayed in the "Available Stands" text box.

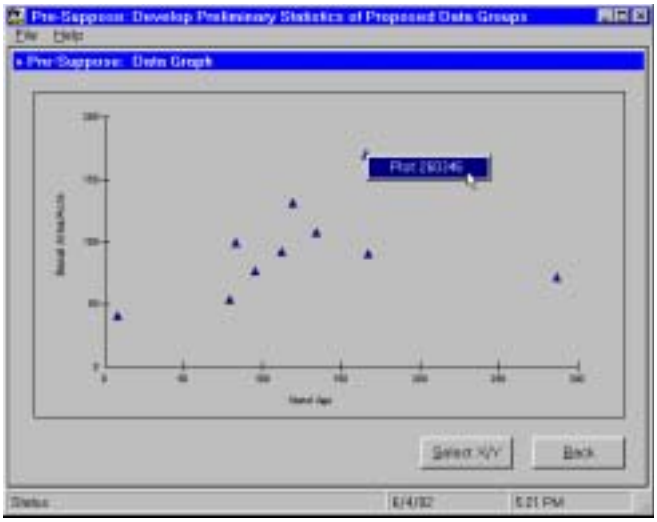

Figure 7—Graphical data display.

Tree Record Queries

Pre-Suppose generates the Plot Summary Statistical Analysis Report based on data in the database plot tables. These tables contain one record per plot. In contrast, the tree tables contain one record per tree. Thus, the plot tables are significantly smaller in size than the tree tables. Processing of the plot tables requires less input/output of records, which allows faster reporting. However, there are situations when a forest analyst needs information at the tree level. In this instance, the Plot Statistical Analysis Report would render an improper result. It displays all tree records, not just the records associated with the specified tree level attribute.

Suppose a particular tree species is threatened or endangered due to insect, disease, or human cause. No longer are plot summary values of interest. Pre-Suppose can be used to query plots that contain the tree species attribute.

Listing of Tree Records—Pre-Suppose produces a complete listing of each tree record that meets the tree level attribute. Tree measurement data are concatenated with tree calculated data to generate this report. This printout can be large. Prior to printing the entire document, careful examination of the number of pages to be printed is warranted. The *Page* frame at the bottom of the *Print Preview* window (fig. 6) will indicate the total pages.

The "Listing of Plot Attributes" and "Listing of Plot Values" reports can be viewed by selecting the respective radio buttons in the *Plot* frame on the *Print Preview* window (fig. 6). These listings contain the plot records with the tree level attribute. These plots can be captured as the default input plot file for step 2 of the Pre-Suppose Wizard.

Data Base Consideration

Four data tables per location per inventory compose the background database for Pre-Suppose:

1. **Plot Classification** (_Plot_Clss)
2. **Plot Summary** (_Plot_Summ)
3. **Tree Measurement** (_Tree_Meas)
4. **Tree Calculation** (_Tree_Calc)

These categories populate the treeview window on step 3 of the Pre-Suppose Wizard. Each forms a branch node that inherently contains the respective data items. These data fields comprise the columns within the data tables.

There are two additional tables that Pre-Suppose uses for operation: one for input, one for output. The *Code_Definitions* table is developed in conjunction with the plot and tree tables. This table provides the link to the other input tables and is the main driver of the Pre-Suppose program. Users can easily add additional data items to the database by modifying the Code_Definitions table. The *Presuppose* table is created internally by the Pre-Suppose program during the processing phase and renders the output records of the requested query.

Help Support

Pre-Suppose has an embedded help utility that has the look and feel of other popular Microsoft products. Help for Pre-Suppose can be invoked by using the *Help* menu option or by simply pressing the F1 function key. Help topics can be searched by contents or by index.

Applications of Pre-Suppose

The Pre-Suppose program has proven to be a valuable tool for forest planning. In addition, Pre-Suppose has been used for several regional assessments. Disturbance agents such as insects, disease, and fire impact the forest landscape. Assessing their potential risk is an important task and aids decisionmakers in their planning efforts. To date, the Pre-Suppose program has been used for the following projects:

1. USFS R-1: Hazard-Risk Assessment for Montana
2. USFS R-2: Forest Plan Revision, Black Hills National Forest, South Dakota
3. USFS R-3: Hazard-Risk Assessment for Arizona and New Mexico
4. USFS R-4: Hazard-Risk Assessment for Idaho and Utah
5. USFS R-8: Forest Plan Revision, Southern Appalachian. National Forests
6. USFS R-9: Forest Plan Revision, Chippewa - Superior National Forests, Minnesota
7. USFS WO: FY-2000 Senate Appropriations Act Request
8. Bureau of Indian Affairs: Forest Plan Revision
9. Bureau of Land Management: Assessment Projects
10. Private: West Virginia Timber Company

USDA Forest Service Intranet Web access has been developed for Region 8 (fig. 8). Immediate intentions are to provide a similar mode of program and data file access for the entire country. Internet links are being developed to facilitate access for all public and private constituents. A collaborative effort between FIA and FVS staffs has commenced to develop links from the FIADB (FIA presentation database) (Miles 2001) to FVS ready input files.

Future Development

Anticipated future developments for the Pre-Suppose program include producing links to the FSVeg database and addressing process methods for stand examination inventory data sets. Conceptual discussions have already begun.

Pre-Suppose Documentation

A User's Guide (Vandendriesche 2001) is available for Pre-Suppose from the author at the address listed on the front-page footnote of this paper. The User's Guide includes a "How to … " section that contains a step-by-step tutorial. A detailed description is given for each of the output reports. The graphing option is more fully described. A rigorous discussion of the process of linking Pre-Suppose output to Suppose input is provided. An example that explains the process of tree level sorting using Pre-Suppose is presented. Consideration regarding the composition of the background database is given along with an explanation on how to dynamically modify its structure. It is an "everything you wanted to know" guide.

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Vandendriesche, Donald A. 2001. Selected Topics for the Forest Vegetation Simulator. Internal Manuscript. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Forest Management Service Center. 85 p.

Figure 8—Web Page link.

Session 2. Reality Check

Classifying Stand Structure: A Comparison of SVS Images with Plot Visits and FVS-Generated Metrics

T. M. Barrett
F. G. Schurr
K. L. O'Hara

Abstract—FVS is frequently linked with the Stand Visualization System (SVS) to provide computer-generated images of current and projected forest structure for use in research articles, forest planning documents, and public presentations. A small pilot study in the Sierra Nevada focused on whether observers classified stands in the same way from SVS images as from site visits. This survey, conducted in fall 2000, used groups of forest visitors (45 individuals) who toured seven 0.10 acre plots with a variety of stand structures. Results showed these visitors classified tree size, age, and canopy cover differently on real plots than from SVS images. Responses from both field visits and image viewing also differed from commonly used metrics output from the FVS program.

In recent years computer graphic simulation of forests has become more common, with uses varying from prototyping harvest equipment (Block and Fridley 1990) to animated "walk-throughs" of a forest environment (House and others 1998). Computer visualizations can range from the tree to landscape level, and from the abstract to near photographic quality. Several authors have noted the potential of computerized visualizations of forests to mislead as well as inform (McQuillan 1998; Wilson and McGaughey 2001), a problem that may be exacerbated when the goal of the visualization is to produce an illusion of the actual environment (Orland and Uusitalo 2001).

A substantial body of research on the use of computer graphics, simulation, and photography exists in fields such as landscape architecture, psychology, and urban and regional planning, but little is known about the effectiveness of visualization for forestry applications. In particular, uses of visualization specific to forestry, such as illustrating different forest types or demonstrating the effects of silvicultural treatments, have had little research. This research addresses one aspect of a forestry-related application, the use of images to represent classified forest structure.

Although it has been argued that all forest simulations are rhetorical in nature (Luymes 2001), compared to some applications of virtual environments, users of virtual forest representations may be more likely to be trying to provide impartial information (Orland and Uusitalo 2001). A computer visualization to illustrate forest type or structure could be characterized as this type of use; the image creator may be trying to convey a particular piece of information rather than achieve a preferred aesthetic reaction. This can be especially useful for communicating to a lay audience that has no experience with technical forestry terms such as basal area, canopy cover, even-aged, seed tree, or shelterwood. One program that has been used to convey information about forest type and structure is the Stand Visualization System (McGaughey 1998).

The Stand Visualization System, or SVS, is probably the most commonly used visualization program for forestry in the United States. Since the late 1990s, images generated by the program have appeared in journals, conference proceedings, forest management plans and assessments, and numerous presentations. The program creates graphical images of trees and forest stands (fig. 1 to 3) using input of individual tree species, diameter, height, crown width, crown ratio, and tree location. The SVS program can also generate tree location, and additional capabilities include the ability to portray understory vegetation, snags, and logs.

A general question that may interest SVS users is "How well do observers interpret the images?" Because of the frequent use of SVS in illustrating forest structure (the physical spatial distribution of tree vegetation), one indicator that might be useful in answering this question would be to know if people classify SVS images similarly to how they classify actual forested areas. To date, no research has been done on this question. This paper reports the results of one case study addressing this question. We surveyed three groups of visitors to a research forest in fall 2000. The visitors answered identical sets of questions about forest structure for SVS images and for real plots. Although results should not be extrapolated to a larger population or other forests, it is hoped that managers will find this case study useful in understanding some of the issues related to using a data-driven visualization program to convey information about forest structure.

Methods

Blodgett Forest, a 4,600-acre research forest for University of California-Berkeley, is located in the 4,000 to 5,000 feet elevation mixed-conifer region of the west slope Sierra Nevada. The forest is used for research and demonstration,

In: Crookston, Nicholas L.; Havis, Robert N., comps. 2002. Second Forest Vegetation Simulator Conference; 2002 February 12–14; Fort Collins, CO. Proc. RMRS-P-25. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

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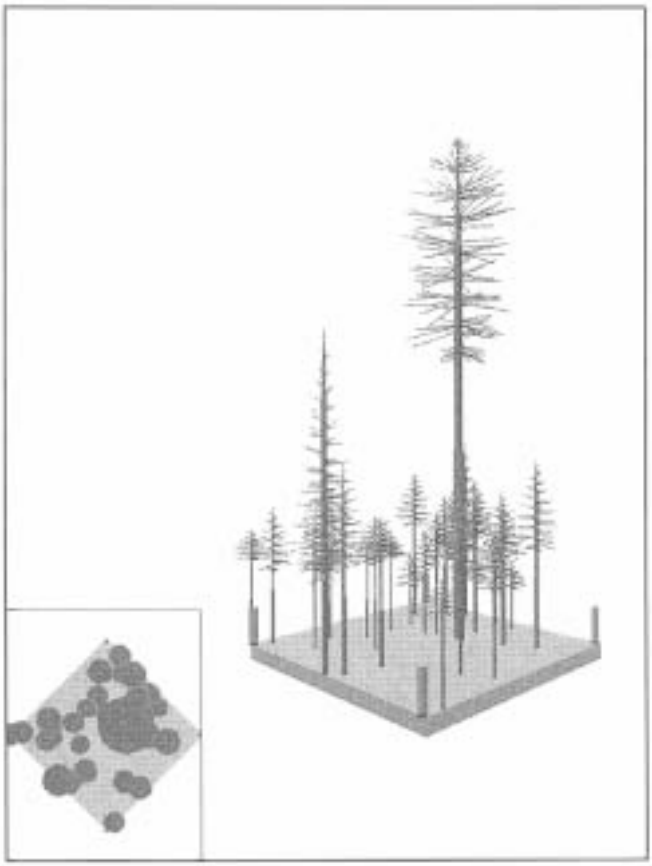

Figure 1—Tenth acre SVS image of plot 7.

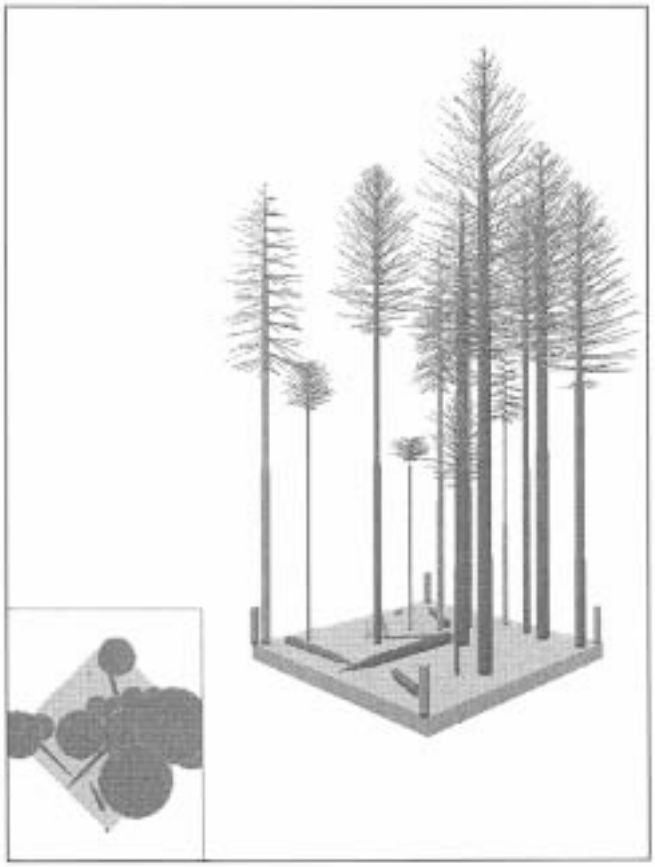

Figure 2—Tenth acre SVS image of plot 2 with logs.

and small groups of visitors occasionally stay at the forest and use the conference center for meetings. The forest was chosen for this case study because of the combination of visitor use and silvicultural demonstration sites.

Seven 0.10 acre permanent plots from the forest's continuous forest inventory (CFI) system were selected for use in the survey, based on proximity to the visitor center. Although in mature second-growth mixed conifer forest, the seven plots provided some diversity of structure: two of the plots were in stands managed as a shaded fuel break, two plots were in unmanaged stands, and three plots were in stands that have been managed using single tree selection.

Data for each plot were put into the 6.21 version of the West Side Sierra Nevada variant of the Forest Vegetation Simulator (FVS) (Dixon 1994; Wykoff and others 1982). Measured values input into the program were tree species, diameter, height, and live crown ratio; trees smaller than 4.5 inches dbh were not included. The FVS program was used to estimate maximum crown width; this estimation procedure uses a linear function of diameter, with species-specific coefficients. Using random spatial placement of trees, the output from FVS was converted into input for the Stand Visualization System 3.31 (McGaughey 2001) to create images.

The SVS default parameters for coloring and branch placement were used for all species, with the default ground surface. Tenth-acre images were created using a perspective view and overhead view (fig. 1). Viewer azimuth, elevation, and distance, lens focal length and aspect were kept constant for each 0.10 acre image. One plot, which contained several large logs, had an additional image created with graphical logs (fig. 2). Half-acre images, which duplicated each individual tree five times, included perspective, profile, and overhead views (fig. 3) and were only created for four of the plots. Both types of images included four orange corner posts scaled at 10 feet high and 2 feet in diameter. Each image also included a written description of the size of the plot and the diameter and height of the four orange corner posts.

In fall 2000, three groups of visitors to the forest participated in the survey: 14 people attending a mycology meeting, 17 people finishing their Forest Service silviculturist certification, and 14 people on a field trip for a college-level silviculture class. Each group viewed a 20-minute PowerPoint presentation of 12 SVS images: seven 0.10 acre images (one for each plot), a 0.10 acre image of one plot with logs, and four 0.50 acre images (for four of the seven plots). For each image, participants were asked questions on the tree size classification of the plot, whether the plot was even-aged or uneven-aged, the canopy cover class of the plot, and whether the image represented "old forest." The questions on the survey were:

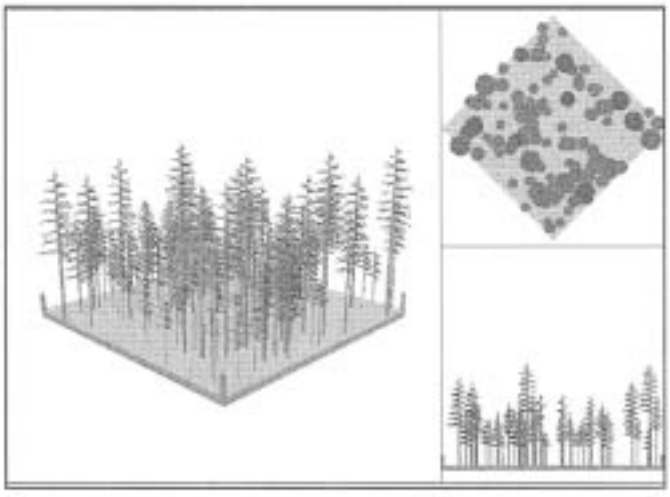

Figure 3—Half acre image of plot 6.

1. Which of the following best describes this image?
- *a. Seedlings (average tree diameter less than 1")*
- *b. Saplings (average tree diameter between 1" and 6")*
- *c. Poles (average tree diameter between 6" and 12")*
- *d. Medium (average tree diameter between 12" and 24")*
- *e. Large (average tree diameter greater than 24")*

2. Which of the following best describes this image?
- *a. Even-aged*
- *b. Uneven-aged*

3. Which of the following best describes this image?
- *a. Sparse (10% to 24% canopy cover)*
- *b. Open (25% to 39% canopy cover)*
- *c. Medium (40% to 59% canopy cover)*
- *d. Dense (60% to 100% canopy cover)*

4. Please give your best estimate of the percent canopy cover: _____

5. Would you describe this image as representing "old forest"? "Old forest" contains old, large trees. _____ (Yes / No)

The first three questions correspond to the California Wildlife Habitat Relationship (CWHR) forest classification system (Mayer and Laudenslayer 1988). Two departures from the system—(a) using average diameter instead of quadratic mean diameter for size class and (b) using the term "uneven-aged" instead of "multistory" —were made to increase participants' understanding of the questions.

These questions were read aloud to the participants to control the pacing of the survey; the 12 images were visually separated from each other by showing a blank white screen for a few seconds. Participants were not informed that some of the images were created from the same plot data. Participants were verbally reminded of the size of each visualized plot (0.10 or 0.50 acres), the size of the orange corner posts, and to estimate canopy cover as "the percentage of the gray square covered by tree canopy."

Following the indoor presentation, each group was given a guided walk to the set of forested plots; plots were separated by about 3 minutes walking time and screened from each other by intervening forest. Trees on the plot had trunks circled with yellow loggers tape, to provide a visual cue separating the plots from surrounding forest. At each plot location, participants answered the same set of questions that had been given for the SVS images. Time on the plot was longer than in viewing the images, due to the logistics of moving a group on and off a small plot with trees. In addition, participants were free to move about the plot and view it from different angles, whereas a single viewpoint was presented in each SVS image. Although each group viewed images and visited plots in the same order, the arrangement of SVS images did not correspond with the order of plot visitation.

Visitor estimates were compared with modeled and observed plot descriptors. Although not used for comparison against visitor estimates, for additional information canopy cover for each plot was also estimated with the FVS program (table 1). The FVS canopy cover estimate uses the method described by Crookston and Stage (1999) and accounts both for overlap and for off-plot trees. Canopy cover was also taken with a GRS densitometer using a grid within each plot of 61 points spaced at 7 foot intervals. This field measurement included only canopy within plot boundaries, using only trees whose stems were on the plot, to correspond to the way participants were asked to estimate canopy cover. Other plot level attributes, such as quadratic mean diameter, were also estimated with the FVS program (table 1).

Table 1—Plot characteristics calculated with FVS (West-side Sierra Nevada variant).

Plot	Trees per acre	Basal area	Stand density index	Quadratic mean diameter	Average diameter	Diameter range	Canopy cover[a]	CWHR[b]
		ft²/acre		*inches*			*percent*	
1	60	258	314	28.1	26.7	13–36	53	5M
2	140	491	623	25.5	22.6	7–42	73	7M
3	80	218	290	22.4	21.3	12–32	50	5M
4	120	196	289	17.3	15.7	7–29	43	4M
5	180	219	342	14.9	13.6	6–24	54	6M
6	250	177	308	11.4	10.0	5–25	50	4M
7	320	185	334	10.3	9.1	5 –31	58	4M

[a]Calculated with overlap correction (Crookston and Stage 1999)
[b]CWHR class as calculated by FVS's California Spotted Owl WHR postprocessor (VanDyck 2001)

Results

Canopy Cover

For all seven plots, the average canopy estimate from participants for the 0.10 acre SVS image was lower than the densitometer estimate (table 2). The discrepancy varied from 14 to 29 percent, with an average difference of 21 percent across the seven plots. The densitometer should give a relatively unbiased estimate of canopy cover compared to most field instruments because it takes a single reading at a vertical angle rather than using oblique angles. However, 61 points per plot result in only moderate precision (table 2). The densitometer estimate gave canopy estimates higher than for the SVS graphical method, even though a densitometer point that hit sky was not considered canopy regardless of whether it fell within the limits of maximum crown width for the tree.

Mean estimates of canopy for the 0.10 acre images were lower than for the corresponding 0.50 acre images for three of the four plots; it should be expected that estimates for 0.10 acre images would be lower because the percentage of canopy that falls outside of plot boundaries is higher for small plots. The mycologist group, silviculture group, and the students had similar estimates for canopy cover (fig. 4); the average difference between group means of canopy cover was less than 3 percent for both SVS images and the actual plots.

The participants' mean field estimates of canopy cover were higher than their estimates from the 0.10 acre images for six of the seven plots. Small saplings on the plot that weren't included on the images, and overlapping canopy from surrounding forest, could contribute to this, although participants were asked to exclude these factors from their estimates in the field. The participants' estimates of canopy cover for the actual plots in the field appeared to be at least as variable as their estimates of canopy cover for the SVS images (table 2).

Table 2—Mean canopy cover estimates by visitors for images (0.10 acre plots and 0.50 plots) and field visits

Plot	Survey responses SVS 0.10 image (with st. dev.)		SVS 0.50 image (with st. dev.)		Field estimate (with st. dev.)		n	Densitometer (with 90% CI)		SVS 0.10 acre[c]
	Percent							*Percent*		
1	40	(8)	—[a]		46	(9)	45	64	(10)	54
2	46	(10)	71	(9)	71	(12)	45	64	(10)	55
3	29	(10)	41	(9)	36	(8)	44	44	(10)	41
4	28	(9)	40	(8)	42	(10)	44	56	(10)	34
5	46	(8)	—		41	(11)	31[b]	61	(10)	56
6	45	(11)	43	(9)	67	(16)	45	66	(10)	50
7	48	(7)	—		55	(15)	45	77	(9)	55

[a]Plots 1, 5 and 7 did not have a corresponding 0.50 acre image
[b]One group did not make a field visit to plot 5.
[c]Canopy cover from SVS image estimated with the graphical method without subplot

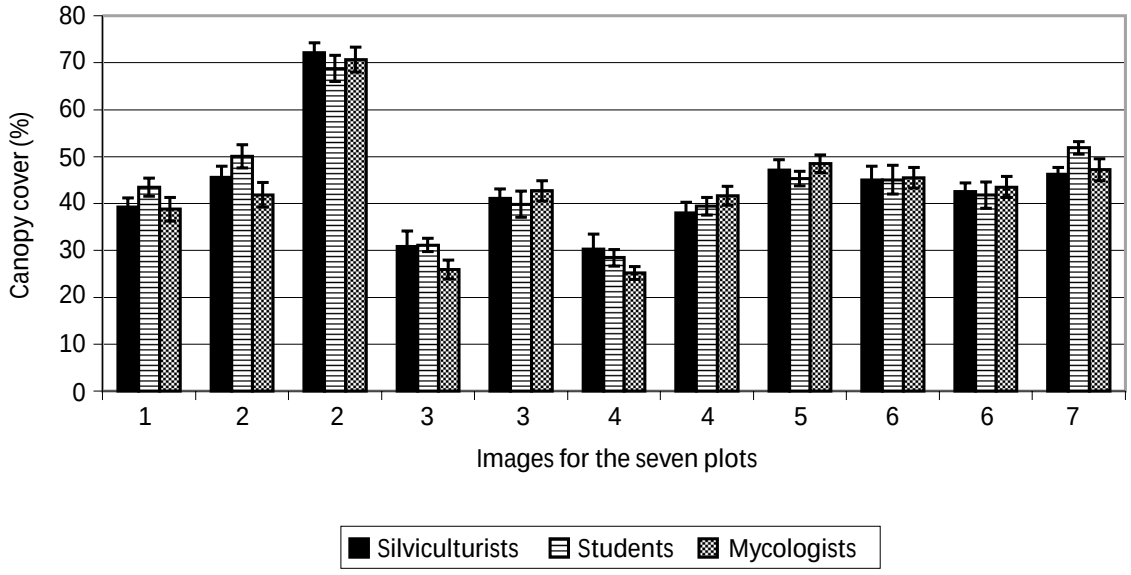

Figure 4—Means and standard deviations of canopy cover estimates for 11 SVS images by the three groups of visitors.

Plot 2 was used to create two 0.10 acre images, one with logs (fig. 2) and one without; these two images had different spatial placement of trees. All 45 participants estimated higher canopy cover for the version with logs; the mean of this difference was 26.3 percent. Estimates for the version with logs were much closer to the estimates made in the field, with a mean difference of less than 2 percent.

Because smaller image sizes have more canopy that falls outside the graphical plot boundaries (fig. 2 and 3) one would expect a greater correlation between canopy cover class responses for the actual plots and for the 0.50 acre images than between canopy cover class responses for the actual plots and for the 0.10 acre images. This was the case, with 53 percent of 180 responses matching for the 0.50 acre images and 36 percent of 300 responses matching for the 0.10 acre images.

The SVS program can compute the graphical cover for each image. Comparing this to participants' responses for canopy cover classes, the overall percentage of responses that were correct was 64 percent for the 0.10 acre images and 66 percent for the 0.50 acre images. For individual plots, this percentage varied from a low of 9 percent correct for the 0.10 acre image for plot 4 to a high of 93 percent correct for the 0.50 acre image of plot 2. For the 169 of 480 cover class responses that were incorrect, 92 percent assigned the image to a smaller-than-actual cover class, and 8 percent assigned the image to a larger-than-actual cover class.

Size Class

There were large differences between estimated tree size class for SVS images and in the field. For the 0.10 acre images, the percent of responses that were identical for the image and the real plot varied from 40 to 61 percent (table 3). For six of the seven plots, individuals classified the image as having smaller trees than the real plot. This tendency was even stronger for the 0.50 acre images; for one plot, 84 percent of individuals classified the real plot as having larger trees than the image (table 4).

Based on quadratic mean diameter (qmd), two of the plots would be in the large size class, three plots would be in the medium size class, and two plots would be in pole size class (table 1). Several of the plots had qmds or average diameters that were near the division point for size class. Of all field responses, 70 percent would have placed plots in categories the same as would the qmd method, ranging from 41 to 94 percent for the different plots. Of all responses for the SVS 0.10 acre images, 56 percent would have placed plots in the same category as the qmd method, ranging from 36 to 69 percent for the different plots.

As with canopy cover, there were differences in responses between the two SVS images with and without the inclusion of logs. While 51 percent of individuals placed the SVS 0.10 acre image for plot 2 in a smaller size category than they did for the real plot, only 22 percent placed the 0.10 acre image

Table 3—Participants' responses for size class of trees: 0.10 acre image compared to actual plot visit.

Plot	Agreement	Visitor image estimate larger than visitor field estimate	Visitor field estimate larger than visitor image estimate	n
		Percent		
1	61	7	32	44
2	47	2	51	45
3	53	9	58	45
4	58	7	36	45
5	52	3	45	31
6	40	2	58	45
7	47	36	18	45

Table 4—Participants' responses for size class of trees: 0.50 acre image compared to actual plot visit

Plot	Agreement	Visitor image estimate larger than visitor field estimate	Visitor field estimate larger than visitor image estimate	n
		Percent		
2	11	4	84	45
3	44	0	56	45
4	25	7	68	45
6	56	13	31	45

with logs in a smaller size class. The number of people placing the image in a larger size class than the real plot increased from 2 to 6 percent with the inclusion of logs. In addition to the inclusion of logs, the two images had differences in the spatial placement of trees, and this could also be a possible cause for differences in responses.

Structure: Even-Aged or Uneven-Aged

A total of 77 percent of responses showed identical classification of structure (even-aged or uneven aged) for the 0.10 acre image and the actual plot. The proportion varied somewhat by plot but was similar between the 0.10 acre images and the 0.50 acre images. The type of discrepancy – whether calling the image uneven-aged and the real plot even-aged, or calling the image even-aged and the real plot uneven-aged – varied by plot. For example, 42 percent of visitors called the SVS image shown in figure 3 even-aged but the real plot uneven-aged; and only 4 percent of visitors called the image uneven-aged and the real plot even-aged. In contrast, 11 percent of visitors called the SVS image shown in figure 1 even-aged but the real plot uneven-aged; but 33 percent of visitors called the image uneven-aged and the real plot even-aged.

Adding logs to the 0.10 image of plot 2 appeared to have no effect on the proportion of people who called the stand even-aged or uneven-aged.

Forest Age

Dominant trees in the forest surrounding Blodgett are generally around 80 to 120 years old. The percent of responses for whether the real plots were "old forest" ranged from 4 to 76 percent for the seven plots, perhaps indicating the variety of forest structure present. For these visitors, whether they answered identically for the real plot and the SVS image, appeared to vary by plot and image size (fig. 5). With the inclusion of logs in the 0.10 acre image for plot 2, the percent of people calling the plot (but not the image) old decreased from 22 to 4 percent, and the proportion of people calling the image (but not the plot) old increased from 9 to 18 percent.

The three groups differed in responses to the question about whether the plot was "old forest." Fewer silviculturists called plots old forest than students or mycologists (18 percent of all responses compared to 34 and 33 percent, respectively). Participants were also asked whether they considered themselves forestry professionals, and about half of the respondents answered yes. Fewer of those who responded affirmatively called real plots "old forest" (12 percent compared to 33 percent), and fewer called SVS images "old forest" (25 percent compared to 38 percent).

Complete Classification System

The California WHR classification system includes size class, canopy cover, and evenness of layering. When all three of the questions related to this classification system are included, for the plot with the greatest correspondence, only 32 percent of responses were identical for the 0.10 acre SVS images and the real plot. For the plot with the worst correspondence, only 4 percent of the responses were identical.

Discussion

Tree size class, evenness of structure, and canopy cover are common elements of many classification systems, just as they are of the California WHR system used in this study. Of these three elements, tree size class had the greatest discrepancy between participants' answers for the field visit and the SVS image.

Judging average diameter or qmd for a plot can be difficult, particularly for irregular or uneven size stands. Participants' field responses identical to an "average diameter" method of tree size classification were 69, 16, 51, 82, 94, 41, and 76 percent for the seven plots, respectively. Participants' field responses corresponding to CWHR tree size class metrics generated by the FVS postprocessor (VanDyck 2001) were 69, 84, 49, 82, 94, 59, and 13 percent for the seven plots,

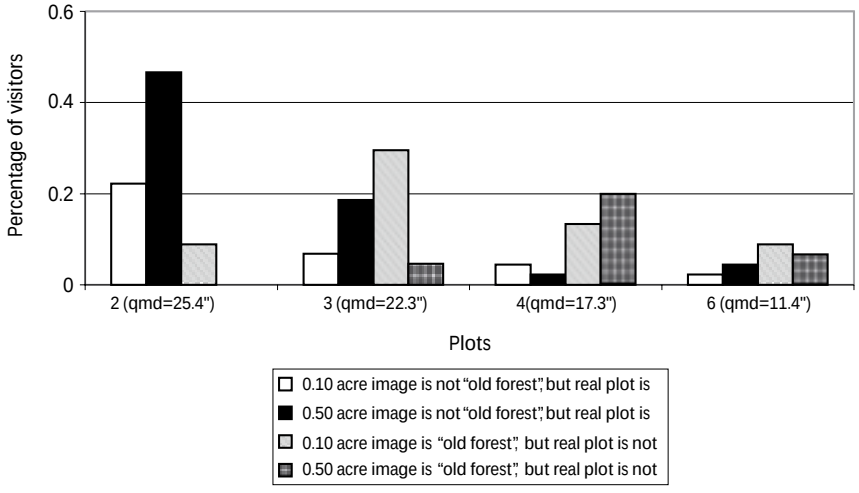

Figure 5—Discrepancies for responses for whether images and real plots were "old forest."

respectively. If real plots are difficult to classify "correctly," it is not surprising that there would be a variety of responses for size class of images, where tree trunks may be only a few pixels wide and where some trees may be hidden behind others. However, although the difficulties of estimating size class for both real plots and images might lead to a large amount of noncorrespondence, it would not explain systematic differences in classification. Overall, 45 percent of the 525 responses gave a smaller size class to the images than to the real plots, and only 8 percent gave a larger size class to the image.

This research was intended as a pilot study, to identify questions for further research and to estimate sample sizes needed to answer such questions. Because this was a noninferential case study, we cannot assume that misjudging the size class of trees in SVS images is a typical problem for other populations or other forests. But in some ways, these participants may have been better prepared to correctly interpret the size class of trees in SVS images than would be typical for many viewers. As forestry professionals, forestry students, or mycologists, the participants of this survey could be expected to be more familiar with trees than would be typical of the general public. In addition, the images contained a visual clue to tree size in the four corner posts, and the attention of the participants was directed to these posts both verbally and with written messages on each image.

It would be tempting to dismiss as an anomaly the one plot where more participants thought the tree size on the SVS image was larger than for the real plot. However, some characteristics of the structure on this plot may have led to this difference. This plot had a single large tree – 30 inches in diameter and 140 feet tall – and a fairly dense understory of smaller trees. In the SVS image, as can be seen in figure 1, this single large tree is quite noticeable. On the plot, however, the upper portion of this tree is obscured by the understory trees, and only the trunk is clearly visible. It is possible that the complexity of what influences people's classification of forest structure, both on the ground and in computer generated images, will make it difficult to draw simple generalizations about the relationship between the two.

The differences in estimation of canopy cover, size class, and age for the two 0.10 acre images of plot 2 – with and without the inclusion of logs – was a surprising but interesting result. A few of the other plots also had logs and branches on the forest floor, along with understory vegetation, or small trees that were not included in the SVS images. How the inclusion of these elements affects people's interpretation might prove a fruitful topic of further research. In addition, different spatial placement of trees in the images, the effect of distance and angle of view, and different choices for foliage or branches were not tested in this project, but could affect interpretation. Given the increasing use of computerized visualization tools, further research in this area would be helpful.

The general question facing SVS users may be "How well do observers interpret the images?" This research only addresses a narrow aspect of this question, by looking at the similarity of classifications of forest structure for images and real plots. There are a number of other important questions that researchers might consider for future work: Do images effectively communicate the results of silvicultural treatments? Can images be used to illustrate the dynamic nature of forest structure? Do they help individuals have a greater understanding of the variation among forest types?

Many of the visualization programs being developed for forestry are data-driven; in other words, the sizes of images of trees are determined through actual forest inventory measurements. It is important for managers and researchers to communicate to the public that this data-based aspect of visualization programs does not guarantee similarity between the images and the actual forest. Managers who are using computer visualization programs to illustrate the type of structures that were, are, or will be on their forests may wish to make sure that they consider this question: Is your audience interpreting the information in the image as you intended?

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Validation of the Forest Vegetation Simulator Growth and Mortality Predictions on Red Pine in Michigan

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Abstract—Validating a model's performance is an essential part of model development and revision. Previously, the only subregional validation of LS-TWIGS and FVS-LS was done on hardwood stands on 5- and 10-year growth. This paper examines validation results for red pine in Michigan. Red pine covers a large percentage of Michigan timberlands and is considered one of its most important commercial softwood species. Validation was run on two red pine sites in Michigan. In simulations that included calibration (scaling), FVS-LS almost always predicted d.b.h. within ±1 inch for projections up to 27 years long. FVS-LS predicted mortality and density better for the Upper Peninsula site than the Lower Peninsula site.

The red pine timber industry is an important part of the Michigan economy. In 1992 red pine production was valued at $25.3 million (Potter-Witter 1995). Red pine covers 897,200 acres of Michigan timberland, 641,200 acres in the Lower Peninsula, and 256,000 acres in the Upper Peninsula (Leatherberry and Spencer 1996). Average net annual growth (1980 through 1987) was 78,310,000 ft^3 and removals were 15,980,000 ft^3 (Leatherberry and Spencer 1996).

Given the importance of red pine in the Lake States it is important that landowners have a model that correctly predicts growth to compare alternative treatments. The Lake States TWIGS variant of the Forest Vegetation Simulator (FVS-LS) (Bush and Brand 1995) uses the growth and mortality functions based on Lake States TWIGS. One important difference is that Lake States TWIGS uses annual increments, while FVS-LS calculates 10-year growth by multiplying the annual increment by 10 and then scaling back if the growth period is less than 10 years. FVS-LS is an individual tree distance independent model. This paper will explore FVS-LS prediction of individual tree and stand level attributes on two long-term red pine study sites in Michigan.

The only subregional validation of Lake State TWIGS for Michigan involves upland hardwoods in the northern Lower Peninsula (Guertin and Ramm 1996). It found 5-year diameter growth was predicted within ± 0.3 inch for the five species studied. Mean errors for basal area projections were within ± 5 ft^2/acre for all species and mean error for trees per acre (TPA) was within ± 20 TPA for almost all species studied. A followup study 5 years later on FVS-LS found that 10-year diameter growth was predicted within ± 0.5 inch for all of the seven hardwood species (Canavan 1997). This study is the first to validate red pine projections for Michigan.

Data

The validation data were collected from two long-term study sites in Michigan, one on the Hiawatha National Forest and one on the W. K. Kellogg Experimental Forest. The Hiawatha National Forest is on the eastern side of the Upper Peninsula. The Kellogg Experiment Forest, on the Lower Peninsula in southwestern Michigan, is owned and managed by Michigan State University's Department of Forestry.

The Hiawatha site was planted in 1938 with approximately 6 by 6 foot spacing. In 1962 it became a thinning study set up as a randomized complete block design with four blocks. Each block contained 16 treatments, with each treatment being 0.10 acre (table 1). This study examined 12 of the treatments. Measurements were taken in 1962, 1965, 1969, 1976, 1982, and 1992 and thinned in 1962, 1969, 1976, 1982, and 1992, except for a few plots in which basal areas were too low to thin in 1982 and 1992.

The Kellogg study site was planted in 1936 and 1937 with approximately spacing of 7 by 8 feet. In 1960 it became a thinning study with nine thinning treatments applied in a randomized complete block design with four replications of each treatment (table 2). These treatments

Table 1—Hiawatha National Forest thinning treatment.

Treatment	Description
BAr30	30 ft^2/acre residual BA after thinning
BAr45	45 ft^2/acre residual BA after thinning
BAr60	60 ft^2/acre residual BA after thinning
BAr80	80 ft^2/acre residual BA after thinning
BAr100	100 ft^2/acre residual BA after thinning
BAr130	130 ft^2/acre residual BA after thinning
BAr160	160 ft^2/acre residual BA after thinning
Row2	Every other row removed
Row3	Every third row removed
Row4,2	Every fourth row removed; at second thinning remove center row of remaining 3 rows
Row4	Every fourth row removed
Control	Control - no thinning

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Table 2—W.K. Kellogg Forest thinning treatments.

Treatment	Description
Row2	Cut every 2nd row, BA 85
Row3	Cut every 3rd row, BA 100,105
Row4	Cut every 4th row, BA 115, 120
Row4,2	Cut every 4th row, middle row, BA 110
BAr90	90-95 ft^2/acre residual BA after thinning
BAr70	70-75 ft^2/acre residual BA after thinning
BAr110	110-115 ft^2/acre residual BA after thinning
BAr130	130-135 ft^2/acre residual BA after thinning
Control	Control – no thinning

were also 0.10 acre each. Measurement and thinning occurred in 1960, 1964, 1967, 1972, 1980, 1985, and 1991.

For both study sites diameter at breast height (d.b.h) of each tree was measured, and height was measured on three to five trees in each plot. Basal area and trees per acre were calculated for each plot.

Methods

Two types of simulations were run for each treatment. One with FVS calibration turned off, abbreviated 'NA' for no ancillary data, meaning that past diameter growth data were not used to scale the growth equations. The other type of simulation included FVS calibration, abbreviated 'D'. All runs included plot name, age, site index (base age 50 years), d.b.h. (1965, Hiawatha; 1964, Kellogg), height if measured, and the year the tree was thinned. The ΔD simulations also included diameter growth, which was calculated from the diameter from the simulation start date and subtracting the previous diameter measurement. The Hiawatha growth measurements were from age 25 to 28, and Kellogg growth measurements were from age 27 to 31. Hiawatha had a 3-year growth measurement and Kellogg a 4-year growth measurement period that FVS used to scale or calibrate the growth equations to more closely match the growth that was occurring in the plantation at that time. Three growth and stand-level characteristics were used to calculate prediction error by treatment and projection length. The three characteristics used were individual tree d.b.h., stand basal area, and trees per acre. Each tree's projected future d.b.h. was compared to its actual d.b.h. Also, each stand's projected basal area and trees per acre were compared to its actual basal area and trees per acre. Mean error and standard deviation were then calculated from the difference between actual and predicted measurements. In the FVS tree list, all trees were coded with the species code "RP" indicating red pine plantation trees.

Results

The Hiawatha simulations projected growth from 1965 through 1992, with cycle boundaries at 1969, 1976, 1982, and 1992. The Kellogg simulations projected growth from 1964 through 1991, with cycle boundaries at 1967, 1972, 1980, 1985, and 1991.

D.B.H. Error

The sample size for each d.b.h. error calculation was dependent on the treatment and cycle. Treatments with heavy thinning had smaller sample sizes. Sample size also decreased over time as trees were thinned during each cycle (tables 3 and 4).

Hiawatha—FVS-LS on average predicted diameter growth with better accuracy for the ΔD simulations than for the NA simulations (table 3). For both types of simulations FVS-LS overpredicted diameter growth, except in treatments with low residual basal area. Both simulation types showed low mean errors (less than 1 inch) in almost all of the treatments. Those treatments that did have an error over 1 inch were all in the 27-year projection period and tended to be in treatments with larger residual basal areas. No treatment had an error greater than 1.78 inches in d.b.h. In almost all the runs, as the length of the projection increased so did the error.

Kellogg—Unlike the Hiawatha results, FVS did not necessarily predict diameter growth with better accuracy for the ΔD simulations than for the NA simulations (table 4). FVS-LS overpredicted growth for all trees in the NA projections except for the thin every fourth row treatment (row 4) where growth was underpredicted. In both runs as projection length increased so did the error. The NA and ΔD simulations with projections lengths of 3 and 8 years all had a d.b.h. mean error of less than 1 inch. Almost all of the ΔD simulations had an error of less than 1 inch, except for the longer projection lengths in the control, thin every fourth row, and 70 ft^2/acre thinnings. Only treatments thin every second row and thin to a basal area of 90 ft^2/acre of the NA simulation had error of more than 2 inches. These errors occurred in the 27-year interval.

Basal Area Error

Mean error and standard deviation were calculated for the four plots for each treatment and projection length.

Hiawatha—ΔD simulations projections were more precise than the NA simulations. The absolute mean error was two to three times as great is the NA as in the ΔD simulations. As with the d.b.h. mean error projections, the ΔD simulations were more likely to underpredict in treatments with low residual basal areas, and tended to overpredict in treatments with high residual basal areas (table 5).

Kellogg—Unlike with the Hiawatha results, in most cases the NA simulations projected more precisely than the ΔD simulations. The ΔD projections were more likely to underpredict basal area, while the only NA projection that underpredicted was the thin every fourth row treatment. The difference in the absolute mean error between the two simulation types was not as large as that in the Hiawatha simulations (table 6).

Trees Per Acre Error

As with the basal area calculations of mean error, the TPA mean error is based on a sample size of four for each treatment.

Table 3—Hiawatha mean error ($\bar{e}$) and standard deviation (s) of mean error for estimated diameter at breast height by treatment and projection length for the two types of simulation. Error expressed as predicted value minus observed value.

				NA simulation		ΔD simulation	
Treatment	**Projection length**	**Age**	**n**	$\bar{e}$	**s**	$\bar{e}$	**s**
BAr30	65-69 = 4yrs	32	59	–0.52	0.23	–0.47	0.27
	65-76 = 11yrs	39	30	–0.77	0.30	–0.78	0.51
	65-82 = 17yrs	45	21	–0.99	0.45	–0.97	0.74
	65-92 = 27yrs	55	21	–0.59	0.62	–0.58	1.02
BAr45	65-69 = 4yrs	32	85	–0.28	0.25	–0.44	0.73
	65-76 = 11yrs	39	46	–0.48	0.50	–0.37	0.49
	65-82 = 17yrs	45	29	–0.91	0.62	–0.80	0.61
	65-92 = 27yrs	55	29	–0.26	2.59	–0.11	2.56
BAr60	65-69 = 4yrs	32	121	–0.05	0.57	–0.04	0.56
	65-76 = 11yrs	39	71	–0.26	0.97	–0.29	0.96
	65-82 = 17yrs	45	47	–0.54	1.40	–0.60	1.42
	65-92 = 27yrs	55	47	–0.30	1.72	–0.41	1.76
BAr80	65-69 = 4yrs	32	173	0.13	0.22	0.05	0.21
	65-76 = 11yrs	39	110	0.07	0.40	–0.15	0.36
	65-82 = 17yrs	45	73	–0.26	0.47	–0.56	0.45
	65-92 = 27yrs	55	58	–0.24	0.63	–0.65	0.59
BAr100	65-69 = 4yrs	32	220	0.19	0.17	0.12	0.17
	65-76 = 11yrs	39	146	0.28	0.31	0.08	0.34
	65-82 = 17yrs	45	105	0.33	0.77	0.04	0.82
	65-92 = 27yrs	55	84	0.62	1.51	0.22	1.55
BAr130	65-69 = 4yrs	32	302	0.29	0.38	0.17	0.38
	65-76 = 11yrs	39	218	0.51	0.58	0.18	0.58
	65-82 = 17yrs	45	162	0.53	0.97	0.08	0.98
	65-92 = 27yrs	55	130	0.68	1.25	0.08	1.27
BAr160	65-69 = 4yrs	32	395	0.38	0.54	0.20	0.54
	65-76 = 11yrs	39	305	0.73	0.71	0.31	0.72
	65-82 = 17yrs	45	241	0.89	1.00	0.32	1.03
	65-92 = 27yrs	55	200	1.27	1.37	0.53	1.41
Row2nd	65-69 = 4yrs	32	231	0.19	0.29	0.08	0.29
	65-76 = 11yrs	39	138	0.26	0.53	–0.03	0.53
	65-82 = 17yrs	45	96	0.21	0.73	–0.19	0.73
	65-92 = 27yrs	55	79	0.56	1.54	0.00	1.53
Row3rd	65-69 = 4yrs	32	332	0.31	0.23	0.13	0.23
	65-76 = 11yrs	39	212	0.56	0.47	0.10	0.49
	65-82 = 17yrs	45	158	0.61	0.67	–0.03	0.72
	65-92 = 27yrs	55	129	1.16	2.12	0.32	2.13
Row4,2	65-69 = 4yrs	32	331	0.36	0.46	0.19	0.45
	65-76 = 11yrs	39	224	0.71	1.09	0.28	1.10
	65-82 = 17yrs	45	159	0.97	1.75	0.36	1.80
	65-92 = 27yrs	55	129	1.55	2.60	0.73	2.69
Row4th	65-69 = 4yrs	32	366	0.35	0.40	0.16	0.41
	65-76 = 11yrs	39	218	0.69	0.82	0.17	0.87
	65-82 = 17yrs	45	161	0.71	1.15	0.00	1.23
	65-92 = 27yrs	55	118	1.06	1.92	0.10	2.03
Control (no thin)	65-69 = 4yrs	32	470	0.36	0.33	0.18	0.34
	65-76 = 11yrs	39	470	0.76	0.49	0.38	0.52
	65-82 = 17yrs	45	470	0.95	0.77	0.54	0.81
	65-92 = 27yrs	55	470	1.78	2.25	1.51	2.26

Table 4—Kellogg mean error ($\bar{e}$) and standard deviation (s) of mean error for estimated diameter at breast height by treatment and projection length for the two types of simulation. Error expressed as predicted value minus observed value.

				NA simulation		ΔD simulation	
Treatment	**Projection length**	**Age**	**n**	$\bar{e}$	**s**	$\bar{e}$	**s**
BAr70	64-67 = 3yrs	31	150	0.16	0.76	-0.35	0.77
	64-72 = 8yrs	36	150	0.31	1.64	–0.52	1.87
	64-80 = 16yrs	44	77	1.01	3.18	–1.29	3.31
	64-85 = 21yrs	49	69	1.13	3.68	–1.15	3.48
	64-91 = 27yrs	55	69	1.63	4.20	–1.67	4.39
BAr90	64-67 = 3yrs	31	168	0.21	1.46	0.00	1.48
	64-72 = 8yrs	36	115	0.94	2.98	0.41	2.72
	64-80 = 16yrs	44	91	1.77	3.86	0.85	3.92
	64-85 = 21yrs	49	83	1.92	4.40	0.84	4.48
	64-91 = 27yrs	55	83	2.17	4.68	0.97	4.77
BAr110	64-67 = 3yrs	31	205	0.08	1.01	–0.10	1.02
	64-72 = 8yrs	36	135	0.26	1.68	–0.23	1.71
	64-80 = 16yrs	44	104	1.23	3.45	0.36	3.49
	64-85 = 21yrs	49	93	1.59	4.19	0.59	4.24
	64-91 = 27yrs	55	93	1.98	4.56	0.85	4.61
BAr130	64-67 = 3yrs	31	255	0.18	1.14	0.01	1.14
	64-72 = 8yrs	36	184	0.61	2.10	0.18	2.09
	64-80 = 16yrs	44	147	1.61	3.54	0.85	3.53
	64-85 = 21yrs	49	131	1.81	4.05	0.92	4.06
	64-91 = 27yrs	55	131	1.94	4.32	0.96	4.34
Row2nd	64-67 = 3yrs	31	159	0.18	1.35	–0.08	1.35
	64-72 = 8yrs	36	159	0.70	2.34	0.23	2.35
	64-80 = 16yrs	44	106	1.38	3.55	0.27	3.72
	64-85 = 21yrs	49	85	1.64	4.37	0.35	4.48
	64-91 = 27yrs	55	85	2.08	4.62	0.63	4.87
Row3rd	64-67 = 3yrs	31	194	0.02	0.64	–0.25	0.64
	64-72 = 8yrs	36	122	0.07	0.97	–0.65	0.97
	64-80 = 16yrs	44	98	0.83	2.85	–0.47	2.90
	64-85 = 21yrs	49	81	1.34	4.02	–0.22	4.05
	64-91 = 27yrs	55	81	1.49	4.30	–0.30	4.34
Row4,2	64-67 = 3yrs	31	250	0.06	0.69	–0.18	0.69
	64-72 = 8yrs	36	171	0.62	1.93	0.03	1.94
	64-80 = 16yrs	44	123	1.09	3.02	0.00	3.09
	64-85 = 21yrs	49	109	1.22	3.51	–0.07	3.61
	64-91 = 27yrs	55	109	1.40	4.12	–0.04	3.86
Row4th	64-67 = 3yrs	31	232	–0.10	0.27	–0.21	0.19
	64-72 = 8yrs	36	158	–0.18	0.74	–0.47	0.56
	64-80 = 16yrs	44	110	–0.42	1.21	–0.97	0.74
	64-85 = 21yrs	49	86	–0.75	1.45	–1.39	0.73
	64-91 = 27yrs	55	86	–0.53	2.27	–1.23	1.72
Control (no thin)	64-67 = 3yrs	31	293	0.18	0.69	–0.06	0.70
	64-72 = 8yrs	36	293	0.45	0.80	–0.10	0.82
	64-80 = 16yrs	44	293	1.09	1.57	0.25	1.64
	64-85 = 21yrs	49	293	1.51	2.19	0.60	2.27
	64-91 = 27yrs	55	293	1.96	2.76	1.04	2.83

Table 5—Hiawatha mean error ($\bar{e}$) and standard deviation (s) of mean error for estimated trees per acre and basal area by treatment and projection length for two types of simulation. Error expressed as predicted value minus observed value.

			BA NA		BA ΔD		TPA NA		TPA ΔD	
Treatment	**Projection length**	**Age**	$\bar{e}$	**s**	$\bar{e}$	**s**	$\bar{e}$	**s**	$\bar{e}$	**s**
BAr30	65-69 = 4yrs	32	–7.06	2.44	–6.46	3.19	–0.18	0.02	–0.18	0.02
	65-76 = 11yrs	39	–6.75	1.92	–6.69	4.51	–0.25	0.02	–0.25	0.02
	65-82 = 17yrs	45	–7.20	1.76	–6.97	4.52	–0.27	0.03	–0.27	0.03
	65-92 = 27yrs	55	–5.48	3.38	–5.22	8.14	–0.43	0.04	–0.43	0.04
BAr45	65-69 = 4yrs	32	–5.32	1.71	–4.02	1.14	–0.26	0.04	–0.26	0.05
	65-76 = 11yrs	39	–6.32	1.73	–5.03	0.62	–0.38	0.06	–0.38	0.06
	65-82 = 17yrs	45	–9.17	2.83	–8.12	1.57	–0.37	0.05	–0.37	0.05
	65-92 = 27yrs	55	–6.50	5.90	–4.85	4.48	1.91	4.96	1.91	4.96
BAr60	65-69 = 4yrs	32	–2.25	2.62	–2.05	1.65	2.14	4.97	2.14	4.97
	65-76 = 11yrs	39	–6.38	4.92	–6.91	4.12	1.91	4.93	1.91	4.93
	65-82 = 17yrs	45	–10.01	3.83	–10.83	5.23	1.90	4.92	1.90	4.92
	65-92 = 27yrs	55	–8.57	7.15	–10.32	10.21	1.55	4.88	1.55	4.88
BAr80	65-69 = 4yrs	32	4.45	2.25	1.96	0.71	–0.52	0.02	–0.52	0.02
	65-76 = 11yrs	39	1.22	5.18	–4.38	1.29	–0.91	0.04	–0.91	0.04
	65-82 = 17yrs	45	–5.87	3.55	–11.87	1.40	–0.93	0.03	–0.93	0.03
	65-92 = 27yrs	55	–5.68	5.29	–13.36	2.29	–1.17	0.05	–1.18	0.05
BAr100	65-69 = 4yrs	32	7.01	3.98	3.09	1.56	–0.66	0.08	–1.10	0.85
	65-76 = 11yrs	39	8.92	4.51	2.46	6.43	–1.21	0.14	–1.22	0.16
	65-82 = 17yrs	45	6.94	3.81	–2.11	7.99	1.16	4.94	1.14	4.92
	65-92 = 27yrs	55	11.63	7.34	1.75	14.33	3.30	5.68	3.28	5.66
BAr130	65-69 = 4yrs	32	14.33	2.06	7.55	1.66	–0.94	0.06	–1.05	0.12
	65-76 = 11yrs	39	21.75	4.71	6.67	2.42	0.66	4.98	0.53	4.95
	65-82 = 17yrs	45	17.55	4.07	–0.05	3.63	2.90	5.79	2.80	5.81
	65-92 = 27yrs	55	20.09	4.79	–1.74	7.34	2.33	5.82	2.22	5.83
BAr160	65-69 = 4yrs	32	22.74	4.87	10.83	3.55	8.66	19.89	7.86	19.74
	65-76 = 11yrs	39	40.34	5.60	14.23	9.06	7.28	19.84	6.26	19.70
	65-82 = 17yrs	45	41.40	10.75	10.65	15.08	9.17	24.81	8.16	24.68
	65-92 = 27yrs	55	53.92	18.01	16.45	22.81	10.62	23.40	9.63	23.05
Row2nd	65-69 = 4yrs	32	6.70	1.36	2.08	0.87	1.67	4.90	1.58	4.84
	65-76 = 11yrs	39	6.80	6.07	–2.15	5.18	1.34	4.97	1.31	4.94
	65-82 = 17yrs	45	3.64	9.68	–6.47	8.45	1.23	4.93	1.20	4.89
	65-92 = 27yrs	55	9.25	13.25	–4.45	10.91	3.33	5.58	3.30	5.54
Row3rd	65-69 = 4yrs	32	15.91	2.03	5.93	1.01	1.14	4.76	0.52	4.43
	65-76 = 11yrs	39	21.86	4.09	1.37	1.47	7.61	7.62	6.97	7.18
	65-82 = 17yrs	45	18.78	5.80	–5.12	3.22	6.92	7.27	6.15	6.72
	65-92 = 27yrs	55	28.68	15.58	–1.19	11.69	18.17	15.14	17.23	15.31
Row4,2	65-69 = 4yrs	32	17.58	3.03	7.59	2.28	8.66	19.84	7.99	19.55
	65-76 = 11yrs	39	24.27	1.25	4.92	2.75	17.65	17.88	16.68	17.60
	65-82 = 17yrs	45	19.98	5.89	–1.23	6.59	28.08	34.29	31.14	30.62
	65-92 = 27yrs	55	30.73	9.90	1.55	12.46	44.24	37.51	43.47	36.87
Row4th	65-69 = 4yrs	32	19.18	2.32	6.90	2.55	6.04	9.56	4.91	9.39
	65-76 = 11yrs	39	24.73	3.79	1.46	6.08	17.86	11.42	17.08	11.49
	65-82 = 17yrs	45	18.32	5.32	–8.47	6.46	19.90	14.78	19.02	14.87
	65-92 = 27yrs	55	20.64	3.44	–10.62	8.82	24.25	16.49	23.26	16.39
Control (no thin)	65-69 = 4yrs	32	25.44	0.58	11.15	5.11	7.77	14.36	5.25	14.97
	65-76 = 11yrs	39	57.49	1.85	23.65	9.55	10.16	22.68	2.75	25.55
	65-82 = 17yrs	45	69.89	2.38	30.33	12.50	24.20	28.10	14.00	29.35
	65-92 = 27yrs	55	89.13	9.46	65.13	18.05	177.55	51.76	179.50	63.05

Table 6—Kellogg mean error ($\bar{e}$) and standard deviation (s) of mean error for estimated trees per acre and basal area by treatment and projection length for two types of simulation. Error expressed as predicted value minus observed value.

			BA NA		BA ΔD		TPA NA		TPA ΔD	
Treatment	Projection length	Age	$\bar{e}$	s	$\bar{e}$	s	$\bar{e}$	s	$\bar{e}$	s
BAr70	64-67 = 3yrs	31	0.70	6.04	–5.45	9.29	14.59	22.38	14.31	22.93
	64-72 = 8yrs	36	4.49	6.04	–8.06	9.29	21.64	22.38	21.04	22.93
	64-80 = 16yrs	44	7.47	6.00	–12.88	10.40	21.49	18.90	21.33	18.99
	64-85 = 21yrs	49	6.73	6.91	–16.82	11.25	23.79	19.09	23.60	19.17
	64-91 = 27yrs	55	14.85	11.35	–13.76	15.34	25.92	23.58	25.68	23.68
BAr90	64-67 = 3yrs	31	1.95	13.88	–5.11	13.95	14.54	33.12	14.29	33.23
	64-72 = 8yrs	36	10.29	13.88	–3.93	13.95	36.64	33.12	36.39	33.23
	64-80 = 16yrs	44	18.24	21.85	–4.95	20.09	46.03	44.37	45.64	44.58
	64-85 = 21yrs	49	16.37	22.02	–9.99	20.38	45.67	44.44	45.22	44.67
	64-91 = 27yrs	55	21.76	20.77	–9.84	19.26	45.11	44.51	44.60	44.76
.										
BAr110	64-67 = 3yrs	31	–1.64	9.32	–9.39	9.52	14.44	23.65	14.14	23.77
	64-72 = 8yrs	36	0.54	9.32	–14.59	9.52	16.51	23.65	16.09	23.77
	64-80 = 16yrs	44	12.21	25.25	–12.06	23.58	41.12	43.78	40.47	43.73
	64-85 = 21yrs	49	13.94	30.61	–13.20	26.91	45.59	48.59	44.98	48.25
	64-91 = 27yrs	55	22.03	35.32	–10.39	31.29	47.46	51.33	46.75	50.88
BAr130	64-67 = 3yrs	31	3.14	19.88	–5.20	15.85	16.73	40.22	16.20	39.99
	64-72 = 8yrs	36	11.13	19.88	–6.26	15.85	33.72	40.22	33.18	39.99
	64-80 = 16yrs	44	27.11	38.89	–0.86	32.35	65.65	62.44	65.21	62.25
	64-85 = 21yrs	49	25.00	42.41	–6.27	33.62	67.79	64.00	67.28	63.72
	64-91 = 27yrs	55	71.86	122.48	35.42	116.64	99.33	118.96	98.72	118.77
Row2nd	64-67 = 3yrs	31	0.81	22.97	–6.81	24.12	14.63	62.45	14.53	62.58
	64-72 = 8yrs	36	9.47	22.97	–5.67	24.12	36.76	62.45	36.51	62.58
	64-80 = 16yrs	44	16.02	35.61	–13.83	31.92	41.22	71.95	41.05	71.88
	64-85 = 21yrs	49	13.37	37.69	–16.82	31.93	41.15	71.77	41.00	71.65
	64-91 = 27yrs	55	22.24	44.20	–14.57	38.96	43.25	76.55	43.06	76.39
Row3rd	64-67 = 3yrs	31	–0.57	5.28	–8.67	4.73	2.00	5.11	1.72	5.30
	64-72 = 8yrs	36	0.10	5.28	–15.17	4.73	1.65	5.11	1.34	5.30
	64-80 = 16yrs	44	9.77	12.20	–15.83	13.21	21.06	32.54	20.62	32.09
	64-85 = 21yrs	49	12.49	17.68	–14.71	20.56	28.37	37.59	27.96	37.06
	64-91 = 27yrs	55	15.41	18.63	–17.87	23.59	27.87	37.33	27.41	36.73
Row4,2	64-67 = 3yrs	31	1.23	12.66	–9.57	11.35	1.68	49.73	0.79	48.74
	64-72 = 8yrs	36	10.00	12.66	–10.78	11.35	33.36	49.73	31.88	48.74
	64-80 = 16yrs	44	10.91	18.50	–21.93	15.38	47.30	47.66	45.56	46.12
	64-85 = 21yrs	49	8.45	18.75	–28.76	15.73	49.20	51.86	47.47	50.47
	64-91 = 27yrs	55	12.66	20.42	–32.41	17.42	48.17	51.12	46.25	49.65
Row4th	64-67 = 3yrs	31	–5.12	19.59	–9.87	4.44	–2.39	4.43	–1.61	2.47
	64-72 = 8yrs	36	–7.49	19.59	–17.45	4.44	–4.05	4.43	–2.92	2.47
	64-80 = 16yrs	44	–13.12	30.82	–28.77	6.74	–2.72	2.70	–1.64	0.22
	64-85 = 21yrs	49	–19.19	33.07	–35.04	5.99	–2.04	1.25	–1.51	0.20
	64-91 = 27yrs	55	–16.36	40.27	–35.04	8.06	–0.01	5.73	0.58	5.11
Control	64-67 = 3yrs	31	6.79	3.73	–6.22	1.94	9.14	9.09	7.43	8.36
(no thin)	64-72 = 8yrs	36	21.12	3.73	–11.68	1.94	10.01	9.09	5.40	8.36
	64-80 = 16yrs	44	48.39	9.64	–7.80	5.51	54.26	24.50	45.45	22.54
	64-85 = 21yrs	49	60.88	16.26	–2.45	11.17	93.61	46.19	82.89	43.23
	64-91 = 27yrs	55	72.89	13.61	6.56	9.13	133.44	15.76	121.49	14.45

Hiawatha—The FVS simulations had a mean error of ± 10 TPA for almost all treatments accept for the high residual basal area treatments. The worst prediction accuracy for FVS was the control treatment (no thinning). The control treatment, with a 27-year prediction interval, overpredicted by more than 175 trees per acre. There was little difference between the accuracy of the NA and ΔD simulations (table 5).

Kellogg—The two simulations showed little difference in mortality prediction. NA and ΔD simulations showed an increase in error as the projection intervals increased.

Treatments with higher residual basal areas, which often had more mortality, showed the greatest error in the prediction of mortality. The worst prediction accuracy for FVS was the control treatment (no thinning). The control treatment with a 27-year prediction interval overpredicted by more than 130 trees per acre (table 6).

Discussion

Prediction was more accurate for the Hiawatha site than the Kellogg site. This is probably because the original equations were developed from plantations in the northern portions of the Lake States (Miner and others 1988).

These validation runs used version 6.2 of the FVS-LS variant with a revision date of 12/01/95. FVS variants are continuously being updated and improved. These same data runs through a current version of the model would yield different results. There are many ways users can make adjustments in an FVS simulation to produce more realistic results. One example of this involves using serial correlation of diameter growth. This feature improves estimates from cycle to cycle by assuming that the error terms from a previous cycle are correlated with error terms of the next cycle. In other words, the error term is not randomly distributed at each cycle. So that trees that were growing well previously continue to grow well, and those that are not growing well continue to grow poorly (Dixon 2002). This feature improves the overall distribution of diameter growth in a stand. This feature was turned off by default in the version used for this validation project. It could have been turned on by the use of a keyword; however, it was not. This feature is now on by default in a more current version of the program.

Overall, the d.b.h. mean errors were better predicted for runs that used past growth (ΔD) information to scale the equations than those that did not (NA). The d.b.h. mean error for the ΔD simulations were on average ± 1 inch. However, for the Kellogg site, prediction of density (BA) and d.b.h. did not show much if any advantage to using the past growth information to scale the equations. The scale factors for Kellogg ranged from 0.42 to 0.75 with a mean of 0.56. The Hiawatha scale factors ranged from 0.47 to 1.163 with a mean of 0.78. On average, these were biased low. This is due to the methodology of how the diameter growth equations were applied. The first thinning occurred (1962, Hiawatha; 1960, Kellogg) at the start of the growth measurement period. If there was any release delay of the trees (after the thinning) then FVS would not have captured the impact of the thinning in the growth measurement period. The scale factor applied to the thinned stand may have scaled down growth too much for the thinned stand. A longer measurement period may have given more accurate results. However, for the Hiawatha site the calibrated runs did improve the accuracy of the predicted d.b.h. of trees and the density. A second reason that the scale factors were biased low was because mortality trees were recorded as "dead" trees in the input tree list instead of "recent mortality" trees. If the trees had been recorded as recent mortality trees, then FVS would have included them in the stand density calculations that then would have effected how the scale factors were calculated. It is important that users realize the impact that the scale factor has on future tree simulated growth. The problem with the measurement periods in these simulations was that they were too short and reflected the prethinned growth, therefore scaling down (slowing) the original growth equations. In addition trees were marked as "dead" instead of "recently dead," making FVS incorrectly predict past density. A third problem is that the repeated growth measurements were not adjusted for bark. Because diameter increments included bark growth, this added another bias to the results.

Mean error for trees per acre were similar between the scaled and nonscaled simulations for both sites. It was expected that FVS would overpredict mortality, because of typically lower mortality in red pine plantations. However, it actually underpredicted. The inventory history indicates that some trees died by snow or ice storms, but no description was given for other trees. However, from the previous inventory, most trees seemed to put on good growth prior to the cycle that death occurred. From this it is assumed that many of the trees died from stochastic events such as wind, ice, snow, insect, or disease. This suggests that when running simulations, in order to get reasonable estimates of mortality, it is imperative to include stochastic mortality events that are typical for the region and species modeled.

For the typical user of FVS who may not have a complete understanding of the system, it is important to realize that many adjustments can be made to FVS to produce more accurate runs. FVS is a complicated growth and yield program. The more the user understands the capabilities of FVS, and the process it uses to compute growth, the better estimates the user will obtain. At the beginning of the research, one of this study's authors was a novice FVS user and found that even without making many adjustments to improve estimates of growth, FVS-LS did perform well in the prediction of individual tree diameters, stand density, and mortality in most cases.

Acknowledgments

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Calibrating FVS for the Chattahoochee-Oconee National Forest Planning Effort

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Abstract—The Forest Vegetation Simulator (FVS) is being used to create yield tables for the Chattahoochee-Oconee National Forest plan revision. The FVS Southern variant was calibrated and adjusted to produce reliable yield tables for this region. The large-tree diameter increment model was calibrated using the self-calibration feature of FVS and through FVS-computed mean correction scale factors. Volume estimates were adjusted to the merchantability specifications and defect estimates for the region. Adjustments to the mortality and regeneration models were not done, but may be needed after further analyses are conducted. This paper reports the steps taken to calibrate the large-tree diameter increment model and adjust the volume specifications for the Chattahoochee-Oconee National Forest plan revision.

The Chattahoochee-Oconee National Forest is one of five National Forests undergoing forest plan revision in the Southern Region of the USDA Forest Service. The Chattahoochee-Oconee National Forest covers 865,043 acres in northern and central Georgia, of which 542,240 acres are suitable for timber production (http://www.fs.fed.us/conf/facts1.htm 2001). There are three predominate ecological sections found on the forest: Blue Ridge Mountains, Southern Ridge and Valley, and Southern Appalachian Piedmont.

Forest Plan revision on the Chattahoochee-Oconee National Forest began in the late 1990s. Elements of the plan revision include determining analysis units/strata and allocating National Forest land to these strata, determining administrative layers, developing silvicultural prescriptions, performing growth and yield forecasting, and evaluating the management alternatives. As part of this process, the Forest Vegetation Simulator (FVS) system was chosen to create the yield tables needed for the growth and yield-forecasting element of the forest plan revision. Output from FVS system will be used as input in Spectrum, the analytical tool used to evaluate forest management alternatives (Spectrum Overview 2001).

The FVS system is a suite of software tools designed to translate forest data, simulate forest growth, and process model outputs into usable forms for other analytical tools. At the heart of this system is the FVS model. The FVS model is an individual-tree, distant-independent growth and yield model that has been calibrated to simulate forest growth for most forest types of the United States (Dixon 2001). This paper presents the FVS model calibration and adjustments used to produce accurate yield tables for the forest plan revision on the Chattahoochee-Oconee National Forest.

FVS Variant Selection and Data

There are two FVS variants available for the Chattahoochee-Oconee National Forest: the Southeastern Variant (SE) and the Southern Variant (SN). The Southern Variant was chosen for two reasons. First, it was fit to a larger geographic region, which enabled all National Forests undergoing plan revision in the Southern Region to use the same model. Second, the Southern Variant is more reliable because it was built using FVS growth relationships, while the Southeastern Variant was based on equations in the Southeast TWIGS model (Lilly 1997; Donnelly and others 2001).

The Southern Variant does not have insect or disease extensions. However, the magnitude of possible insect and disease impacts on the forest is being accounted for through the use of FVS addfiles designed specifically to estimate the severity of pests and pathogens, most notably the Southern Pine Beetle addfile (Courter and others this proceedings).

This planning effort used the FVS-ready FIA data for the Southeast available on the FMSC Intranet Web site. Each Forest Inventory Analysis (FIA) plot contained all the input data needed by FVS to make projections. In addition, diameter increment data were included on some tree records.

FVS Calibration and Adjustments

Tree Growth Functions

By default, the FVS large-tree diameter increment model and the small-tree height increment model undergo a process of self-calibration when sufficient growth increment data are supplied with the input tree data. Self-calibration is the process of scaling the predicted growth increments to more accurately match the measured growth rates of trees in the stand (Stage 1973). Wykoff and others (1982), explain this procedure best:

> The scaling procedure (Stage 1973), when stripped of statistical condiments, is really quite simple. The affected models are both linear and logarithmically scaled dependent variables. Therefore, the model

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intercepts are, in effect, growth multipliers. An increment to match each observed increment for a species is predicted, and differences are sorted. The median difference is then added to the model for that species, on the logarithmic scale, as an additional intercept term.

The diameter increment scale factors are attenuated over time. We assume that, on long-term projections, the base model is a more stable estimate of growth potential than is the scale factor. The attenuation is asymptotic to one-half the difference between the initial value of the scale factor and 1. The rate of attenuation is dependent only on time.

Self-calibration of the large-tree diameter increment model occurs in the Southern Variant if, for a given species, there are at least five tree records with backdated dbh greater than 3 inches that contain measured diameter increments (Dixon 2001; Wykoff and others 1982). Likewise, if there are at least five tree records less than 5 inches dbh that contain height increments, the small-tree height increment model is calibrated for that species. If a species is able to undergo self-calibration, a scale factor will be computed for the growth model of that species. Because the plot data for this plan revision do contain a sample of diameter increments, the large-tree diameter increment model will be scaled automatically when the above conditions exist on any plot. No height increment data were available in the data set for the small-tree height increment model to self-calibrate.

For some species, consistent growth function bias may occur within a given geographic area, ecological section, forest type, and so forth. To correct for this bias, mean correction scale factors may be calculated and added to the simulations as multipliers. These multipliers allow the user to simulate regional growth patterns on all plots, not just on plots that self-calibrate. These multipliers remain in effect for the entire simulation and do not attenuate over time.

For species exhibiting growth bias, mean correction scale factors were calculated within each ecological section. The Calibration Summary Statistics Post-Processor was used to render the mean correction scale factors, which were subsequently entered into the simulations using the READCORD keyword. Due to a low number of diameter growth samples, some species had no or few large-tree diameter increment scale factors computed. Therefore, mean correction scale factors were not computed for these species.

The mean correction scale factors were determined for each ecological section using the following six steps (see Section 6.5.3, Dixon 2001):

1. Insert the CALBSTAT keyword into the keyword set for each stand in the area and process the stands. This will generate the auxiliary file.
2. Examine the values in this file and determine the source of any values that seem extremely high or low.
3. For any stands with unresolved sources of error, or with calibration values that you think are not reflective of the area, remove the CALBSTAT keyword.
4. Rerun the set of stands.
5. Run the Calibration Statistics postprocessing program to determine the average large tree diameter growth scale factor and the average small tree height growth scale factor for the area.
6. If these average scale factor values are different from 1.0, enter these values as multipliers using the READCORD, READCORR, and READCORH keyword.

Table 1 lists the resulting species-specific large-tree diameter increment, mean correction scale factors by ecological section. The mean correction scale factors reported are from an updated Calibration Summary Statistics postprocessor. Actual scale factors used in the forest plan are from a previous version and differ slightly. Notice that there is a general trend between ecological sections. For the most part, species had mean correction scale factors less than 1.0 (stands growing slower than model prediction) for the Blue Ridge Mountain and Appalachian Piedmont ecological sections and mean correction scale factors greater than 1.0 (stand growing faster than model prediction) for the Ridge and Valley ecological section.

Volume Specifications and Adjustments

To get estimates of stand volume and volume harvested consistent with the procedures on the Chattahoochee-Oconee National Forest, merchantability limits and percent defect estimates were set to commonly found values on the

Table 1—Mean large-tree diameter increment correction scale factors by species and ecological section.

Species name	Species number	Blue Ridge Mountains	Appalachian Piedmont	Ridge & Valley
shortleaf pine	5	**	**	1.304
longleaf pine	8	*	**	1.087
eastern white pine	12	0.842	*	*
loblolly pine	13	**	0.720	1.065
virginia pine	14	0.675	0.586	0.851
hickory species	27	**	**	1.041
yellow poplar	45	0.992	**	**
scarlet oak	64	0.728	**	**
chestnut oak	74	0.749	0.797	1.056
northern red oak	75	0.808	**	**

* Species does not occur in ecological section
** Insufficient data to create mean scale factor or no bias present.

Chattahoochee-Oconee National Forest (tables 2 and 3). The BFVOLUME keyword was used to set the species merchantability specifications for sawlog portion of cubic feet and board feet volume equations. The VOLUME keyword was used to set the species merchantability specifications for merchantable cubic feet volume. Sawlog defect was specified using the BFDEFECT keyword (VanDyck 2001).

Additional Considerations

Regeneration Inputs

While the Southern Variant does simulate stump sprouts from cut trees, it does not automatically simulate other types of natural regeneration. Other than sprouting, users must specify the species and quantity (trees per acre) of trees that regenerate. Regeneration estimates may be obtained outside the FVS framework through the analysis of regeneration surveys and consultation with local experts. In addition, within the FVS framework, users have the option of creating regeneration addfiles based on current stand composition with the REgeneration ImPUTation Extractor (REPUTE) postprocessor (Vandendriesche 2001). Sprouting was turned on in the simulations but no other types of regeneration were input into the simulations.

Mortality Functions

When FVS mortality does not correspond to observed mortality, FVS users may use mortality modifier keywords to correct model outputs. Mortality modifier keywords include FIXMORT, MORTMULT, BAMAX, and SDIMAX (Van Dyck 2001). FIXMORT allows users to replace or add to the FVS calculated species-specific mortality rate for a given diameter range. MORTMULT can be used to increase or decrease the species-specific mortality rate for a given diameter range. BAMAX resets the maximum density of the stand. SDIMAX allows users to reset the maximum stand density index by species. There has not been a need to calibrate the mortality functions in the Chattahoochee-Oconee plan revision yet.

Example

The effects of using the above-mentioned FVS calibration and adjustment techniques are depicted in table 4. In this example, 12 plots from the Blue Ridge Mountains Ecological Section, old growth community type 05, sapling age class (11-40 years old) stratum (B05S) used in this plan revision were selected. Four simulations were performed as follows:

Table 2—Default and adjusted cubic feet and board feet volume merchantability specifications for the Chattehoochee-Oconee plan revision.

Default settings	Keyword	Species	Minimum merchantable dbh	Minimum top diameter*	Stump height
Merchantable Cubic Feet	Volume	all	4.0	4.0	1.0
Merchantable Board Feet	BFVolume	hardwoods	12.0	9.0	1.0
Merchantable Board Feet	BFVolume	softwoods	10.0	7.0	1.0
Adjusted settings	**Keyword**	**Species**	**Minimum merchantable dbh**	**Minimum top diameter**	**Stump height**
Merchantable Cubic Feet	Volume	hardwoods	6.0	4.0	0.5
		redcedar	5.0	4.0	0.5
		shortleaf pine	5.0	4.0	0.5
		slash pine	5.0	4.0	0.5
		longleaf pine	5.0	4.0	0.5
		pitch pine	5.0	4.0	0.5
		eastern white pine	6.0	4.0	0.5
		loblolly pine	5.0	4.0	0.5
		Virginia pine	5.0	4.0	0.5
		hemlock	6.0	4.0	0.5
Merchantable Board Feet	BFVolume	hardwoods	12.0	9.0	1.0
		redcedar	9.0	7.0	1.0
		shortleaf pine	9.0	7.0	1.0
		slash pine	9.0	7.0	1.0
		longleaf pine	9.0	7.0	1.0
		pitch pine	9.0	7.0	1.0
		eastern white pine	10.0	7.0	1.0
		loblolly pine	9.0	7.0	1.0
		Virginia pine	9.0	7.0	1.0
		hemlock	10.0	7.0	1.0

* Minimum top diameter is fixed in this variant and cannot be changed.

Table 3—Percent defect by species and diameter. Linear interpolation between diameters is used to calculate percent defect for a given tree diameter.

Keyword	Species	5 inch dbh	10 inch dbh	15 inch dbh	20 inch dbh	25 inch dbh
				Percent		
BFDefect	white oak	0.0	0.0	0.5	3.5	3.6
	swamp chesnut oak	0.0	0.0	0.5	3.5	3.6
	chinkapin oak	0.0	0.0	0.5	3.5	3.6
	cheerybark oak	0.0	0.0	2.5	2.5	2.5
	northern red oak	0.0	0.0	2.5	2.5	2.5
	Shumard oak	0.0	0.0	2.5	2.5	2.5
	chestnut oak	0.0	0.0	0.5	10.0	6.3
	post oak	0.0	0.0	0.5	10.0	6.3
	scarlet oak	0.0	0.0	2.6	13.0	7.4
	southern red oak	0.0	0.0	2.5	13.1	7.4
	blackjack oak	0.0	0.0	2.6	13.1	20.0
	hickory sp.	0.0	0.0	0.8	10.2	1.6
	sugar maple	0.0	0.0	0.0	0.0	17.7
	red maple	0.0	0.0	0.6	9.3	21.6
	American beech	0.0	0.0	0.0	20.0	20.0
	blackfum	0.0	0.0	5.8	20.0	25.0
	yellow-poplar	0.0	0.0	0.4	0.0	2.1
	black locust	0.0	0.0	24.7	65.7	90.1
	Virginia pine	0.0	0.0	15.2	33.0	50.0
	eastern white pine	0.0	0.0	0.0	0.0	20.0

Table 4—Mean stratum responses for simulations in the example at a mean stand age of 113 years. Standard errors (±1) are reported for Sawlog board feet.

Simulation*	Trees per acre	Ave. dbh (inches)	Merchantable cubic feet	Sawlog cubic feet	Sawlog board feet
1	276	9.5	6560	5334	33582 ± 1869
2	276	9.5	6395	4959	31142 ± 1762
3	278	9.5	6343	4920	30798 ± 1750
4	290	9.4	6309	4859	30313 ± 1771

* 1: Simulation with no volume adjustments, no self-calibraiton, and no mean correction scale factors.
2: Simulation with volume adjustments, no self-calibraiton, and no mean correction scale factors.
3: Simulation with volume adjustments, with self-calibraiton, and no mean correction scale factors.
4: Simulation with volume adjustments, with self-calibraiton, and with mean correction scale factors.

1. A simulation with no volume adjustments, no self-calibration, and no mean correction scale factors.

2. A simulation with volume adjustments, no self-calibration, and no mean correction scale factors.

3. A simulation with volume adjustments, with self-calibration, and no mean correction scale factors.

4. A simulation with volume adjustments, with self-calibration, and with mean correction scale factors.

The stratum was grown for 150 years with no management with the FVSStand postprocessor combining the output by age into age-based yield tables. The plots within the stratum were given equal weight in the analyses. The resulting stratum data, presented in table 4, refer to the output obtained when the average stand age within the stratum was 113 years (up to 100 years of projection). Simulation mean responses for trees per acre, average dbh, merchantable cubic feet volume, sawlog cubic feet volume, and sawlog board feet volume obtained from FVSStand are displayed in table 4. The standard error of the mean sawlog board feet volume is also included.

Discussion

Little difference was seen when self-calibration was employed, presumably due to either the attenuation of scale factors over time or relatively few species having an adequate number of growth sample trees to self-calibrate. The largest relative differences in the example came when volume adjustments and mean correction scale factors were added to the simulations. Using the mean correction scale factors allowed for scaling of species that would not have been scaled due to too few growth samples in a particular stand. The scaling affected diameter growth, which then had secondary impacts on mortality. This is depicted in table 4 where the scale factors slowed down the diameter growth, smaller average dbh, which then impacted the SDI based mortality model, greater trees per acre.

Even though the relative growth differences are small, adjusting and calibrating FVS is still warranted. First, this example used a small sample from only one stratum out of a possible 135. Other strata may in fact have large growth

differences. Also, practicality is of the essence. It makes sense to adjust the volume merchantability specifications to those used on your district or forest. It also makes sense to calibrate the FVS growth functions to reflect past stand growth. Using mean correction scale factors helps to alleviate systematic bias of the growth functions, especially when self-calibration does not occur due to too few growth increments per species on a given plot. After further yield table review, it might be necessary to further calibrate the model by including regeneration estimates and modifications to the mortality model. The authors believe that the FVS adjustments and calibration techniques used in the Chattahoochee-Oconee plan revision are necessary and should be employed in other plan revision efforts.

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Session 3. Landscape Applications

Using a Multichange Agent Approach with the Forest Vegetation Simulator on the Boise National Forest, Idaho

Joy C. Roberts

Abstract—Permanent plots from the Boise National Forest, Idaho, were established in 1982 and remeasured in 1987 and 2000 for monitoring the effects of western spruce budworm (*Choristoneura occidentalis*) on mixed conifer stands of grand fir (*Abies grandis*), Douglas-fir (*Pseudotsuga menziesii*), subalpine fir (*Abies lasiocarpa*), and Engelmann spruce (*Picea engelmannii*) tree species. The central Idaho variant of the Forest Vegetation Simulator was used to make two simulations that were then compared to the actual data. A simulation without change-agent impacts causes an underestimation of mortality and overestimation of growth. A multichange agent approach using a variety of pest model models and fixed mortality functions simulates impacts from western spruce budworm and a variety of bark beetles. This simulation more closely represents the mortality and growth indicated by the actual data.

Modeling the process of change in forests is challenging. To assist in this task, forest managers use the Forest Vegetation Simulator (FVS) to simulate changes in stand structure and composition over a specified timeframe. Traditionally, simulating disturbances, referred to as change agents (Steele and others 1996), is accomplished by linking one pest model to the main FVS model. If Douglas-fir beetle (*Dendroctonus pseudotsugae*) is the primary change agent, then one will use the model with the Douglas-fir beetle model. Similarly, other independent pest models are available for western spruce budworm (*Choristoneura occidentalis*), mountain pine beetle *(Dendroctonus ponderosae*), and Douglas-fir tussock moth (*Orgyia pseudotsugata*). Only impacts from dwarf mistletoes (*Arceuthobium* spp.) are simulated as part of the main FVS model. Unfortunately, no single change agent can adequately reflect the total actual mortality and growth impacts on vegetation. Only a multichange agent approach can lead us closer to simulating change.

Since 1991 a multichange agent scenario has been available for use with the central Idaho variant of FVS. The Southwest Idaho Ecogroup Team has utilized it in landscape and project planning on the Boise and Payette National Forests in Idaho. For this analysis, permanent plot data collected on the Boise National Forest in 1982 and remeasured in 1987 and 2000 were used to evaluate the multichange agent scenario. The outputs from the actual data were compared to a no-change agent (nopest) simulation and a multichange agent (pestadj) simulation.

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Methods

To evaluate this multichange agent procedure, 88 permanent plots established in 17 stands in the Boise National Forest in 1982 were analyzed. These stands were established to monitor the impacts of defoliation by western spruce budworm on mixed conifer stands where an outbreak event started in some stands as early 1971. The outbreak grew and continued through 1987 when some unknown event ended the outbreak in all stands. Species composition includes grand fir (*Abies grandis*), Douglas-fir (*Pseudotsuga menziesii*), subalpine fir (*Abies lasiocarpa*), and Engelmann spruce (*Picea engelmannii*). Ponderosa pine (*Pinus ponderosa*), western larch (*Larix occidentalis*), and lodgepole pine (*Pinus contorta*) tree species are also present but are not primary hosts of western spruce budworm.

Originally, stands were selected based on presence of defoliation, size of stand (20 to 65 acres), stand accessibility, land base stratification, and defoliation stratification (Beveridge and Cahill 1984). Remeasurements were taken on stands in 1987 and 2000. Although these stands are maintained to monitor impact from western spruce budworm, their species composition makes them suitable for a multichange agent evaluation.

To prepare stand data for entry to the FVS model, the tree data were compared in each year to correct small discrepancies in tree species and find unreasonable growth measurements. Stands were not included if trees grew smaller or could not be found in every measurement. In the 17 stands that were selected, only trees that were measured in all three measurements were included in the simulated data sets. Additionally, only trees equal to or greater than 1 inch in diameter were included.

The following computer programs and files were used to complete the project:

- Suppose Version 1.14—(Crookston 1997)
- Forest Vegetation Simulator—CIX.EXE (Wykoff and others 1982; David 2001)
- Multichange agent keyword set (Roberts and Weatherby 1997)
- Event Monitor (Crookston 1990)
- Compute2 post processor (Van Dyck 2001)
- Excel spreadsheet—graphics (Microsoft© Excel™2000)

The CIX.EXE program offers the user a multilinked version of FVS. In this version, the Douglas-fir beetle model, the mountain pine beetle model in lodgepole pine, and the

western spruce budworm model are all available to the main FVS program. Due to the low occurrence of mistletoe in these stands, mistletoe was not included in the evaluation.

There is no programmed interaction between the pest models. They run independently and in a sequence. Growth is adjusted and mortality is applied according to each model's specifications. In addition, three mortality functions have been defined to simulate mortality caused by fir engraver beetle in grand fir (Schenk and others 1977), western pine beetle in ponderosa pine (Stevens and others 1980), and spruce beetle in spruce (Schmid and Fry 1976). These functions are executed from the multichange agent keyword set.

All instructions for determining vulnerability of trees to a change agent are also included in the multichange agent keyword set. A set of hazard rating rules is applied to each stand using the event monitor. If the vulnerability is high, based on these rules, the associated change agent model or function is called. For the western spruce budworm model, the Douglas-fir beetle model, and the mountain pine beetle model, the tree mortality caused by the change agent is checked against the background mortality computed by the FVS model. The larger of the two is applied (Marsden and others 1994). On the other hand, the fixed mortality functions for spruce beetle, fir engraver beetle, and western pine beetle add mortality to the background mortality.

Two simulations were compared to the actual data in this evaluation. Data from the actual measurements collected in years 1982, 1987, and 2000 were submitted to FVS for computing the initial stand characteristics for each stand for each measurement year. Then a simulation that contained no-change agent impacts (nopest) was made starting with the 1982 actual data. The simulation grew each stands forward to 1987 and then to 2000. The second simulation (pestadj) started with the 1982 actual data and grew the stands forward applying the rules, models, and functions from the multichange keyword set. Both mortality and growth are impacted by the change agents. The stand summary data displayed in the Summary Statistics Table of the FVS output were used as indicators for comparing differences between the simulations and the actual data. These summary data are recreated in tabular format using the ECHOSUM keyword in the FVS and stored in an output file (.sum).

The stand indicators that were compared are trees per acre, basal area, stand density index, dominant height, quadratic mean diameter, volumes, crown competition factor, and mean annual increment. Additionally, some indicators that were evaluated by species and tree size class include trees per acre, basal area, quadratic mean diameter, and dominant height. These outputs were produced using the event monitor, which is a part of the FVS model. The event monitor keyword SPMCDBH was used to extract the indicator information by species and diameter class. The diameter classes consist of small trees between 1 and 5 inches and large trees greater than 5 inches. Two output files were created using the postprocessor of Suppose. The data from both output files were imported into a Microsoft Excel® spreadsheet program. Using the spreadsheet's pivotal table function and graphing capabilities, the data were summarized and displayed.

Results

In this paper, the basal area indicator will be discussed in detail. By looking at the average basal area by species in figures 1 and 2, it becomes clearer how the change agents have impacted the stands. The bottom bar on the chart represents the actual data, the middle bar is the multichange agent simulation (pestadj), and the top bar is the no-change agent simulation (nopest.) There is a decline in basal area in all species from 1982 to 2000. The largest change in stand species composition was in the subalpine fir species, which declined from 17 percent in 1982 to 13 percent in 2000. Grand fir, the largest component of this mix, remained relatively unchanged, while both Engelmann spruce and Douglas-fir improved position due to the decline in subalpine fir.

The average basal area for the no-change agent simulation (nopest) and the actual data are displayed in figure 3. This no-change agent simulation might be viewed as the best-case scenario. As each change agent is added as a line on the graph, notice the move from the no-change agent scenario toward the actual data. Modeling the change agents explains some of the difference between a no-change agent run and the actual data. Change agents that are not modeled might explain some of the remaining difference. These might include other insects, diseases, and impacts from weather, drought, animals, or humans. Another factor that might influence the remaining difference is in growth rates used in the model. Unadjusted rates may be growing trees faster than the actual growth rates, causing the basal area

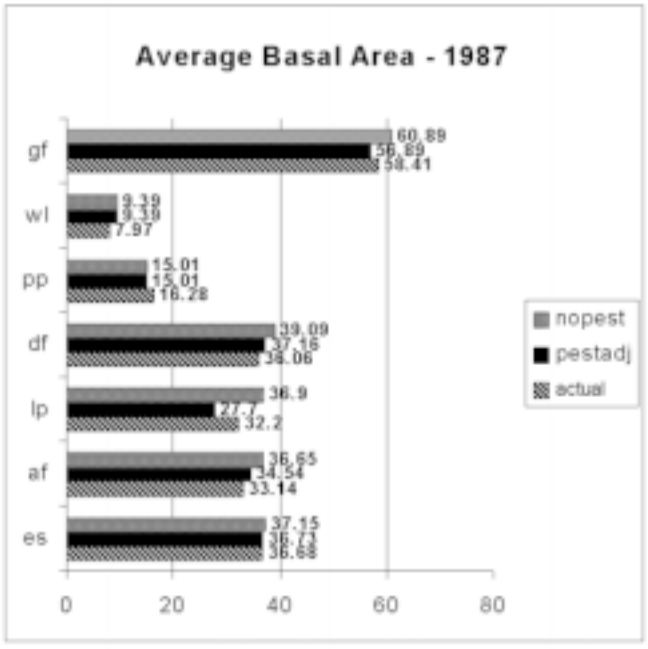


Figure 1—Total basal area (ft^2) and average basal area (ft^2) by species by simulation for 1982 to 1987 cycle. Species codes are: gf = grand fir; wl = western larch; pp = ponderosa pine; df = Douglas-fir; lp = lodgepole pine; af = subalpine fir; es = Englemann spruce.

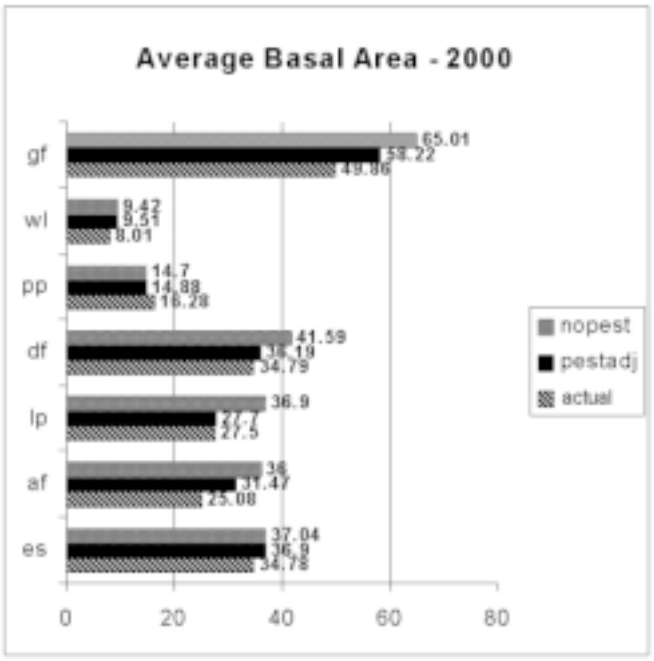
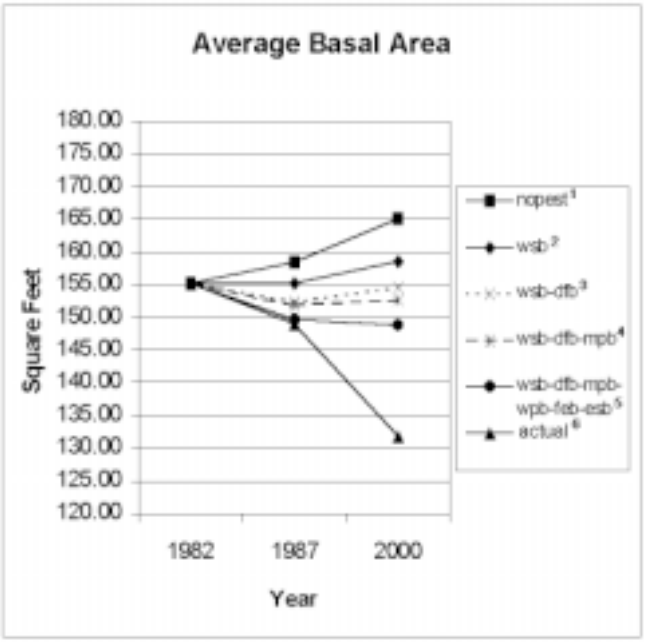


Figure 2—Total basal area (ft^2) and average basal area (ft^2) by species by simulation for 1987-2000 cycle. Species codes are the same as used in figure 1.



[1]A simulation that does not include any change agent impacts.
[2]Impacts from western spruce budworm have been added.
[3]Impacts from western spruce budworm and Douglas-fir beetle have been added.
[4]Impacts from western spruce budworm and Douglas-fir beetle, and mountain pine beetle have been added.
[5]Impacts from western spruce budworm and Douglas-fir beetle, mountain pine beetle, western pine beetle, fir engraver beetle and spruce beetle have been added.
[6]Actual data

Figure 3—Illustrates the change in basal area from 1982 to 2000 for each of the simulations and the actual data.

of the simulations to be higher. Other factors such as competition of trees less than 1 inch that are not included in the simulations might also have an impact.

Western spruce budworm, which impacts Douglas-fir, Engelmann spruce, grand fir, and subalpine fir, causes diameter growth loss, top kill, and mortality due to defoliation in host species (Beveridge and Cahill 1984). In the multichange agent simulation, this is the only agent impacting subalpine fir. By year 2000, the overall difference in subalpine fir from the no-change agent simulation to the actual is 30 percent, of which 13 percent is attributed to western spruce budworm. The remaining mortality in subalpine fir can be attributed to a complex of insects, pathogens, and environmental factors (Bennett and others 2001).

In addition to western spruce budworm, the Douglas-fir beetle model in the multichange agent simulation moved Douglas-fir basal area close to the actual data. There is a 16 percent difference in the actual basal area from the no-change agent simulation but only a 4 percent difference between the multichange agent simulation and the actual data in Douglas-fir.

The impacts from mountain pine beetle in lodgepole pine move the 1987 basal area slightly lower than the actual data. A study of the simulation indicates that outbreaks for mountain pine beetle rated high in some stands in 1982, which triggered an outbreak during the 1982 to 1987 growth cycle. A study of the actual data shows that a large number of lodgepole pine trees actually died during the 1987 to 2000 cycle.

Although a stand may be vulnerable to an attack, it is most difficult to predict when an outbreak might occur. During a simulation using 10–year cycles, mountain pine beetle might have an outbreak in highly vulnerable stands sometime within a 20–year period. Which cycle the outbreak will occur can only be simulated, not predicted. Although the length of reoccurrence is different for different change agents, the problem of predicting when an outbreak will occur applies to all change agents.

In Engelmann spruce, the actual data show that the basal area in this species declined only slightly and increased in percentage composition from 17 percent in 1987 to 19 percent in 2000. Although spruce is present in the majority of stands, no individual stand contained enough contiguous spruce to trigger an epidemic event by spruce beetle. The minor difference in basal area is caused by western spruce budworm.

Overall, grand fir had the largest difference of 24 percent between the no-pest simulation and the actual data by 2000. Of this, only 11 percent is modeled as fir engraver beetle. A fixed mortality function based on risk ratings from Schmid and Frye (1976) has been used to compute vulnerability and outbreak mortality. The remaining mortality can be attributed to other change agents and environmental factors not modeled.

There is minimal impact from western pine beetle as ponderosa pine is a minor component in the stands. Western larch is also a minor component, and although mistletoe is modeled for this species, not enough mistletoe was present to trigger an event. By year 2000, only 55 percent of the difference in basal area between no pest and actual has been explained by change agents. The remaining 45 percent represents mortality that cannot be explained or are impacts by change agents not simulated.

Conclusions

In a no-change agent simulation, the model overestimates indicators used in this analysis. In the actual data, certain tree species were disturbed by some kind of change agent that caused mortality and reduction in growth. Some of this is explained by the individual change agents modeled in the keyword set that processes the models and mortality functions in an independent and sequential procedure. In reality, change agents do not work independently and are in concert with many other change agents including weather, fire, and other insects and diseases (Weatherby and others 1997) not simulated in our analysis. This leaves some unexplained difference between the actual data and our change-agent simulation. Still, a multichange-agent approach offers the modeler a simulation closer to actual change than does a no-change agent approach.

There are several multichange agent methods available besides the multichange agent keyword set used in this analysis. The Western Root Disease Model (Frankel 1998) and the Westwide Pine Beetle Model (Smith 1999) are also available. Modelers are encouraged to work with insect and disease modeling specialists who can assist in using a multichange agent approach.

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FVS-EMAP: A Simple Tool for Displaying FVS Output in ArcView® GIS

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Abstract—The FVS Event Monitor ArcView® Project (FVS-EMAP) is a tool for moving simulation results from FVS into the ArcView® GIS. Using the customized ArcView® project, users can create maps depicting FVS output variables for a multistand landscape throughout simulated time. The tool can also display the maps in time sequence, thereby "animating" the landscape through simulated time. Users generate input for FVS-EMAP via the COMPUTE keyword (part of the FVS Event Monitor), and the *Compute2* postprocessor. An ArcView-based shapefile representing stand boundaries is required as a "template" onto which FVS-EMAP will map COMPUTE variable output. Besides functioning as an FVS postprocessor and landscape analysis tool, the project also contains a pre-processor that creates the supplemental record file (an FVS input file) associated with PPE keyword AREALOCS.

The focus of forest management has recently shifted from emphasizing stands to prioritizing ecosystems. "Landscape analysis" is now an integral part of forest management. Coincident with this shifting focus has been a surge of computing and geographic information system (GIS) technology. Early development of landscape-scale modeling tools within the Forest Vegetation Simulator (FVS) "family" of models began with the Parallel Processing Extension (PPE; Crookston and Stage 1991), which permits the simulation of stands altogether (in parallel) through simulated time—instead of serially (one stand after another)—thereby making possible the modeling of landscape-scale processes, such as pest contagion (see for example Beukema and others 1997). Other tools have been developed that extend FVS landscape analysis capabilities, including: Pre-Suppose, a preprocessor that assists users in retrieving data for groups of stands from a database (Vandendriesche, these proceedings); and the Event Monitor (Crookston 1990), a program within FVS that allows user to more easily schedule activities across a simulated landscape.

In this paper, we describe a new FVS postprocessing tool, the FVS Event Monitor ArcView® Project (FVS-EMAP), that helps users create maps depicting FVS projection output on a multistand landscape. Such landscape scale maps can be useful for forest managers conducting landscape analyses using FVS.

In addition to being a postprocessor, FVS-EMAP can also be used as an FVS preprocessor to quickly generate the input data file associated with the FVS/PPE keyword AREALOCS. This supplemental record file contains geographical coordinates and areas of stands to be simulated. The FVS-EMAP extracts this information from an ArcView® shapefile (defined below) and writes it to a file, appropriately formatted for PPE.

Overview of FVS-EMAP

The FVS Event Monitor ArcView® Project (FVS-EMAP) is a customized ArcView® project (an *.apr* file) that simplifies the joining of FVS output data with a stand-based shapefile. A *shapefile* is ArcView's native spatial data format and comprises at least three files, denoted by the extensions *.shp*, *.shx*, and *.dbf* (it may comprise more than these three files). Users having spatial data as ARC/INFO coverages, instead of as shapefiles, can easily convert the data to a shapefile format in ArcView®.

The FVS-EMAP is essentially a "blank" ArcView® project that differs from a standard ArcView® blank project in that it contains three additional scripts, written in ArcView's Avenue® programming language, that have been compiled and embedded into the project. Each of these scripts performs a specific action or "function" (table 1). These functions are accessed via buttons on the project interface's buttonbar (fig. 1).

Table 1—Descriptions of the three functions embedded in FVS-EMAP.

Function	What the function does:
1	(1) Prompts the user to locate a *.cp2* file—an FVS output file containing values of all Event Monitor COMPUTE variables; (2) prompts the user to locate a shapefile; and (3) joins the *.cp2* file output to the shapefile.
2	"Animates" the active View by displaying each Theme in the View one-at-a-time in two-second intervals, from top to bottom (which will be in chronological order if the Themes are positioned by Function 1).
3	Creates a supplemental record file for PPE keyword AREALOCS. The function: (1) extracts polygon areas, and x- and y-coordinates of polygon centers, and (2) launches an external program which will rewrite the extracted data into a text file, appropriately formatted for FVS.

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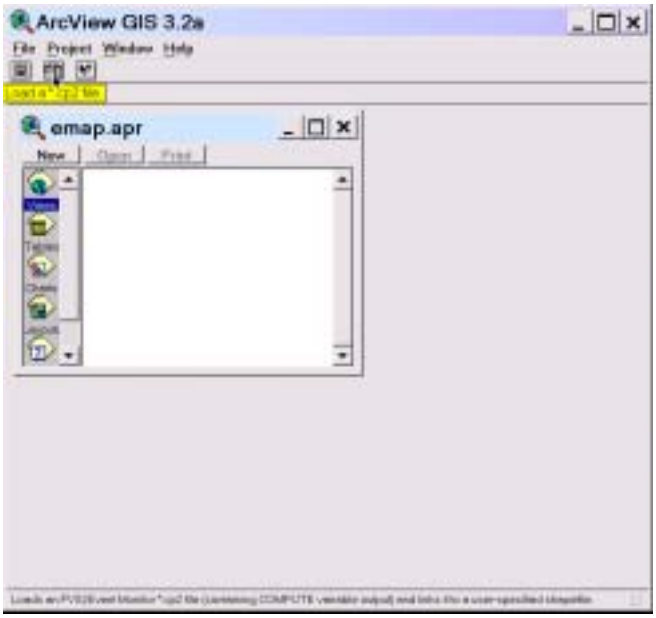

Figure 1—The FVS-EMAP project interface. The project interface resembles a typical "blank" ArcView® project. Note the "join" button and tool tip (at cursor, upper left), and the associated "help" information in the status bar (bottom).

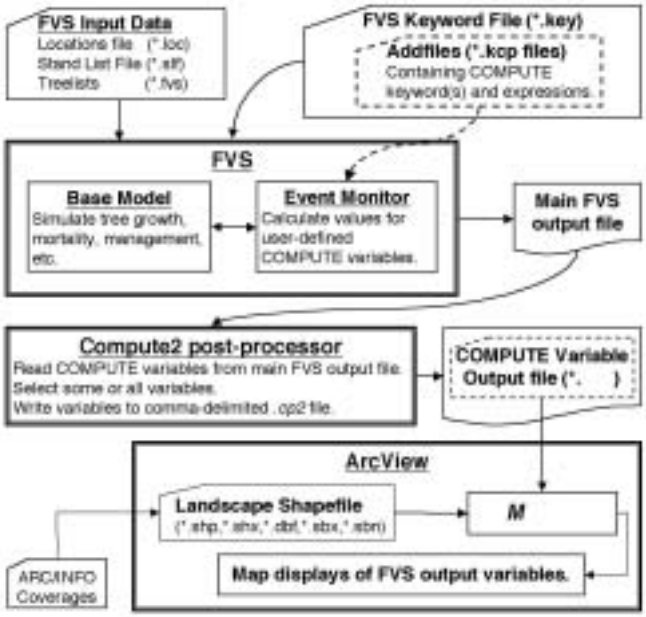

Figure 2—Flowchart diagramming the flow of information from FVS and the Event Monitor into the FVS-EMAP ArcView® projerct.

Function 1 "loads" FVS COMPUTE variable output data (from a *.cp2* file) and joins those data to a shapefile. It is designed to help the user quickly and easily make time-series map displays portraying FVS simulation output data. Function 2 "animates" the mapped data, portraying maps one-at-a-time in short intervals in such a way as to show how the modeled landscape might change over time. The third function, unlike the first two functions, is a preprocessor that extracts information from a shapefile and writes those data to a file to be used in an FVS simulation along with the FVS/PPE keyword AREALOCS. The bulk of this paper focuses on function 1, joining *.cp2*-file output with a shapefile; however, functions 2 and 3 are also discussed.

Using FVS-EMAP to create map displays of FVS output variables involves three basic steps (fig. 2). The first two steps occur at the FVS simulation set-up phase (before FVS-EMAP is launched).

The first step is to incorporate the FVS Event Monitor keyword COMPUTE, along with accompanying mathematical expressions, into an FVS simulation. This will generate the output to be mapped. The second step is to invoke the *Compute2* postprocessor, which rewrites the COMPUTE variable output to a form usable by the FVS-EMAP. The third step is running the custom ArcView® project, *EMAP.apr*. We only briefly discuss the first two steps; further information about the Event Monitor and the *Compute2* postprocessor can be found in Crookston (1990) and Van Dyck (2001), respectively.

To use FVS-EMAP, users must have: (1) standard FVS software and stand data files; (2) an appropriate FVS keyword file; (3) an ArcView® shapefile, which provides the information needed to map the boundaries of the stands being simulated; (4) ArcView® GIS software, version 3.2 or higher (currently available for all USDA Forest Service personal computers); and (5) the customized ArcView® project, *EMAP.apr*, available from the Forest Health Technology Enterprise Team (FHTET; contact information provided below).

Using the Event Monitor to Generate Input Data for FVS-EMAP

The COMPUTE keyword is an Event Monitor keyword that provides the user the ability to insert into an FVS simulation mathematical expressions that will be evaluated for stands throughout the simulation. The mathematical expressions incorporate predefined or previously defined Event Monitor variables. Users can use the COMPUTE keyword to have FVS report values of variables it (FVS) is already keeping track of (for example, basal area per acre); or it can be used to calculate elaborate user-defined mathematical expressions, such as a stand hazard rating scores or habitat suitability indices. For example, the map depicted in figure 3 depicts mountain pine beetle hazard ratings for stands as defined by Randall and Tensmeyer (2000). This hazard rating system was "coded" into the FVS simulation using COMPUTE statements and included for all stands in the simulated National Forest compartment. A number of such Event Monitor keyword component files (*.kcp* files, or "addfiles") that calculate stand hazard ratings to various insect pests are available from FHTET. Also, packaged with FVS-EMAP is an addfile that generates output containing all of the metrics in the main FVS stand summary statistics output table, thus making these variables available to be mapped. Further details about using the Event Monitor to generate output variables of the user's choice can be found in

Crookston (1990), as well as in the user's guides accompanying the FHTET-provided addfiles.

In conjunction with the COMPUTE keyword, the *Compute2* postprocessor must be used to generate a comma-delimited output file reporting the COMPUTE variables in a machine-readable format. The Compute2 postprocessor is available in Suppose (FVS graphical user interface). When included in a simulation, it automatically reads all COMPUTE variable output data (for all stands and all years in which it was generated) from the main FVS output file. It then rewrites the variables to their own comma delimited output file (a *.cp2* file), organized by stand identification code (stand ID) and by year. This *.cp2* file is the file that will be read in by FVS-EMAP. Further details about the Compute2 postprocessor can be found in Van Dyck (2001).

These features of FVS are used to generate the data for input into FVS-EMAP because:

1. The Event Monitor and the COMPUTE keyword can be used to access a large number of simulated tree, stand, and site variables.
2. The COMPUTE keyword allows users to mathematically manipulate any predefined or user-defined Event Monitor variable, thus allowing users to create a large number of *user-defined* variables, such as hazard ratings or habitat suitability indices.
3. The *Compute2* postprocessor reads all user-requested COMPUTE variables from the main FVS output file and rewrites them to their own comma-delimited output file (a *.cp2* file). Having these variables written to their own file, comma-delimited, and indexed by stand ID and simulation year greatly facilitates the subsequent readability of the data by ArcView® GIS.

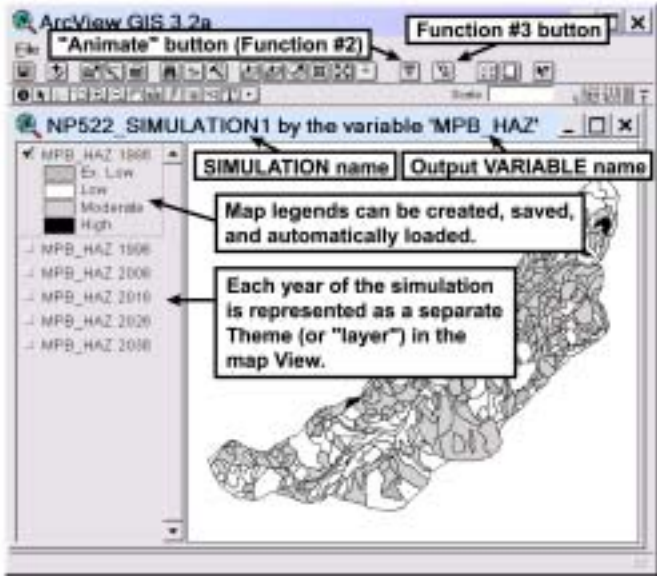

Figure 3—Example map View created via FVS-EMAP. The View will portray the FVS-simulated, user-chosen COMPUTE variable of interest on the user-provided shapefile. This map depicts mountain pine beetle hazard in 1986 for a National Forest compartment. There are map "layers" for each year in the output file. Predefined map legends, if installed, can be automatically applied.

Portraying FVS Data Spatially

After generating the desired FVS output data, the user launches the ArcView® GIS project *EMAP.apr*. The "blank" project interface will appear nearly identical to a "traditional" blank ArcView® project, except there will be at least one new button on the button bar (fig. 1). This button activates function 1.

Invoking function 1 begins the process of "loading" data from a *.cp2* file into the project and "joining" the data to a shapefile. Once the user begins this process, the project will prompt the user for information. There are five main steps involved in the map-creation process. (The project may, however, provide more than the following five queries, depending upon how the user decides to have map legends created.) The five steps, outlined briefly here, and discussed below, are:

1. Input the FVS output data for analysis by "loading" the appropriate *.cp2* file.
2. Input a stand-based shapefile containing the boundaries of the simulated stands.
3. Select an output variable to map.
4. Identify the field in the shapefile's *.dbf* table corresponding to the stand ID used in FVS.
5. Select a preformed map legend (if available), or begin the legend-creation process.

After the user responds to these five prompts, FVS-EMAP will create a map depicting the values of the output variable for the simulated stands. The map—actually a multi-Themed map *View*—will contain one map layer (a *Theme*) for each year reported in the *.cp2* file (fig. 3).

For step 1, the project presents a dialog box prompting the user to navigate to the appropriate output file containing the data to be displayed. Typically this will be a *.cp2* file. However, any appropriately formatted comma-delimited file is "readable" by the project. Additionally, the project can read in output files from the Westwide Pine Beetle Model (Beukema and others 1997), a landscape-scale bark beetle model extension to FVS.

For step 2, the project prompts the user to locate a stand-based shapefile containing the boundaries of the simulated stands. The user must provide the shapefile. The *.dbf* file associated with this shapefile must have a field containing data that are identical to the stand identification codes used in the FVS simulation. That is, the stand IDs used in FVS (which are the identifiers reported in a *.cp2* output file) must have an identical counterpart in the shapefile *.dbf*. It is these matching stand identification codes that allow the project to join the *.cp2* file output data with the shapefile (see step 4 below).

For step 3, the project will provide a list of all of the output variables that were read in from the *.cp2* file. The user may create map displays for only one output variable at a time.

For step 4, the project will offer a listing of all of the column headings (field names) from the shapefile's *.dbf* table. The user must then identify the field name associated with the column of data containing stand identification codes. There must be a record for every stand reported in the *.cp2* file. In other words, for every FVS-simulated stand, there must exist a polygon in the shapefile; the project will not allow the mapping of output onto a nonexistent polygon.

Step 5, the legend-creation process, can occur different ways depending upon what type of legend the user wants to use. If a preformed legend file exists (an *.avl* file, in a "Legends" subdirectory), with a filename matching the variable name being mapped, then the project will offer to use that legend. If no such corresponding preformed legend exists, or if the user declines using the preformed legend, then the project will create a legend. It offers the user the choice of creating a "unique values" legend (for use with discrete variables) or a "graduated" legend (for use with continuous variables). If a graduated legend type is chosen, the user is queried as to how many groups the data should be categorized into. The project then queries the user to choose a color scheme for the legend. Users can always "manually" edit legends in ArcView®. Once a desired legend is created, the user may save it to the "Legends" directory. If the new legend is given a filename that corresponds to a COMPUTE variable name, then it can be automatically applied by FVS-EMAP next time that COMPUTE variable is loaded and mapped.

After the FVS data View is created, two new buttons will appear on the project interface (fig. 3). One of these buttons will invoke the project's second function: animating the display. Selecting this button begins the process of displaying the map layers one by one, in two-second intervals. This gives the user an animated "slices-in-time" view of the landscape, thus providing users a convenient way to see how the output variable changes over simulated time.

Generating an AREALOCS Supplemental Record File

The AREALOCS supplemental record file is a file needed by the FVS/PPE keyword AREALOCS. It contains data regarding the location and area of stands. The four fields of data in the supplemental record file are: Stand ID, x-coordinate of stand center, y-coordinate of stand center, and stand area. These data are not necessarily needed by the PPE but may be needed depending upon how one intends to use the PPE. If for example a user wants to run the Westwide Pine Beetle (WWPB) Model extension to FVS, keyword AREALOCS, along with its appropriately formatted list of supplemental records, is *required*.

The third function built into FVS-EMAP streamlines the procedure for creating this supplemental record file. Together with a separate FORTRAN program—*arealocs.exe* (which accompanies the FVS-EMAP package)—FVS-EMAP will create the supplemental record file containing coordinates of stand centers, and areas for all of the polygons (stands) in a shapefile.

Once a shapefile is loaded into FVS-EMAP and a View created (regardless of whether or not FVS output data are being portrayed), function 3 becomes available. This function:

1. Extracts stand centroid information (x- and y-coordinates of stand centers) and stand area from an ArcView® shapefile (note that the shapefile must be projected in a planar coordinate system, such as the Universal Transverse Mercator [UTM] System).
2. Optionally writes this information into the shapefile's *.dbf* file.
3. Writes and saves a separate *.txt* file (comma delimited) containing only the four fields of data needed as supplemental records with keyword AREALOCS.
4. Then launches a Fortran executable program that reads the newly created *.txt* file and then writes the data, appropriately formatted, to a file.

This new file can then be used as an AREALOCS supplemental record file in a PPE/FVS simulation.

Summary

FVS-EMAP is a tool that can be used to make maps displaying results from FVS simulations on groups of stands. Its usefulness becomes more significant as a collection of stands representing a *landscape* is simulated. Once FVS output data are loaded into ArcView®, various spatial analyses may be performed (using the ArcView® Extension *Spatial Analyst*, for example). This allows users to address landscape-level and ecosystem-level management questions (for an example, see Smith and others, in these proceedings). Such ecosystem-scale and landscape-scale analyses are becoming increasingly important for forest managers, and tools such as FVS-EMAP are playing an increasingly important role.

The FVS-EMAP project software, documentation, and sample Event Monitor addfiles that calculate various stand statistics are available free of charge from FHTET at:

http://www.fs.fed.us/foresthealth/technology/products

or by contacting:

Forest Health Technology Enterprise Team
USDA Forest Service
2150 Centre Ave (NRRC), Bldg A, Suite 331
Fort Collins, CO 80526-1891
Attn: Eric Smith (elsmith@fs.fed.us)

Acknowledgments

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Landscape Analysis Application of the Westwide Pine Beetle FVS Extension

Eric L. Smith
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Thomas Eager

Abstract—Landscape level analyses of forest management projects are necessary to consider many of the relevant future conditions and project impacts. Applications of FVS to landscape analyses are often hindered by incomplete inventory coverage of the landscape and the difficulty of representing and modeling spatial interactions between stands. The Westwide Pine Beetle (WWPB) extension to FVS operates on a multistand basis using the Parallel Processor Extension (PPE). The WWPB model simulates interactions of bark beetles and stand characteristics both within stands and among stands within a multistand landscape. To illustrate its functions, results are presented from an application of the WWPB model to a proposed forest management project on the Piney Analysis Area, Holy Cross Ranger District, White River National Forest, Colorado. The problems encountered in this application, such as data availability, and approaches for addressing them, are presented. Outputs from the simulation include both stand and landscape level displays. Stand results display projected tree mortality and stand structure changes as a function of stand composition and beetle outbreak intensity. Landscape outputs include both summary tables and ArcView-based map displays. Effects of stand management are shown both at the stand and landscape levels.

Forestry in Time and Space

In the past, forestry concentrated on tree growth over time, using the stand as its basic unit of analysis. Spatial analysis tools were not needed as long as growth and yield was the major concern. However, over the past 20 years, concern for spatial relationships between stands, and the spatial relationship of stand management treatments, has emerged. Wildlife ecologists and others have concentrated on spatial relationships but have employed few temporally dynamic tools.

As with other forms of wildlife, bark beetles move between stands, and the population dynamics of these beetles encompass landscapes that include hundreds to thousands of stands. In environments where pine bark beetles have a significant role in shaping forest structure, a stand-level approach to modeling their impact and response to management is inadequate. The likely future impact of pine bark beetles on a single stand depends on whether it is surrounded by a landscape of forests suitable or not suitable as beetle habitat. The Parallel Processor Extension (PPE) (Crookston and Stage 1991) of the Forest Vegetation Simulator (FVS) was developed to consider the spatial interactions between adjacent stands. The Westwide Pine Beetle extension employs PPE for its ability to model stand interactions and to consider the spatial distances between stands. The availability of Geographic Information Systems (GIS) has also been a key factor in the feasibility of landscape analysis. Not only do these systems allow easy storage and display of spatial data, they incorporate powerful spatial analysis routines needed for landscape analysis.

In this paper, we provide examples of how the Westwide Pine Beetle model (WWPB; Beukema and others 1997; FHTET in press)—a landscape-scale extension of the FVS—can be a useful tool in performing landscape analyses. These results illustrate the types of questions that may be addressed by the model and demonstrate features of model behavior.

Scales and Complexity in Landscape Analyses

Landscape analyses can be conducted at a number of different spatial and/or temporal scales. An analysis ought to reflect the scale at which the model processes occur and address analysis-specific questions.

We categorize these scales of landscape analysis into five "levels" (table 1). These levels increase in complexity and each relate to a different "category" of analysis-related questions.

The first two levels are "nonspatial" in the sense that the physical location of the units of the landscape is not accounted for. Level 1 of landscape analysis considers the *aggregate conditions* of the stands in the landscape. For example, estimating landscape average host basal area per acre might suggest a landscape's susceptibility to a bark beetle epidemic.

Level 2 considers average stand characteristics for *subsets* of the stands in the landscape, grouped, for example, by cover type or structural stage. Characterization by subsets of stands can provide information describing how *heterogeneous* a landscape is. Although these simple landscape analyses do not consider spatial relationships between the

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Table 1—Levels of landscape analysis.

Increasing level of complexity Level	Example type of analysis	Addresses questions and issues pertaining to
1	Summary statistics about landscape conditions	Average conditions
2	Analysis of landscape by stand condition classes (e.g. proportion of landscape in each class)	Homogeneity Heterogeneity
3	Analysis of the spatial distribution of the stand condition classes; this possibly gives rise to the creation of new condition class units ("emergent units"), via the aggregation of stand level units	Connectivity Fragmentation
4	Analysis of spatial arrangement of emergent condition class units	Edge/Configuration
5	Location within natural and cultural environment	"Place"

stands, they do provide a summary at a spatial scale "above" that of individual stand-level analyses. Such a landscape analysis could prove to be more relevant than stand-level analyses. For example, a stand that would have a high hazard rating for beetle attack in a single-stand analysis might be viewed differently if it was analyzed in the context of an otherwise low hazard landscape.

Level 3—the simplest analysis using spatial data—considers the size distribution of contiguous conditions within a landscape. This kind of analysis provides *fragmentation* and *connectivity* statistics. For example, after categorizing stands in a landscape according to some bark beetle risk rating system, one could "coalesce" adjacent stands of similar ranking into new units. The size distribution of these new units of similar risk could provide insight, for example, into the relative effectiveness of treatment alternatives to preserve unfragmented areas of wildlife habitat when faced with tree mortality from beetle outbreaks.

Level 4 considers the *spatial relationships* among different conditions and can provide information about distance between units, spatial patterns among units, amount of edge within and among units, and so forth. Continuing from the example above, one could analyze whether moderate risk units are *near* high risk units or *share substantial edge* with high risk units — findings that may have ecological significance. This more complex level of analysis—attained when the relationships of all stands (or other landscape units) are considered as elements of a landscape—may reveal ecologically important patterns and relationships that might otherwise be overlooked.

Even the most complex landscape analyses often stop at this fourth level. A level 5, however, is also possible, in which the location (or "place") of stands or groups of stands within a particular natural and cultural environment. Two different landscapes, for example, can be essentially alike in terms of the trees they contain, but if one of them represents critical habitat for an endangered animal species or a valued scenic resource to an urban population center, the importance placed on these places requires an analysis of these specific places in the landscape. Landscape averages or aggregate indices are not adequate if they do not give specific information about these specific places.

Input Data Considerations in Landscape Modeling

The techniques and models for spatial and landscape analysis developed over the past two decades have grown increasing sophisticated and complex (Sklar and Costanza 1991). These tools are not often employed in forestry, however. One of the reasons for this nonuse is that it can be difficult to directly relate the results of the analyses to management goals. For example, an analysis of habitat fragmentation can rarely be used to accurately predict future species population levels. Perhaps more important is the problem of data quality and quantity. Stand-level inventories used as input data for FVS are not often available for large, contiguous forest areas. For landscape applications of FVS, lack of "wall-to-wall" stand data will remain a significant challenge for most users.

Meaningful landscape analyses can, however, still be performed even without comprehensive inventories. Imprecision resulting from incomplete input data can be mitigated in various ways. Even if complete stand inventories do not exist, some information is generally available for the forested areas in the landscape. This information can be used through imputation techniques to fill in these areas with tree lists from inventoried stands. In our analyses, some portions of the landscape were occupied by tree species that are not susceptible to pine beetles. For areas of aspen (*Populus tremuloides* Michx.) stands in the landscape, for example, it was not too important to know precisely the structure of these stands. In other cases, areas were known to have been recently clearcut and regenerated with lodgepole pine (*Pinus contorta* Douglas var. *latifolia* Engelm.). Simulation alternatives that thin stands to a target density eliminate some of the uncertainty, because postthinned conditions can be assumed to be close to the management prescription. Stands with average size and stocking conditions for regeneration units of this age were assigned to these areas. These trees will not be of sufficient size to be

attacked by pine bark beetles during the projection period, so more precise data are not needed. In some cases, more sophisticated imputation procedures could be employed to populate the landscape where stand data are missing (Moeur and Stage 1995).

Some times data will be missing from stands that are central to the analysis. For these areas, a sensitivity analysis approach can be used (Ruckelshaus and others 1997). In our example case, the sample stands that were simulated represent the range of stand conditions in the landscape, in the proportion they appeared in a sample inventory. The sample selected may underestimate the proportion of high hazard stands that actually exist in the landscape; in our case, highly stocked stands with higher proportions of larger diameter pine. To determine the sensitivity of the analysis to this source of sample error, the sample-based simulation results can be compared with those from a landscape populated by a higher (and lower) proportion of high hazard stands.

Finally, some portions of the analysis area are likely to be of more interest than others. For example, stands in a specific location may be important components of wildlife habitat, but stand inventories may not be available for all the stands this area. Again, a sensitivity analysis may be used to determine if simulated future habitat conditions in this area are sensitive to the assumption that sampled conditions also represent the unsampled conditions. If so, then it may be possible to gather additional data in areas where the simulation results are critical to decisions.

In all cases, one must remember to treat simulation model results as imperfect summaries of present and future conditions. Stand inventory data are only samples of what actually exists, and FVS and the WWPB extension are only statistical tools and abstractions of reality.

Westwide Pine Beetle Model

As an extension to the FVS—in conjunction with PPE—the WWPB model simulates between-stand bark beetle contagion processes across a landscape, as well as within-stand growth and mortality processes (FHTET, in press). The importance of landscape-level mountain pine beetle (MPB; *Dendroctonus ponderosae* Hopkins) populations has been recognized as significant in determining risk at the stand level (Shore and Safranyik 1992). The model is capable of simulating the effects of three beetle species: the mountain pine beetle, the western pine beetle (WPB; *Dendroctonus brevicomis* LeConte), and *Ips* species. Our example applications simulate MPB in lodgepole pine.

Beetle populations per se are not simulated. Instead, beetles are represented in terms of "Beetle Kill Potential" or BKP. One unit of BKP represents an amount of beetles able to kill 1 square foot of basal area. BKP is allocated to and from stands annually. The amount of BKP allocated among stands is a function of the amount of BKP present in each stand, stand conditions in both the donor and recipient stands, and the distance between donor and recipient stands. Once allocated to a stand, BKP is assigned to specific tree size classes based on stand conditions. With sufficient BKP, trees are simulated as being killed. The amount of BKP in the following year is primarily a function of the diameters and numbers of trees that were killed the previous year.

Three spatial scales exist within the WWPB model:

1. Individual forest stands.
2. The collection of stands that compose the landscape.
3. A larger area (outside of, and encompassing, the landscape) referred to as the "outside world," which serves as a "source" and "sink" for landscape BKP.

The spatial relationships of stands within the landscape are explicitly considered. Being a landscape-scale model, the WWPB model is designed primarily to evaluate scenarios at the **landscape** scale. That is, it can be used to address questions such as:

- What *proportion* of a landscape might experience severe beetle mortality (given a specific outbreak scenario)?
- What *types* of stands are most vulnerable to beetle attack?
- If certain areas experience an outbreak, how quickly—and how far—might an outbreak spread?
- How might specific management actions affect future beetle dynamics?

At the **stand** level, the model may be used to address questions such as:

- How will a severe bark beetle outbreak affect stand structure?
- How long might stands experience high levels of beetles?
- What levels of mortality might some stands experience?

Note that these stand-level questions are posed in a general way. The model is *not* designed to predict precisely *which* individual stands in a landscape *will be* attacked or impacted by bark beetles. Rather, the model is designed to provide insight as to what *kinds* of stands in this landscape might experience beetle mortality, and how much mortality might occur. This can be simulated for different management and outbreak scenarios. In other words, although the *grain* of the WWPB model involves stands, its *extent* is the landscape, and that is the scale at which interpretation of output is most meaningful. To the degree that the spatial arrangement of stands in the landscape is known, some spatial information is inherent in the model results. For example, areas in the landscape that do not have host trees will not experience mortality.

Objectives and Dimensions of this Analysis

The objectives for this analysis are to use the WWPB model to help address the following questions:

- How will MPB outbreaks of varying intensity affect the landscape (defined below) as a whole?
- How will outbreaks of varying intensity affect the component stands?
- How will beetle-induced mortality manifest itself temporally and spatially across the landscape?
- How will specific management actions affect bark beetle dynamics?

We addressed these questions by organizing our simulations and analyses around the following *dimensions* of analysis.

- Distribution of stands within the landscape
- Time (as it affects growth and mortality)
- Treatments (thinnings)
- Outbreak intensity scenarios
- Stand-level responses and conditions
- Landscape conditions

A thorough discussion of all of these dimensions is beyond the scope of this paper. We address the first four dimensions—which are especially relevant during the simulation set-up phase of the analysis—only in a cursory way. This paper focuses primarily on the last two dimensions of the analysis: stand-level and landscape-level responses to the MPB, as projected by the WWPB Model.

Methods

Our analysis addresses a 23,000-acre landscape in the Piney Analysis Area, Holy Cross Ranger District, White River National Forest in Colorado. This area was the subject of a previous forest health assessment that used the single stand Mountain Pine Beetle FVS extension to analyze the possible impact of this insect on selected stands (Angwin and others 1996). Sources of information used for imputing stand information and setting up the simulation included:

- Recent stage 2 stand inventories for the area
- Digital cover type maps for the area
- Maps of past treatment areas
- Known proposed treatments and treatment areas
- Knowledge of current beetle conditions and likely outbreak dynamics
- Online Vail, CO, climate information (to provide insight into the frequency, duration, and magnitude of stress events)

Lodgepole pine is the primary species (percent of total stand basal area in host ranged from 66 to 100 percent), with additional components of subalpine fir (*Abies lasiocarpa* (Hook.) Nutt.), Engelmann spruce (*Picea engelmannii* Parry ex Engelm.), and aspen. Stand basal areas ranged from 48 to 232 square feet per acre; quadratic mean diameters (Q.M.D.) ranged from 2.6 to 14.2 inches. The area has experienced recent MPB activity.

Because digital stand maps were not available, we subdivided the landscape into 221 "stands," each 0.6 km by 0.7 km (approximately 100 acres). Using digital vegetation-type maps and hand-drawn district stand maps, we estimated the actual percent of the landscape stocked to host pine types, and the locations (in our simulated landscape) for proposed silvicultural treatments and previous clearcuts. We populated the stands with treelists from 19 representative stand inventories in such a way as to maintain a quantitatively accurate distribution of cover type, basal area distribution, and MPB risk rating across the landscape (spatial accuracy was also maintained for cover type). "Replicating" inventories in the landscape served two purposes: it facilitated analyzing the effect of stand location on beetle dynamics, and it "filled in" the landscape to account for uninventoried stands.

BKP was initialized in the simulated landscape at low (endemic) levels. Under base case conditions for this landscape, the WWPB model projects gradually increasing endemic mortality over a 20-year period. One of the features of the model is that "stress events," which can simulate conditions such as droughts, can be imposed. These events cause tree resistance to bark beetles to decline. Events were simulated to create MPB outbreaks of two intensities: one designated as a "severe" outbreak, another designated as a "moderate" outbreak. The stress event variable (field 3 of VARYRAIN keyword) has a default value of zero; it can be changed to be positive or negative. When it is set to be positive, tree vigor is increased and resistance to beetle attacks is increased. This approach was used to create outbreak scenarios that collapsed in realistic fashion.

Simulated thinning alternatives were constructed based on actual management proposals for this site. Treatments were simulated as thins-from-below to a residual basal area of 80 or 100 square feet per acre. The base case for managed scenarios applied treatments to about 10 percent of the area.

Simulations were run for 30 years, beginning in inventory year 1994. Simulated MPB outbreaks commenced in 2004, triggered by the use of the VARYRAIN keyword.

Results

Stand-Level Responses

Simulated MPB outbreaks differentially affected stands. During a simulated "severe" outbreak, mortality rates ranged from zero in the sparsest stands, to nearly 60 percent basal area mortality over 5 years in the densest stands, with an apparent "threshold" of somewhere between 100 and 120 square feet of basal area, below which only very low levels of mortality occurred (fig. 1). Host basal area mortality rates (10-year) sometimes exceeded 75 percent (fig. 2a). Peak 5-

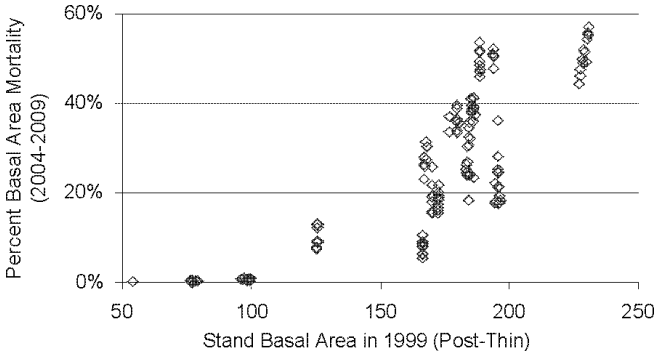

Figure 1—Simulated beetle-induced mortality rates over 5 years (2004-2009) as a percentage of the preoutbreak (postthin) basal area. Each point represents one of the 163 simulated stands. Stands with 1999 basal areas of 80 and 100 sq ft per acre were thinned (from below) to these levels in 1999.

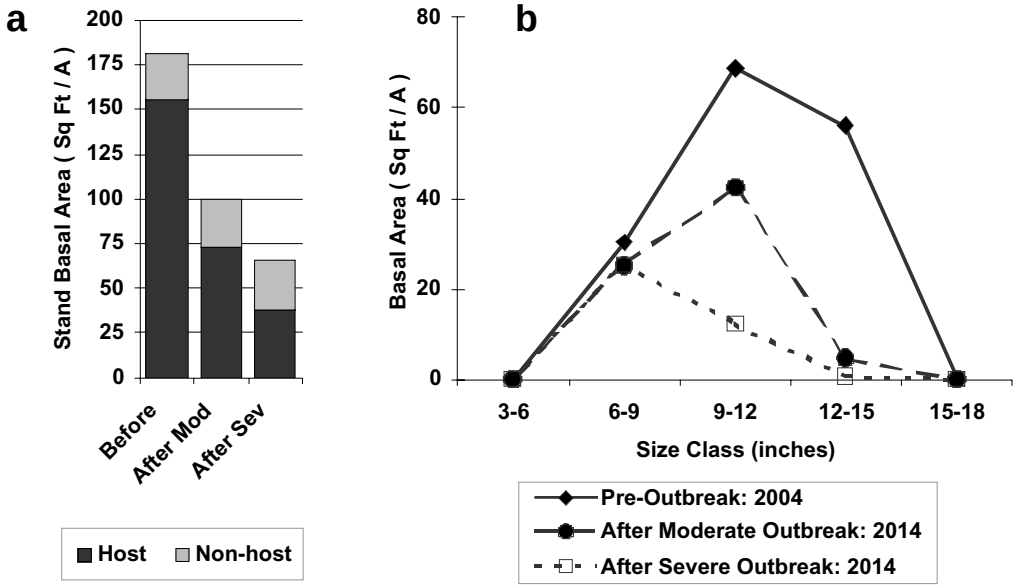

Figure 2—(**a**) Stand basal area by host and nonhost in 2004, and in 2014 after simulated "severe" and "moderate" MPB outbreaks for one stand in the landscape. (**b**) Basal area by tree size class for the same stand and time period as shown in (**a**).

year percent basal area mortality was approximately 40 percent for the moderate outbreak (data not shown).

Within stands, beetle-caused mortality occurred primarily in the largest size classes for both severe and moderate outbreak scenarios (fig. 2b). Resulting stand structures after simulated outbreaks are noticeably different depending upon the severity of the outbreak. Over time, smaller size classes are attacked (fig. 3).

Within-stand temporal trajectories of beetle outbreak varied significantly, stand to stand (fig. 4). Generally, denser stands with larger trees experienced more rapid mortality rates, followed by a relatively rapid decline of BKP levels. Conversely, lower basal area stands with smaller Q.M.D. experienced BKP pressure later in the simulation and for longer periods, sometimes even well after the landscape-wide outbreak had subsided.

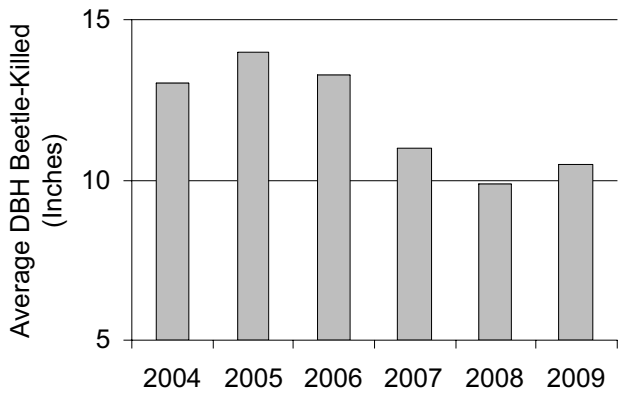

Figure 3—Landscape average diameter at breast height of beetle-killed trees by year during the simulated "severe" outbreak.

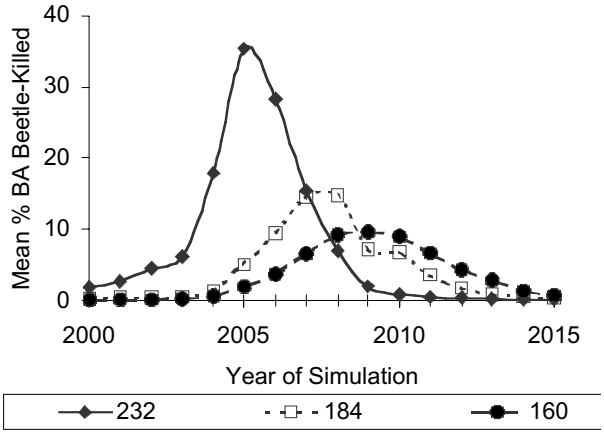

Figure 4—BKP levels for three stands during a simulated severe MPB outbreak. These "temporal trajectories" show how landscape-scale outbreaks manifest differently in different stands. Legend indicates each stand's 1984 (beginning of simulation) basal area.

Thinned stands experienced little if any beetle-caused mortality (fig. 1 and 5). This thinning effect was observed in spite of stands having, after thinning, higher proportions of host and a larger host Q.M.D., characteristics that generally are attractive to beetles.

Landscape-Level Responses

Simulated outbreaks took on different trajectories (landscape wide) depending upon how severe the outbreak was (how negative of VARYRAIN values were used and for how long), and how intensely the outbreak was "collapsed" (how

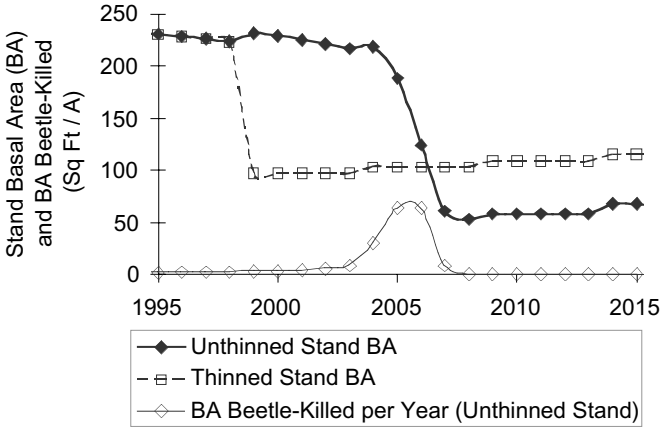

Figure 5—Stand basal area for two "replicate" stands, identical at the beginning of the simulation, during the severe outbreak simulation. One was thinned in 1999. Beetle-induced basal area mortality (per year) also is shown for the unthinned stand.

positive of a VARYRAIN keyword was used). We present four scenarios: a severe outbreak, collapsed; a severe outbreak, not collapsed; a moderate outbreak, collapsed, and a moderate outbreak, not collapsed (fig. 6). The severe outbreak scenarios resulted in landscapewide BKP rate increases that were higher than in the moderate outbreak scenarios. Rates of BKP increase appears to be controlled more by the stress event or beetle dynamics rather than on the stand conditions per se. Uncollapsed outbreaks—which eventually subsided because relatively few adequate trees remained in the landscape (data not shown)—took about twice as long to subside (approximately 10 years) than did the collapsed simulations.

Figure 4, which represents outbreak trajectories for individual stands in the severe outbreak, collapsed scenario, suggests a landscape scale phenomenon not revealed by the landscape-scale average graph (fig. 6). Although landscapewide the outbreak appears to have subsided by 2010, notice that some individual stands are just then attaining their peak BKP levels.

Distribution, landscapewide, of stand basal area per acre changes significantly after simulated outbreaks (fig. 7). This result follows from the individual stand phenomena suggested by figure 2b.

Figure 1 suggests the significance of stand location in the landscape. As discussed, tree inventories used to populate the stands in this landscape were replicated. Because replicates had similar stand basal area in 1999 (among themselves) before the simulated outbreaks, the difference in beetle mortality experienced by identical stands in different locations in the landscape is represented by the vertical range among the replicates, which appear together in vertical lines in the figure.

Discussion

The review of the analysis presented here illustrates the following:

1. Through use of the PPE extension, FVS can be used to represent interstand contagion processes that occur over a large number of stands (at least a few hundred) and that may occur at time steps less than a typical FVS cycle.
2. Spatial processes that take place at a landscape scale cannot be reliably modeled at the stand level; the stand-level outcome can be affected by both the entire landscape conditions and the conditions immediately surrounding the stand.
3. The amount of meaningful analysis that can be performed on a landscape with FVS is limited by the amount of data available for the landscape and the validity of the models being employed; but through sensitivity analysis and use of imputed data, useful landscape projections and comparisons can still be made.

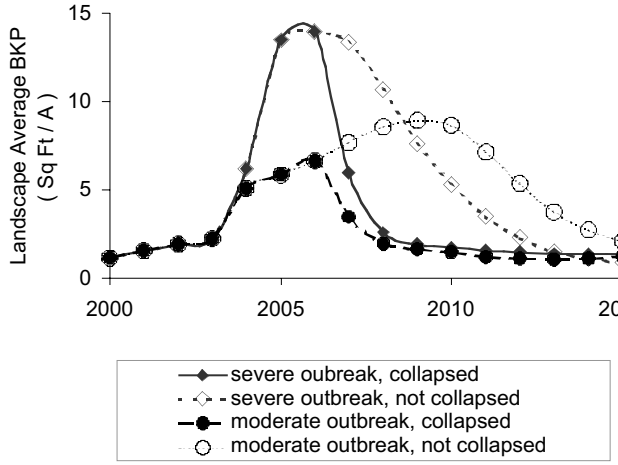

Figure 6—Landscape average BKP per acre over time for four simulation scenarios, showing that simulated outbreaks can have different temporal trajectories.

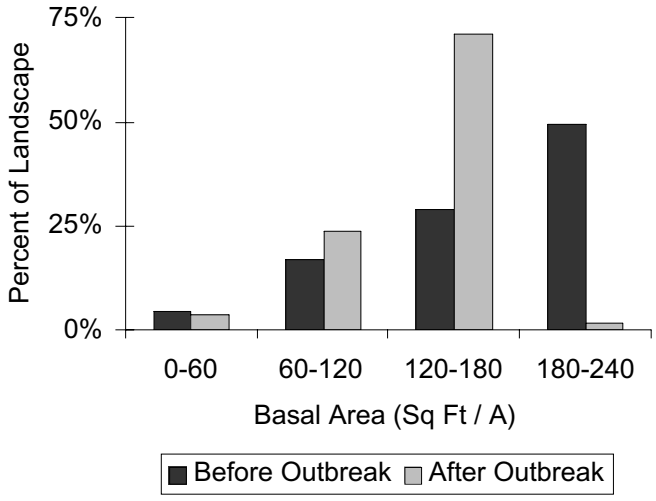

Figure 7—Frequency distribution of stand basal area classes landscapewide, before and after a simulated severe outbreak. (The sum of each of the two series equals 100 percent.)

Spatially explicit analyses can be performed on WWPB output by importing the results to a Geographic Information System such as ArcView®. Such analyses are not meaningful for this example because only the types of stands from the actual landscape, and not their spatial arrangement, are represented. Specific functions included in the WWPB software package facilitate moving output directly into ArcView®. FVS-EMAP (McMahan and others, this proceedings) is a flexible tool designed to perform this function for general FVS applications.

Though not presented here, GIS analyses can be used to describe the spatial effects of WWPB model outputs. A relatively simple procedure is to dissolve boundaries between stands with similar characteristics (such as cover type and age class) and display the distribution of sizes of these contiguous areas. A number of more sophisticated procedures have been developed and are routinely employed by landscape ecologists (O'Neill and others 1988; Turner 1990; Cullinan and Thomas 1992).

Several other multistand processes and conditions, including fire, wildlife habitat, and watershed hydrology, could be modeled with an approach similar to that used by WWPB. Such models, including WWPB, could be linked so that landscape impacts over time and space of landscape disturbances could be better understood and displayed.

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Methodology for Modeling the Spatial and Temporal Effects of Vegetation Management Alternatives on Late Successional Habitat in the Pacific Northwest

Helen Maffei
Brian Tandy

Abstract—A 10-step methodology was developed to facilitate the analysis and communication of vegetation management treatments on short-term and long-term late successional habitat and overall landscape stability in eastern Cascade forests. This methodology was first used to evaluate proposed management effects on spotted owl habitat for a large project area within a late successional reserve (LSR) in central Oregon. Modeling tools and analysis techniques included: stratifying and classifying the LSR by focal species habitat and habitat stage; hazard rating systems, Forest Vegetation Simulator (FVS), pest impact models, and most similar neighbor analysis procedures. Data sources used include: stand exams, forest inventory data, field surveys and a photo-interpreted forest layer. Custom event monitor variables and keyword component files (kcp files) were written to describe and evaluate project objectives, proposed silvicultural treatments; and to model key disturbance events where off-the-shelf FVS models were not available. FVS projections to predict long-term effects were composed entirely of kcp files, which were assigned to appropriate stands using specialized software. Results of these projections were imported into GIS and displayed spatially, by treatment alternative, over time. Spatially explicit graphic and numerical displays of effects on spotted owl habitat over time helped demonstrate the need, and develop a base of support, for the management proposed by the project.

Over the past century, eastern Cascade grand fir and Douglas-fir series communities have changed from relatively open stands dominated by large shade-intolerant ponderosa pine (*Pinus ponderosa* Laws.) and Douglas-fir (developed under a low intensity fire regime), to dense multicanopy forests dominated by shade tolerant trees (Hessburg and others 1994). Species such as spotted owl (*Strix occidentalis caurina*) have found this combination of large legacy trees and multilayered dense fir in-growth to be suitable habitat and have established breeding populations in these altered mixed conifer communities. Late successional reserves (LSRs) have been established in these areas with the objective of protecting spotted owl and other species associated with late successional habitat (USDA Forest Service and USDI Bureau of Land Management 1994).

The changes in mixed conifer communities that have resulted in habitat conducive to northern spotted owl, have also resulted in a vegetative shift toward greater instability. Much of the "new" spotted owl habitat may be transient because replacement Douglas-fir and ponderosa pine nest trees are unlikely to develop given the present stand densities (Everett and others 1997). In addition, mixed conifer communities are now much more susceptible to severe impacts from insects, diseases, and wildfires (Agee and Edmonds 1992; Hessburg and others 1994). Thus, broad-scale losses of habitat can occur over very short periods. For example, over a decade, we estimate that 70 percent of spotted owl nesting, roosting, and foraging habitat (NRF) was lost as a result of the combined effects of western spruce budworm, root diseases, and bark beetles in the McCache project area in Oregon (fig. 1).

Given the inherent transience of much of the spotted owl habitat east of the Cascades and given that the USDA Forest Service is directed to manage for spotted owl habitat over time (USDA Forest Service and USDI Bureau of Land Management 1994), the agency is faced with a delicate balancing act for eastern Cascades spotted owl habitat that is both spatially and temporally complex. The agency is challenged with protecting and maintaining a portion of the existing habitat, developing future habitat, and at the same time, maintaining an overall condition of landscape stability.

Silvicultural treatments such as thinning and prescribed burning can be effective techniques to progress toward this goal. However, traditional treatment proposals, analysis procedures, and communication techniques have been inadequate for gaining support for these types of actions. The impacts and benefits of the proposals to late successional habitat are often not clear to wildlife biologists, line officers, or the public. This lack of common understanding among stakeholders has resulted in frustration, heightened controversy, and lawsuits.

To address this problem, the authors have developed a 10-step analysis procedure to help land managers:

- Predict spatially explicit effects to habitat over time
- Communicate these effects
- Evaluate logic and rationale of proposed actions
- Make more informed resource management decisions

A number of analysis tools and data are used including: (1) The Forest Vegetation Simulator (including the western

In: Crookston, Nicholas L.; Havis, R. N., comps. 2002. Second Forest Vegetation Simulator Conference; 2002 February 12–14; Fort Collins, CO. Proc. RMRS-P-25. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

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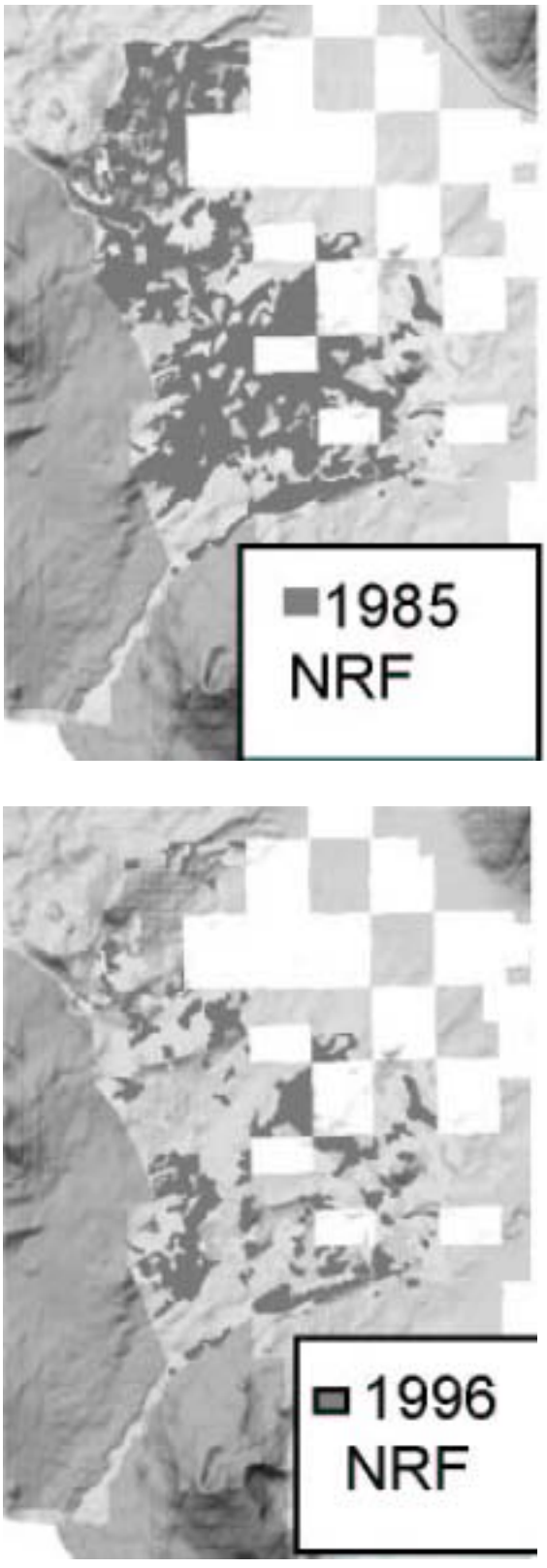


Figure 1—Northern spotted owl nesting roosting and foraging habitat (NRF) mapped in the Cache LSR in 1985 and in 1995. The dramatic change in NRF illustrates the rapid rate at which habitat can become nonhabitat in unstable forest structures. The 1985 condition was developed by reconstructing tree lists for 1985 stands from stand exams done in the early to mid 1990s.

root disease and dwarf mistletoe impact models), (2) stand exams, (3) forest inventory data, (4) global data (in our case, photo-interpreted data), and (5) Most Similar Neighbor inference (MSN) (Moeur and Stage 1994). This 10-step procedure was first applied to alternative analysis for the 15,350-acre McCache Vegetation Management Project area, located in the Cache LSR, on the Sisters Ranger District, Deschutes National Forest. The objective of this paper is to describe the methodology using examples from this initial McCache project analysis.

Methods

Part 1: Defining Existing Condition, Project Goals, and Objectives

Step 1. Stratify the Late Successional Reserve by focal species area. Focal species areas are portions of the landscape that have the best potential biological capability to provide late successional habitat for an identified focal or indicator species. For example, in the mixed conifer plant associations, the late successional focal species is northern spotted owl. For the ponderosa pine plant associations the focal species may be white-headed woodpecker (*Picoides albolarvatus*) or northern goshawk (*Accipiter gentiles*). Many eastern Cascades late successional reserves have more than one focal species because they encompass plant communities with different late successional indicator species. The Cache LSR assessment identified three major focal species areas within the McCache project area. For most of the mixed conifer plant associations the focal species is northern spotted owl. For the ponderosa pine plant associations, white-headed woodpecker is the focal species, and black-backed woodpecker (*Picoides arcticus)* is the focal species for the lodgepole (*Pinus contorta* var. *latifolia*) forest type.

Step 2. Describe the basic structural features of late successional habitat in measurable terms. A shared understanding of what you are trying to achieve is crucial to any successful project. The second step of our analysis methodology is, therefore, to describe late successional habitat in terms of measurable stand structure features. For the Cache LSR northern spotted owl focal species area, spotted owl habitat was quantified based on available scientific literature, adapted to observed local spotted owl nesting and dispersal behavior on the Deschutes National Forest (Thomas and others 1990; Forsman and others 1984; Buchanan and others 1995; Maffei and others 1997; Everett and others 1997). Structural features of two types of spotted owl habitat were described:

1. Nesting, roosting, and foraging habitat (NRF) has all the structural characteristics required for successful reproduction. Spotted owls typically nest low in the canopies of larger, dominant trees. Multilayered canopy cover is required for protection from predators. For the McCache Analysis, spotted owl NRF was described in terms of a sliding scale of numbers of large overstory trees (represented as trees over 21 inches d.b.h.) and canopy cover (table 1).

Table 1

Number of large trees per acre[1]	Percent Canopy Cover[2]
8-10.9	60+
11-14.9	55-59.9
15-17.9	50-54
18-21.9	45-49.0
22+	40-44.9

[1]Large trees are as those with 21 inch or greater d.b.h.
[2]Canopy cover provided by trees larger than 6 inches d.b.h.

2. Dispersal habitat is used by spotted owls to travel from one NRF area to another. It must have the structural characteristics necessary for owls to travel safely between NRF areas. For the McCache analysis, a stand was defined as dispersal habitat if there was a minimum of 35 percent canopy cover provided by trees greater than 6 inches d.b.h.

Step 3. Describe management objectives in measurable terms. The following objectives probably apply to most eastern Cascades late successional reserves:

a. Protect all or a portion of the existing late successional habitat.
b. Promote the development of future late successional habitat.
c. Promote an overall condition of productivity, stability, and low risk of catastrophic disturbance.

For habitat that is inherently high risk, "protection" of habitat is described in terms of the stability of the landscape around it. We chose to depict vegetative stability on the landscape in terms of hazard to "stochastic" disturbance agents that are likely to promote sudden loss of habitat. For mixed conifer systems we used hazard-rating models for stand-replacing wildfire, western spruce budworm, and bark beetles. Hazard rating for western spruce budworm was based on Carlson and Wulf's (1989) system, bark beetle hazard on local stocking guides (Hall 1987). Stands were rated as having a high potential for severe wildfire based on vertical structure and fuel loading. Stands with high stocking levels and multiple canopies and/or stands with fuel loads in excess of 20 tons/acre were rated as high hazard. Forest diseases, if present and significant, could be described in terms of a hazard-rating system. However, we chose to model the effects of these slow, progressive disturbance agents on habitat directly, using the western root disease model and the dwarf mistletoe impact model. Achievement of habitat is described in terms of the quantifiable features of habitat or in terms of quantifiable benchmark indicators of progress toward the desired habitat structural condition.

Step 4. Classify each stand in the focal species area in terms denoting the stand's present structure relative to the elements needed for habitat (habitat stage). This classification could be approached any number of ways but for our spotted owl focal species habitat areas we assigned each stand into one of four general groups (fig. 2):

1. Stands with sufficient numbers of large trees and levels of canopy cover to presently fit the definition of NRF.

2. Sufficient canopy cover to fit the definition of dispersal habitat. Depending on the number of large trees present, current dispersal habitat could develop into NRF in a short time, a relatively long time, or may not ever develop into NRF.

3. Sufficient large tree structure but not enough canopy cover to be NRF. At this stage, not treating and allowing the process of fir in-growth to continue could foster NRF.

4. Nonhabitat. Insufficient numbers of large tree structure or sufficient canopy cover to be classified as NFR or dispersal habitat. These stands are the furthest temporally away from being NRF because first the large tree structure needs to be developed, followed by the development of a layered, shade-tolerant understory.

Figure 3 shows this classification system applied to the 346 stands in the McCache project spotted owl focal species area.

Step 5. For each habitat stage develop a list of treatment objectives and prescriptions. For each habitat stage, assign a list of possible silvicultural treatment objectives and associated treatments. No treatment is always an option for each habitat category. Table 2 displays assigned objectives and treatment possibilities based on our four-category habitat classification for stands in northern spotted owl focal species areas. Note, that for nonhabitat stands, the prescription to regrow habitat mirrors the long-term two-stage process that initially produced it (grow large-tree-dominated fire climax forest first; then allow fir to grow underneath).

Step 6. For each alternative, the Interdisciplinary Team assigns a silvicultural treatment to each stand (no treatment is considered a treatment in this case). Proposed treatments are not assigned solely on individual stand conditions. Broader landscape considerations will also play an important role. For example, spatial concerns and connectivity issues such as the need for dispersal corridors or continuity of green fuel breaks, and unique stand characteristics, may all drive the final proposed stand treatments.

Part 2: Projection of Future Effects Using FVS

The following steps involve using FVS to model spatially explicit outcomes of the selected alternatives over time. FVS (Stage 1973) and associated software (Crookston 1997; McGaughey 1997) constituted the model of choice because:

- Event monitor allows for the creation of custom variables that tie directly to the project issues and objectives
- The model uses standard field inventory data
- Insect and disease impact models are available
- It is easy to project and summarize, and it spatially displays large amounts of data
- Links to external databases and GIS
- Calibrated to central Oregon
- USDA Forest Service supported and maintained

Step 7. Fully populate the stand exam database for each focal species area. In order to have a data-driven spatial display for future scenarios, it is necessary for each stand to be represented by a sample tree list so that it can

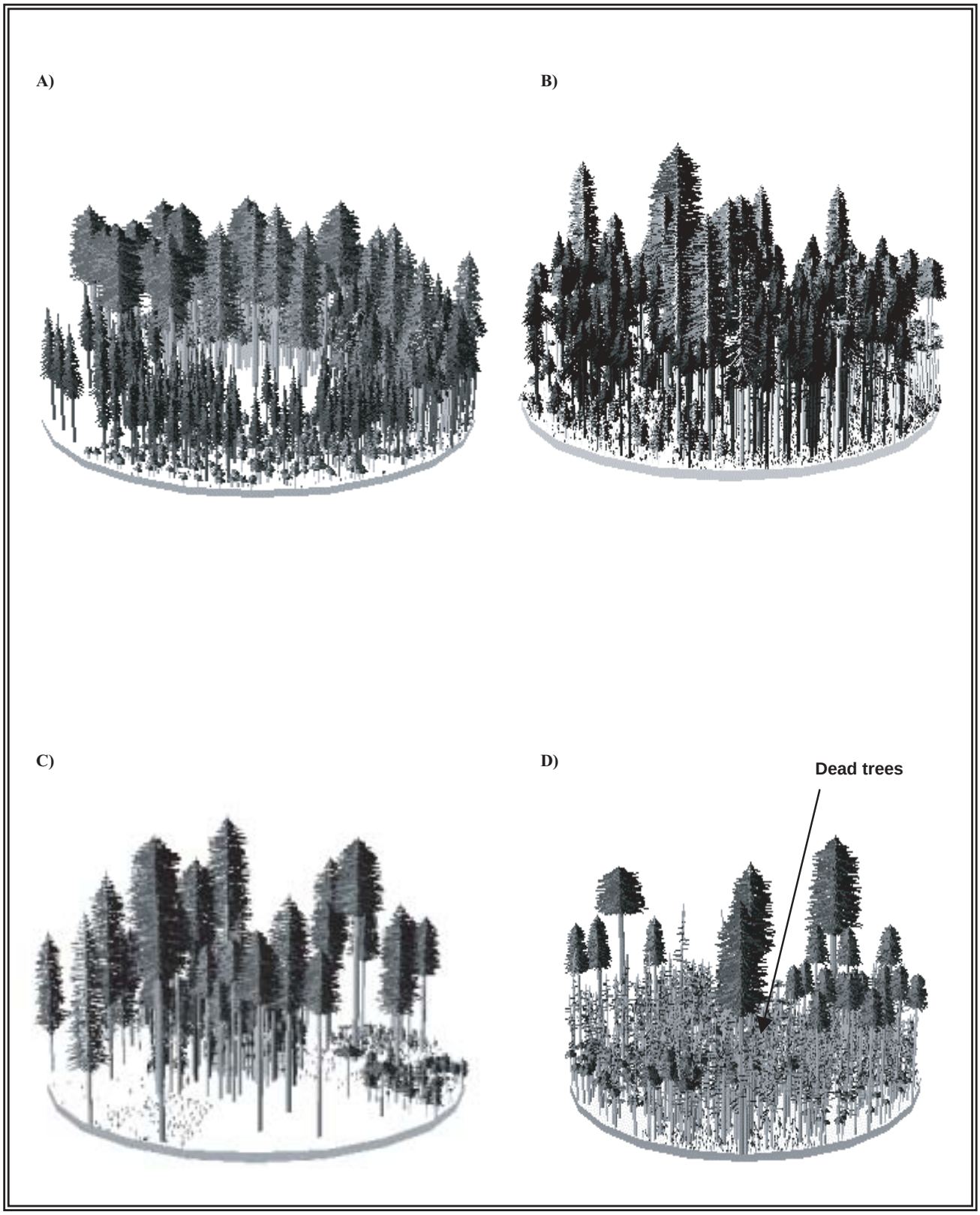


Figure 2—Habitat Stage Classifications for the northern spotted owl focal species area: (A) Stand is nesting roosting and foraging habitat (NRF); (B) Stand is dispersal habitat; (C) Stand has sufficient large trees but not enough canopy cover to be NRF; (D) Stand is nonhabitat — it has neither enough large trees nor enough canopy cover to be considered NRF or dispersal habitat.

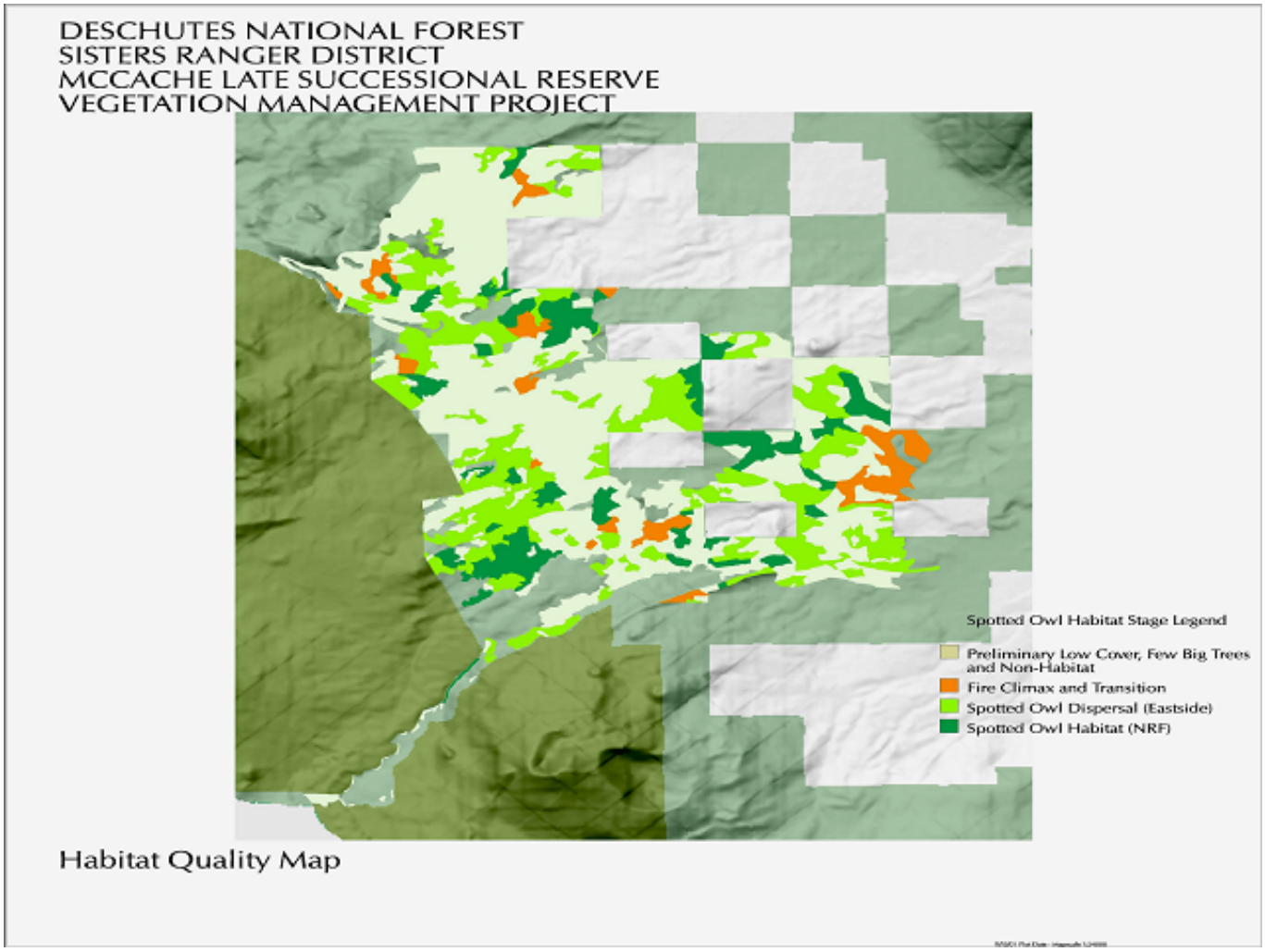


Figure 3—Northern spotted owl habitat stage classifications spatially mapped over the spotted owl focal species habitat area for McCache Vegetation Management Project.

Table 2

Northern spotted owl focal species habitat stage	Probable stand management objectives	Prescription
NRF	Desired condition has already been met	No treatment
Dispersal Habitat	Develop into NRF	No Treatment or
	Reduce fire hazard	Thin from below to 20% below the upper management zone[1]
	Maintain tree vigor and species composition.	
Sufficient Large Trees	Allow fir understory to develop	No Treatment or
	Fire hazard reduction	Thin from below to 20% above the lower management zone[1]
	Maintain health of large trees	
Non-habitat	Retain as travel corridor for other late successional species	No treatment or
	Restore large tree structure as the first step of creating NRF long term	Remove dead trees
	Reduce fire hazard	Remove all true fir under 21 inches d.b.h.
		Thin residual trees or plant a mixture of ponderosa pine and Douglas-fir, if necessary

[1]Stocking levels based on Cochran 1992

be projected in FVS. For the McCache vegetation management project, nearly complete stand exam coverage "with the exception of the plantations" was available. However, partial stand exam coverage is more often the case. We are currently working on another analysis area where only half of the area was inventoried. Stands exams from stands of similar structure (diameter class distribution), density (basal area/acre), and species composition were assigned to the noninventoried polygons to obtain the desired coverage. The assignments were made using the most similar neighbor analysis procedure (MSN) (Moeur and Stage 1994; Moeur and others 1995). Interpreted aerial photography provided the global data layer for the MSN analysis.

Step 8. Construct keyword component files for runstreams; calibrate and select appropriate models and submodels. FVS runs using our technique are constructed entirely of keyword component files (kcp files). These kcp files can be composed of a combination of base and submodel commands as well as custom variables created within the event monitor. For each stand, these keyword component files (kcp files):

- Calibrate the base model
- Call and calibrate appropriate FVS submodels
- Simulate important successional processes not available as off-the-shelf submodels with the user's FVS variant (for example, natural regeneration)
- Assign hazard ratings for important disturbance agents over time
- Simulate proposed silvicultural treatments for each alternative (including followup treatments in later years)

For example, each of the 346 stands in the McCache spotted owl focal species area was assigned four or five kcp files. Kcp files are available upon request:

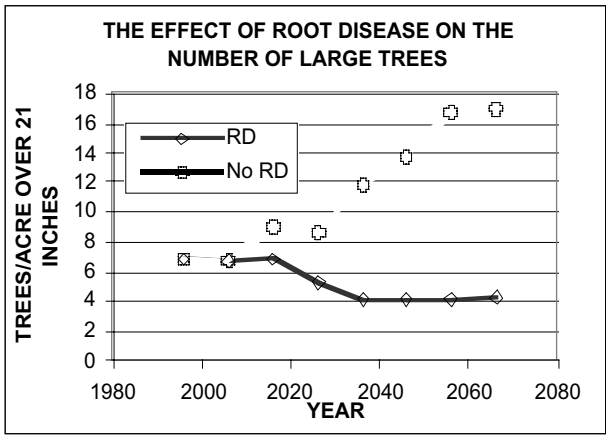
- The first kcp file calibrated the base model (in terms of site quality and growth); modeled natural regeneration and endemic as well as density-induced mortality from mountain and western pine beetle. In brief, this kcp file addressed live tree regeneration, growth, and mortality processes given the no action alternative.
- The second kcp file initialized and calibrated the western root disease model. Root disease was severe and widespread throughout the area but was not adequately represented in the stand exams. An estimated stand root disease condition was, therefore, assigned based on model ready keyword sets from forest inventory data (Gregg and Goheen 1997) plots in the project area and a 1980s root disease survey of a portion of the project area.
- The third kcp file classified the stand in terms of spotted owl habitat stage, by cycle.
- The fourth kcp file modeled hazard to stand-replacing wildfire.
- The fifth kcp file modeled western spruce budworm hazard.
- The sixth kcp file modeled the prescription assigned to the stand by alternative, including any additional natural regeneration promoted by ground-disturbing activities. This kcp file was not included for untreated stands.

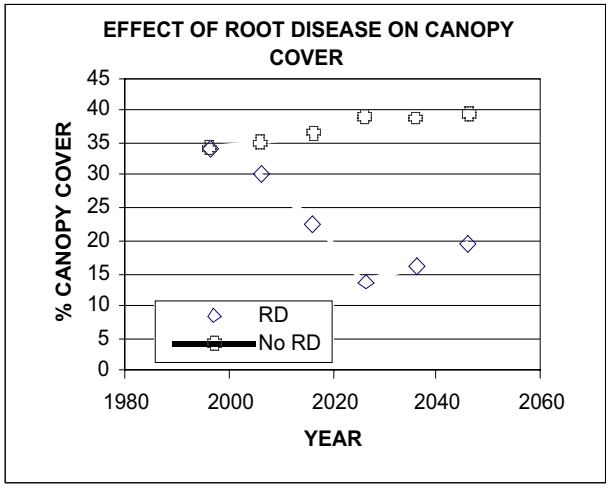
The inclusion of appropriate disturbance models for the long-term projections is critical. For example, the spotted owl focal species area in the McCache project is moderately to severely infected with root disease. As such, root disease will have a significant effect (fig. 4) on the outcomes of proposed alternatives. Without modeling this important disturbance process, future hazardous fuel loads will be underestimated, and projections of spotted owl habitat will be overoptimistic. Figure 4 compares projected habitat development and fuel buildup using and not using the root disease model.

Step 9. Structure runs for processing multiple stands, by alternative, with appropriate kcp files. Because this is a spatially explicit landscape analysis, FVS projection runs commonly consist of many hundreds of stands. Thus, an efficient process for creating the run stream is essential. We recommend that each project share a common Suppose.loc file, but that there be Stand List Files (SLF files) for each alternative. Within each SLF file, kcp files are assigned on a stand-by-stand basis. This assignment is based on the individual stand's focal species area, site quality, insect and disease occurrence, and proposed management treatment. Given the number of stands involved, it would be laborious to manually edit the SLF files and Suppose.loc file to make the necessary kcp files assignments. For the McCache analysis, a project-specific visual basic program was written (by Don Vandendriesche, Forest Management Service Center) and used to expedite the assignment of the kcp files to appropriate stands.
An interactive visual basic program to make these assignments for any project of this type has since been written (by Leo Yanez, Deschutes National Forest). In order to assign stands to groups and/or kcp files to stands, the program edits the Suppose.loc and SLF files referencing user-provided lists of stand exam names. These lists designate group membership and kcp files assigned to the stands. For example, each stand in the McCache LSR project spotted owl focal species area was assigned one of three levels of root disease severity based on forest inventory and survey data. Thus, there are three versions of the root disease kcp file that initialize and calibrate the western root disease model. The user specifies which stand goes with which version in the form of three text file lists of stand names. The process is repeated with other kcp files including the prescription kcp file and the site/quality natural regeneration kcp file. This program is available upon request.

Step 10. Make projection runs, and summarize and display data. Projected variables for each stand can be tied to GIS and mapped so that users can spatially view projected outcomes over time. Tables of outcomes of effects by acres can also be generated with ease as well. Figures 5 and 6 show projections from the McCache LSR comparing the most dramatic action alternative versus the no action alternative, in terms of habitat stage and fire hazard over a 30-year period. Figures 5 and 6 also illustrate the following:

- High fire hazard will persist long term without treatment.
- Damage will continue from disease and insect hazard will increase without treatment.
- Treatment can promote greater stability and initiate the process of developing new late successional habitat.
- Reduced fire hazard comes at the expense of dispersal habitat.





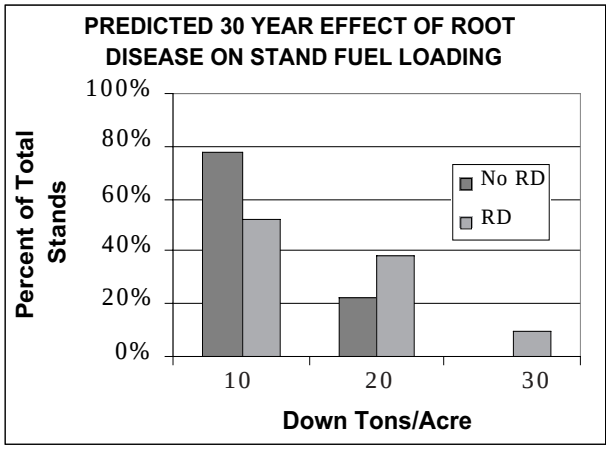


Figure 4—Predicted effects on two key components of spotted owl habitat—large tree structure and percent canopy cover provided by 6 inch d.b.h., or greater, trees and fuel loading. A stand in the McCache project area was projected over a four-decade period using FVS. Projections were made both with and without incorporating the impacts of root disease via the western root disease model. Levels of root disease used for the projections were the actual levels found in the stand.

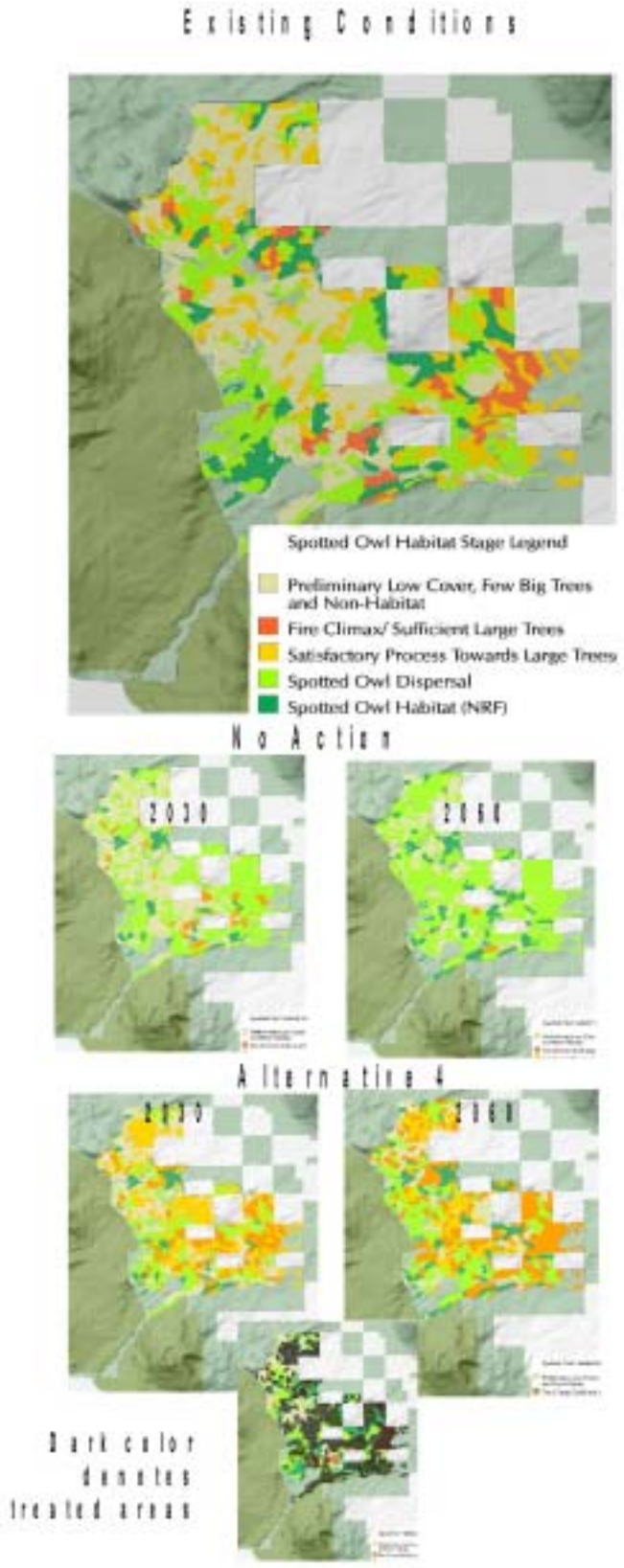


Figure 5—Projected spotted owl habitat stage over time for most dramatic treatment alternative versus the no action alternative for the spotted owl habitat focal species area in the McCache project area.

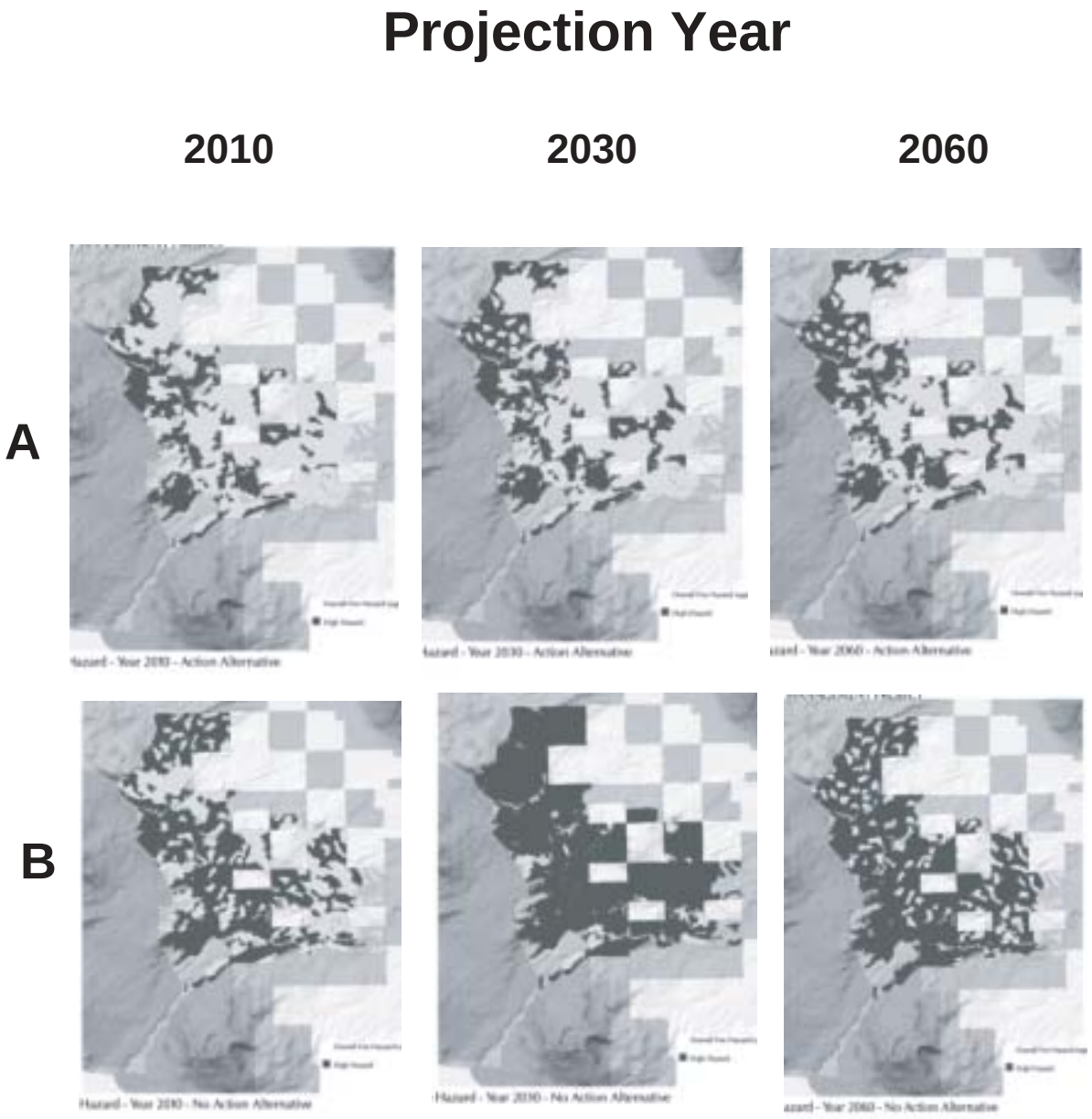


Figure 6—Projected fire hazard over time for most dramatic treatment alternative (A) versus the no action alternative (B) for the spotted owl habitat focal species area in the McCache project area.

Results

In the case of the McCache analysis, the clearly depicted effects established agency and interagency support for the most dramatic action alternative proposed. It demonstrated that, without treatment, late successional habitat was unlikely to regrow on its own (primarily due to insect and disease activity) and that susceptibility to severe wildfire impacts would continue over the long term. The proposed treatments would result in lower fire hazard and promote redevelopment of late successional habitat. The decision notice for this project was recently signed.

Conclusions

We believe this methodology is a helpful and objective landscape analysis tool for evaluating vegetation management projects in late successional reserves and other old growth areas. At the least, it can help convey to stakeholders a common understanding of the logic and rationale driving the proposed actions. It can also help clarify the expected immediate and long-term benefits and tradeoffs between alternatives in terms of the resource of interest, late successional habitat. Spatially explicit graphic and numerical displays of effects on spotted owl habitat over time helped

explain the logic and rationale of the project, demonstrate the need for treatment, and communicate expected effects of alternatives to stakeholders. As a result, understanding and a base of support were developed among stakeholders for the active management proposed by the project.

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

S. Hummel
D. Calkin
J. Barbour

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.

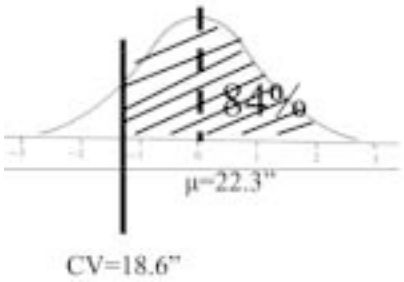
Results

Implications of the Diameter-Limit Treatment

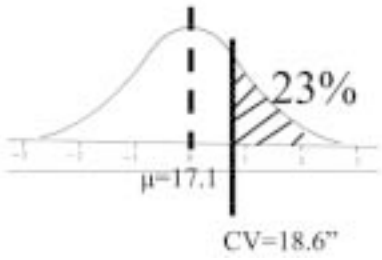
The diameter-limit treatment resulted in many of the units being categorized as LSF over time. Scheduling the treatment on some units increases the amount of LSF up to some point, which means that the relationship between treatment and LSF is complementary. We used a simple optimization algorithm to 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.

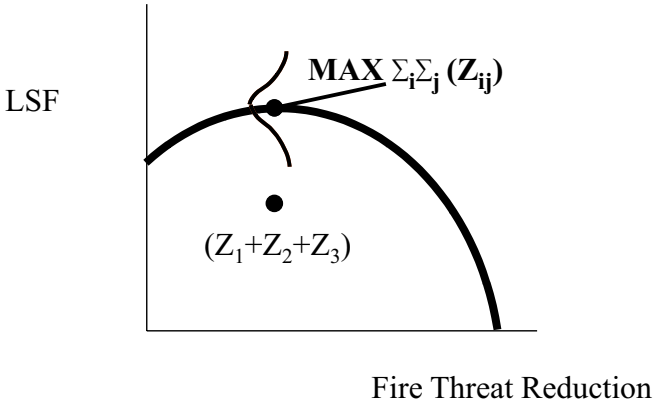


Figure 2—Hypothetical tradeoff between two landscape resource goals: late-successional forest (LSF) and fire threat reduction.

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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Analyst Hazards When Assessing Fire, Insect, and Disease Hazard in Montana Using FIA Data with FVS: Or Alligators We Didn't See Coming

David Atkins
Renee Lundberg

Abstract—The Forest Vegetation Simulator (FVS), with the Fuels and Fire Effects and Insect and Pathogen Extensions, was used to characterize forest health hazards in Montana. Forest Inventory Analysis (FIA) data were processed through FVS to characterize current and future hazards related to fire, insect, and disease. While conducting this Statewide analysis, several weaknesses in the base model and extensions were discovered. The paper presents problems encountered, how they were resolved, recommendations for future FVS development, and research needs.

The potential for wildfires to put lives, property, and environmental values at risk is a much discussed and debated topic in recent years. It is important for managers, policy makers, and the public to understand potential wildfire behavior and effects, along with the potential for insect and disease activities and their potential interaction with fire. Describing changes that may occur across an entire State requires a consistent dataset across ownerships and the tools to analyze these data. Using the Forest Inventory and Analysis (FIA) Database and the Forest Vegetation Simulator Model (FVS) program provides this opportunity. Atkins and Lundberg (in preparation) used FIA plot data processed through FVS (Wykoff and others 1982; FMSC 2001) to predict current and future hazards related to fire, insect, and disease. In the process of conducting this Statewide analysis, several weaknesses in the base model and extensions were observed. The objectives of this presentation are:

- To provide FVS users with an overview of our results.
- To share the problems we encountered and how we dealt with them.
- To submit recommendations for future system development and research needs.

In: Crookston, Nicholas L.; Havis, Robert N., comps. 2002. Second Forest Vegetation Simulator Conference; 2002 February 12–14; Fort Collins, CO. Proc. RMRS-P-25. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

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Overview of Results

The original work had two objectives: (1) to develop methods to use FIA data and FVS, incorporating its Fuels and Fire Effects (FFE) (Beukema and others 2000) and the Insect and Pathogen (I&P) (FHTET 2001) Extensions, to characterize current and simulated future forest conditions; and (2) to use the methods developed to describe the conditions of Montana forests now and in 50 years.

Methods

We used FIA data for the State of Montana (USDA 2000; Conner and others 1993; O'Brien and Conner 1991; USDA 1988) for this analysis. There are a total of 3,721 forested plots from all ownerships, with the exception of National Park Service lands that have not yet been inventoried. The 2,343 National Forest System (NFS) plots were inventoried between 1993 and 1998. There are 1,378 plots on private and other public lands, which were inventoried in 1988 and 1989. For purposes of display, all plots were modeled with 2000 as the inventory year. Our results do not reflect changes in the forest condition from fires, insect, disease, or management activities that may have occurred between the inventory year and 2000.

Fire, insect, and disease potential are affected by a variety of variables that describe and influence how much and where hazardous conditions exist. We used these variables to stratify the data:

- Forest type
- Potential vegetation groups
- Stand structure
  - o Size class
  - o Stand layering
- Ecoregions (fig.1)

The Eastern Montana (EM) and North Idaho (NI) variants of FVS were used in modeling the FIA plots. The FVS model was modified to allow both FFE and I&P extensions to model fire, and insects and diseases simultaneously. This was important because insect and disease processes directly affect fuel loadings and subsequent fire behavior. Insect and diseases behave somewhat differently in varying environmental settings (Hagle and others 2000). To account for these variations we used the action probability indices (APIs) from the results of Hagle and others (2000) to create

Figure 1— Ecoregions in Montana.

the FVS keyword files by habitat type groups for east and west of the Continental Divide.

The FVS Fuels and Fire Effects Extension provides indicators of fire effects including tree mortality, exposed mineral soil, and fuel consumption. We chose fire type and crown index as our measures of fire hazard. Mortality is influenced by the intensity of the fire, species of trees in the stand, and their size, both diameter and height. We show fire type, forest type, and basal area loss to illustrate potential fire mortality. The I&P extensions simulate mortality from various agents, including root disease, bark beetles, and mistletoe, as FVS projects the forest through time. We show bark beetle hazard as an example.

Fire behavior and effects vary considerably with short-term weather and longer term climatic conditions (drought) through time. Although these variables occur along a continuum, we chose to simulate two conditions. One represents the average summer day weather and average climatic conditions. The second represents extreme fire weather conditions and very dry climatic conditions. They are displayed in table 1.

Down woody debris data were available on 88 percent of the NFS plots. These measured fuel loadings were used in the FVS simulations. For the plots without measured fuel data, the default values from the FFE model were used. Fuel loadings directly affect flame lengths, fire intensity, and fire effects. By incorporating actual fuel loadings, the simulations better reflect the variation that exists in Montana forests.

After the plots were processed by FVS, the output was run through a custom program to extract specified report fields and then loaded into an Access database, which facilitated summarization and analysis.

Table 1—Weather conditions used in FVS to represent average and extreme fire scenarios.

Weather conditions	Average fire	Extreme fire
20 foot wind speed	15	40
Temperature	75	90
Fuel Moistures:		
1 hour (0-1/4")	6%	4%
10 hour (1/4-1")	8%	6%
100 hour (1-3")	10%	7%
1000 hour (3"+)	15%	12%
duff	100%	65%
live	90%	60%

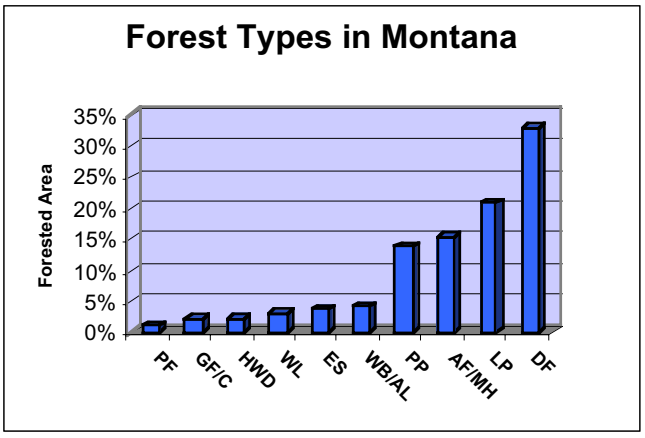
Results

In order to understand and display the potential for fires, insects and disease and their possible effects, we first summarized the inventoried conditions, forest type, structure, layering, size class, and hazard rating for bark beetles. Then we related these characteristics to FFE outputs: fire type, crown index, and mortality. The results also included some 50-year projections.

Figure 2 shows that Douglas-fir *(Pseudotsuga menziesii)*, lodgepole pine *(Pinus contorta)*, subalpine fir *(Abies lasiocarpa)*, and ponderosa pine *(Pinus ponderosa)* forests are dominant types across the State. Douglas-fir and lodgepole pine compose over half of the forest types, and these four types represent 83 percent of the forests in Montana.

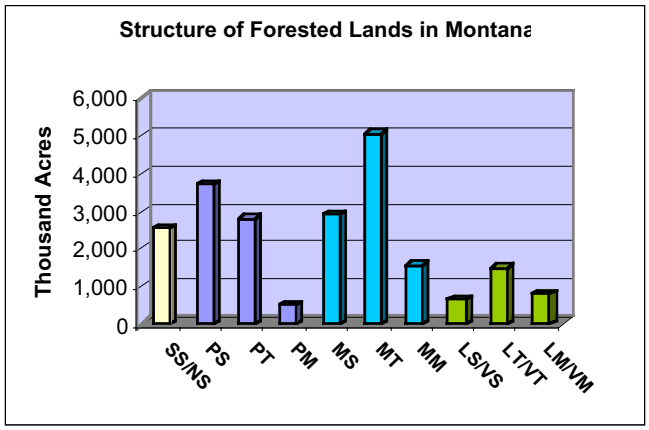
Figure 3 shows that medium two storied stands are the most common condition in the State. Figure 3 also illustrates that two-storied and multistoried stands (layered stands with fuel ladders) are abundant, representing approximately 12.3 million acres.

Figure 4 shows the relative abundance of the four size classes. The medium size class is most abundant. The pole class is next in abundance with the seedling/sapling and large size classes present in lesser amounts. This size class distribution is reflective of fire suppression and the logging history. This distribution of size classes has important ramifications for fire, insect, and disease hazard.



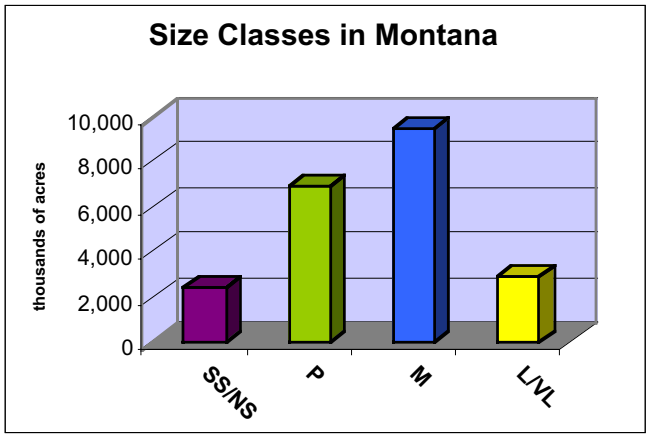
PF–limber pine, GF/C-grand fir & cedar, HWD-hardwood, WL-western Larch, ES-Englemann spruce, WB/AL-whitebark pine & subalpine larch, PP-ponderosa pine, AF/MH- subalpine fir and mountain hemlock, LP-lodgepole pine, DF- Douglas-fir

Figure 2—Percent of forested area in Montana by forest type.



SS/NS–Seedling/Sapling & Non-stocked
P-Pole, M-Medium, L/V Large & Very Large
S-Single Story, T-Two Story, M-Multi-story
Example: MT – Medium Two Story

Figure 3—Number of acres by structure group for forested lands in Montana.



SS/NS–Seedling/Sapling & Non-stocked
P-Pole, M-Medium, L/V Large & Very Large

Figure 4—Number of acres by size class in Montana.

Insects, particularly bark beetles, can have a substantial effect on fuel loading and stand structure over time. Figure 5 illustrates that approximately 8.6 million acres are in moderate and high hazard conditions from bark beetles. These figures indicate stand conditions that could support an outbreak given the right combination of conditions. Some of these acres have been, or are currently being, attacked since the plot data were collected in the late 1980s to the late 1990s. It can be seen that lodgepole pine and Douglas-fir forest types have the greatest amount of hazard. This is partly a reflection of the size class distribution illustrated earlier in figure 4.

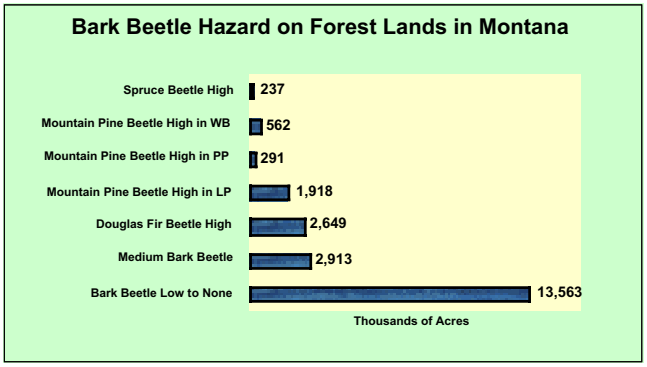


Figure 5—Number of acres by bark beetle hazard rating for forested lands in Montana. Note host species are indicated where hazard rated as high (WB - whitebark pine, PP - ponderosa pine, LP - lodgepole pine). Medium and low hazard area include all host species forest types.

The FFE simulates wildfire type based on the conditions *within* the particular stand that is modeled. The FFE classifies fires behavior into three types:

- **Surface fire:** The fire burns on the ground through the dead and down material, and crowns do not burn.
- **Passive fire:** The fire burns on the ground, and some crowns will burn as individual trees or groups of trees torch, but fire is not sustained in the crown.
- **Active fire:** The fire is a running through the crowns burning all crowns, thus killing all trees.

The potential for fire is a function of weather, fuel conditions, and topography, and the interplay of these variables. We modeled two weather conditions to provide a sense of how weather influences fire behavior and effects. Figures 6a and 6b display the percent of area by fire type for the inventoried conditions, given average and extreme weather parameters. With the extreme conditions, the amount of active fires increased eight-fold, while the passive and surface fires decreased.

Stand layering has two somewhat contrary effects on fire behavior. One is to add ladder fuels that facilitate flames reaching into the canopy of the forest resulting in passive or active fires. The second effect is to reduce the within-stand wind speed on the fire, which can reduce the potential for the flames to reach the forest canopy, thus reducing the amount of passive and active fire. The FFE model accounts for this interaction by using crown base height and canopy closure calculations to determine if fire can get into the crown. If the crown canopy is within reach of predicted flame lengths and there are adequate ladder fuels, then torching and crowning fires will result. The model uses percent canopy cover to calculate mid-flame wind speed, thus incorporating density effects on within-stand wind speed.

Figures 7a and 7b show the percentage of fire types for average and extreme weather conditions. The amount of

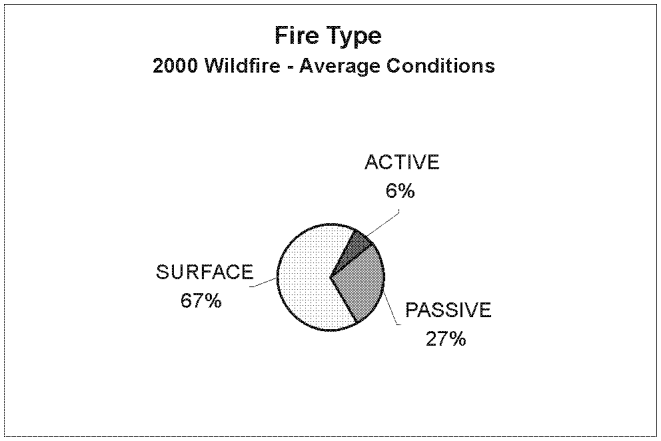


Figure 6a—Percent of forested area in the three FVS simulated fire types, using average fire conditions and current/inventoried plot data.

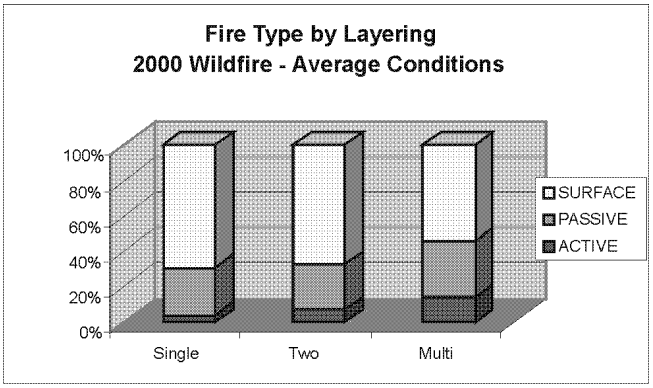


Figure 7a—Percent of forested area in the three FVS simulated fire types, for single story, two story and multi-story conditions, using average fire conditions and current/inventoried plot data.

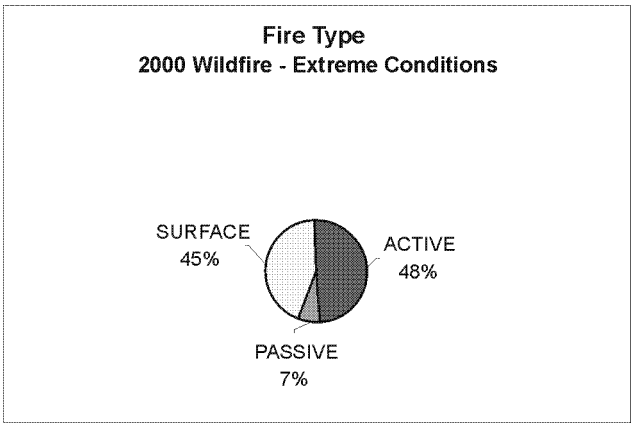


Figure 6b—Percent of forested area in three FVS simulated fire types, using extreme fire conditions and current/inventoried plot data.

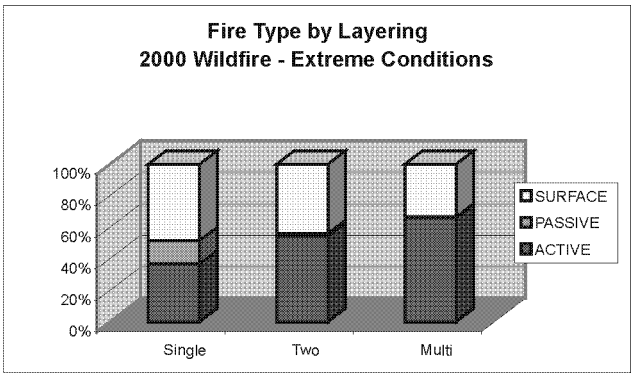


Figure 7b—Percent of forested area in the three FVS simulated fire types, for single story, two story and multi-story conditions, using extreme fire conditions and current/inventoried plot data.

passive fire behavior in average conditions increases from 4 percent for single-storied stands to 14 percent for multistoried stands. With extreme fire conditions, the active fire increases from 37 to 66 percent as layering increases from single to multistoried stands. The fire intensity increases with the number of layers, regardless of weather conditions.

The simulated fire type reflects fire behavior *based on the fire originating in that stand*. It does not reveal how a fire might spread into the stand from an adjacent stand. This is an important point when interpreting the results. Fires that burn hundreds to tens of thousands of acres are primarily a function of fire spread from stand to stand.

Two fire indices are produced by the FFE model: crowning index and torching index. The interplay of these indices, with the specified weather and fuel loadings, results in a fire type being assigned (Beukema and others 2000). The torching index indicates the wind speed needed to move the flames burning in the ground fuels into the tree crowns. Crown base height is an important variable in computing this index.

The crowning index indicates the wind speed needed to sustain a crown fire. This is largely a function of crown bulk density. The denser the canopy and the steeper the slope, the less wind is needed to sustain a crown fire. Crowning index gives an indication of the potential for fire to spread from stand to stand, the behavior that drives medium to large fires.

Figure 8 shows the percentage of forested area in three crowning index classes. If a stand is in class 1, winds of 15 mph or less will sustain a running crown fire; in class 2, winds of greater than 15 to 40 mph will sustain a crown fire. This index is important because a stand classified as surface-fire type may have a low crowning index, which means it lacks ladder fuels to help fire get into the crown. But once

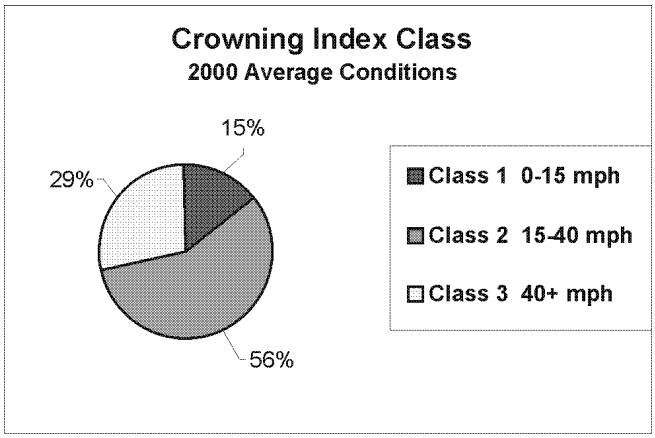


Figure 8—Percent of area in three crown index classes, using average fire conditions and current/inventoried plot data.

in the crown, fire is easily sustained. Figure 9 shows the acres in three crowning index classes by fire type for average conditions. Note that 7.8 million acres of surface-fire type would sustain a crown fire, spreading from another stand, if winds were greater than 15 to 40 mph. An additional 1.8 million acres of crown-fire type could be sustained with wind speeds less than 15 mph winds. Over 4.6 million acres of passive-fire type would sustain a crown fire with winds between 15 to 40 mph. In total over 15.7 million acres have crown indices in the 0 to 40 mph wind classes, which indicates 71 percent of Montana's forests are at risk of crown fire, even though modeled weather conditions relegated them to the surface- or passive-fire type categories.

It is important to consider fire hazard using both fire type and crown index. The fire type indicates the potential for fire moving vertically within a stand, and the crown index shows the potential for fire moving horizontally across the landscape as an active fire. Both aspects are important when determining how to reduce fire hazard.

Figure 10 shows the basal area mortality for Montana's forest types by fire type. The variation in mortality illustrates that forest types dominated by species resistant to fire have substantially less mortality. For example, a surface fire in the lodgepole type results in an average of 67 percent mortality, while the average is 32 percent in the ponderosa pine type. For passive fires, there is less variation in the mortality between forest types, but the trend between types is similar.

Figure 11 illustrates that there is little difference in mortality related to layering, which indicates that a similar type of fire produces similar mortality regardless of layering. However, as illustrated in figure 7, layering does affect the amount of fire type, with single layer stands having the

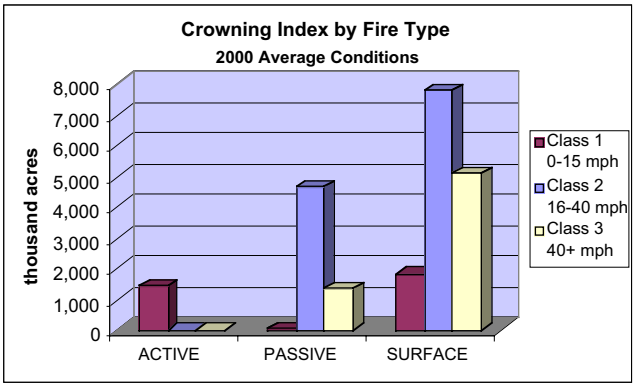
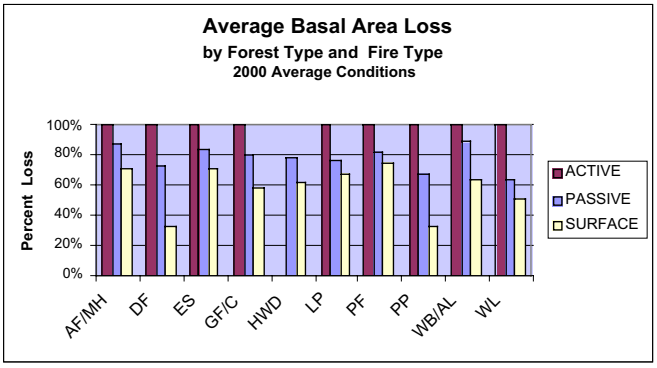


Figure 9—Acres by crown index class for the three FVS simulated fire types, using average fire conditions and current/inventoried plot data.



PF–limber pine, GF/C-grand fir & cedar, HWD-hardwood, WL-western Larch, ES-Englemann spruce, WB/AL-whitebark pine & subalpine larch, PP-ponderosa pine, AF/MH- subalpine fir and mountain hemlock, LP-lodgepole pine, DF- Douglas-fir

Figure 10—Average percent basal area loss by forest type, for the three FVS simulated fire types; using average fire conditions and current/inventoried plot data.

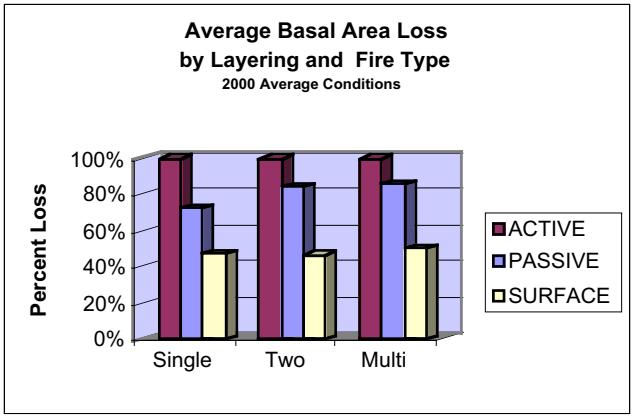


Figure 11—Average percent basal area loss in single story, two story and multi-story areas, for the three FVS simulated fire types, using average fire conditions and current/inventoried plot data.

least and multilayer stands the greatest distribution of active and passive fire. Therefore, mortality is affected by layering because it affects the type of fire simulated. Mortality does vary by size class as shown in figure 12. For surface fires, mortality decreases from 66 percent in seeding/saplings to 34 percent in the large/very large class. The implication is that forests composed of fire resistant species and larger size classes suffer less mortality given the same fire type.

Analysis Problems/Challenges

In this section we describe the challenges we encountered, how we calibrated the model, and suggest system developments that would improve and streamline analysis. We also highlight research needed to improve model behavior.

Model Calibration and Improvements

During the analysis we encountered several problems with default values and made adjustments, described below. Other limitations were identified, and recommendations for future improvements are presented.

Ingrowth and small tree mortality—Model runs with default parameters resulted in outputs inconsistent with our knowledge and that of others with considerable experience in Montana. The NI variant projected a 70 to 90 percent decrease in understory trees per acre over 50 years. Experience and fire history studies (Smith and Arno 1999) indicate an increase of small trees when fire has been excluded.

We used Flathead National Forest permanent growth plot data (Northern Region, unpublished) to provide a basis for adjusting model performance. Analysis of the data revealed the base FVS model was killing too many tolerant species, such as subalpine fir, and not enough of the intolerant species, such as western larch. Also the permanent growth plots indicated a substantially greater number of tolerant species becoming established through time. We adjusted the model using the MortMult and Estab keywords.

Our adjustments used only the Flathead growth plots because they were the only data set available at the time. A more thorough analysis of all the permanent growth plot data is needed and consideration given to calibration of the NI and EM variants of FVS based on this analysis.

Fuel load initialization—Actual fuel loading data were available on most of the NFS plots. We used the FuelInit keyword to initialize fuel loading for these plots. For plots without data, default values were used. We compared the average measured fuels to the default fuels and found the default loadings were lower. As a result, the flame lengths and subsequent fire behavior are most likely underestimated for the plots modeled with default values.

FIA fuel transect data could be used to refine the default fuel loadings. Analysts are encouraged to use field measurements where available.

Decay rates—The decay rates of woody debris in the version of the model that we used seemed high. We expected to see an increase in fuel loading over time. The average fuel loading during our 50-year projections remained about same, even though no burning or harvesting activities occurred. However, we would have expected fuel loadings to increase due to ongoing insect, disease, and suppression mortality. As a result, we feel fire behavior is underestimated for the 50-year projections.

Another concern is the same decay rate applies to all habitat types. Decay rates are a function of moisture and temperature, so we would expect variation by habitat type. Since our work was completed, the model has been adjusted. However, the knowledge of decay rates is limited, indicating an area needing further research.

"Other" species—FVS uses OT (other) for less common species such as whitebark pine, alpine larch, and hardwoods. FVS's definition of OT species depends on the variant. We need to be able to model and display all species. It is becoming more important to be able to quantify and predict the effects of fire, insect, and diseases for all species. This may mean additional research in a number of areas including fire response, crown bulk densities, growth and regeneration, or others.

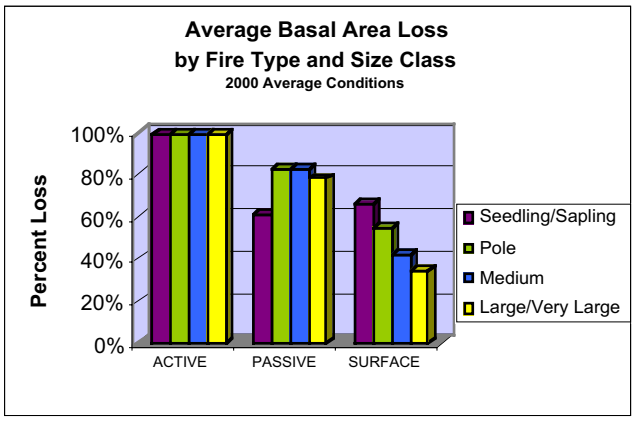


Figure 12—Average percent basal area loss by size class, for the three FVS simulated fire types using average fire conditions and current/inventoried plot data. Seedling/Sapling class includes seedling, sapling and non-stocked areas.

Programming Needs

Several improvements in data processing are needed to make this type of analysis more efficient. Our project required substantial assistance from a several data managers and programmers. The following is a list and discussion of improvements that would streamline analysis.

Software that migrates FIA data into FSVEG—When we started our project, FIA data were not available in FVS format. The USDA Forest Service's FSVEG database has the capability to do this. However, the FIA data have not been loaded into FSVEG at this time. All users need to be able to access FVS-formatted FIA data for both NFS plots and non-NFS plots.

Adding attributes to data sets—A programmer modified the FVS files by attaching attributes such as action

probability indices (for insect and diseases), inventoried fuel conditions, and habitat type groups. This step greatly simplified running the model. There is a need to develop more automated tools that would give users the ability to modify or supplement the FVS data without getting specialized help from programmers.

FVS output/reports—We used a custom program to extract selected report fields. This program only works for the output data fields we chose. This "extract" program enabled us to load selected report fields into an Access database, and to analyze and graphically display results. There is a need for an FVS postprocessor that would put user-defined fields in a flat-file format, so that large data sets could be easily moved into other software applications. This would greatly facilitate postmodeling analysis.

Postprocessing analysis—We wanted to quantify how insects, diseases, growth, and mortality change forest types and fire conditions, but we were unable to compare inventoried, FIA forest type with the simulated stand forest type after 50 years. A postprocessor routine that reclassifies forest type is needed for this type of analysis. This application is under development.

Mortality source identification—We were not able to distinguish the cause of mortality between bark beetles, root disease, or suppression. With current reports it is impossible to discern the influence of insect and disease activity on fire type, fuel models, and stand conditions. The way the I&P extensions operate, more than one agent can kill the same tree. To assess the impacts of insect and pathogens, and determine the source of fuels, a methodology to track mortality by agent for each cycle would be useful.

Non-NFS plots do not have a National Forest—Some FVS variants use National Forest (NF) in growth calibrations. The default for the NI variant is St. Joe NF, and the EM variant uses the Custer NF. This was unsatisfactory for our analysis since the plots were from across the whole State. We solved this by assigning a National Forest based on ecosection and county. This was added to the Montana FVS stand list files. It is desirable to have a preprocessing option available to allow all users to add National Forest.

Additional Research Needs

- It is apparent that permanent growth plot data and FIA data, used separately and in conjunction with each other, could be used to calibrate and improve FVS predictions.
- Research on ingrowth, small tree mortality, fuel loading, decay rates, and crown dynamics is needed and should be incorporated into FVS as information becomes available.
- Because crown bulk density is a critical factor in predicting and managing fire behavior, but not easily measured, research is needed to find a readily applicable field technique to characterize it.
- There is a need to develop a better overall measure of fire hazard that integrates fire type with crown index and torch index.

Conclusions

Our project demonstrates the utility of using FIA data in combination with the FVS model, and its extensions, for examining fire, insect, and disease hazard for large geographic areas, such as the State of Montana or subregions of the State. Where data are available, they can also be applied to a multi-State level. The flexibility of the model allows it to be parameterized for a variety of different environmental conditions. Our conclusion is the model and data provide a powerful tool to help land managers and policymakers assess conditions and provide a basis for making decisions.

The model was useful in describing specific indicators, which allowed us to depict current conditions related to fire, insect, and disease hazard. The results lead us to the following conclusions:

- An abundance of medium and pole sized forests exist, and the fire hazard is not just a small tree problem. There are too many medium sized trees as well.
- An abundance of forests with two or more layers exist, which provide fuel ladders for fire.
- An abundance of forests exist with crowning index ratings that indicate high potential for crown (active) fires, which leads to the highest mortality.
- The extreme weather conditions resulted in much higher amounts of active fire, and subsequently the mortality and effects are greater than with average conditions.
- It is important for decisionmakers to consider both fire type and crowning index when assessing the overall fire hazard.
- Stand structure and composition that favor fire resistant species, larger diameter trees, lower crown bulk densities (the major factor in crown index), and less stand layering reduce fire intensity and mortality predicted when fires do occur. This gives managers options for taking action to change hazard level, where desired.
- An abundance of forests are rated as moderate to high hazard for bark beetle attack.

A number of caveats and limitations need to be recognized by analysts and decisionmakers when using these tools and data:

- Small tree mortality and ingrowth should be adjusted for the forest conditions being modeled because they can substantially change the results.
- On the non-NFS plots (37 percent of the plots), all of the 0 to 5 inch diameter trees may not have been recorded because survey methodology was to determine which plots were "stocked." Therefore ladder fuels are underestimated, resulting in less active and passive fire types.
- The default fuel loads appear to be underestimated, which leads to underestimating fire type intensity.
- The decay rates appear to be too high, which reduces the fuel load, which would tend to underestimate the intensity of the fire type.
- The use of only Flathead NF permanent growth plots for calibrating the small tree mortality and ingrowth may have resulted in overestimating ladder fuels for some areas, which would tend to overestimate the intensity of the fire type.

Future analyses could be made more efficient by:

- Making model improvements, such as adding tree species and recalculating growth and mortality functions, thereby producing more realistic results.
- Adding improved data input/output options to streamline data analysis, and reducing the number of helpers needed to format and manipulate data.

Remember what George E. P. Box said, "All models are wrong but some are useful!" Models are simplified abstractions of reality. We believe the results of this analysis are useful for showing overall trends in hazards and the factors that contribute to hazards. The model also provides information as to the potential effects that may occur. Therefore, even though we know these simulations cannot predict reality, they are useful for indicating patterns of likely outcomes and options for managers to alter fire effects.

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Simulating Fire Hazard Reduction, Wood Flows, and Economics of Fuel Treatments with FVS, FEEMA, and FIA Data

Glenn A. Christensen
Roger D. Fight
R. James Barbour

Abstract—This paper demonstrates protocols to analyze and illustrate trends in the long-term effects of repeated fire hazard reduction entries at broad state-level scales. The objectives of this analysis are to determine the effectiveness of two stand treatment options designed to immediately reduce and maintain lower wildfire hazards. Long-term effects of fire hazard reduction are reported for and the stocking, size, and species mix of trees logs that might be removed for wood products. We developed methods that use readily available tools to provide this information and relate it to treatment effectiveness in reducing fire hazard over time. The scope of the project covers all forested areas of Montana and New Mexico. Analysis is based on data collected by the Forest Service's Forest Inventory and Analysis (FIA) program for both States, but other types of inventory data for smaller land areas also could be used. The primary tools for this analysis are FVS, the Fire and Fuels Extension (FFE) model, and the Financial Evaluation of Ecosystem Management Activities (FEEMA) model. Model output from more than 1,000 plots is summarized using macros written for Microsoft Excel, SAS statistical software, and Microsoft Access. These protocols can be used to simulate a variety of broad-scale management options using stand level data that are readily available. This information could be invaluable to evaluate future management options over a wide range of spatial and temporal scales.

Substantial funding has recently been allocated to understanding options for long-term fire suppression effects and hazard reduction options for the Intermountain West. One such study is, "Assessing the Need, Costs, and Potential Benefits of Prescribed Fire and Mechanical Treatments to Reduce Fire Hazard in Montana and New Mexico" (Barbour and others, unpublished paper). Some of the methods used for that study are described in this paper. The analysis is part of the Joint Fire Sciences Program to develop protocols for use in determining hazard reduction treatment needs, treatment cost, and associated benefits at a State level. The objectives of the study were to (1) quantify existing stand conditions for major forest types in terms of density, structure, and species composition, and prioritize by need for hazard reduction treatment, (2) develop and compare alternative cutting and prescribed burning prescriptions for reducing high-hazard conditions in major forest types, (3) determine treatment costs, (4) determine potential revenue from timber products generated from the hazard reduction harvest treatments, (5) compare the future mix of timber products under alternative treatment scenarios, and (6) describe the potential for analyzing noncommodity resources under treatment and no-treatment scenarios (Barbour and others, unpublished paper).

Our objective was to simulate broad-scale wildfire reduction options using readily available tools and stand-level data. This paper describes the tools and analytical approaches used. The scope of the analysis includes all forested lands in Montana and New Mexico. Our analysis determined and illustrated trends in the long-term effects of repeated hazard reduction entries: the long-term effects in terms of the stocking, size, and species mix of stands, and the long-term effects, in terms of size and species mix, of trees and logs that might be removed and utilized for wood products. We also wanted to accomplish this analysis using readily available models, software, and data typically collected as part of comprehensive forest inventories.

Flow of Analysis

Analysis was based on data collected by the Forest Service's Forest Inventory and Analysis (FIA) program for both States, but other types of inventory data could also be used such as stand exam data. The primary tools for this analysis were the Forest Service's Forest Vegetation Simulator (FVS) growth and yield model (Stage 1973; Wykoff and others 1982), the FVS Fire and Fuels Extension (FFE) (Beukema and others 2000), and the Financial Evaluation of Ecosystem Management Activities (FEEMA) model (Fight and Chmelik 1998). To provide exact control of treatment execution and specific output variables, the Event Monitor (Crookston 1990) within FVS was used extensively. Microsoft Excel and Access were used to format, sort, and summarize data.

Our approach was to (1) extract the most recent forest inventory data, (2) apply a hazard reduction treatment using FVS, (3) use the FFE model to determine prefire and postfire hazard conditions for treated stands, (4) use a listing of removed trees from FVS as input to FEEMA (a customized version) to buck each tree into logs, calculate volume, and

In: Crookston, Nicholas L.; Havis, Robert N., comps. 2002. Second Forest Vegetation Simulator Conference; 2002 February 12–14; Fort Collins, CO. Proc. RMRS-P-25. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

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assign a dollar value, (5) store results from FVS, FFE, and FEEMA in a database so that summary statistics for any variable may be easily generated for any variable and subtotaled by any desired classification, and (6) report these data via standardized, tabular formats (fig. 1).

The large size of the study area poses challenges in obtaining current inventory data for the entire area (for example, for all ownerships) and in getting these data into a useable format. Because several models are used, custom linkages between them are needed to build an integrated analytic system, and because hundreds, perhaps thousands, of plots may be processed, this linkage needs to be as automated and seamless as possible. After data from each plot completes simulation, results need to be calculated. In order for results to be based on any desired grouping or subset, output from each plot for each year, each treatment, and each tree needs to be tracked. Finally, all of this information has to be distilled into a meaningful package that provides enough detailed information to make informed decisions, but not so detailed that extracting important results is overly laborious. The following sections describe how we overcame these obstacles and developed a methodology that can be readily used for analysis of forest lands where multiple plots need to be evaluated. The analysis is divided into three basic parts: data preparation, model simulations, and output summarization.

Data Preparation

The first and most important part of the analysis is to obtain inventory data that reflects as accurately as possible current vegetation for the area of interest. For our analysis we used the latest FIA inventory covering all forested ownerships of Montana and New Mexico. These data were gathered with assistance from the Forest Service's Forest Management Service Center (FMSC) and the Rocky Mountain Research Station. A total of 1,278 plots, roughly half from each State, are used in the analysis. These plots are not necessarily on an evenly distributed systematic grid. To

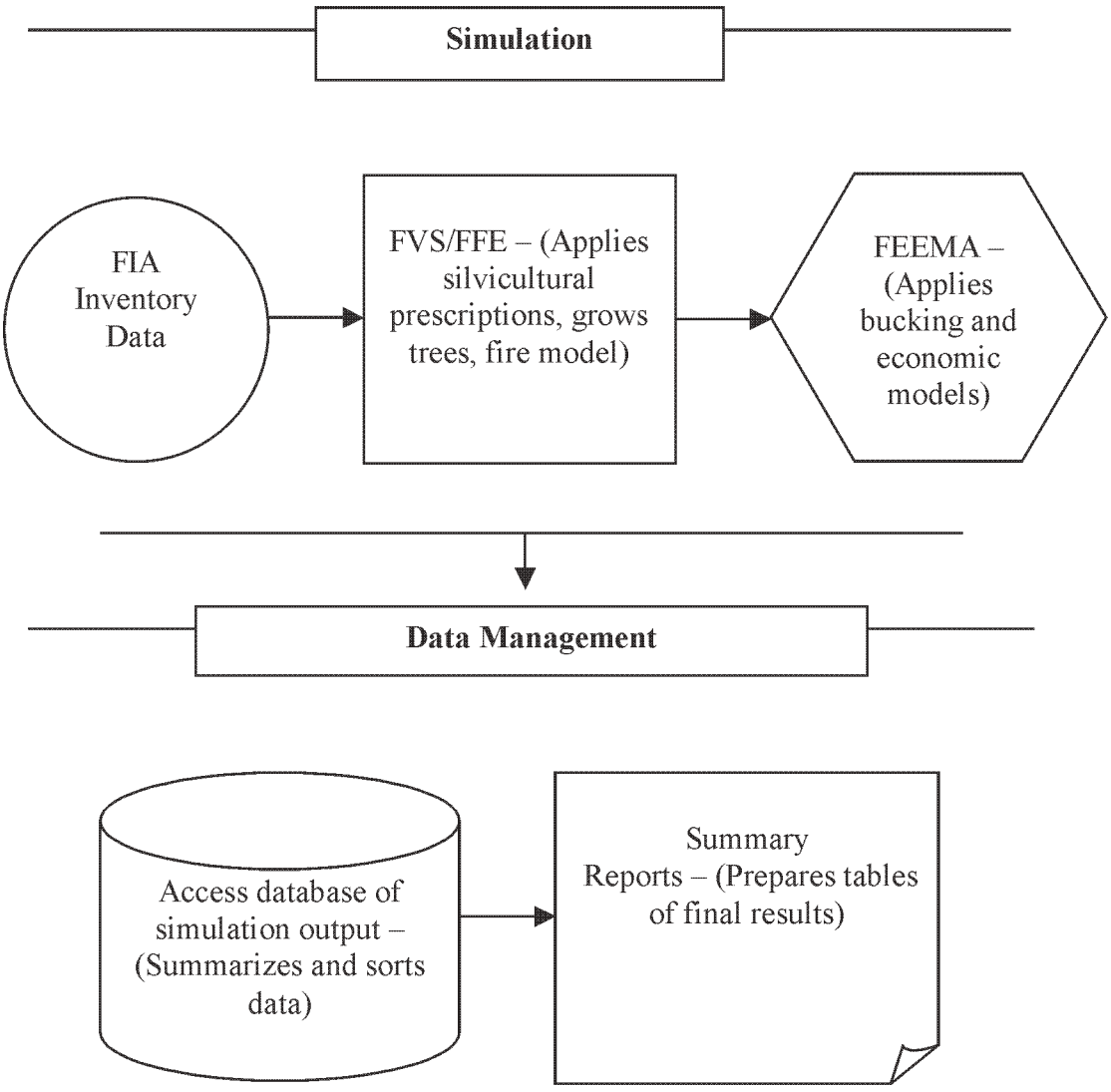


Figure 1—General flow of simulation and result reporting.

compensate for this, results are summarized to provide mean values weighted by each plot's expansion factor. The basic data needed to run FVS from the inventories include plot level information such as slope, the number of acres each plot represents (expansion factor or sampling factor), specific sampling design information, and site index. Tree level measurements included species, diameter at breast height (d.b.h.), height, and crown ratio.

Before FVS could be used, inventory data had to be in a specific FVS readable format, with one file per FIA plot. This format differs by region and even within a region from one inventory to the next. Using one of the conversion utilities that have been developed and with help from the FMSC, data were reformatted and the needed FVS files assembled. Two types of files were created for FVS. The tree list file contained measurements for every tree on a plot and the stand list file contained attributes (for example, measurement date, file path to the tree data file, age, habitat type, sampling information, and file path to any files with additional information) for every plot.

Next, stand list files were resorted to group plots into "cases" (combinations of forest type, region, ownership, slope, and current fire hazard). Silvicultural prescriptions were developed that could be applied to each case. These prescriptions are all formatted for FVS using a keyword file. To facilitate tracking of simulation results in the final database, all plots are renumbered using a system that allows identification of the plot, case, year, and treatment. A macro written in Excel was used to rename each plot and build new stand list files for each case. The macro worked from three worksheets: one listing a cross-reference of old to new plot numbers, one that is a stand list file for all plots, and one listing plot numbers desired in the new stand list file. The macro produces a new worksheet that is saved as a space delimited text file (FVS format) and used as the new stand list file. The macro also provides the file path to a specific keyword file used for that case. Treatment keyword files are created using the Suppose interface (Crookston 1997) for FVS. The keyword file includes the commands FVS uses to apply thinning treatments, run the FFE model, and additional calculations needed such as trees per acre harvested or posttreatment basal area.

Before plots could be assigned to a specific case, the current fire hazard rating needed to be determined. We accomplished this by running all plots through FFE. To obtain an initial rating for this analysis, we used crowning index as a proxy for potential fire hazard (Fielder and others, unpublished paper). Crowning index is the wind speed necessary to sustain a fire within the crown layer of a stand. To ensure that all stands were current, FVS was used to grow the stands to a common starting year of 2000. Stands were rated as "low" or "high" hazard based on their crowning index at year 2000.

Model Simulations

All FVS and FFE simulations were initiated from the Suppose interface. For every case, treatment and growth were simulated for 100 years for each silvicultural prescription. For this analysis, we used two prescriptions, each a thinning from below (a thinning that removes the smallest trees first) to a diameter or basal area limit. A diameter limit of 9 inches d.b.h. and a basal area limit of 50 percent were used for both States. The diameter-limit treatment removed all trees less than the target d.b.h. but was further bounded by a minimum reserve basal area to ensure acceptable stocking in the residual stand. The 50 percent basal area treatment removed from below half the basal area. This treatment has no upper diameter limit but is also bounded by a minimum reserve basal area to ensure enough overstory trees remain. Minimum reserve basal area varied from 40 ft^2 to 80 ft^2 per acre, depending on forest type, State, and geographic region within the State. To reduce fire hazard (that is, to increase crowning index), thinning from below reduced the overall stand density, helped remove ladder fuels, and reduced crown bulk density. Crown bulk density is one of the primary variables that determine crowning index. In addition to thinning, each treated plot also received a prescribed burn in association with each treatment interval. In some cases, plots that may have not been eligible for thinning were still treated with a prescribed burn. For this analysis we used the default prescribed burn values in FFE. Thinning reentry and burning schedules are defined for each case in the keyword file. If a plot was initially rated as "low" fire hazard, treatment was delayed by one entry interval.

The Event Monitor ensured that FVS applied each silvicultural prescription as intended. This allowed us to use IF/THEN statements to evaluate each plot for treatment eligibility. If a plot met the initial criteria, the Event Monitor provided precise control over which trees were removed. Another advantage of using the Event Monitor is the COMPUTE keyword. By using this keyword, we were able to create custom variables that calculate specific information such as pre and posttreatment conditions (for example, basal area, trees per acre, quadratic mean diameter) and information on exactly what was removed (for example, volume, trees per acre, and basal area by diameter class). By using these variables in conjunction with IF/THEN statements, residual stand conditions could be calculated before FVS applied the actual treatment.

After each case was processed through FVS and FFE, output from both models was used as input for further analysis with FEEMA (fig. 1). FEEMA uses a listing of harvested trees, available via the CUTLIST and TREELIST keywords in FVS, as input for bucking, log allocation, and financial analysis. An import utility within FEEMA allows direct importing of FVS tree list files to create FEEMA stand files for each cut list. Note that a stand file in FEEMA is not the same as a stand list file in FVS; in this analysis, a stand in FEEMA is the same as a plot in FVS. Because stand file names are concatenations of the plot name used in the FVS run and the year of removal (indicated for each cut list header), it is essential to adopt a plot naming convention. In addition to using the tree list files from FVS, the output files are also used to obtain results. FVS output files contain pre and posttreatment plot variables calculated via the "COMPUTE" keyword and fire related data generated by FFE.

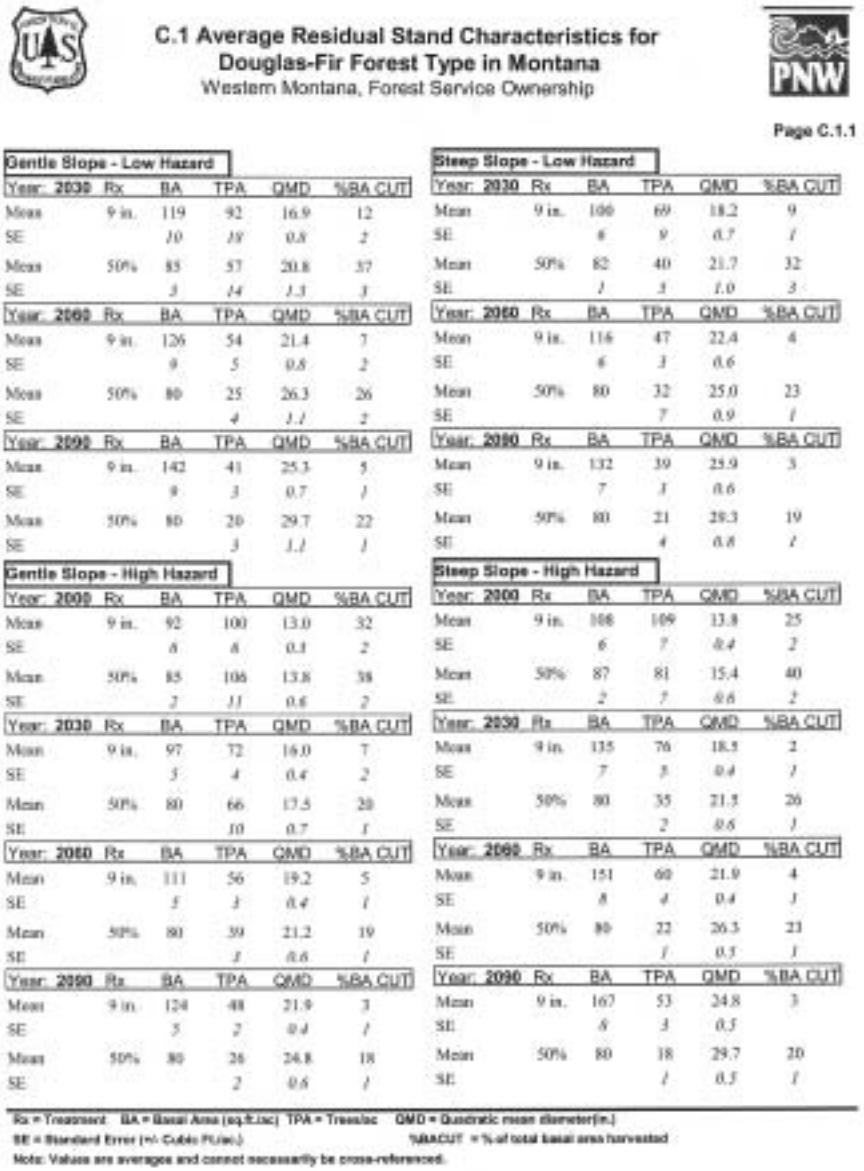
The FEEMA model was used to summarize volume and species composition of utilized trees, volume of logs by size class, and the net value of thinning treatments. To provide information on the logs that would be available to industry rather than specific products, the analysis was done with log

pricing rather than final product pricing. The customized version of FEEMA allowed results to be processed through a series of macros written in Excel that placed the needed data items into one Excel worksheet for importing into an ACCESS database.

Output Summarization

At this point of the analysis all FIA plot data had been processed with FVS, FFE, and FEEMA. FEEMA results have been summarized and are now ready to be imported into Access database tables (fig. 1). FVS output files have been produced and are now ready to be summarized. Because FVS writes its output report as a text file, macros were written using a text editor capable of recording and playing macros that manipulate these files. Macros were written to search each FVS output file for specific data from each plot. These raw data were then copied and pasted into a space-delimited file amenable to import into Access. For this analysis, these data included plot name, information in the FFE reports, and all the COMPUTE variables.

Final summary reports were assembled from the Access table of output. Each row in this database represents a tree that can be tracked to a specific treatment, case, year harvested, and plot. Reports on total number of plots and acres treated can be easily generated by simple summation. For this analysis, plots in Montana represent an average of approximately 6,000 acres and for New Mexico approximately 6,600 acres; however, this value can vary from less than 1,000 acres to more than 10,000 acres depending on the forest strata. Thus, observations are weighted by plot expansion factors before summation. More complex summaries are also possible—for example, mean and error statistics by forest type, region, ownership, and so forth—through the use of Access queries and reports. Examples of final tables (fig. 2, 3, and 4) show the range of attributes that can be summarized.



C.1 Average Residual Stand Characteristics for Douglas-Fir Forest Type in Montana
Western Montana, Forest Service Ownership

Page C.1.1

Gentle Slope - Low Hazard

Year: 2030	Rx	BA	TPA	QMD	%BA CUT
Mean	9 in.	119	92	16.9	12
SE		10	18	0.8	2
Mean	50%	85	57	20.8	37
SE		3	14	1.3	3
Year: 2060	**Rx**	**BA**	**TPA**	**QMD**	**%BA CUT**
Mean	9 in.	126	54	21.4	7
SE		9	5	0.8	2
Mean	50%	80	25	26.3	26
SE			4	1.1	2
Year: 2090	**Rx**	**BA**	**TPA**	**QMD**	**%BA CUT**
Mean	9 in.	142	41	25.3	5
SE		9	3	0.7	1
Mean	50%	80	20	29.7	22
SE			3	1.1	1

Steep Slope - Low Hazard

Year: 2030	Rx	BA	TPA	QMD	%BA CUT
Mean	9 in.	100	69	18.2	9
SE		6	9	0.7	1
Mean	50%	82	40	21.7	32
SE		1	3	1.0	3
Year: 2060	**Rx**	**BA**	**TPA**	**QMD**	**%BA CUT**
Mean	9 in.	116	47	22.4	4
SE		6	3	0.6	
Mean	50%	80	32	25.0	23
SE			7	0.9	1
Year: 2090	**Rx**	**BA**	**TPA**	**QMD**	**%BA CUT**
Mean	9 in.	132	39	25.9	3
SE		7	3	0.6	
Mean	50%	80	21	29.3	19
SE			4	0.8	1

Gentle Slope - High Hazard

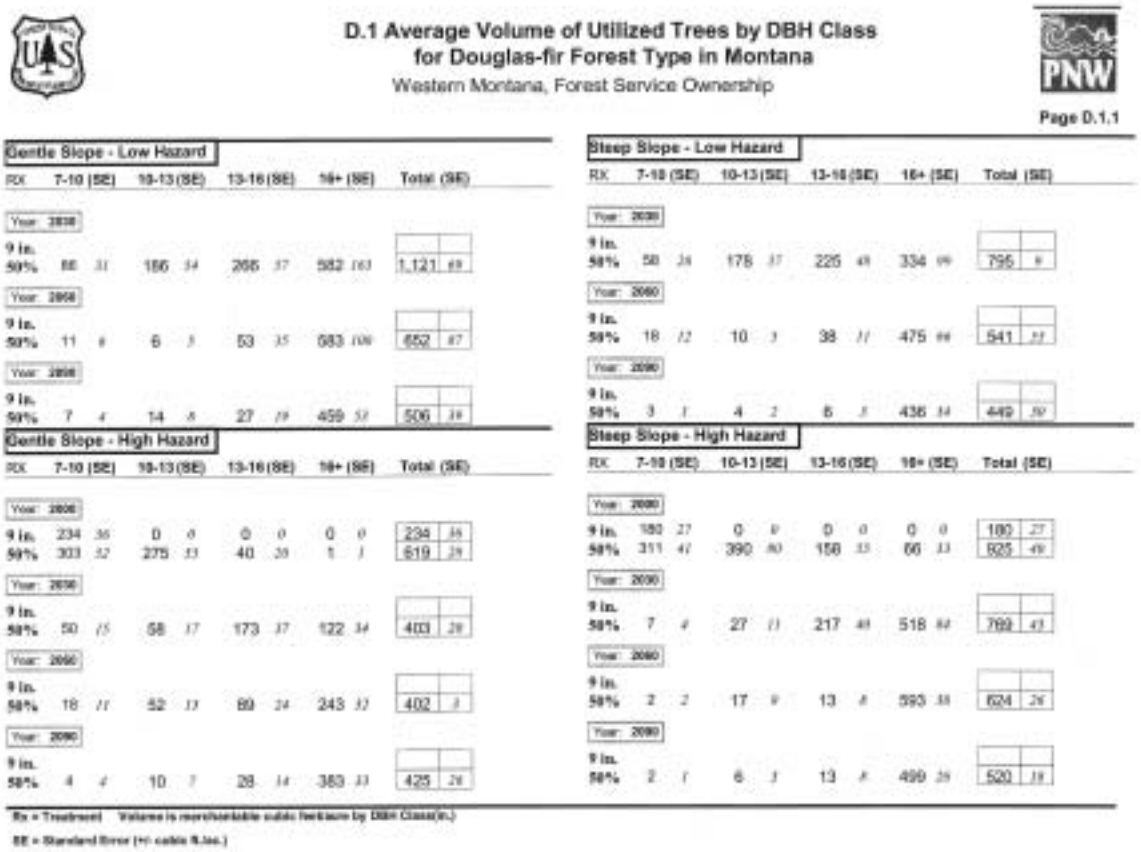
Year: 2000	Rx	BA	TPA	QMD	%BA CUT
Mean	9 in.	92	100	13.0	32
SE		6	6	0.3	2
Mean	50%	85	106	13.8	38
SE		2	11	0.6	2
Year: 2030	**Rx**	**BA**	**TPA**	**QMD**	**%BA CUT**
Mean	9 in.	97	72	16.0	7
SE		5	4	0.4	2
Mean	50%	80	66	17.5	20
SE			10	0.7	1
Year: 2060	**Rx**	**BA**	**TPA**	**QMD**	**%BA CUT**
Mean	9 in.	111	56	19.2	5
SE		5	3	0.4	1
Mean	50%	80	39	21.2	19
SE			3	0.6	1
Year: 2090	**Rx**	**BA**	**TPA**	**QMD**	**%BA CUT**
Mean	9 in.	124	48	21.9	3
SE		5	2	0.4	1
Mean	50%	80	26	24.8	18
SE			2	0.6	1

Steep Slope - High Hazard

Year: 2000	Rx	BA	TPA	QMD	%BA CUT
Mean	9 in.	108	109	13.8	25
SE		6	7	0.4	2
Mean	50%	87	81	15.4	40
SE		2	7	0.6	2
Year: 2030	**Rx**	**BA**	**TPA**	**QMD**	**%BA CUT**
Mean	9 in.	135	76	18.5	2
SE		7	5	0.4	1
Mean	50%	80	35	21.5	26
SE			2	0.6	1
Year: 2060	**Rx**	**BA**	**TPA**	**QMD**	**%BA CUT**
Mean	9 in.	151	60	21.9	4
SE		8	4	0.4	1
Mean	50%	80	22	26.3	23
SE			1	0.5	1
Year: 2090	**Rx**	**BA**	**TPA**	**QMD**	**%BA CUT**
Mean	9 in.	167	53	24.8	3
SE		6	3	0.5	
Mean	50%	80	18	29.7	20
SE			1	0.5	1

Rx = Treatment BA = Basal Area (sq.ft./ac) TPA = Trees/ac QMD = Quadratic mean diameter(in.)
SE = Standard Error (+/- Cubic Ft/ac.) %BACUT = % of total basal area harvested
Note: Values are averages and cannot necessarily be cross-referenced.

Figure 2—Example of residual stand characteristics report.



D.1 Average Volume of Utilized Trees by DBH Class
for Douglas-fir Forest Type in Montana
Western Montana, Forest Service Ownership

Page D.1.1

Gentle Slope - Low Hazard

RX	7-10 (SE)	10-13 (SE)	13-16 (SE)	16+ (SE)	Total (SE)
Year: 2030					
9 in.	88 31	186 54	266 57	582 163	1,121 69
50%					
Year: 2050					
9 in.	11 6	6 3	53 35	583 106	652 87
50%					
Year: 2070					
9 in.	7 4	14 8	27 19	459 52	506 39
50%					

Steep Slope - Low Hazard

RX	7-10 (SE)	10-13 (SE)	13-16 (SE)	16+ (SE)	Total (SE)
Year: 2030					
9 in.	58 24	178 37	225 49	334 99	795 9
50%					
Year: 2050					
9 in.	18 12	10 3	38 11	475 69	541 53
50%					
Year: 2070					
9 in.	3 1	4 2	6 3	436 34	449 30
50%					

Gentle Slope - High Hazard

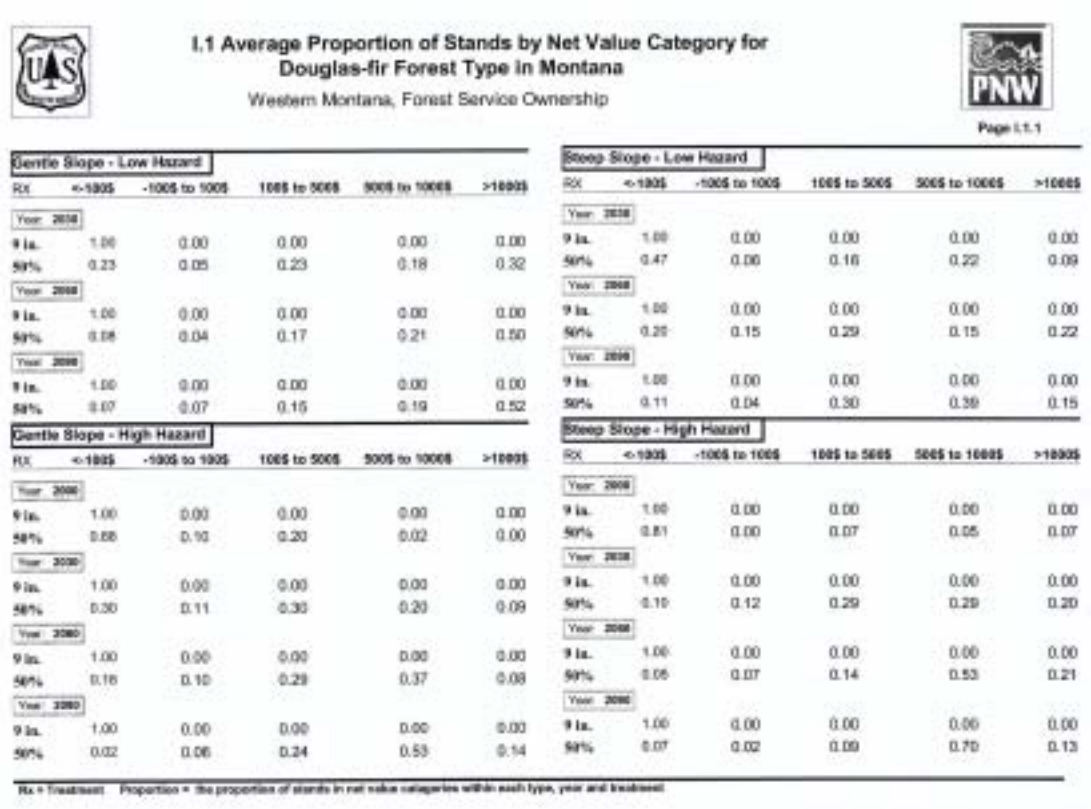
RX	7-10 (SE)	10-13 (SE)	13-16 (SE)	16+ (SE)	Total (SE)
Year: 2030					
9 in.	234 36	0 0	0 0	0 0	234 36
50%	303 32	275 33	40 26	1 1	619 29
Year: 2050					
9 in.	50 15	58 17	173 37	122 34	403 28
50%					
Year: 2070					
9 in.	18 11	52 13	89 24	243 32	402 3
50%					
Year: 2090					
9 in.	4 4	10 7	28 14	383 33	425 28
50%					

Steep Slope - High Hazard

RX	7-10 (SE)	10-13 (SE)	13-16 (SE)	16+ (SE)	Total (SE)
Year: 2030					
9 in.	180 27	0 0	0 0	0 0	180 27
50%	311 47	390 80	156 33	66 33	925 49
Year: 2050					
9 in.	7 4	27 11	217 49	518 84	769 43
50%					
Year: 2070					
9 in.	2 2	17 9	13 8	593 38	624 26
50%					
Year: 2090					
9 in.	2 1	6 3	13 8	499 29	520 18
50%					

Rx = Treatment Volume is merchantable cubic feet/acre by DBH Class(in.)
SE = Standard Error (+/- cubic ft./ac.)

Figure 3—Example report of volume of utilized trees by diameter class.



I.1 Average Proportion of Stands by Net Value Category for
Douglas-fir Forest Type in Montana
Western Montana, Forest Service Ownership

Page I.1.1

Gentle Slope - Low Hazard

RX	<-100$	-100$ to 100$	100$ to 500$	500$ to 1000$	>1000$
Year: 2030					
9 in.	1.00	0.00	0.00	0.00	0.00
50%	0.23	0.05	0.23	0.18	0.32
Year: 2050					
9 in.	1.00	0.00	0.00	0.00	0.00
50%	0.08	0.04	0.17	0.21	0.50
Year: 2070					
9 in.	1.00	0.00	0.00	0.00	0.00
50%	0.07	0.07	0.15	0.19	0.52

Steep Slope - Low Hazard

RX	<-100$	-100$ to 100$	100$ to 500$	500$ to 1000$	>1000$
Year: 2030					
9 in.	1.00	0.00	0.00	0.00	0.00
50%	0.47	0.06	0.16	0.22	0.09
Year: 2050					
9 in.	1.00	0.00	0.00	0.00	0.00
50%	0.20	0.15	0.29	0.15	0.22
Year: 2070					
9 in.	1.00	0.00	0.00	0.00	0.00
50%	0.11	0.04	0.30	0.39	0.15

Gentle Slope - High Hazard

RX	<-100$	-100$ to 100$	100$ to 500$	500$ to 1000$	>1000$
Year: 2030					
9 in.	1.00	0.00	0.00	0.00	0.00
50%	0.66	0.10	0.20	0.02	0.00
Year: 2050					
9 in.	1.00	0.00	0.00	0.00	0.00
50%	0.30	0.11	0.30	0.20	0.09
Year: 2070					
9 in.	1.00	0.00	0.00	0.00	0.00
50%	0.18	0.10	0.29	0.37	0.06
Year: 2090					
9 in.	1.00	0.00	0.00	0.00	0.00
50%	0.02	0.06	0.24	0.53	0.14

Steep Slope - High Hazard

RX	<-100$	-100$ to 100$	100$ to 500$	500$ to 1000$	>1000$
Year: 2030					
9 in.	1.00	0.00	0.00	0.00	0.00
50%	0.81	0.00	0.07	0.05	0.07
Year: 2050					
9 in.	1.00	0.00	0.00	0.00	0.00
50%	0.10	0.12	0.29	0.29	0.20
Year: 2070					
9 in.	1.00	0.00	0.00	0.00	0.00
50%	0.05	0.07	0.14	0.53	0.21
Year: 2090					
9 in.	1.00	0.00	0.00	0.00	0.00
50%	0.07	0.02	0.09	0.70	0.13

Rx = Treatment Proportion = the proportion of stands in net value categories within each type, year and treatment

Figure 4—Example report of financial results using FEEMA output.

Conclusions

This analytic approach has been extended for other study areas, including the Blue Mountains Demonstration Project in Northeastern Oregon, where a detailed analysis of fuels reduction treatments on three National Forests (Umatilla, Malheur, and Wallowa-Whitman) is under way. The FIA BioSum model, which seeks to evaluate potential biomass available from fire hazard reduction treatments in the Western United States, has significantly expanded the capability and complexity of this analytic framework by adding spatially explicit representation of biomass accumulation potential over existing road networks.

The analytic approach and software summarized here, built on a foundation of publicly available data and models, enable managers to address questions concerning forest management over a large area with great detail. The scope of silvicultural prescriptions that can be evaluated is limited only by an analyst's imagination and the capabilities of the models. By using the Event Monitor within FVS, complex treatments can be simulated. The FFE model allows analysis of wildfire potential, response to treatments, and use of prescribed burning. If only these models were used, summary would be possible at a tree level, but by using FEEMA, each harvested tree can be evaluated even further by accounting for treatment costs and conducting log level analyses. Finally, using Access database tables to store all raw simulation output, results can be sorted and summed using custom defined criteria and classes. This allows results from hundreds or thousands of plots to be quickly compiled into manageable, meaningful results. The report-writing feature of Access can be used to automate result generation for commonly requested table formats.

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Using the Fuels and Fire Effects (FFE) and Economic (ECON) Extensions to the Forest Vegetation Simulator (FVS) to Evaluate the Impacts of Silvicultural Regimes

David L. Renner
Fred C. Martin

Abstract—The FFE and ECON extensions to FVS were used to evaluate the impacts of five silvicultural scenarios on a dry ponderosa pine (*Pinus ponderosa*) plantation and a moist, mixed-species stand. Scenarios ranged from no treatments to traditional thinning to thinning with prescribed fire management. Present net value (PNV), total cubic foot volume productivity, and fire hazard, defined by torching index, crowning index, and predicted fire type under wildfire conditions, were computed. Greatest PNV difference among all regimes was approximately $600 per acre at simulation end. Greatest difference in total cubic foot volume production among regimes at simulation end was approximately 2000 cubic feet per acre. Productivity was greatest for mechanical treatment only regimes. Regimes containing prescribed fire treatment generally had lower total productivity, with multiple fire treatment regimes generally producing less volume than single fire treatment regimes. Greatest difference in fuel concentration was approximately 45 tons per acre for the ponderosa pine plantation at 100 years. Surface fuel concentrations, for both fine fuels and total fuels, were consistently higher for the no treatment regimes for both stands, with marked increases occurring when stands reached 60 to 100 years old. Using the FFE and ECON extensions provides managers with quantitative measures for evaluating both the economic benefits and wildfire hazards of different silvicultural scenarios.

Several extensions to FVS (Stage 1973; Wykoff and others 1982) have been developed over the years to provide managers with quantitative information about forest management activities, beyond the basic dynamics of tree growth provided by FVS. The latest extensions are the Fuels and Fire Effects Extension (FFE) (Beukema and others 2000) and the Economic Extension (ECON) (Renner 2002, in preparation). The FFE is designed to simulate effects of fire on stand characteristics and stand development, and to simulate the effects of stand development and management actions on fuel dynamics, fire behavior, and fire effects. The FFE consists of three major modules: (1) snag module that monitors decay and fall down of snags, (2) fuels module that simulates accumulation and decomposition of surface fuels, and (3) fire module that simulates fire intensity, effects on trees, smoke production, and mineral soil exposure.

The ECON extension computes economic measures associated with stand management activities including present net value (PNV), soil expectation value (SEV), internal rate of return, benefit/cost ratio, value of reproduction, undiscounted cash flow, and the value of an existing stand. ECON allows for three types of economic analyses: (1) analysis of an existing stand over a finite investment horizon (PNV), (2) analysis of an infinitely repeating management regime (SEV), and (3) a combined analysis of an existing stand followed by application of an infinitely repeating management regime (PNVPLUS). ECON features include: (1) computation of harvest revenues based on either tree d.b.h. or log size, (2) evaluation of multiple rotation ages or harvest timings within a single FVS simulation via the PRETEND keyword, (3) full integration with FVS allowing for dynamic specification of management activities based on economic measures using the Event Monitor (Crookston 1990), (4) production of log stock tables with associated revenues, and (5) flexible specification of fixed and variable costs and revenues.

Case Studies

Two case studies illustrate the use of the FFE and ECON extensions in evaluating the impacts of silvicultural regimes. Five silvicultural regimes, including a no treatments option, were specified for each case study. Regime treatments, along with their associated economic costs and revenues, were provided by silviculturalists and fire management personnel currently involved in managing the stands. PNV, total cubic foot volume productivity, fuel profiles, fire-related mortality, and three measures of fire hazard rating were computed for each regime. The three fire hazard metrics used were: (1) torching index defined as the 20-foot wind speed (that is, wind speed at 20 feet above ground level) required to carry a fire from the ground surface into tree crowns; (2) crowning index defined as the 20-foot wind speed required to maintain an actively crowning fire, thereby killing all trees in the stand; and (3) predicted fire type under severe burning conditions (that is, "surface" fire when the fire is confined to the ground with no scorching of crowns, "passive" fire when the fire scorches and consumes groups of crowns resulting in scattered mortality, or "active" fire when the fire consumes all crowns within the stand resulting in

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Table 1—Silvicultural regimes for the ponderosa pine plantation. The stand was simulated beginning in year 2000 in order to include economic costs associated with stand establishment.

Year	Age	1a	1b	1c	2a	2b
2000	0	Plant	Plant	Plant	Plant	Plant
2020	20	Precommercial thin to 350 trees/acre (t/a); no residue treatment	Precommercial thin to 350 t/a; no residue treatment	No treatment	No treatment No treatment	No treatment
2030	30	No treatment	No treatment	No treatment	Throttle-back understory burn	Throttle-back understory burn
2060	60	Commercial thin to 130 sq ft + jack-pot fuel burn	Commercial thin to 130 sq ft; residue removed from stand	No treatment	Commercial thin to 130 sq ft + jack-pot fuel burn	Commercial thin to 130 sq ft; residue removed from stand
2120	120	Clear-cut	Clear-cut	No treatment	Clear-cut	Clear-cut

complete stand mortality). Prescribed fire treatment types used in the study were: (1) throttle-back broadcast burn, (2) low intensity "free to burn" broadcast burn, and (3) jackpot fuel burn. The throttle-back prescribed fire is a broadcast burn that affects the entire stand, with the fire confined to thin strips. The free to burn broadcast burn is a low intensity understory burn affecting the entire stand, while the jackpot fuel burn affects only concentrations of fuels within the stand.

Case Study 1 – Ponderosa Pine Plantation

The first stand used in the analysis was a ponderosa pine plantation with the following characteristics: located in Nez Perce National Forest, Idaho, 35 years old, *Pseudotsuga menziesii/Physocarpus malvacens* habitat type, 20 percent slope, southeast aspect, 4,500 feet elevation, 510 trees per acre, composed of 70 percent ponderosa pine, 20 percent Douglas-fir (*Pseudotsugamenziesii*), and 10 percent western larch (*Larix occidentalis*) on a trees per acre basis. The stand had no previous management treatments. The five silvicultural regimes applied to the stand are listed in table 1, and the input economic parameters used are listed in table 2.

PNV for each regime, displayed in figure 1, shows that the mechanical treatment only regime, 1b, generated the greatest PNV at simulation end, while the no treatment regime, 1c, had the lowest PNV. Regimes using prescribed fire treatments, 1a, 2a, and 2b, generated intermediate PNV values with slightly lower values for the regimes performing a jackpot fuel burn in 2060 (1a and 2a). Total cubic foot volume production, displayed in figure 2, shows that the mechanical treatment only regime, 1b, generated the greatest total cubic foot production, while the regime applying prescribed fire treatments at ages 30 and 60 years, 2a, was

Table 2—Input economic parameters for ponderosa pine plantation.

Economic parameter	Value
Discount rate	5.0%
Annual cost	$2.50/acre
Planting cost	$175.00/acre
Burn site prep cost	$200.00/acre
Precommercial thin fixed cost	$100.00/acre
Harvest variable cost	$25.00/mbf
Harvest fixed cost	$100.00/acre
Average harvest revenue	
Western white pine	$339.75/mbf
Western larch	$366.40/mbf
Douglas fir	$366.40/mbf
Grand fir	$339.75/mbf
Western hemlock	$339.75/mbf
Western red cedar	$366.40/mbf
Lodgepole pine	$339.75/mbf
Englemann spruce	$339.75/mbf
Sub-alpine fir	$339.75/mbf
Ponderosa pine	$384.00/mbf

mbf = thousand board-feet

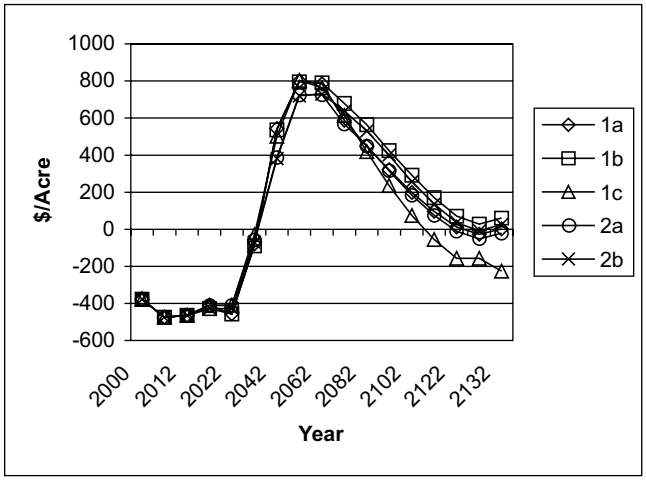

Figure 1—PNV for ponderosa pine plantation.

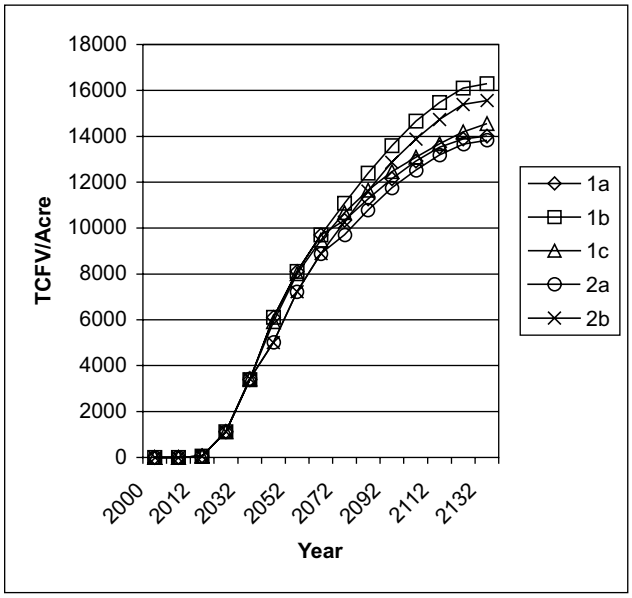

Figure 2—Total cubic foot volume production for ponderosa pine plantation.

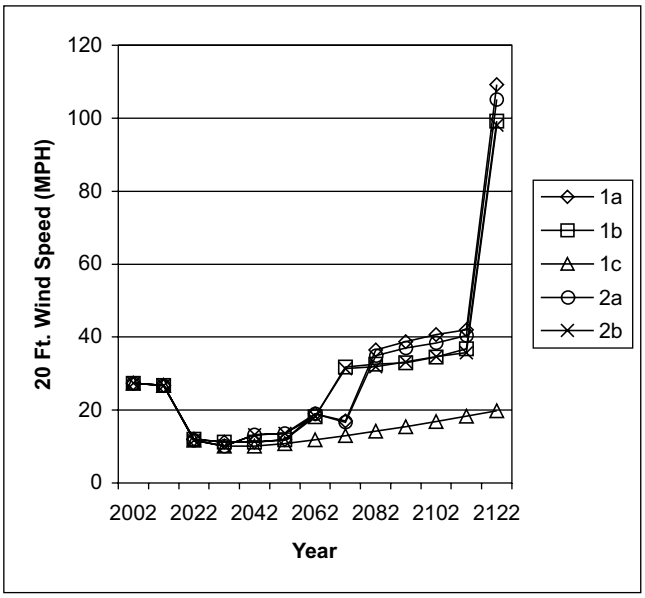

Figure 4—Crowning index for ponderosa pine plantation.

least productive. The no treatment regime, 1c, was intermediate in productivity. Although PNV and cubic volume differences among regimes were relatively small, greatest differences occurred between the no treatment regime and the more active management regimes.

Torching and crowning indexes for the ponderosa pine plantation are displayed in figures 3 and 4, respectively. Increasing values for both torching and crowning index represent *decreasing* wildfire hazard. Fire hazard decreased for all regimes during years 2022 through 2042 due to reduction of ladder fuels as a result of thinning and understory burning (fig. 3). However, regimes with mechanical treatment only at year 2020, 1a and 1b, resulted in a much larger increase in torching index in years 2032 through 2042 compared to regimes specifying fire treatments at year 2030 (2a and 2b). Wildfire hazard for the no treatment regime, 1c, was intermediate compared to the other regimes during this period and is most likely due to increased height to the base of crown that occurs as a result of self-pruning. Crowning index declined and remained low for all regimes between 2020 and 2050 in spite of the precommercial thinning/understory burn treatments at years 2020 and 2030 (fig. 4). This suggests that decreased stand density resulting from precommercial thinning/understory burn treatments was not sufficient to offset posttreatment growth and expansion of tree crowns. After 2060, however, thinning in all of the active management regimes substantially reduced crown fire hazard compared to the no treatment regime.

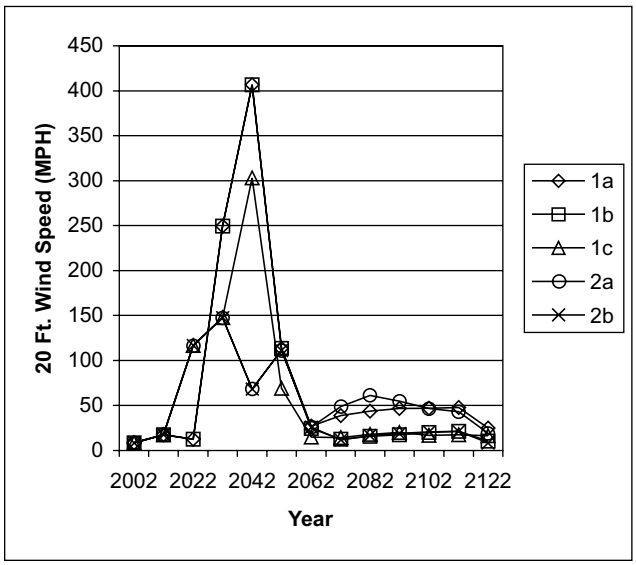

Figure 3—Torching index for ponderosa pine plantation. Values are identical for regimes 1a and 1b, and 2a and 2b, at year 2040.

Predicted fire type under wildfire conditions, defined as 30 m.p.h. winds under very dry moisture conditions, indicate all regimes were effective in reducing fire hazard between 2032 and 2052 as indicated by the transition from active to surface fire type (table 3). However, treatments at 2062 had a markedly different effect on the predicted wildfire type for the duration of the simulation. The no treatment regime, 1c, resulted in greater wildfire hazard as indicated by the active fire type. Regimes 1a and 2a, which utilized prescribed fire for treating fuels in 2062, provided the greatest reduction in hazard as indicated by the surface fire type. Regimes 1b and 2b, which specified commercial thinning at 60 years without prescribed fire, provided intermediate reduction in hazard rating as indicated by the passive fire type.

With the exception of the no treatment regime, 1c, PNV of the different silvicultural regimes varied little. Regimes

Table 3—Potential fire type under wildfire conditions for ponderosa pine plantation silvicultural regimes.

Year	Age	1a	1b	1c	2a	2b
2002	2	Active	Active	Active	Active	Active
2012	12	Active	Active	Active	Active	Active
2022	22	Active	Active	Surface	Surface	Surface
2032	32	Surface	Surface	Surface	Surface	Surface
2042	42	Surface	Surface	Surface	Surface	Surface
2052	52	Surface	Surface	Surface	Surface	Surface
2062	62	Active	Active	Active	Active	Active
2072	72	Surface	Passive	Active	Surface	Passive
2082	82	Surface	Passive	Active	Surface	Passive
2092	92	Surface	Passive	Active	Surface	Passive
2102	102	Surface	Passive	Active	Surface	Passive
2112	112	Surface	Passive	Active	Surface	Passive
2122	122	Passive	Passive	Active	Passive	Passive

that provided mechanical treatment only at age 60 years, 1b and 2b, resulted in slightly higher PNV values at the end of the simulation compared to regimes using a combination of commercial thinning and fire-based fuel treatments at age 60, 1a and 2a. This slight difference appeared to result from fire-induced mortality of larger, more valuable trees. PNV of the no treatment regime, 1c, was lower at the end of the simulation than other treatments, with an ending maximum difference of approximately $250 per acre among treatments. Total cubic foot volume productivity was also greatest for the mechanical treatment only regime, 1b. Regimes combining commercial thinning with fire-based fuel treatment at age 60 years, 1a and 2a, were least productive with the no treatment option, 1c, being intermediate in value.

Silvicultural regimes with slightly greater total cubic foot volume production and PNV values, 1b and 2b, also represented the scenarios of greater risk of loss under wildfire fire scenarios (passive versus surface fire type). Wildfire hazard risks were mixed, with the no treatments regime, 1c, having the greatest risk by all three measures—predicted wildfire type, torching index, and crowning index. While the use of prescribed fire as a treatment alternative in the early stages of stand development afforded no major differences in fire hazard risk compared to mechanical treatments, reduction in fire hazard was predicted in later years for the regimes that combined commercial thinning and fire-based fuel treatment at age 60 years, 1a and 2a.

Case Study 2 – Mixed-Species, Multistory Stand

The second case study was a mixed-species, multistory stand with the following characteristics: located near Colville National Forest in Eastern Washington State, approximately 60 years old, *Abies grandis/Clintonia uniflorum* habitat type, level (0 to 5 percent) slope, north aspect, 2,500 feet elevation, 335 trees per acre, composed of 50 percent lodgepole pine (*Pinus contorta*), 20 percent ponderosa pine, 20 percent western larch, and 10 percent Douglas-fir on a trees per acre basis. The stand was commercially thinned in 1990. The five silvicultural regimes applied to the stand are listed in table 4, and the input economic parameters are listed in table 5.

PNV was greatest over the simulation period for mechanical treatment only regimes 1a and 1d (fig. 5). PNV for the no treatment regime, 1c, was the lowest at the end of the simulation, while regimes 1b and 1e were intermediate in value. Regimes using prescribed fire, 1b and 1e, caused a reduction in economic benefit compared to regimes 1a and 1d that used mechanical only treatments. In addition, the regime specifying two prescribed fire treatments, 1e, registered a smaller PNV than the regime composed of one fire treatment, 1b. The effects of fire treatment on stand stocking may explain this trend, as fire-related mortality was often considerable even in larger diameter classes. Stocking reduction, particularly in the diameter classes that typically represent the highest economic values, would be expected to have such an adverse effect on economic value.

The mechanical treatment only regime, 1a, had the highest cubic foot volume productivity followed by the no treatment regime, 1c, and the mechanical treatment only regime 1d (fig. 6). Regimes applying prescribed fire treatments, 1b and 1e, were least productive, with the regime containing two fire treatments, 1e, registering the lowest total productivity at end of the simulation. The reduced volume in the

Table 4—Silvicultural regimes for the mixed-species stand.

Year	Age	1a	1b	1c	1d	1e
1990	60	Commercial thin to 300 trees/acre (t/a)	Commercial thin to 300 t/a + throttle-back understory burn	No treatment	Commercial thin to 300 t/a	Commercial thin to 300 t/a
1995	65	No treatment	No treatment	No treatment	Sanitation thin from below to 195 t/a	Sanitation thin from below to 195 t/a + low intensity broadcast understory burn
2010	80	Commercial thin to 110 sq ft	Commercial thin to 110 sq ft	No treatment	Commercial thin to 110 sq ft	Commercial thin to 110 sq ft + low intensity broadcast understory burn
2030	100	Clear-cut	Clear-cut	No treatment	Clear-cut	Clear-cut

Table 5—Input economic parameters for the mixed-species stand.

Economic parameter	Value
Discount rate	5.0%
Annual cost	$2.50/acre
Planting cost	$175.00/acre
Burn site prep cost	$200.00/acre
Precommercial thin fixed cost	$100.00/acre
Harvest variable cost	$25.00/mbf
Harvest fixed cost	$100.00/acre
Average harvest revenue	
Western white pine	$268.00/mbf
Western larch	$240.00/mbf
Douglas fir	$240.00/mbf
Grand fir	$200.00/mbf
Western hemlock	$200.00/mbf
Western red cedar	$200.00/mbf
Lodgepole pine	$200.00/mbf
Englemann spruce	$200.00/mbf
Sub-alpine fir	$200.00/mbf
Ponderosa pine	$285.00/mbf

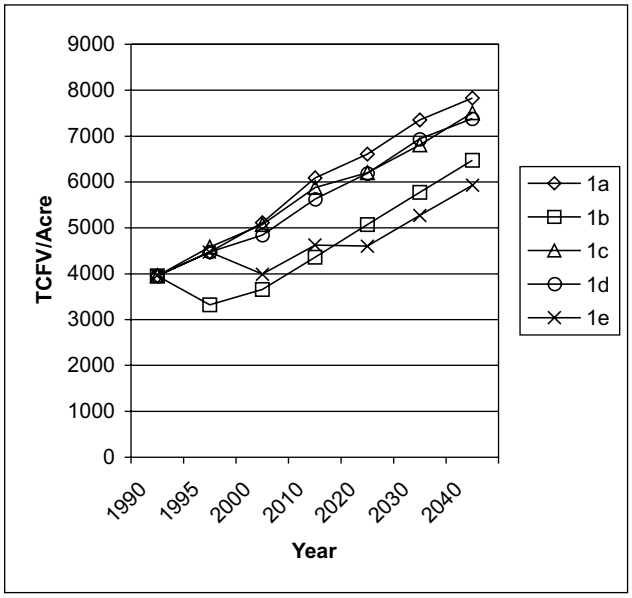

Figure 6—Total cubic foot volume production for the mixed-species stand.

prescribed fire regimes was the result of fire-induced mortality of larger trees.

Torching index initially declined for all regimes at year 2000 (fig. 7). The no treatment and mechanical treatment only regimes, 1a, 1c, and 1d, subsequently increased at year 2010 before declining again. Regimes using prescribed fire, 1b and 1e, remained low throughout the simulation. Crowning index increased for all regimes at year 2000, but then declined in future years. Decreases in crowning index were greater for regimes using prescribed fire, 1b and 1e, than for other regimes.

Predicted fire types under wildfire conditions for the mixed-species stand are listed in table 6. Wildfire conditions were defined as 30 m.p.h. wind speed under moist conditions. Treatments applied at stand age 60 to 70 years resulted in markedly different wildfire types. The no treatment regime, 1c, resulted in only surface fire conditions, while regimes that applied commercial thinning with no accompanying fire treatment, 1a and 1d, resulted in predictions of active crown fires. There were virtually no differences in fire hazard, however, at stand ages between 90 and 100 years. Regardless of silvicultural regime, active crown fires were predicted to prevail under severe burning conditions.

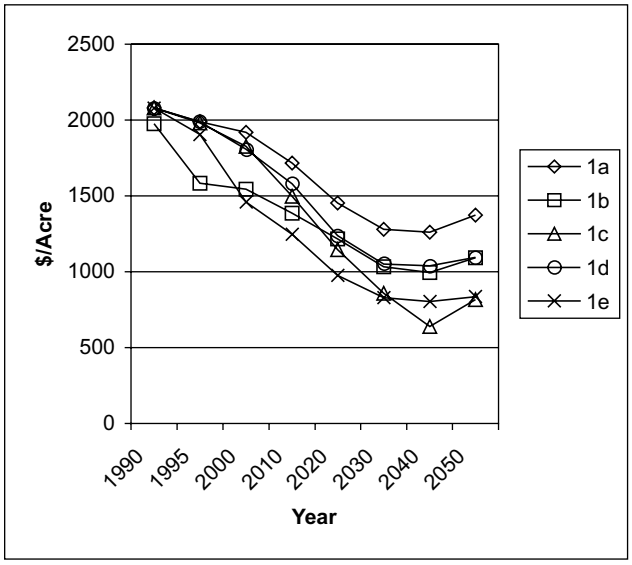

Figure 5—PNV for mixed-species stand. Stand establishment costs are not included.

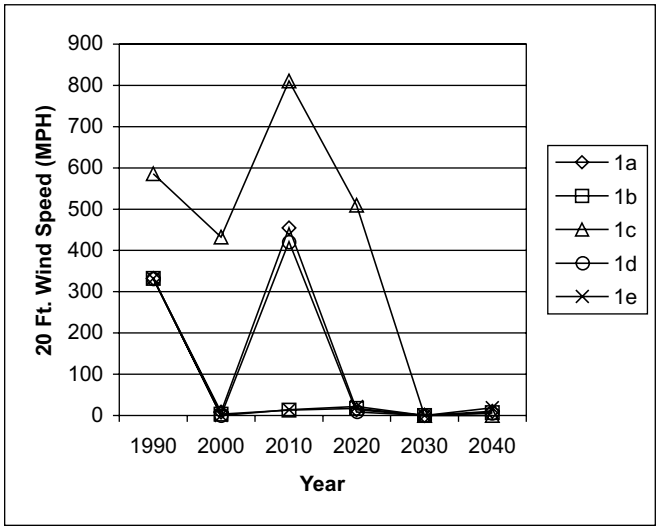

Figure 7—Torching index for the mixed-species stand. Values are identical for regimes 1a and 1b, and 1d and 1e, at year 1990.

Table 6—Potential fire type under wildfire conditions for mixed-species stand silvicultural regimes.

Year	Age	1a	1b	1c	1d	1e
1990	60	Surface	Surface	Surface	Surface	Surface
2000	70	Active	Passive	Surface	Active	Passive
2010	80	Surface	Active	Surface	Surface	Passive
2020	90	Active	Active	Surface	Active	Active
2030	100	Active	Active	Active	Active	Active

Fire hazard trends for the mixed-species stand, as expressed by torching index, were somewhat unexpected. Major reductions in fire hazard were observed for regimes using no treatment or mechanical only treatments at year 2010 (1a, 1c, and 1d). Hazards were significantly greater during the period between 2000 and 2020 for regimes containing prescribed fire treatments (1b and 1e). The rapid increase in fire hazard at year 2000 was the result of a large impulse of natural regeneration following the commercial thinning, with the resultant lowering of height to crown base to ground level and an increase in ladder fuels. The increase in torching index at 2010 for the mechanical treatment only regimes was likely due to the removal of understory ladder fuels at the time of thinning.

Crowning index increased in year 2000 as a result of thinning done in 1990. The thinning was effective in reducing crown bulk density and thus reducing the potential for crown fires within the stand (fig. 8). This hazard reduction was short lived for the single fire treatment regime, 1b, but was maintained for several decades for the two-fire treatment regime, 1e. Reduction in crown bulk density for regime 1e, 4.5 times lower than that for regime 1b, was apparently sufficient to provide a lower hazard level.

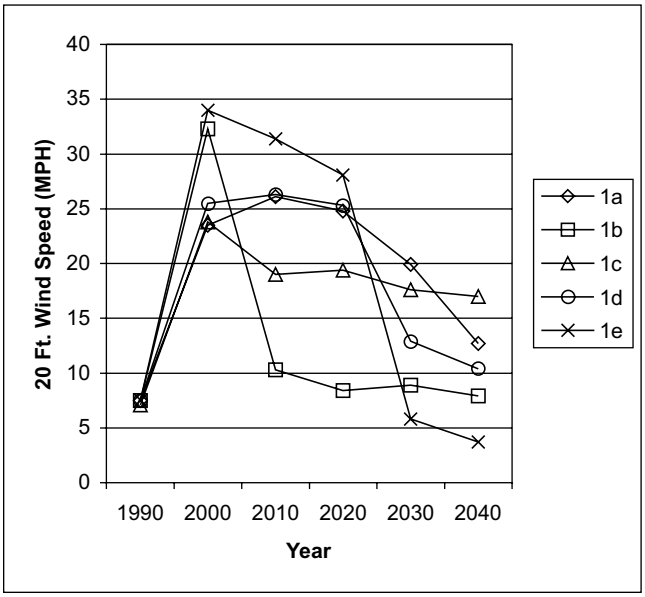

Figure 8—Crowning index for the mixed-species stand.

Discussion and Conclusions

Silvicultural regimes can have a significant effect on both the economic benefits and the fire hazard status of forest stands. The case study results presented here suggest a significant tradeoff exists between the economic benefits realized and the fire hazard risk associated with treating and maintaining a forest structure through time that provides those benefits. In the ponderosa pine plantation case study, there was little benefit in terms of fire hazard reduction from prescribed fire-based regimes early in the life of the stand. This effect appeared to be important, however, in the later stages of the stand's development. Reduction in fire hazard was associated with slightly reduced economic benefits as indicated by the lower PNV values for fire-related regimes. Differences and similarities in trends existed for the mixed species stand compared to the pine plantation. In the mixed-species case study, mechanical treatment only regimes, 1a and 1d, provided the largest PNV and total cubic foot volume production values. However, in the mixed-species stand, fire hazard reduction in response to treatment is accomplished only for initial treatments at ages 60 and 65, while subsequent fire treatment at age 80 provided no hazard reduction. The steady influx of natural regeneration in the mixed-species stand, along with its multistoried characteristics, showed that the use of fire as a tool for discriminating among tree classes and tree species is difficult. In both case studies the timing of fire treatments at specific points in the development of the stands appeared to be important in determining not only the economic benefits realized but also the susceptibility to catastrophic fire losses.

In any event, results from these analyses suggest that any reduction in fire hazard as a result of silvicultural treatment is short lived. This is consistent with the findings of Fiedler (Fiedler and others 2001) who observed that certain types of silvicultural regimes provided only a temporary reduction in fire hazard. Thus, management objectives calling for ongoing fire hazard reduction will likely entail repeated applications of fire as a silvicultural treatment. Managers considering a wide range of multiple-use objectives can use the FFE and ECON extensions to FVS to better evaluate the impacts of silvicultural scenarios on economic values and their effects on creating and maintaining a diverse forest structure capable of reducing wildfire risk.

Acknowledgments

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Using FVS and Its Fire and Fuels Extension in the Context of Uncertain Climate

Albert R. Stage

Abstract—While the prospect of a static climate is no longer tenable, the direction of change for particular localities is not yet clear. Modelling vulnerability of silvicultural options to various scenarios of climate change requires a modelling system that can represent major processes affected by climatic variability. The Forest Vegetation Simulator (FVS), through its Keywords and Event Monitor commands modifying the underlying model, can be used for such analyses. In this report, we document an FVS-based analysis of four scenarios of climate change: warmer-dryer, warmer-wetter, cooler-dryer, and cooler-wetter. Regeneration rates and species composition of regeneration and rates of mortality and accretion are expected to respond differently under the four scenarios. Development of forest stands in the example locales (northwestern Montana and central Washington) is strongly influenced by fire, and conversely, fire behavior is influenced by stand structure. We describe how analyses illustrating the interplay of these hypotheses were formulated using FVS and its Fire and Fuels Extension (FFE). Our hypotheses of how processes might change in response to varying climate are qualitatively consistent with our understanding of the ecosystem represented. Furthermore, the present range of weather variability is sufficient to test each of the component hypotheses independently by monitoring how their rates change in response to weather variation.

Application of the Forest Vegetation Simulator for evaluating the effects of hypothesized changes in climate has been described by Stage and others (2001). In that report, we evaluated four possible scenarios: warmer-dryer, warmer-wetter, cooler-dryer, and cooler-wetter. This report provides more detail on how FVS and its Fire and Fuels Extension (FFE) (Beukema and others 1997) were used in the analysis. Critical for the analysis were the capabilities of the Event Monitor (Crookston 1990) to define variables and the use of computed functions of those variables to modify the processes represented by the underlying FVS model.

The essence of the scenarios for stand development was represented by differences in mean and variance of seasonal moisture stress and length of growing season (table 1) (Zahner and Stage 1966; Rehfeldt and others 1999).

These parameters of climate were hypothesized to affect rates and species composition of regeneration, rates of mortality and accretion, probability of wildfire, and rates of fuel accumulation. Management options included thinning, pruning, and prescribed burning. Separate keyword files were prepared for each combination of climatic scenario and management alternative. Within the keyword file, management alternatives were defined by separate ADDFILES for each alternative.

Table 1—Scenarios of moisture stress. Present MS = 9.2 ± 3.0 inches.

	Warmer	Cooler
Wetter	8 ± 3	5 ± 2
Dryer	13 ± 4	10 ± 4

Several of the processes being modelled have large stochastic variation in addition to the variation in the climatic parameters. These include wildfire frequency, regeneration, and accretion. Therefore, the outcomes of each scenario were represented by the mean and standard deviation of 40 replications of each simulation, initiated by reseeding the random number generator.

Temporal Change in Climatic Effects

Four variables define the temporal progression from present conditions to the conditions represented by the four climatic scenarios: MS, the scenario mean moisture stress; SIGMS, its annual standard deviation; STRESS, the stochastic realization of scenario stress applicable to the current cycle in the projection; and STR, the departure from current stress including the 50–year transition from present to future mean conditions. NYEAR is the length of each cycle. Although usually 10 years, it was calculated to make the conversion from annual to periodic rates explicit. Keywords implementing temporal change follow:

```
COMPUTE
   DEV = BOUND (–2., NORMAL(0., 1.),+2)
   NYEAR = CENDYEAR + 1. –YEAR
   STRESS = MS + SIGMS*DEV/SQRT(NYEAR)
   STR= (STRESS–9.2)*DECADE(0.1, 0.3, 0.5, 0.7, 0.9, 1.0)
END
```

FVS Processes Responding to Scenarios

All three of the principal processes represented by FVS, mortality, accretion, and regeneration were modified by the moisture stress variables. In addition, the height increment component of accretion was reduced for the cooler scenarios to account for increased frost-damage to terminals.

In: Crookston, Nicholas L.; Havis, Robert N., comps. 2002. Second Forest Vegetation Simulator Conference; 2002 February 12–14; Fort Collins, CO. Proc. RMRS-P-25. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

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Mortality

Response of mortality rates to the interaction of moisture stress and stand stocking was derived from a thinning study on the Flathead Reservation (Khatouri and Moore 1993; Cheng and Moore 1996). Those data, however, were not sufficiently comprehensive for a completely new fitting of the logistic mortality submodel. Therefore, the analysis used the present northern Idaho variant (Hamilton 1986; Wykoff and others 1982) as the null model. Then two new terms modifying the argument of the exponential function were added: a multiplicative term (P6= RIPMLT), and an additive term (P7= RIPAD). P7 varied by moisture stress and species.

Ham = linear function in NI variant

$$\text{Mort} = \frac{1}{1+\exp(-P_6 * HAM - P_7)}$$

$P_6 = 1.6482$
$P_7 = -0.4683*$ STR $- 2.0882$ for Pondersa pine
$P_7 = -0.4683*$ (STR +1) -2.088 for Douglas-fir
$P_7 = -0.4683*$ (STR +2) -2.088 for Grand fir

Entering these two new parameters required modifying FVS to add two additional fields to the MORTMULT keyword and to use the new parameters in the calculation of the probability of mortality. Modifying the argument of the exponential function in the probability of mortality submodel permitted analysis of the mortality data in the same format as the original analysis. Furthermore, the modified rates are still bounded by zero and unity. Therefore, this approach was considered a better solution than simply multiplying the mortality rate, which was the original function of MORTMULT.

Therefore, the keywords modifying mortality for ponderosa pine, Douglas-fir and grand fir were:

```
COMPUTE
  RIPMLT = 1.648163
  RIPAD = –0.468393*STR – 2.088163
  RIPAD3 = RIPAD – 0.468393
  RIPAD4 = RIPAD – 0.468393*2.
END
  MORTMULT      0.    PARMS(10,1.0,0.0,99.0,1.0,
                      RIPMLT,RIPAD)
  MORTMULT      0.    PARMS(3,1.0,0.0,99.0,1.0,
                      RIPMLT,RIPAD3)
  MORTMULT      0.    PARMS(4,1.0,0.0,99.0,1.0,
                      RIPMLT,RIPAD4)
```

Accretion

Basal area increment of large trees was assumed to change by 5 percent for each inch of departure from mean moisture stress (Zahner and Stage 1966). In the norhtern Idaho variant, the submodel for height increment of large trees includes diameter increment as a driving variable. Therefore, no further modification for moisture stress was required. However, predicted increment was reduced by an additional 4 percent for normal top damage. Height increment of small trees, however, must be changed in concert with the effects on height increment of the large trees. In the logarithmic large-tree height increment model, the coefficient of logarithm of diameter increment is approximately 0.5. Therefore, a multiplier that is the square root of the diameter multiplier is appropriate. The necessary keywords are:

```
COMPUTE
  GSTR=1.– (STR/20)
END
  BAIMULT       0.    PARMS(0., GSTR)
  HTGMULT       0.    0.      0.96
  REGHMULT      0.    PARMS(0., SQRT(GSTR)*0.96))
```

Regeneration

Disturbances trigger the addition of regeneration to the list of trees in the stand. In these analyses, there are three kinds of disturbances: wildfire, prescribed fire, and thinning with slash burning. The combinations of management actions and climatic scenarios were hypothesized to affect the rates of stocking, the species composition, and the extent of site preparation (proportion burned in these analyses). Stocking rate is made quite sensitive to moisture stress (Mika 2000). Then, conditional on the small regeneration plot (1/300 acre) being stocked, the relative proportions of drought-tolerant species are increased if moisture stress is above present average, and conversely, decreased if moisture stress is below present average. The SPECMULTs are shown for ponderosa pine (10), Douglas-fir (3), and grand fir (4). Ponderosa pine was sparsely represented in the regeneration model for the northern Idaho variant. Therefore, its presence was increased manyfold by the arbitrary 70, multiplying the stress effect.

```
ESTAB
  STOCKADJ      0.    PARMS(GSTR**2)
  SPECMULT      0.    PARMS(10, 70.0*EXP(STR*0.5))
  SPECMULT      0.    PARMS(3, EXP(STR*0.3))
  SPECMULT      0.    PARMS(4, EXP(STR*0.2))
END
```

Event Timing

Wildfire frequency (FIRFREQ) was calculated as a function of moisture stress using an approximation of the return intervals shown in table 2 with a further increase of 40 percent to represent effects of suppression (Agee 1993). The suite of management options also included prescribed fire at intervals of 30 years. However, in the event of a wildfire, the next prescribed fire would be rescheduled for 30 years after the wildfire (NXTFRYR2). If the wildfire event is triggered for a cycle, then a particular year for the fire to occur (FIRYEAR) is chosen at random within the

Table 2—Fire return intervals for four scenarios.

	Warmer	Cooler
Wetter	150 years	300 years
Dryer	20 years	40 years

cycle. This date is used in the regeneration keywords as the date of disturbance. Site preparation for the regeneration model is set to 100 percent for wildfire disturbances. Here are the keywords:

```
COMPUTE
      FIRFREQ = 1.4*EXP (7.39 – 0.34*(STR + 9.2) )
      PFIRE= 1. – (1.– 1./FIRFREQ)**NYEAR
      FIRYEAR = YEAR +INT( RANN*NYEAR )
      RNDM = RANN
END
IF
      PFIRE GE RNDM
THEN
      COMPUTE        0.0
            NXTFRYR2 = FIRYEAR + 29.9
      END
      ESTAB
            TALLY        9.0   PARMS(FIRYEAR)
            BURNPREP  9.0   100.
      END
ENDIF
```

Prescribed fire keywords were filed in an ADDFILE along with the silvicultural options. If a run was to consider prescribed fire, it was invoked with the following keywords:

```
IF
  (PFIRE LT RNDM) AND (YEAR GE NXTFRYR2)
THEN
      FMIN
            FIRETYPE    1.0    2.
            FIRECOND    1.0    3.     4.    70.     1.
      END
      COMPUTE      2.0
            NXTFRYR2 = YEAR + 30.
      END
      ESTAB
            TALLY        9.0   PARMS(YEAR+1.)
            BURNPREP   9.0   50.
      END
ENDIF
```

Fire and Fuels

Duff and woody debris loading was initialized with default loadings applicable to the habitat type. Ideally, the fuels inventory should be obtained directly from the subject stand.

Modelled fuels are augmented by detritus from the growing stand using parameters in the Fuels extension. Then they decay at rates specified by the FUELDCAY keyword (table 3). In the runs reported earlier, fuel decay rates were held constant at values specified in table 3 throughout the span of simulated time. Hence, there is a discrepancy with the trends in moisture stress, which followed a linear trend over the 50–year transient between present mean and the climate-scenario mean. A more realistic assumption would use the moisture stress (STRESS) applicable to the current cycle to interpolate among the values in table 3.

Model Execution in Suppose

The Suppose user interface for FVS was a critical adjunct to the analysis beyond the obvious assistance with entering routine keywords. The first step, "Select Simulation Stands," involved searching the inventory database for suitable stands to be used as examples. The 40 replicates were created by successively doubling the list of replications of the selected stand. Then the "Edit Simulation File" operation was used to open and append the keyword files for the particular combination of climatic scenario and management options. "Run Simulation" produced the output files, including those requested by keyword. Finally, "Generate Report" was used to parse the output for the variables to be displayed, averaged over the 40 replications, and transmit summary statistics to a spreadsheet for further display.

Recommendations for Model Modifications

FVS

- Provide two added parameters to Keywords modifying probabilities as additions to, and multipliers of, the argument in the exponential term in logistic function: for example, MORTMULT, STOCKADJ, SPECMULT, and so forth.
- Incorporate within-stand variability of stocking into accretion and mortality models (Regeneration Establishment already has it) (Stage and Wykoff 1998).
- Update specifications for inventory design. FVS could not accommodate Yakama Nation inventory without revision. For example, use Byrne and Stage (1988) protocols.

FFE

- Incorporate within-stand variability of stocking into fire behavior model.
- Improve linkage between stand attributes and fire behavior.

Table 3—Dead and downed fuel decay rates (proportion of weight loss per year) by fuel size.

Scenario	Litter	Duff	0-0.25"	0.25–1"	1–3"	>3"
Warm-wet	1.000	0.0040	0.200	0.120	0.120	0.060
Warm-dry	0.650	0.0026	0.130	0.078	0.078	0.039
Cool-wet	0.350	0.0014	0.070	0.042	0.042	0.021
Cool-dry	0.250	0.0010	0.050	0.030	0.030	0.015

Suppose

- Provide capability to routinely replicate stands. (Needed to address concerns of Hamilton (1991) that FVS users do not recognize the implications of random variation.)
- Augment computation of means over multiple stands with computation of their standard deviations.

Conclusion

These analyses describe how FVS was used to evaluate silvicultural alternatives in the context of changing climate in forests where fire is a significant process in stand dynamics. We reduce the problem of predicting future weather variables such as daily temperature, humidity, and precipitation to the more accessible problem of predicting a few key parameters—seasonal moisture stress and growing season length. Response to changes in these parameters can and should be estimated from direct observation of existing forests. Furthermore, quantifying these responses to weather variations would be useful in evaluating current model biases.

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Using the Forest Vegetation Simulator to Reconstruct Historical Stand Conditions in the Colorado Front Range

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Abstract—Presettlement ponderosa pine/Douglas-fir forests of the Colorado Front Range were open and heterogeneous. Logging, grazing, and fire suppression over past 100 to150 years have altered stand structure by changing diameter distributions and increasing overstory density. In an effort to guide forest restoration toward presettlement conditions, we are currently using the Forest Vegetation Simulator (FVS) to validate estimates of 1900 forest structure, and calibrate the model for future use, for an unmanaged landscape (unlogged, ungrazed, but fires suppressed since 1900). In 1997, tree data were collected in 15 0.1-ha plots at Cheesman Lake. For trees larger than 1.4 m tall, diameter at breast height, height, species, live/dead status, age, and diameter growth increment were recorded; for trees less than 1.4m tall, basal diameter, height, species, live/dead status, age, and height growth increment were measured. FVS was first calibrated with diameter and height growth increments from the plots so that it more adequately depicted our study area. A 1900 tree data file was derived from data collected in 1997 for each plot by including only the tree records that pre-dated 1900, and measuring 1900 d.b.h. on increment cores. The plot was then grown forward to 1997, with natural regeneration added each decade to represent ingrowth in the plot since 1900. The modeling results were compared to the actual data. Growth and mortality multipliers were modified and FVS was rerun until FVS-generated 1997 diameter distributions, stand densities, and canopy covers were similar to those observed in 1997. Results from this intermediate phase of research will help to guide restoration activities in the South Platte Watershed, Colorado, and will also be critical in future stages of our research.

Stand structure in ponderosa pine/Douglas-fir (*Pinus ponderosa*/*Pseudotsuga menziesii*) forests of the Colorado Front Range has changed dramatically in the past 150 years. Prior to Euro-American settlement in the late 19th century, these forests were open and heterogeneous in age and size (GLO Field Notes 1879, 1882; Jack 1900). Logging, grazing, and fire suppression over the past 100 to 150 years have altered stand structure by removing many of the large or old trees and by allowing more regeneration to become established (Marr 1961; Veblen and Lorenz 1986; Kaufmann and others 2000). As a result, the current forest structure is younger, denser, and more homogeneous, and shade-tolerant Douglas-fir has become more prevalent on the landscape.

Restoring ponderosa pine/Douglas-fir ecosystems to historical stand conditions is vital if we wish to maintain ecological sustainability and reduce the risk of catastrophic, stand-replacing forest fires. Treatment projects intended to restore ponderosa pine ecosystems to a historical condition require an understanding of what this historical condition was.

We are fortunate to be able to study at the Cheesman Lake landscape, a relatively undisturbed 35- km^2 ponderosa pine/Douglas-fir forest in the Upper South Platte Watershed of the Colorado Front Range. Cheesman Lake, a reservoir created on the South Platte River at the beginning of the 20th century, and the surrounding land are owned and managed by Denver [City] Water. Unlike most montane forests in the Colorado Front Range, this landscape has experienced only minimal, localized logging (mostly below the current water line of the reservoir during the time of dam construction). At the time of dam completion in 1905, a six-strand barbed-wire fence was erected around the property, which has excluded domestic grazing. Wildfires, however, have been suppressed since the early 1900s.

We used the Forest Vegetation Simulator (FVS; Spruce-Fir submodel of the Central Rockies variant, version 6.31) to "de-grow" plots on the current Cheesman Lake landscape to 1900, just prior to the effects of fire suppression during the 20th century (fig. 1). FVS was first calibrated with diameter and height growth increments so that it more adequately depicted our study area. A 1900 tree data file was then derived from data collected in 1997 for each plot by removing all trees that germinated after 1900, and estimating the 1900 diameter for all pre-1900 trees. Each 1900 plot was grown forward to 1997, with natural regeneration added each decade to represent ingrowth in the plot since 1900. The modeling results were compared to the current data. Growth and mortality multipliers were modified, and FVS was rerun until FVS-generated 1997 diameter distributions, stand densities, and canopy covers were similar to those observed in 1997. Results from this research will help guide restoration activities in the South Platte Watershed, and will also be critical in future stages of our research.

In: Crookston, Nicholas L.; Havis, Robert N., comps. 2002. Second Forest Vegetation Simulator Conference; 2002 February 12–14; Fort Collins, CO. Proc. RMRS-P-25. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

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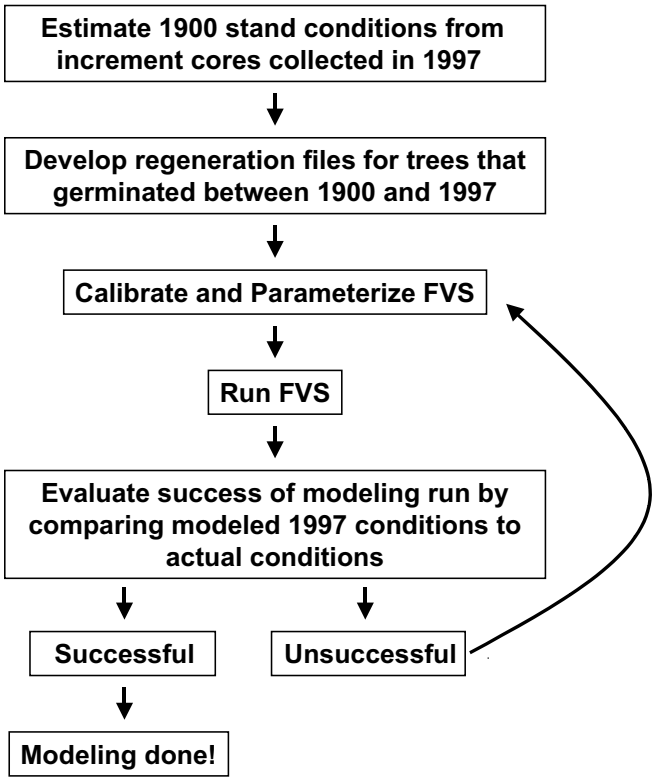

Figure 1—Flow chart depicting the methods used to "degrow" the plots at Cheesman Lake.

Estimating Plot Condition in 1900

In 1997, we established 15 0.1-ha (0.25 acre) plots within a 4-km^2 portion of the Cheesman Lake landscape (Kaufmann and others 2000). Five plots were randomly located in the 4 km^2 area on each of three topographic categories: north-facing slopes, south-facing slopes, and east- or west-facing slopes. In each plot, for all trees taller than breast height (1.4 m), tree diameter at breast height (d.b.h.), species, and live or dead status were recorded. Basal diameter, species, height, and 5-year height growth increment were measured for trees less than breast height tall. Also in each plot, 20 randomly selected live trees were cored for age at 30 cm above the ground; every tree in the plot that appeared to be over 200 years old was also cored (Kaufmann and others 2000). Tree germination dates were then determined by crossdating with a local chronology (Stokes and Smiley 1968; Kaufmann and others 2000). If a tree's germination date was not measured, it was predicted using a kernel density function (Venables and Ripley 1999). We also measured 10-year diameter growth increments on the cores.

We relied on our increment cores to reconstruct the 1900 stand condition. For all increment cores taken from trees that germinated prior to 1900, we measured the distance from the pith to the ring that was laid down in 1900. This 1900 radius was doubled to get the 1900 diameter (inside the bark and at a coring height of 30 cm). We then estimated the tree's 1900 diameter at breast height (outside the bark) from allometries developed by VanDeusen (1975).

For trees that were not cored but whose estimated germination date was prior to 1900, we ran backward stepwise regressions to predict 1900 d.b.h. from age, 1997 d.b.h., and 1997 height for the rest of the pre-1900 trees. Only variables that were significant at the alpha = 0.15 level were retained in the backward stepwise model.

We also relied on our increment core data to estimate tree recruitment that occurred in the plots since 1900. For trees that germinated after 1900, we determined the number of trees, by species, that germinated in each decade between 1900 and 1997.

The pre-1900 stand conditions were entered into FVS as tree data files ('.fvs'). The tree data files contained the species, live or dead status, and 1900 d.b.h. for all trees that germinated prior to 1900. We used the 'NATURAL' keyword to enter the number of trees (by species) that germinated in each decade between 1900 and 1997. To compensate for trees that were alive at some time between 1900 and 1997 but have since died, we assumed a mortality rate of 2 percent per decade.

Calibrating, Parameterizing and Running FVS

Several keywords were used to calibrate and parameterize FVS. These keywords can be divided into two groups: those whose values were fixed for all FVS runs for an individual plot, and those whose values were adjusted for each FVS run so that the FVS simulation results more closely matched what was observed in the plot.

The keywords that were fixed for all simulation runs of a plot were 'READCORD,' 'READCORR,' and 'SDIMAX'. 'READCORD' is a multiplier for the large tree diameter growth model. The values for this keyword were determined by FVS, based on diameter increment measurements. 'READCORD' was 0.651 for Douglas-fir and was 0.749 for ponderosa pine. 'READCORR' is a multiplier for the small tree height growth model. FVS determined the values for this keyword from height growth measurements on small trees. 'READCORR' was 0.708 for Douglas-fir and 0.928 for ponderosa pine. The 'SDIMAX' keyword changes the maximum stand density index (SDI) for a stand, and how maximum SDI affects a stand's density dependent growth and mortality rates. While we did not alter maximum SDI, we did decrease the percent of maximum SDI where density dependent mortality begins (field 5) from 55 to 40 percent. We also decreased the percent of maximum SDI where the stand reaches maximum density (field 6) from 85 to 70 percent. A stagnation effect, where tree growth stagnates when plot density exceeds 70 percent of the maximum SDI, was also invoked (field 7). These alterations to 'SDIMAX' were based on our plot data.

The keywords whose values were changed for any individual simulation run were 'REGHMULT,' 'FIXDG,' and 'MORTMULT'. 'REGHMULT' is a multiplier for the height growth of small trees. 'FIXDG' is a multiplier for diameter growth of large trees. We entered this keyword into our simulation file five times, so that growth rates of trees 0 to 10 cm d.b.h., 10 to 20 cm d.b.h., 20 to 30 cm d.b.h., 30 to 40 cm

d.b.h., and greater than 40 cm d.b.h. could be adjusted independently of each other. 'REGHMULT' and 'FIXDG' varied from 0.1 to 1.9 (plus or minus 90 percent of the default value); 'MORTMULT' varied from 1.0 to 2.0. Note that these values were not changed during a simulation (that is, from decade to decade), but were changed for any individual simulation. During a simulation, the values for these parameters remained constant.

During each simulation, we computed the number of trees per hectare in 10 cm d.b.h. classes (0 to 10 cm, 10 to 20 cm, 20 to 30 cm, 30 to 40 cm, 40 to 50 cm, and greater than 50 cm d.b.h.). We also computed total canopy cover. The 'Compute 2' postprocessor was invoked so that the output file ('.cp2') could be read into SAS for evaluation with the observed plot data (SAS release 8.1, SAS Institute Inc.).

Evaluating the Success of the FVS Run

To determine whether an FVS run was successful at producing the observed 1997 plot conditions from a given set of inputs, we evaluated our FVS run in four ways. The first way was qualitative; histograms of the d.b.h. distributions for the plot and the FVS output were visually compared. If the histograms appeared similar, the modeling run was deemed successful by this method. Second, we calculated a 10 percent "confidence interval" for each d.b.h. class; if the FVS-generated output was within these confidence intervals for at least four of the six d.b.h. classes, the modeling run successfully passed this test. The third way we compared the FVS output to the plot data was with a chi-square goodness-of-fit test. An FVS modeling run successfully mimicked the plot data if the p-value was greater than or equal to 0.80. Fourth, percent canopy cover for the plot and the FVS output were also compared, and if the FVS-generated canopy cover differed from the plot canopy cover by 10 percent or less, then the modeling run was successful by this method.

When an FVS run successfully passed all four "tests," it was considered acceptable. If all of the above conditions were not met, then the keyword parameters were altered and FVS was rerun until the conditions were met. We will use one plot, 'CL0111,' as an example, and describe each of these evaluations for both an unparameterized (default) FVS run, and a parameterized (modified) run.

We generated histograms for a graphic comparison of the plot and the FVS-generated data, shown in figures 2a, b, and c. Figure 2a shows the number of trees per hectare by d.b.h. class observed in plot CL0111 in 1997. Plot CL0111 has the classic inverse-j shaped curve characteristic of uneven-aged stands. While the diameter distribution of our unparameterized stand (where the keywords 'REGHMULT,' 'MORTMULT,' and 'FIXDG' are all equal to the default values) does not really mimic what is on the ground, our parameterized run looks similar to real life (fig. 2b, c).

We calculated a 10 percent "confidence interval" for the number of trees per hectare in the plot in each diameter class. It is important to note that what we calculated was not a true confidence interval; rather, it was the number of trees per hectare by d.b.h. class observed in the plot, plus or minus 10 percent. Results from an unparameterized FVS run and a parameterized run are shown in tables 1a and 1b. While the number of trees predicted by FVS for each d.b.h. class is never within 10 percent of those observed in the plot (never 'OK') in the unparameterized run, the parameterized run is 'OK' in five of the six d.b.h. classes.

The third way that we evaluated the success of our modeling run is with a chi-square goodness-of-fit test. Again, our FVS run with the default parameters does not match observed conditions as well as the parameterized FVS run (unparameterized run: $p=0.0005$; parameterized run: $p=0.9882$).

Evaluating canopy cover is important for us because canopy cover serves as a link to apply the results from our plots to the rest of the Cheesman Lake landscape in the next phase of our research. Canopy cover (calculated by FVS) for CL0111 in 1997 was 38.6 percent; the unparamaterized model estimated canopy cover to be 45.8 percent, while the parameterized model estimated it to be 40.6 percent. Again, the FVS run with the modified parameters more closely mimicked what is actually on the ground.

Preliminary Results and Their Application To Date

Table 2 shows modeled 1900, observed 1997, and modeled 1997 canopy covers for all plots, averaged by aspect. Values for our example plot, which is east-facing, are also included. Average historical forest density for our plots was estimated to range from 13 to 22 percent canopy cover, while average current forest density (actual data) ranged from 39 to 65 percent. For plots that were successfully modeled, FVS canopy cover was within 10 percent of the actual data for all aspects.

Table 3 lists the parameter values for all the keywords that were used in each FVS simulation. Five plots could not be successfully degrown, given the bounds we put on our parameters. Of these five plots, two were very sparse (14 or fewer trees per plot, or 140 trees per hectare), and one was very dense (canopy cover was greater than 70 percent). While we are generally satisfied with the results of our modeling runs, we realize that several of our assumptions may be affecting their success. Our assumption that parameters are constant for all decades in a simulation may not be valid. These parameters may change over time as stand density and tree size increases through the decades. Also, these parameters may change over time because of changes in climate.

We mapped 2,500 polygons from 1:6000 color infrared aerial photographs for the entire Cheesman Lake landscape, based on canopy closure and diameter class distribution (Huckaby and others 2001). Of these polygons, 580 were within the 4-km^2 study area.

Based on the preliminary results from this modeling work and the polygon coverage for the 4-km^2 study area, we developed relationships between 1997 canopy cover and 1900 canopy cover for each of the 585 polygons. Aspect and an aspect-by-1997 percent canopy cover interaction variable were initially considered in the regression but were removed because they were not significant predictors. While the correlation between 1900 and 1997 canopy covers is not strong (Adj. $R^2 = 0.19$, s.e. = 8.83), an initial version of estimated 1900 canopy cover for the 4-km^2 study area (top),

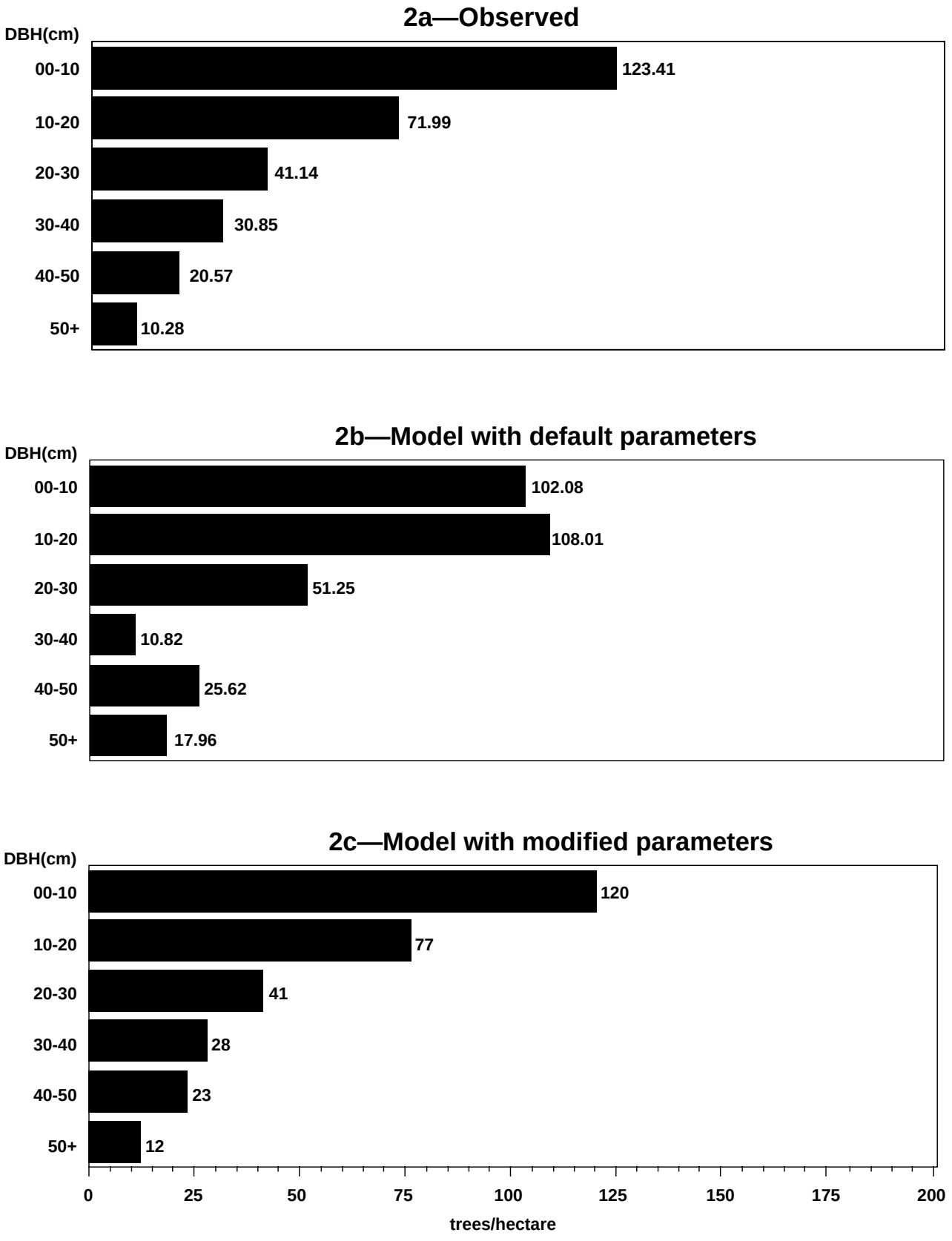

Figure 2—Example output for plot CI0111. The histograms of diameter class distribution were used to evaluate the success of an FVS run. Figure 2a is the histogram for the actual plot data in 1997. Figure 2b is the histogram for the unparameterized FVS run, and figure 2c is the histogram for the parameterized FVS run. The diameter distribution produced by the parameterized FVS run better reproduces the actual data.

Tables 1a and b—"Confidence interval" evaluation for plot CL0111. Table 1a (top) is the output for the unparameterized FVS run, and table 1b (bottom) is the output for the parameterized FVS run. We calculated a 10 percent "confidence interval" for each d.b.h. class; if the FVS-generated output was within these confidence intervals for at least four of the six d.b.h. classes, the modeling run was successful. While the number of trees predicted by FVS for each d.b.h. class is never plus or minus 10 percent of those observed in the plot (never 'OK') in the unparameterized run, the parameterized run is 'OK' in five of the six d.b.h. classes.

D.B.H. class	Trees per ha for actual plot	Trees per ha estimated by FVS	Low 'confidence interval' (–10%)	High 'confidence interval' (+10%)	High, low, or OK?
a. Unparameterized Run					
0 to 10 cm	123	102	111	136	Low
10 to 20 cm	72	108	65	79	High
20 to 30 cm	41	51	37	45	High
30 to 40 cm	31	11	28	34	Low
40 to 50 cm	21	26	19	23	High
50 cm plus	10	18	9	11	High
b. Parameterized Run					
0 to 10 cm	123	120	111	136	OK
10 to 20 cm	72	77	65	79	OK
20 to 30 cm	41	41	37	45	OK
30 to 40 cm	31	28	28	34	OK
40 to 50 cm	21	23	19	23	OK
50 cm plus	10	12	9	11	High

Table 2—Canopy cover, averaged by aspect class, for 1900, 1997_{Plot}, and 1997_{FVS}. Percent canopy covers for our example plot, CL0111, are also listed. 1900 and 1997_{Plot} percent canopy cover averages are for all plots, not just plots that were successfully degrown; 1997_{FVS} percent canopy covers are only for the plots that were successfully degrown (this number of plots is reported in parentheses next to the canopy cover value).

	Average percent canopy cover		
Aspect[a]	1900	1997_{Plot}	1997_{FVS}
N	21.5	65.4	66.7 (n = 4)
E/W	15.7	45.3	43.0 (n = 2)
CL0111	18.0	38.6	40.6
S	12.9	40.1	40.8 (n = 4)

[a]E/W= East/West, N=North, and S=South.

along with the 1997 estimates from air photos (bottom) is shown in figure 3. Changes in canopy cover from 1900 to 1997 are dramatic. These preliminary results indicate that, in 1900, approximately half of the 4-km^2 study area had a canopy cover of 10 percent or less, and none of the polygons had a canopy cover exceeding 40 percent. Conversely, less than one quarter of the 4-km^2 study area had a canopy cover less than 10 percent in 1997, while more than one quarter of it had a canopy cover exceeding 40 percent. Although this research work is in an intermediate stage of development, these results are supported by historical photographs taken at Cheesman Lake (fig. 4; Denver Water Archives, Denver, CO), by written records from the turn of the century (GLO Field Note 1879, 1882; Jack 1900), and by what we know about the fire history for the 4-km^2 area (Brown and others

Table 3—Parameter values, by plot. Multiplier values of '—' indicate that the plot was not successfully degrown.

		READCORD		READCORR		REGH	FIXDG	FIXDG	FIXDG	FIXDG	FIXDG	MORT	
Plot	Aspect[a]	DF[b]	PP[c]	DF	PP	MULT	0-10	10-20	20-30	30-40	40+	MULT	P-value
							- - - - - - - - - - - - - - - - - *cm* - - - - - - - - - - - - - - - - -						
CL0111	E/W	0.65	0.75	0.71	0.93	0.70	1.00	1.10	1.50	0.60	0.20	1.50	0.9882
CL0113	N	0.65	0.75	0.71	0.93	0.60	1.30	1.30	0.80	0.80	0.80	1.00	0.9194
CL0420	E/W	0.65	0.75	0.71	0.93	—	—	—	—	—	—	—	—
CL0701	N	0.65	0.75	0.71	0.93	0.40	0.80	1.70	0.70	0.90	0.60	2.00	0.9946
CL0904	N	0.65	0.75	0.71	0.93	0.70	1.10	1.20	0.95	0.50	0.50	2.00	0.9503
CL1208	E/W	0.65	0.75	0.71	0.93	—	—	—	—	—	—	—	—
CL1312	S	0.65	0.75	0.71	0.93	1.00	1.00	1.00	1.00	0.70	1.10	2.00	0.9505
CL1632	N	0.65	0.75	0.71	0.93	—	—	—	—	—	—	—	—
CL1711	S	0.65	0.75	0.71	0.93	0.80	0.80	1.00	1.00	0.40	0.10	1.00	0.9653
CL1916	E/W	0.65	0.75	0.71	0.93	—	—	—	—	—	—	—	—
CL2202	S	0.65	0.75	0.71	0.93	1.20	1.20	1.20	1.00	0.65	0.60	1.50	0.9671
CL2316	S	0.65	0.75	0.71	0.93	—	—	—	—	—	—	—	—
CL2408	S	0.65	0.75	0.71	0.93	0.50	0.83	1.90	0.70	1.00	0.90	1.20	0.9221
CL2503	E/W	0.65	0.75	0.71	0.93	1.00	1.00	1.00	1.00	1.00	1.00	1.70	0.9745
CL2613	N	0.65	0.75	0.71	0.93	1.00	1.00	1.70	0.80	0.30	0.30	1.00	0.9562

[a]E/W= East/West, N=North, and S=South.
[b]DF= Douglas-fir.
[c]PP= ponderosa pine.

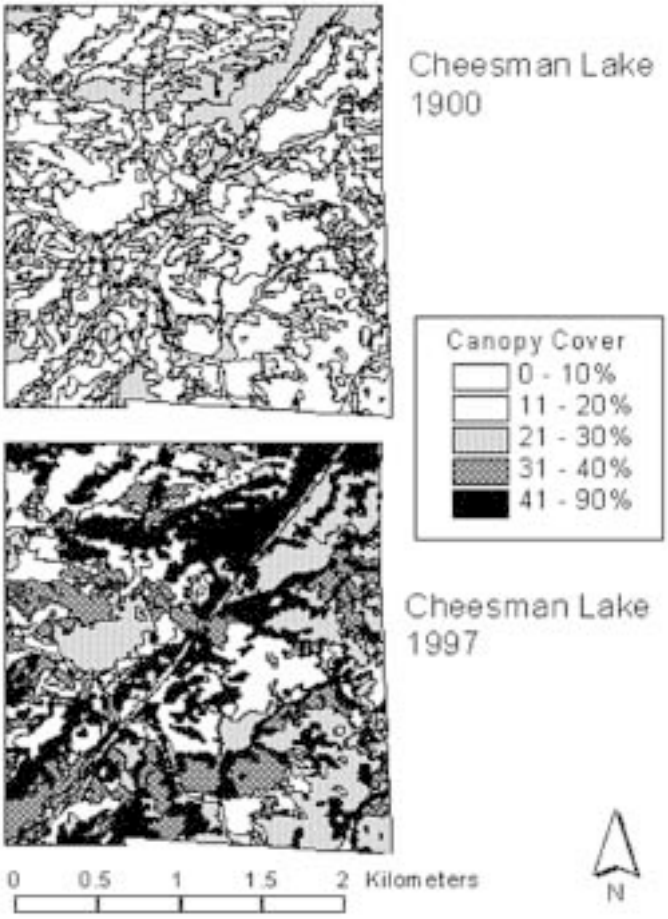

Figure 3—Map of percent canopy cover at Cheesman Lake. The 1900 map (top) was developed from a correlation between 1900 and 1997 percent canopy cover for our 15 plots. Using this correlation, we were able to calculate 1900 canopy cover from the 1997 canopy covers assigned to each polygon. The 1997 map (bottom) was developed from aerial photograph interpretation of 1:6000 color infrared photographs, based on canopy cover and d.b.h. distributions.

1999). The fire history indicates that most or all of this area burned in 1851 as a mixed-severity or stand-replacing fire, where many trees were killed. Consequently, canopy covers in 1900 would be likely to be low, and our results reflect this.

Future Research

The research effort outlined here is an intermediate stage in our overall goal of estimating historical stand conditions, and also in determining what current forest conditions would be at Cheesman Lake if 20th century fires had not been suppressed. Future research will involve incorporating data for 51 additional 0.1 ha plots that are distributed across the entire 35-km^2 Cheesman Lake landscape, and degrowing all of our plots using methods similar to those outlined above, while incorporating the two following changes.

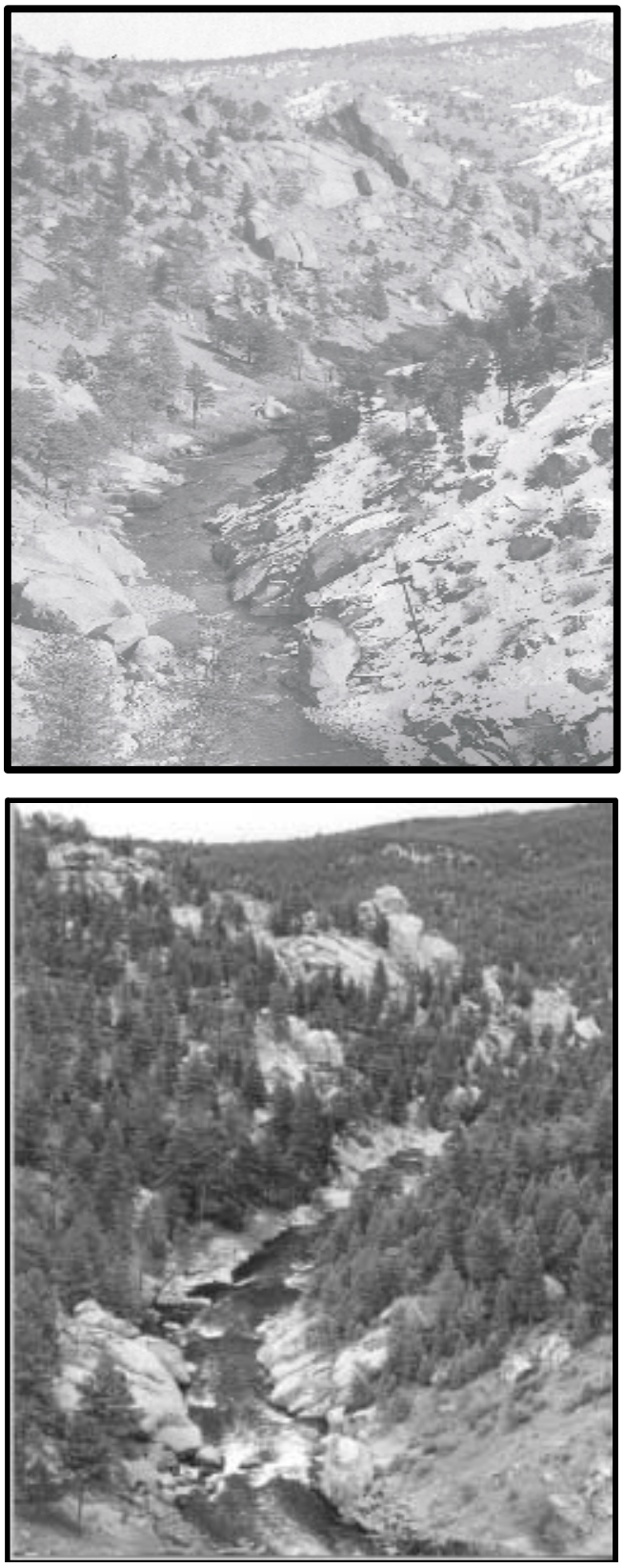

Figure 4—Paired photographs showing forest condition along the South Platte River, just below the Cheesman Lake Dam. The photo on the top was taken in 1903 (courtesy Denver Water Archives), and the photo on the bottom was taken in 1999 (courtesy Laurie Huckaby).

First, we will begin working with a test version of FVS that allows tree age measurements to be incorporated into an FVS tree data file ('.fvs'). Incorporating a tree's actual age into an FVS run will allow us to modify growth rates based on age, rather than d.b.h., and will likely increase our modeling success. While it is generally true that age and d.b.h. are related, they are often not well correlated, especially when growing conditions are extreme and highly variable. Our increment core data indicate that patterns of tree growth rates are more closely related to tree age than to tree size. In the Colorado Front Range, it is not uncommon for two ponderosa pine trees of the same d.b.h. to differ in age by 100 years or more. For example, the two ponderosa pine trees in figure 5 have similar diameters, but differ in age by nearly 130 years.

We will also use a program written by Don Vandendriesche at the Forest Management Service Center in Fort Collins, CO, to perform sensitivity analyses for the keywords that we modify (Hamilton 1997a). This program, named the 'Keyword Iteration Navigator' ('KIN'), allows a user to specify minimum, maximum, and step increments for various keyword parameters that are being used in a simulation (Vandendriesche 2001). In our work for this paper, we varied parameters for seven keywords ('REGHMULT,' five 'FIXDG' keywords, and 'MORTMULT'). To vary these keywords in the ranges used for this paper by increments of 0.1 would require hundreds of thousands FVS runs per plot. Using KIN, we will generate all possible parameter combinations and run them through FVS in much less time and with much less effort than if we did it manually. We will import the KIN output into SAS to determine which of the simulation(s) successfully mimic what we know to exist in the plot. Keyword combinations that are illogical, but are successful by our criteria, will need to be eliminated manually (Hamilton 1997b). Doing this may give us multiple "pathways" with which to grow our forest.

Once we have reparameterized the current 15 plots and the 51 additional plots using the age-enhanced FVS variant and KIN, we will attempt to determine the 2000 forest condition at Cheesman Lake, under a plausible natural fire regime. Based on the Cheesman Lake fire history and knowledge of fires that were suppressed, we suspect that there were 4 years that had potential to be big fire years at Cheesman Lake during the 20th century (Brown and others 1999). These fire years are 1912, 1954, 1963, and 2000. Trees in Cheesman Lake were scarred by fire in all of these years, but the fires were probably suppressed. The 1912 fire scarred trees in the southeastern portion of Cheesman Lake, and the 1954 fire scarred trees in the northeastern portion of Cheesman Lake; the extent of these fires is unknown. Fire scars and written records indicate that the 1963 fire burned in the southeastern corner of the Cheesman Lake property and burned 50 to 100 ha before it was suppressed. The 2000 fire burned in the northwestern portion of Cheesman but was suppressed before it exceeded 10 ha. We speculate that if these four fires had not been suppressed, based on their ignition locations and what we know about historical fire size, they would each have burned approximately half of the Cheesman Lake property, so that the entire property would have burned twice (with variable intensity) in the past 100 years. This is consistent with the fire history for the area (Brown and others 1999). We hope to use the results of this study, along with our plot data, the 1997 polygon coverage, FVS, and the Fire and Fuels Extension of FVS to help depict the landscape just before and after each of these fires, with forest structure reflecting the effects of these four fires had they been allowed to burn as natural fires.

Figure 5—Photograph of an older tree (left) and a younger tree (right) growing side by side. While both of these trees are of similar d.b.h. and height, the older tree has a pith date of 1761 (d.b.h. is 33.6 cm or 13.2 inches), and the younger tree has a pith date of 1889 (d.b.h. is 31.7 cm, or 12.4 inches). The photograph is courtesy of Laurie Huckaby.

Results from this research and previous research using FVS are currently being used to guide restoration efforts on the South Platte Restoration Project (Kaufmann and others 2001). The Upper South Platte Watershed is important in the Colorado Front Range because it provides 70 percent of Denver's water supply and provides the people of the greater Denver area with access to fishing, hiking, and other recreational activities (Foster Wheeler 1999). Because of the watershed's proximity to Denver, it also contains a large area of urban-wildland interface. Two stand-replacing fires well outside the range of historical variability have occurred in the Upper South Platte Watershed since the mid-1990s. The 1996 Buffalo Creek fire, which burned 4,820 hectares (11,900 acres), and the 2000 Hi Meadows fire (4,250 hectares, or 10,500 acres) illustrate the huge risk of wildfire and

postfire erosion in these dense forests. Future research results will better guide restoration activities and reduce the risk of catastrophic wildfires such as Buffalo Creek and Hi Meadows, and the research will promote ecological sustainability in these ponderosa pine/Douglas-fir ecosystems.

Acknowledgments

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Sensitivity of Forest Vegetation Simulations to Scale of the Input Data and Impact to Estimates of Key Habitat Indictors, Tree Size, and Density

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Abstract—We demonstrate that the results of landscape-level vegetation projections using FVS differ depending on the strategy used to aggregate the input data. To illustrate the point, we picked landscape-level variables that are important to addressing habitat components for old forest-dependent species, a contemporary forest management issue for the Sierra Nevada Bioregion, California. The approach was to compare FVS results using: (1) Traditional strata maps developed by USDA Forest Service Region 5 for regional planning where the "average" condition of all the relevant FIA plots is aggregated into a series of timber strata representative of large landscapes. (2) Modified strata maps developed by calculating the "mode" of the relevant FIA plots but also aggregated into timber strata. (3) Projections of the individual FIA plots without aggregation. Interpretation of two continuously valued variables we studied did not vary significantly between aggregation methods, but the interpretation of the discretely classed variables greatly differed. Our inspection of the results suggested that the unaggregated data gave more realistic projections of size and density distribution that seemed to best represent fundamental ecological processes. Nonetheless, we argue that using aggregated data is necessary when the spatial integrity of the analysis needs to be maintained. The implications of our observations on landscape analysis are discussed.

The paradigm for management of the California National Forest lands has shifted away from management for resource production such as timber and mining and into management strategies for preserving and enhancing habitat characteristics (Committee of Scientists 1999). The change is driven by the conflicts among the legal requirements for species preservation, reflecting a shift in societal perspectives, a burgeoning population (approaching 35 million within the State alone), the popularity of the diverse recreational activities offered by National Forest lands, and the continued need of the forests to provide water and other historic resources in support of local communities.

In an effort to reconcile the complicated interactions and conflicts among the many stakeholders, the Sierra Nevada Framework Project was established. The framework's original charge was to combine the best of the scientific knowledge within the Forest Service's Pacific Southwest Research Station and the best of the management experience within the interdisciplinary teams from Region 5 to prepare an Environmental Impact Statement for modifying the forest plans of the 10 National Forests and the Lake Tahoe Management Unit that occupy the Sierra Nevada Bioregion (Final Environmental Impact Statement 2000).

The work was intended as an outgrowth of the Sierra Nevada Ecological Project (Sierra Nevada Ecosystem Project 1996) submitted as a Congressional report. Out of that project, five key topics emerged as the most serious threat to the health and sustainability of Sierran ecosystems (Record of Decision 2001):

- Protect, increase, and perpetuate old forest ecosystems and provide for the viability of native plant and animal species associated with old forest ecosystems.
- Protect and restore aquatic, riparian, and meadow ecosystems and provide for the viability of native plant and animal species associated with these ecosystems.
- Manage fire and fuels in a consistent manner across the National Forests, coordinate management strategies with other ownerships, integrate fire and fuels management objectives with other natural resource management objectives, address the role of wildland fire, and set priorities for fire and fuels management actions.
- Reduce and, where possible, reverse the spread of noxious weeds.
- Maintain and enhance hardwood forest ecosystems in the lower westside of the Sierra Nevada.

The charge of the Framework was to use all available tools to define, analyze, evaluate, and present probable consequences of eight independent management alternatives developed to address the five key topics. To do so, the Forest Vegetation Simulator (FVS) was used in combination with several other models to produce a set of scenarios where the needs of forest, woodland and riparian habitats were balanced with needs of fire protection, while attempting to return Sierran ecosystems to a more natural fire regime and ecological balance.

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The Sierra Nevada Bioregion occupies roughly 15 million acres, of which the Forest Service manages 11.5 million acres. The remaining lands are a polyglot of private, State, National Parks, and other Federal agency ownership. The primary range extends for about 800 miles, roughly north-south and about 120 miles in the east-west direction. The elevations start at near sea level on the western edge and climb to the highest peak in the continental United States at Mount Whitney at over 14,000 feet. Because of the huge diversity in geological formations leading to widely varying landscapes, California contains the highest number of individual ecosystems of any U.S. State. Half of that natural diversity in California resides in the Sierra Nevada Bioregion (Sawyer and Keeler-Wolf 1995). Human population forecasts indicate between 1.8 and 2.0 million people will occupy the region in 2040, mostly at elevations below 7,000 feet (Duane 1996). The population densities are heaviest in the central and southern part of the bioregion. In addition to permanent residents, the Sierra Nevada draws millions of visitors every year. Like the permanent settlements, visitor days tend to be heaviest in the central part of the region. The management emphasis on several of the individual National Forests has slowly shifted from resource extraction to recreation, both of which can have significant impacts on habitat quality (Final Environmental Impact Statement 2000).

Sierran ecosystems are highly heterogeneous with patches of dense, young trees immediately adjacent to open stands of very old trees, large trees emerging from shrub patches, and an interdigitation of ecosystems that makes accurate mapping and identification difficult at a scale appropriate for the characterization of habitat for many animals. Understanding and projecting vegetation characteristics that are key to habitat values is a relatively new science. By far the most challenging aspect of habitat projections is simply identifying key vegetation characteristics required by specific species in a quantitative manner. And, obviously, key characteristics are species-dependent, thus highly variable in scale. What might be an important requirement for foraging habitat for the Sierran fisher would be of little quantitative use in understanding habitat for yellow-legged frogs.

Many of the metrics used in standard FVS modeling such as tree size and density were useful for vegetation modeling for habitat characteristics. Other metrics need to be modified or developed such as distribution patterns of trees and growth projections for nontree species. This being said, however, the FVS offers the best and most comprehensive model for landscape-scale evaluation of forest responses to management alternatives.

Two primary sources of input data are available for Sierrawide modeling — the Forest Inventory Assessment (plot-based) data, and the Region 5 strata maps, developed from satellite imagery. The two data systems have been coordinated so that strata map information corresponds to plot information and vise-a-versa. The strata maps use broad forest-type categories and for the most part, underrepresent nontimber types. For example, the presence of as little as 10 percent conifers in a stand of oaks is enough to have the stand classified as a conifer-type. However, the maps are important visual tools for decisionmaking and for presentation to stakeholders and the public at large. The FIA plot data, on the other hand, includes species composition, vegetation distribution patterns, and historical information but can only represent a small sampling of particular places. It is impossible to derive map products from the FIA data alone. In the Sierra Nevada, because of the scale and heterogeneous nature of the forests, the statistical variation within a cluster plot may exceed the variation across plots.

An effort was made to combine the two data sets in a way that allowed for reclassification of the forest strata data based on the FIA distribution information and then use FVS projection of this new hybrid data to estimate changes over time. An interesting problem occurred during this hybridization process: the results of vegetation projections for the eight proposed alternatives differed substantially depending on whether the strata average, strata mode, or pure FIA plot data were used for the input data source.

What follows is a summary of the approach for combining map-based information with the FIA data, the results of the different data reduction schemes and a brief discussion of the use of the FVS in evaluation of key habitat indicators. This paper explores the sensitivity of a number a continuous variables such as the number of large trees, and class habitat data such as serial stage, under various level of data aggregation from the plots, to the stand, the stratum, and the landscape. The implications for using these data at different scales are discussed.

Methods and Materials

Vegetative Mapping and Stratification

The forests within Sierra Nevada Bioregion were mapped from Thematic Mapper satellite imagery. Map polygons representing forest species type, tree size classes, and crown cover density were defined by processing the satellite imagery data by a combination of supervised and unsupervised classification systems. Vegetation maps were produced first using spectral analysis of data combined with ecological modeling. Polygons representing stands of trees defined by major forest type, tree size, and canopy closure density class were the primary sampling units for assignment of the ground plot data used to describe these strata. These vegetation-type polygons are the basic unit for which management decisions are made and are the unit areas for which wildlife habitat type is typically assigned within Region 5.

Linking Ground Plot Data to Map Polygons

Approximately 2,900 Forest Inventory and Analysis (FIA) plots were distributed across the 10 National Forests in Region 5. The individual sample plots are aggregated into vegetation classifications according to a vegetation map defined above. This map is the primary bookkeeping tool for tracking vegetation on the forests, based on summaries of the plots sampled within each strata.

Forest inventory ground data were linked to forest type or polygon maps through the strata label attribute. That is, the unique vegetation labels from the FIA data were aggregated into similar classes and then ground plots were allocated to vegetation polygons. Traditionally, these strata were defined for the purpose of sampling timber volume. Each vegetation polygon was then assigned to a stratum which

had an associated set of FIA plot data. The total number of acres on a particular national forest associated with a given stratum label was estimated by summing among map polygons with identical stratum labels. For example, the total number of large trees (those greater than 30 inches d.b.h.) associated with map areas within a given stratum label were estimated by calculating the per acre average from the inventory data and multiplying by total number of acres as determined from the vegetation type map.

The Region 5 method of using vegetation-type maps to stratify and assign ground plots was designed to describe general conditions, relative to timber, especially stocking measured by cubic volume. There was no intent to provide detail description of vegetation condition in any specific place, much less all places. As a consequence, data from 2,978 plots used in this analysis cannot be used to describe any other polygon than the one sampled.

CWHR System

The California Wildlife Habitat Relationships System (CWHR) is a generalized model of habitat relationships for 643 resident or regularly migrant terrestrial vertebrate species in California (CWHR 1988). The University of California at Berkeley and the California Department of Fish and Game developed it, cooperatively. The CWHR models were originally designed to closely approximate the timber strata presented in FIA system. The system allows a user to predict the occurrence and habitat quality for any of these species based upon the presence of specific habitat types or habitat elements. It includes species notes for each species including life history, range maps, legal status, habitat requirements, and so forth. The CWHR habitat system, like many other vegetation classification systems, uses the combination of plant species, size, and density to classify habitats. The CWHR system then uses this habitat classification to identify habitat relationships between the vegetation and the wildlife specie likely to be found in that area.

The CWHR models are designed to evaluate wildlife response to habitat change over relatively large spatial and temporal scales. CWHR was considered an appropriate approach to a quantitative analysis at the bioregional scale for a large array of species that occur in the Sierra Nevada. The accuracy of this model for many species is often enhanced with information on special habitat elements such as snags or dead and down material. CWHR was conceived to operate using existing timber type maps. Thus for the most part, the definition related to size and canopy closure was similar to those used for FIA.

Differing Needs, Conflicting Strategies — One Forest

One objective when developing a vegetation classification system is to create enough classes so that management activities can be modeled, while at the same time restraining the number of classes so that the modeling does not become excessively complex. The Region 5 planning efforts found that creating 16 to 50 vegetation classes or forest strata within an individual National Forest planning unit is the most appropriate for modeling activities over time at that scale. Without a stratification scheme, each of the Sierran Forests would contain between 350 and 800 individual vegetation types. Other than making the modeling effort cumbersome, collecting plot-level data for 350 to 800 independent vegetation types is unrealistic under the current FIA protocols and enormously expensive for the individual Forests to undertake on their own. Lumping vegetation types, however, reduces the depth of information available to conduct ecosystem assessments for key species or critical habitats. Many of the ecosystems (or habitat types) of greatest concern occupy small land areas, thus perhaps lost in the large classification schemes. Therefore, the variation among plots within strata is equally important as the average trend of the strata. We tracked this variation by classifying each plot in a consistent manner and then tabulating the number of plots of each class found within each stratum. Plots, which are stand-level characterizations, were classified first into forest types according to a standardized rule set developed by Region 5, and then into size and canopy closure classes based on the CWHR typing scheme (table 1).

Table 1—Definition of California Wildlife Habitat Relations tree classifications.

CWHR HABITAT STAGES			YOUNG				MATURE		
			size class 0	size class 1	size class 2	size class 3	size class 4	size class 5	size class 6
			non-stocked	seedling	sapling	poles	small tree	large tree	multi-canopy
				<1-in DBH	1-5.9"-DBH	6-10.9"-DBH	11"-23.9"-DBH	>23.9"-DBH	size 5 over 4 or 3
OPEN	no cover	<10% canopy cover	non-stocked	stocked					
OPEN	sparse cover (S)	10-24% canopy cover		1x	2S	3S	4S	5S	
OPEN	open cover (P)	25-39% canopy cover			2P	3P	4P	5P	
CLOSED	moderate cover (M)	40-59% canopy cover			2M	3P	4M	5M	
CLOSED	dense cover (D)	60-100% canopy cover			2D	3D	4D	5D	6

Application of the Forest Vegetative Simulator to Habitat Assessment

The FVS is the basic tool for simulating forest dynamics at the plot or stand level. Projections of management activities on changes in tree size class and density are a critical part of the National Forest analytical process for habitat assessment. Inspection of initial projections using ecological principles indicated a bias in the results and suggested that the bias might be due to the original starting condition data set. To test this hypothesis, the starting condition was adjusted to reflect three statistical approaches:

Stratum Average Condition: This is the traditional way of modeling forest dynamics by aggregating like FIA plot data from the same vegetation zone into a single stratum. Projections were then made using data that were aggregated by strata label as the initial condition.

Stratum Modal Condition: This method applies the most frequently encountered value (the mode) of all plots, rather than the arithmetic average. This value is then applied to the stratum. It most closely reflects timber type maps from which the CWHR stand classifications were based. Projections in FVS were based on the aggregated strata as the initial condition.

Plot Average Condition: Each vegetation-type plot was treated separately. Proportionate weight of the plots relative to the landscape is based on the total area represented by the plot within the stratum. For example, if there were six plots used to describe a stratum of 12,000 acres, each plot would carry a weight of 1/6 of 12,000 or 2,000 acres. Each of these 2,000 acre "plots" were then projected individually, rather than beginning with an aggregated strata. Following each period of projections, the total number of acres was reapportioned based on the percent of land occupied by that plot within the stratum, and then a new round of modeling would begin.

Results

Three examples of outcomes from FVS modeling of Sierran forests based on differing input data are shown in figure 1. Each panel represents a tree size and stand density that was identified as suitable habitat for old forest dependent species. The size classes for the trees are species dependent. In general, size class 4 would be saw timber less than 24 inches dbh, class 5 would be trees greater than 24 inches dbh. The "D" in the delineation indicates a dense stand. Size class 6 is unique in that it takes into account understory structure as it contributes to a multilayered stand of tall, large trees with smaller trees and large shrubs in the understory. The measure used in the analysis was acres occupied by each size class and density class, regardless of the species composition.

These data demonstrate three patterns in modeling results. The size class 4D begins with a relatively similar number of acres across the different input data; the plot-based data are slightly lower than the strata and mode data (which are nearly identical) (fig. 1A). Over the 150-year projection, the number of acres consistently decline, but the rates of decline differ so that projections 150 years out using the plot data indicate more acres than either the strata mean or mode data. The example shown for the 5D class begins with different starting acres (fig. 1B). Neither the strata mean nor the mode data include any initial acres in this class, while the dataset that maintains the richness of the individual plots indicates roughly 16,500 acres. The projections for future acres also differ substantially. The projections using the modal data indicate no change in acreage until the eighth decade, an increase to about 10,000 acres, and a subsequent decline back to near zero by the end of the period. The strata mean-based data starts with a 25,000 increase in the first two periods and then a drop back to nearly the starting point. This type of outcome seems most prevalent in class-based data; the fewer the classes and the bigger the categories, then the more likely stands are prone

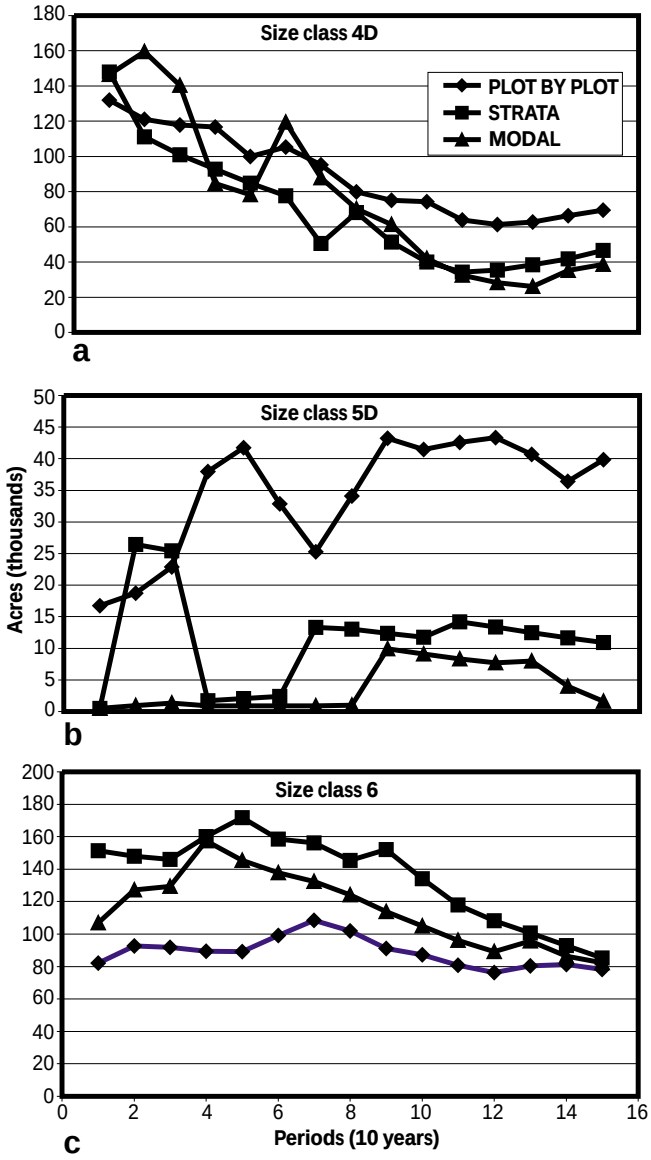

Figure 1—Projected changes in acres of tree size classes and tree densities assumed to be important to old forest dependent species.

to sudden jumps from one class to another. A second jump occurs in the seventh period, and the number of acres remains fairly stable, or perhaps decreases slightly. The more detailed plot data illustrates an entirely different result. Not only is the starting point much greater, acres increased over the modeled period. A loss of more than 10,000 acres is shown in year 70, but the loss seems to be recovered 20 years later. Using acres classed as 6, the starting data differs by about 2.5 fold, but all three datasets converge at 55,000 acres after 150 years (fig. 1C). All results indicate a decline in acres. The plot-based dataset starts at about 57,000 showing the smallest decline, while the averaged strata data decline to less that half of its starting acres.

In contrast, the continuous variables (number of trees greater than 30 inches and number of snags) show little dataset-based differences (fig. 2). A slight increase in the number of large trees is observed for the plot data. The mean and mode data indicates a slight increase in the first seven decades and subsequent decline back to the starting point by year 150. Snags (an admittedly difficult parameter to model, for lack of empirical data) increase by about 13 percent in all cases.

If it is assumed that the total acres in forested lands do not change over time, by plotting all size classes and densities together in a single figure one can ascertain (within the model) how stands change over time (fig. 3). In comparing the projections by input dataset, changes based on plot data are smoother than either of the other datasets. Both the strata mean and strata mode start with larger inventories of 4M (smaller saw timber in moderately dense stands), smaller inventories of seedlings, and sparse and light stands, and particularly in the strata mean approach size classes 5D and 6. Most of the difference between the methods occurs in the first half of the modeling period.

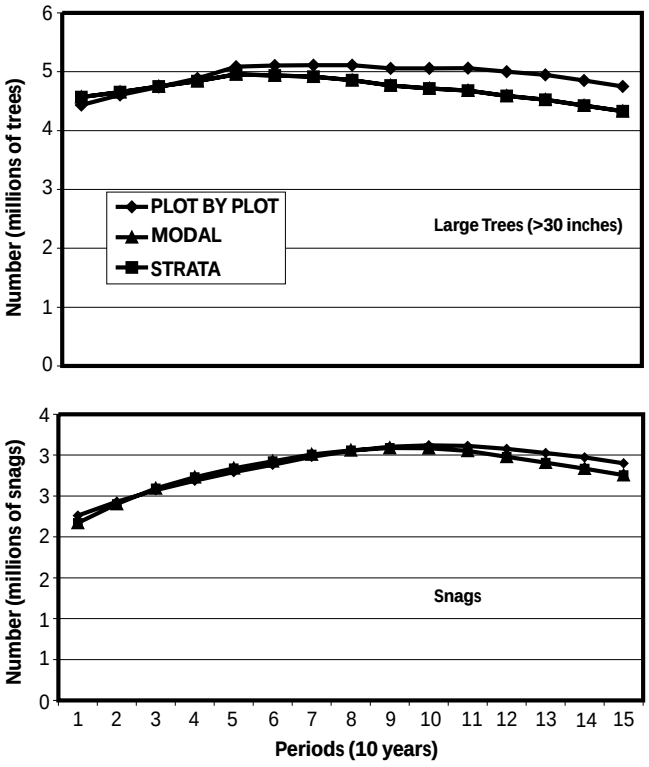

Figure 2—Projected changes in the number of large trees and snags, continuous variables, over a 150-year modeled period.

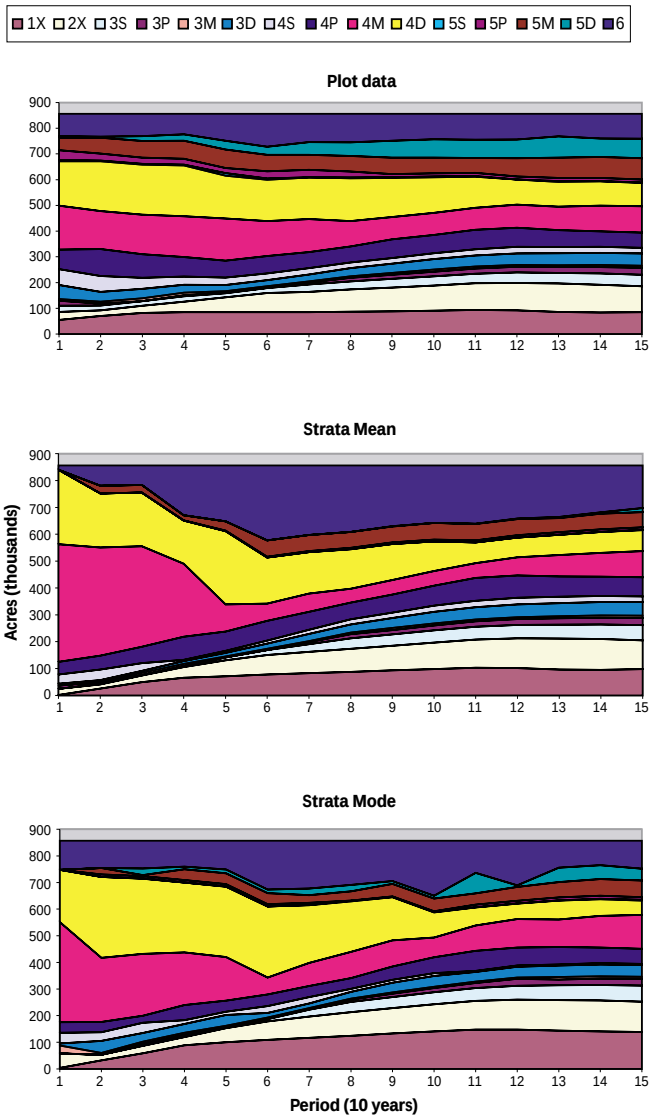

Figure 3—Combined changes in all size classes and tree densities over a 150-year modeled period.

Discussion

Each input source had its own strengths and weaknesses depending on the objective of the projections and the needs of the analysis. Using nonaggregated plot data allows us to maintain the data richness of the plots, but we lost spatial integrity. When aggregations based on the mean and modes were used, we lost track of very small or very large size classes and densities but maintained the spatial integrity of large geographic images.

The problem with assessing habitat condition using the individual FIA plots as the input data source is that there are more polygons within the stratum than there are FIA plots to represent the polygons. This means that the majority of polygons are not sampled on the ground and therefore, no direct linkage between the mapped data and the plot data can be maintained. Because the plot data cannot be mapped as a continuum, one loses the geographic integrity of a map.

Averaging plots, on the other hand, may create a model "vegetation stratum" that does not actually occur, especially if the distribution of plot stand conditions is not a normal distribution. However, the geographic coverage is maintained and a map product can be produced. An alternative to averaging plot data is to use the statistical mode of the plot data. Under this scheme, polygons are classified based on the most frequent or modal condition found within or between stands within the same stratum. This method most closely imitates the traditional interpretation of aerial photos used to develop timber types maps that were most of the source material when CWHR system was developed.

Forest Vegetation Simulator projection of continuous variables such as the number of large trees or the number of snags indicated close correspondence among the three data input variants. In contrast we found large differences among the three approaches when discrete data sets, such as size and density classes, were projected. Stratum averages or modes tend to promote large numbers of acres into the next class, resulting in gains or losses of particular classes in timeframes that seem unrealistic from an ecological perspective.

Scale is a key concept in habitat analysis. However, managers, biologists, and other specialists often fail to adequately consider the impacts of scale especially when developing desired future condition or rules to limited or restrict activities. Improvements and ease in digital processing vegetative mapping and plot data have made conducting analyses at appropriate scales and resolution both more important and at the same time more difficult. Increasingly, forest managers are expected to assess the implications of management activities beyond the site being treated and to broader landscape impacts. This necessitates sampling and using remote means to provide maps and descriptions of various habitats. This can be problematic when variables such as species, size, density, and spatial arrangement of the vegetation are considered important. Maps and related data tables can be valuable tools for understanding; however, they may mislead investigators. Analysts share the responsibility to ensure that habitat information used in decisionmaking are instructive generalizations and not misrepresentations.

In conclusion, forest management objectives shift in response to population pressure and changes in the public desires from their lands. In California forests, and other regions adjacent to large urban centers, human activities and expectations of the National Forest System are often conflicting. The ability to understand and project the outcomes of management activities and decisions is crucial to planning. Not only are habitat and ecosystem assessments used within the forest management teams but also for interactions with the public. The Forest Vegetation Simulator is a powerful information tool but care must be taken in understanding the scale at which the primary data are used and interpreted.

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Prognosis EI: A Detailed Watershed-Level Environmental Indicators Model

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Abstract—The new Prognosis Environmental Indicators model (Prognosis EI) was designed to assist forest management planning. The model provides detailed, quantitative environmental impact projections and expected timber flows under user-defined scenarios. Prognosis EI is a linked set of models: the base FVS variant, the western root disease extension, the fire and fuels extension (FFE), and the new environmental indicators model (EI). These components operate within the Parallel Processing Extension (PPE). The model produces all the standard outputs normally produced by FVS, the FFE, and the PPE. As well, it generates indicators specific to the EI model. These include stand structural indicators such as understory condition; species-specific wildlife indicators such as measures of foraging, nesting, roosting, and denning habitat for pileated woodpeckers, bats, ungulates, grizzly bears, and black bears; landscape spatial indicators such as patch size distribution or amount of interior old growth; water quality indicators, visual quality indicators, and active roads. Model outputs can be viewed and analyzed using a flexible custom software interface that requires ArcView GIS. Prognosis EI has been used in a case study to evaluate 21 alternative management and natural disturbance scenarios in the West Arm Demonstration Forest in southeastern British Columbia, Canada. In addition to providing information with which to evaluate the merits of alternative scenarios, the simulation results suggest a number of general conclusions regarding the impacts of root disease, snag retention practices, unauthorized firewood cutting, and recurrent underburns.

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Forest managers are increasingly being asked to develop forest management plans that demonstrate the ability of the forest to meet a wide range of timber and nontimber goals over a long period. Assessing the consequences of different actions on various indicators can be complex and challenging. Models can help the decisionmaking process, but few models exist that combine the ability to project both forest conditions and environmental characteristics. The goal of the Environmental Indicators (EI) model was to create a single tool with which to simulate the projection of timber and nontimber attributes at the landscape level. The approach was to integrate appropriate existing Forest Vegetation Simulator (FVS; Stage 1973, Wykoff and others 1982) tools, and to create additional quantitative indicators where necessary, based primarily on information already available in the other FVS tools.

The Model

The overall system combines the Southeastern Interior variant of FVS (Robinson 1998) with the Fire and Fuels Extension (FFE, Beukema and others 2000), the Western Root Disease Model (WRDM, Beukema and others 1998), and the new Environmental Indicators (EI) Model. These four components operate within the Parallel Processing Extension (Crookston and Stage 1991). To predict nontimber attributes, the EI model uses the projected data about trees, fuels, and snags from the other three components as well as EI-specific input data containing information about stand adjacencies and groupings, roads, and understory vegetation.

As part of the EI model, two ArcView GIS postprocessing tools were also created. One tool uses the projected information and performs various spatial analyses to produce output on landscape characteristics. The other tool allows users to easily display maps and graphs of various indicators over time or at selected points in time.

Indicators

The overall model produces three general types of indicators: stand-level, spatial, and species-specific. Stand-level indicators include all the standard output from the base FVS model, the FFE, and the WRDM, such as tree information

(from FVS), snags (from the FFE), and coarse and fine woody debris (from the FFE). Descriptions of the type of outputs and the methods by which they are calculated can be found in the appropriate documentation. The EI part of the model produces additional stand-level indicators about stand developmental stage and the percent cover of nontree vegetation such as herbs, shrubs, epiphytes, mosses, lichens, and liverworts. The stand developmental stage is calculated using information about BEC variant, habitat unit, stand age, percent crown cover, and percent cover of selected species (Greenough and others 1999a). The developmental stage is then used to look up the predicted amount and types of understory vegetation (Greenough and others 1999a). The change in vegetation is not simulated explicitly. FVS will predict changes to stand structure due to growth, mortality, and management, which can cause a change in developmental stage, which in turn will affect the predicted understory vegetation.

All spatial indicators are produced either by the EI model during the simulation or by the EI's postprocessing spatial analysis tool. These indicators include the location, amount, and size distribution of age-based patches or of interior old growth, age and seral stage distributions, length of active roads, conditions of designated viewsheds, and 11 measures related to water quality. The definition of which ages define a patch or define old growth, the buffer required to be considered "interior," the road network (including stream crossings or adjacencies, and length of roads on unstable soils), the viewsheds, and some of the water-related information are all defined by the user. Once the road network is in place, management activities simulated by FVS will activate appropriate road segments. Roads are assumed to be deactivated after a user-defined period. The water quality indicators that are simulated are 11 of the ones specified by the Interior Watershed Assessment Procedures guidebook (BC Ministry of Forests and BC Ministry of Environment 1995). Many of these depend on knowledge of the active road and stream network, as described by Greenough and others (1999a, b).

The third category of indicators applies to four wildlife groups: ungulates, pileated woodpeckers, bats, and bears. For ungulates, the model predicts the amount of winter foraging habitat based on stand attributes such as BEC zone, aspect, age, crown closure, tree size, and presence of particular understory forage species. Predefined management units can be used to track the effects of management strategies. Two indicators are predicted for bats: edge foraging habitat and roosting trees. Edges are defined as any boundary between stands with a low height and those with a much greater height and a large amount of basal area. Bat roosting trees are large, hard snags found in stands containing at least five such snags per hectare. There are three snag and habitat indicators for pileated woodpeckers. The model determines the number of drumming snags as large hard snags that are sufficiently taller than the main canopy height. Winter foraging snags are those that are a minimum size and a given species and that are within a certain distance of a large hard snag. Nesting habitat quality is determined by the amount of large snags that are present. Finally, bear habitat quality is calculated as a function of habitat type and stand developmental stage, while denning locations (trees and snags) are measured as a function of BEC variant, stand slope, and tree or snag size and type. The specific criteria that are used to measure each of these indicators are described by Greenough and others (1999a).

Case Study

The model was developed using a case study. The study area is in the West Arm Demonstration Forest near Nelson, BC, located on the north side of the west arm of Kootenay Lake. The study area included the complete Redfish Creek watershed and two adjacent face units. The area was about 3,300 ha (8,154 acres), with five ecological zones. The simulations used between 699 and 1,507 stands depending on the management scenario.

For input data, the model required maps with the various management zones and the road network. For the stand data, few sample tree lists were available, but some general characteristics, such as slope, aspect, elevation, habitat, and cover, were known about all locations. The sample and summary information was used with a Most Similar Neighbor Analysis (Moeur and Stage 1995) to assign a tree list and initial fuel levels to each stand. Root disease levels were then assigned based on habitat type, age, and species composition.

The case study simulated 21 scenarios, which explored a range of different management systems and harvest schedules (Greenough and others 1999c). The scenarios also used different assumptions about the presence of root disease or underburns, removal of snags, and road activation.

Example Results

Output was produced for each of the indicators discussed above. This section does not attempt to provide a comprehensive analysis of the 21 scenarios (see Greenough and others 1999c for the complete results). Rather, it demonstrates some of abilities of the model and the methods of examining the output.

One of the key requirements of the model was that it provide planners with a single tool that can show the results of both timber and nontimber indicators in a way that can be used for evaluating the tradeoffs between different assumptions. One method of doing this is to produce a table with some of the key indicators. For example, table 1 compares the values of seven indicators from four scenarios. The "best" and "worst" values are highlighted for each indicator. An analyst can immediately tell that there is no single scenario that is best for all indicators, and can see some of the key questions that will need to be considered. For example, if it is crucial to be able to produce some volume from the landscape, then scenario 4 is not an option, even though it produces the highest values for three out of the seven indicators. If the minimum requirement for old seral stage is below 29 percent, then scenario 9 may be a good option because it is best for three of the indicators and intermediate for three others.

The EI model has an ArcView-based postprocessing tool that allows users to select one or more indicators and one or more scenarios and to produce graphs or maps. Graphs are

Table 1—Example values for seven indicators from four scenarios. The "best" value for each indicator is shaded in grey, while the "worst" value is circled. This table is for demonstration purposes only. Many more scenarios and indicators are available in the case study (Greenough and others 1999c).

Scenario	Merch. vol. harvest ('000 m^3/ha)	Bear den sites (number)	Deer winter forage (ha)	Bat forage edges (km)	Wood-pecker snags ('000)	Old seral stage (% area)	High concern watersheds (number)
1: patch	723	244	75	925	195	43	7.3
4: partial	490	221	198	244	126	60	5.5
7: unman	0	746	80	245	142	64	4.0
9: Lg CC	917	288	292	395	264	29	5.9

produced for indicators that vary over time, and multiple scenarios can be plotted on a single graph (fig.1 and 2). This can readily be used to assess how values change over time and how the relative merit of each scenario may differ over time. For example, in the figures both indicators show relatively little difference between the scenarios for the first 20 to 30 years, implying that in the short-term, the choice of scenario may not affect these indicators. By the end of the simulation, however, the scenarios are each different, and the choice of "best" scenario is precisely opposite for each indicator. The unmanaged scenario produces the most denning snags but the least number of woodpecker foraging snags.

The tool automatically produces several maps in one of three ways: showing one indicator and one scenario at several points in time, showing one indicator for several scenarios at one point in time, or showing several indicators for one scenario at one point in time. This facilitates comparison between indicators and scenarios.

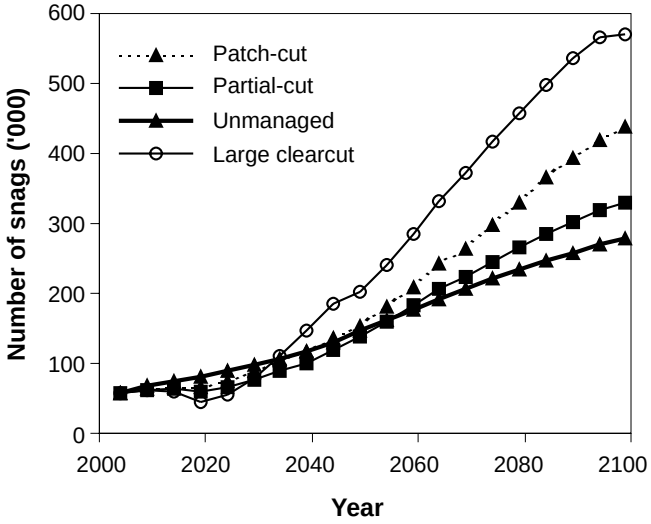

Figure 1—Number of pileated woodpecker foraging snags in four scenarios.

Applying the EI Model in Other Locations

The EI model was designed and tested in southeastern British Columbia, Canada. Like all other FVS extensions, with some customization it can be applied to areas in other regions for which an FVS variant exists. The minimum requirement is that the appropriate variant of FVS and the EI model are linked to the PPE. If indicators that require knowledge of snags or coarse woody debris are desired, the corresponding FFE variant would also need to be linked into the PPE framework.

Once linked to the PPE, and with the appropriate input data, the EI model will run for the selected landscape. Many indicators, however, depend on the understory species composition look-up table, on the developmental stage logic developed for the case study, or on the ecological zones represented in the SEI variant of FVS. Each of these would need to be redefined and coded into the new EI variant. Many of the other relationships in the model, such as the tree species or minimum sizes of snags required by different wildlife species, can be controlled through keywords (Beukema and others 1999).

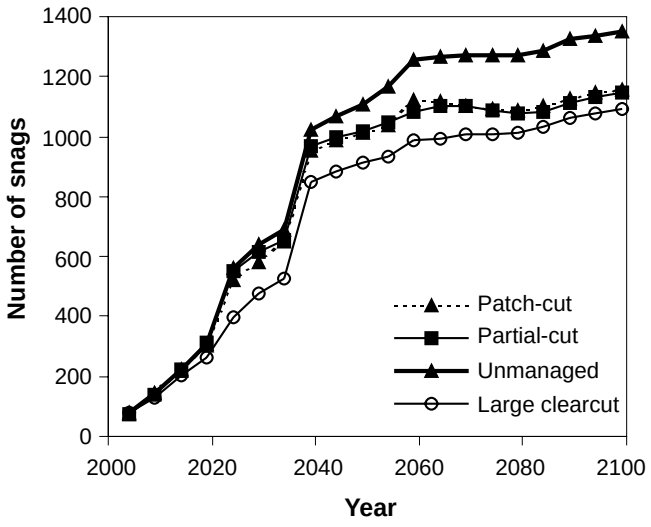

Figure 2—Number of black bear denning snags in four scenarios.

One of the greatest challenges faced when doing a landscape analysis is the availability of spatial data. The EI model requires input about several spatial relationships that provide, for each stand:

- A list of other stands that are within a given distance of the center of the focal stand.
- A list of other stands that share a border with the focal stand.
- Which deer management unit the stand belongs to, if any (optional).
- Which viewshed the stand belongs to, if any.
- The length of stream within the stand, if any.
- The road segment that is within the stand, if any.

Many of these can be produced by a GIS technician if the applicable landscape, stream, road, viewshed, and deer management unit maps are provided.

In addition to these stand-based maps, the model also requires information about the road network. It assumes that the roads in the landscape have been divided into different segments that join to form the complete road network. For each road segment the model needs to know, at a minimum, the length of the segment and the road to which it connects. If the watershed indicators are desired, the model also needs to know for each road segment the length on erodable soils, number of stream crossings, and length of the road within 100 m of a stream (see Beukema and others 1999 for more details).

With this information, in addition to a treelist for every stand, the EI model would be able to run in other areas. If some information is missing, then the indicators could simply be ignored. For example, if the watershed assessment rules are not appropriate for a different area, then the model would not need to know anything about the relationship between roads and streams or soils. Deciding before doing a simulation which indicators may be important could facilitate the process of gathering the required information.

Conclusions

The EI Model combines FVS, the FFE, and WRD with the PPE and a new tool to project timber and environmental indicators at the stand and landscape level. It combines all the forecasting and simulation abilities of each of the individual components (such as the growth and mortality of trees, creation of snags and coarse woody debris, and prediction of management options) and provides additional output on new stand and landscape indicators such as wildlife-specific habitat quality or quantity, active roads, seral stage distributions, or water quality measures. The model has been applied successfully in southeastern BC and the results are summarized in several reports. The EI model can be readily applied in other locations using regional parameter sets and the appropriate variant of each of the FVS tools.

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Linking Prognosis^{BC} to Aerial Attributes for Timber Supply Analysis in British Columbia

H. Temesgen
V. LeMay

Abstract—In British Columbia, the forestland is divided into various strata based on forest cover types and aerial attributes for forest inventory purposes. To manage forest resources in perpetuity, several growth and yield models have been developed and used in various parts of the province. Among these models, Prognosis^{BC} (adapted from the northern Idaho variant of FVS) is used in the southeastern interior of the province. However, the estimates from this model have not been linked to aerial attributes nor have they been used to update the existing inventory databases. This paper discusses how Prognosis^{BC} can be linked to aerial attributes and inventory databases when there are large and widely varied land bases and insufficient ground data. Differences in observed and estimated species composition, tree, and stand attributes are also discussed.

A revised version of the paper presented at the conference is to be published elsewhere: Temesgen, H.; LeMay, V.M.; Froese, K.L.; Marshall, P.L. In press. Imputing tree-lists from aerial attributes for complex stands. For. Ecol. & Mgmt.

In: Crookston, Nicholas L.; Havis, Robert N., comps. 2002. Second Forest Vegetation Simulator Conference; 2002 February 12–14; Fort Collins, CO. Proc. RMRS-P-25. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

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Using the Labeling Capabilities and Parallel Processing Extension of the Forest Vegetation Simulator for Resource Supply Analysis

Don Vandendriesche

Abstract—"Label Processing" is a little known feature within the Forest Vegetation Simulator (FVS). When used in combination with the Parallel Processing Extension (PPE), it can provide a powerful analytical tool. Labels within FVS link forest stands to activities. These activities can be either silvicultural or managerial in context. The PPE can be used for several purposes, including resource supply analysis where labels relate activities to groups of stands that are being managed to meet a specific objective. An example from the Flathead National Forest is presented that employs the labeling and parallel processing capabilities of FVS to solve a resource supply problem.

Many forest planning problems can be solved using the policy labeling capabilities of the Parallel Processing Extension (PPE) (Crookston and Stage 1991) of the Forest Vegetation Simulator (FVS) (Dixon 2001). The advantage of using these tools in combination would be that inventory information and associated silvicultural prescriptions would already be set up within the projection model [FVS]. Preparing data and developing stand management options are prerequisites to any planning exercise. Labeling and the PPE facilitate the final planning step — namely decision analysis for multi-stand processing. This paper provides an introduction to policy labeling rules and demonstrates the utility of the Parallel Processor in solving resource supply problems.

Policy Labeling Feature

Specifying management policies using rules is a little known feature embedded within the FVS model. This process is spun through every aspect of FVS: the Suppose interface, the base model, the event monitor, and the model extensions. There are three levels of labels within FVS. Beginning with individual stand polygons and working toward a landscape perspective, they are:

- Stand Policy
- Activity Group Policy
- Multistand Policy

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You may not have heard of stand policy labels, but if you have used the Suppose interface (Crookston 1997), you certainly have unknowingly encountered them. Stand Policy Labels are synonymous with *Grouping Codes*. Grouping codes come into play when you invoke the "Select Simulation Stands" command button from the main Suppose window. Grouping codes populate the middle windowpane on the Select Simulation Stand screen (fig. 1). They are used to help identify common characteristics among individual stands. In figure 1, the DF grouping code is used to equate forest stands that are predominantly Douglas-fir forest cover type. Unbeknown to most users, this is also a Stand Policy Label for this grouping of forest stands.

The Suppose interface obtained these grouping codes from the Stand List File, Record Type C. Data translation programs such as Pre-Suppose (Vandendriesche, these proceedings) can assist in assigning grouping codes to common plot sets.

Silvicultural activities can be related to groups of stands using *Activity Group Policy* labels. Activity Group Policy labels were incorporated into FVS with the introduction of the Event Monitor (Crookston 1990). A keyword, AGPLABEL, is used to designate an Activity Group Policy label. This keyword is used in conjunction with *conditionally scheduled* silvicultural events such as thinnings and plantings. In other words, when a user inserts an "If…Then…EndIf" sequence in an FVS projection, by default, an Activity Group Policy label is associated with this treatment. Refer to figure

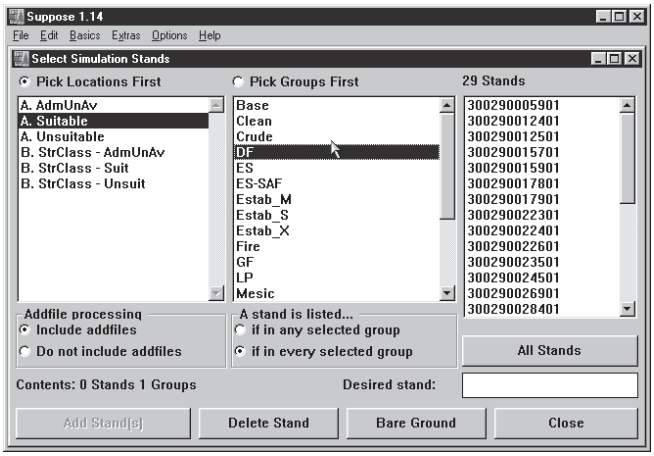


Figure 1—FVS Stand Policy Labels are built by Suppose from grouping codes.

2 for an example of Activity Group Policy labeling within a conditionally scheduled event.

Implementation of a forest plan requires setting standards and guidelines for distinct management areas. Many stands may be affected by a policy decision established at the programmatic level of planning. An optimal prescription for a given stand may not be feasible when viewed in the context of the entire forest setting. There are many planning models available to forest analysts. To simplify solving such rich problems with FVS, the Parallel Processing Extension was developed. As with any FVS entity, there is an associated set of mnemonic keywords. To handle management directions involving many stands, *Multistand Policy Labels* were created. For the resource supply example demonstrated in this paper, four inputs direct the PPE. The first involves the management objective or target for the resource. The second involves the criteria for selecting which stand among many will contribute to meeting the management goal. The third involves the unit value of the contributing factor. The fourth is the text string defining the Multistand Policy Label (fig. 3). For example, if the management policy objective were to harvest a specified allowable sale quantity (ASQ) from a particular group of stands within a designated land type, a predetermined selection criterion would dictate the order in which stands are harvested (such as oldest stands first). The unit value would be in terms of volume rendered (such as cubic feet, board feet). The multistand policy label associates the stands and activities that may be scheduled to meet the objectives of the policy.

Parallel Processing Capabilities

Lets expand this discussion to the second facet of this paper, the Parallel Processing Extension of the Forest Vegetation Simulator. At this time, the PPE has the capability to address four types of problems:

1. Multistand treatment scheduling
2. Resource supply trends
3. Contagion in pest dynamics
4. Decision trees

```
**********************************************************************
*   RegHarv Rx:
*      Minimum Bd. Ft. harvest >= 2000
*      - If stand age >= 80 years LP
                         90 years other forest types
*           QMD >= 5"
*      - Then
*           regeneration harvest via CC
*      - Initialize Regen Harvest Interval
**********************************************************************
MinHarv             0        0.     2000.        0.
If                  0
_Strata EQ _Type and (Age GE _RHAge and BaDBH GE 5.0)
Then
ThinDBH             0    Parms(0, DBHDist (3,3), 1.0, 0.0, 0.0, 0.0)
ThinDBH             0    Parms(DBHDist (3,3), 999., 1.0, 0.0, 9, 0.0)
AGPLABEL
   Suitable_Convert
EndIf
```

Figure 2—The Activity Group Policy Label is specified using the AGPLABEL keyword.

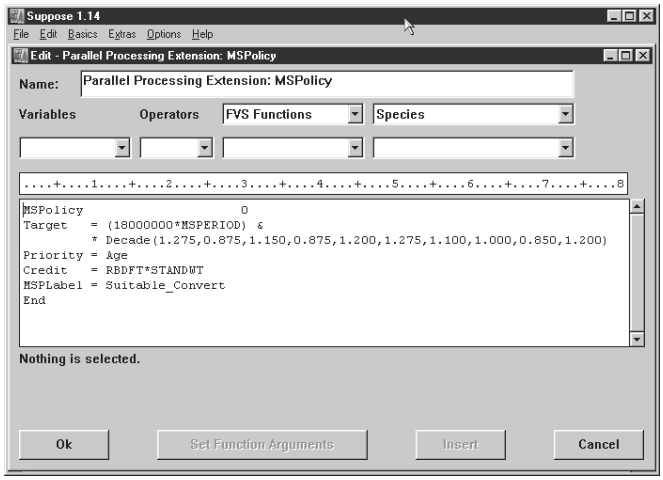


Figure 3—Multistand Policy Label is used to associate a multistand policy to a group of stands and the activities used to achieve the policy's objectives.

Multistand treatment scheduling involves tradeoff analysis. For example, suppose a forested area comprising many stands was used for elk hiding cover and timber production. Favoring one entity impacts the other. The PPE allows examination of these tradeoffs. Resource supply analysis involves gaming analysis. For example, suppose a forest analyst wanted to determine if a specified level of timber harvest were sustainable. The PPE, based on resource supply and public demand, can determine the level of diminishing return. A detailed example will be presented later in this paper. Contagion in pest dynamics deals with spatial analysis. For example, suppose a mountain pine beetle epidemic was devastating an area. The PPE can be used to chart the progression of an insect or disease pathogen from one stand to another. Decision trees are used for decision analysis. For example, suppose a silviculturalist was trying to decide on the timing options for a thinning treatment. The PPE could be used to replicate a stand along several pathways to determine the best solution.

For each of these solution processes, labeling plays a vital role. Through the use of unions and intersections of the various text labels (in other words, stand policy, activity group policy, multistand policy), the Parallel Processing Extension performs its magic.

Flathead National Forest Example

In conjunction with the passage of the fiscal year 2000 Forest Service budget, the Senate Appropriations Committee requested a report summarizing current timber growth, inventory, and mortality, including projections for the next 10, 20, and 50 years for the National Forest System. To the extent practicable, the report was to include age class and/or structural stage distribution of the stands represented by the data. The Flathead National Forest in northwestern Montana was chosen by the Forest Management Service Center as a representative example in responding to this inquiry.

A systematic approach was developed to perform the required analysis. A framework similar to that used for forest management planning was employed. The major steps in the process were: formulating a forestland classification strategy, prescribing silvicultural choices, forecasting growth and yield, evaluating management polices, and allocating resource assignments. Relevant aspects of each of these steps are presented.

Forestland Classification

The Forest Inventory and Analysis (FIA) data set was used as the empirical basis for the analysis. The systematic sampling design of FIA provided acreage values as well as per acre estimates of important plot and tree attributes. A strategy was developed to guide forestland classification assignments. Removing nonforest parcels from the acreage base and stratifying by administrative availability and management suitability rendered a hierarchal flow for data sorting. Physiographic class and condition class further defined each of the major stand types. Refer to figure 4. Stand types were developed within each land unit using the Pre-Suppose program. Stand Policy Labels (grouping codes) embedded in the Stand List Files guided the assignments (fig. 1).

Silvicultural Options

Silvicultural treatments followed a conceptual framework. Rule sets for vegetation management were developed based on historic fire regimes. Departure of current vegetation due to missed fire return intervals resulted in an invasion of shade-tolerant tree species. Treatment opportunities were postulated to achieve an ecosystem in proper balance with regard to natural fire frequency. The diagram in figure 5 defines *condition classes* by major forest cover type and size class. Mechanized treatments and prescription fire compose the available tools for stand management. Disturbance agents such as insects, disease, and wildfire have an impact on resultant forest structure. Each of these factors were identified and addressed.

Condition Classes—Four prescription (Rx) options were recognized: maintenance, restoration, conversion, and deferment. A brief description of each follows.

Maintenance (Maintain) Rx: Applied to young stands. Favorable species exist on a given habitat type. Missed one or fewer fire intervals.

- Precommercial thin overstocked stands.
- Prescribe fire for fuel reduction.
- Deferring of activities, let grow.
- Commercial thinning as stands mature to regulate stocking and maintain health.

Restoration (Restore) Rx: Applied to older stands. Favorable species exist on a given habitat type. Missed two or fewer fire intervals. Slight invasion of shade tolerant species.

- Improve stand composition to seral species.
- Precommercial thin overstocked stands.
- Prescribe fire for fuel reduction.
- Commercial thinning as stands mature to regulate stocking and maintain health.

Conversion (Convert) Rx: Applied to older stands. Unfavorable species exist on a given habitat type. Missed two or more fire intervals. Massive invasion of shade-tolerant species.

- Improve stand composition to seral species.
- Precommercial thin overstocked stands.

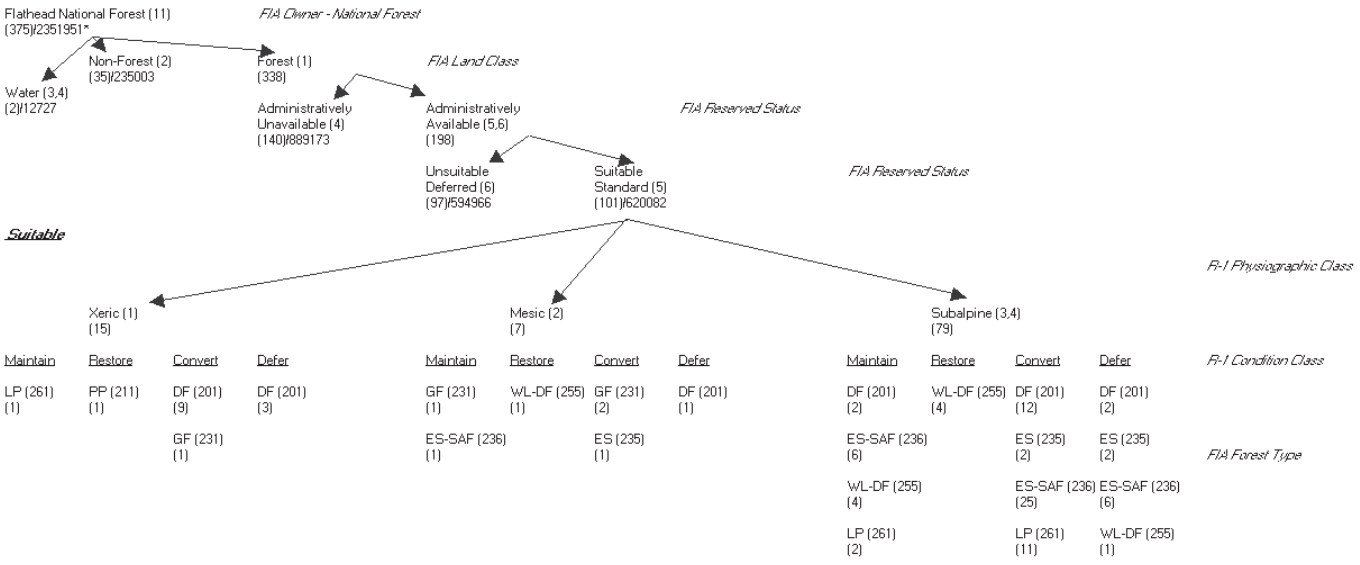


Figure 4—Forestland classification diagram.

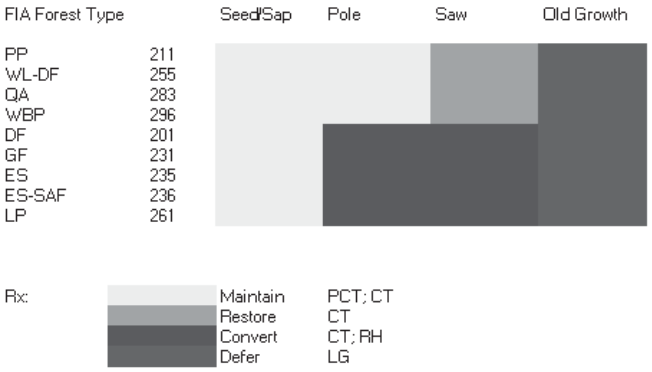


Figure 5—Silvicultural options.

- Prescribe fire for fuel reduction.
- Commercial thinning as stands mature to regulate stocking and maintain health.
- Regeneration harvest to shade-intolerant species as opportunity allows based on habitat.

Deferment (Defer) Rx: Applied to old growth, defined as stands with 10 or more trees per acre greater than 20 inches dbh.

- Deferring of activities, let grow.
- Monitor stand age and structure.

Silvicultural Prescriptions—Mechanical treatments such as precommercial thinning, commercial thinning, and regeneration harvesting could only be implemented on the *Suitable* forestland base. The following parameters were used in designing the keyword sets for projection with the Forest Vegetation Simulator.

Pre-Commercial Thinnings (PCT): Thin to 500 trees per acre. Favor retention of seral species.

- Stands less than 80 years old.
- Stands less than 5 inches quadratic mean diameter.
- Stands greater than 1,500 trees per acre.

Commercial Thinnings (CT): Thin to 70 square feet, basal area. Favor retention of seral species.

- Stands at least 20 years old.
- Stands at least 5 inches quadratic mean diameter.
- Stands at least 2,000 bd. ft./acre cut volume.
- A 40-year re-entry period.

Regeneration Harvest (RH): Even-aged methods. Favor establishment of seral species.

- Stand at least age 80 for LP, age 90 for other forest types.
- Stands at least 5 inches quadratic mean diameter.
- Stands at least 2,000 bd. ft./acre cut volume.
- Leave nine Legacy Trees for snag replacement.

Let Grow (LG) Rx: Defer young and old growth stands.

- Young stands less than 40 years old (generally).
- Young stands less than full stocking.
- Old stands greater than 120 years old (generally).
- Old stands with 10 trees per acre greater than 20 inches dbh.

Prescription Fire—Controlled burns could be used on both *Suitable* and *Unsuitable* forest areas as a low cost treatment to enhance species composition. Although a Fire and Fuels Extension had been developed for the FVS model, linkage with the Parallel Processor Extension had not been made at the time. The PPE was used as the modeling tool to bring the associated analytic pieces together. Keyword sets that simulated low and moderate intensity prescription fire scenarios were developed. Attributes of the prescription fire keyword sets were as follows:

Prescription Fire—Low Intensity

Applicable only to shade-intolerant and LP types (that is, PP, WL-DF, WBP, QA, LP). Used "FixMort" keyword to simulate fire-induced mortality.

- 50 percent mortality in trees 0 to less than 3 inches dbh.
- 30 percent mortality in trees 3 to less than 5 inches dbh.
- 20 percent mortality in trees 5 to less than 9 inches dbh.
- 10 percent mortality in trees 9 to less than 16 inches dbh.
- 0 percent mortality in trees greater than 16 inches dbh.
- Indiscriminate to all species.
- Applicable only to *Suitable_Maintain* and *Restore* forestland classes.
- Targeted 2,500 acres annually.

Prescription Fire - Moderate Intensity

Applicable only to shade mid-tolerant and tolerant types (that is, DF, GF, ES, ES-SAF). Use "FixMort" keyword to simulate fire-induced mortality.

- 80 percent mortality in trees 0 to less than 3 inches dbh.
- 60 percent mortality in trees 3 to less than 5 inches dbh.
- 50 percent mortality in trees 5 to less than 9 inches dbh.
- 30 percent mortality in trees 9 to less than 16 inches dbh.
- 20 percent mortality in trees greater than 16 inches dbh.
- Indiscriminate to all species.
- Applicable only to *Unsuitable_Convert* forestland class.
- Targeted 3,500 acres annually.

Forest Health—Forest pests can significantly impact the current and future development of a stand. The USDA Forest Service Northern Regional Office developed forest pest risk maps for all Montana forests including the Flathead National Forest. Root rot, bark beetle, and dwarf mistletoe incidence were recorded on the FIA plots. Overlaying risk maps with the FIA plots enabled forecasting potential hazard sites. The Northern Region Forest Health Specialists developed associated FVS keyword file sets to simulate pest effects. By using the Western Root Disease Extension, these health issues were incorporated into the projections.

Fire Impacts—The Flathead National Forest had compiled a report of recorded wildfires during 10 years from 1985 to 1994. Based on this information, FVS keyword file sets were developed to randomly burn the approximate acreage as cited. The following parameters were used:

Wildfire - 1985-1994 period

Forest land class	Acres burned 10 years	Low intensity 15%	Moderate intensity 65%	High intensity 20%
Suitable	12,250	1,837	7,962	2,450
Unsuitable	7,650	1,148	4,973	1,530
Wilderness	2,600	390	1,690	520
Total:	22,500	3,375	14,625	4,500

FVS keyword sets were written to describe each of these facets. Activity Group Policy Labels were assigned within conditionally scheduled events (If … Then … EndIf keyword sequences) to link grouping of stands with their associated treatment/disturbance activity. Refer to figure 2 for an example.

Yield Forecast

Stand projections were performed using the Forest Vegetation Simulator for a 100-year time horizon. Yield estimates were compared and calibrated to measured data as observed from the Flathead FIA data set.

Management Direction

The essence of the Senate Appropriations Committee's request was that given a specified level of harvest based upon current production output, what would be the resultant condition of the forest in terms of growing stock and mortality rates over the next 50 years. An inference of the current harvest activity needed to be made.

Sale Quantity—The most recent Forest Plan for the Flathead National Forest cited an allowable sale quantity of 54 million board feet per year from *suitable* lands. However, due to market constraints, pending litigation, threatened and endanger species considerations, and other unforeseen issues, the programmed financed sell had been 23 MMBF during the period from 1995 to 1999. This was the harvest level used for the analysis.

Implementation Strategy—Intermediate harvests (commercial thinnings) were targeted for the younger merchantable size classes of the *maintain* and *restore* condition classes (target 5.0 MMBF). Regeneration harvests were targeted for the older merchantable size classes of the *convert* condition class (target 18.0 MMBF). Also, high bark beetle hazard plots were prioritized for regeneration treatment. Stand improvement treatments (such as precommercial thinnings) were restricted to 10 percent of the potential area to aid in metering out the acres treated.

Resource Allocation

The Parallel Processing Extension was used to solve the forest trend inquiry. For resource supply analysis, PPE is easy to implement.

PPE Set up—The Suppose interface distinguishes FVS keywords for PPE as one of three component types: top, bottom, and report. Relevant keywords used for resource allocation were as follows:

Top Components

Exact - Instructs PPE to use partial stands to meet target objectives.

Bottom Components

MsPolicy - Signals that a multistand policy will be entered.

LabWts - Request that labels and weights be written to an auxiliary file. Used for post processing of stand structure statistics.

Report Components

Yields - Prints composite yield statistics table.

The MsPolicy keyword establishes the parameters associated with the *Multistand Policy* (fig. 3). This label is used to link groups of stands (Stand Policy) and their proposed silvicultural treatment (Activity Group Policy). For example, within the *suitable* forest land class on the Flathead, there were 29 Douglas-fir stands (fig. 1). The *convert* condition class was comprised of a subset of 12 stands (fig. 4). Regeneration harvest can only be applied to the *suitable_convert* activity group (fig. 2). The overall multistand-ASQ target for the *suitable_convert* forest land class was 18.0 MMBF (fig. 3). The priority for stand selection to meet target objectives was to harvest the oldest stands first. Their contribution to meeting the target goal was a factor of the stands' removal board foot volume and its size in acres. Therefore, if Douglas-fir stand within the *suitable_convert* forestland class was the oldest stand available at that point in the projection, it would be selected for regeneration harvest to meet the target ASQ objective of 18.0 MMBF.

PPE Reports—Within the main output report of FVS, two important PPE tables related to resource supply analysis are generated. The first, the *Targeted Resources Table* (fig. 6), displays a listing of stands selected to meet the

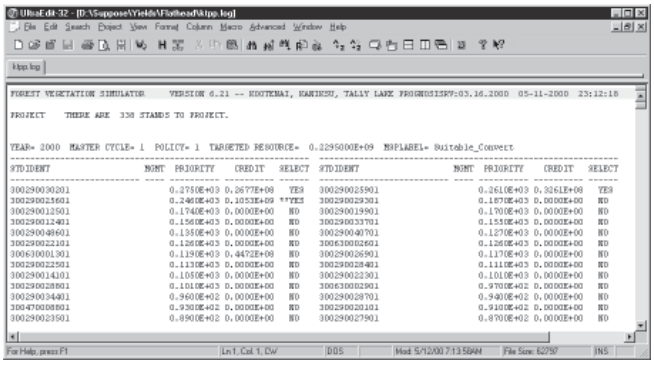
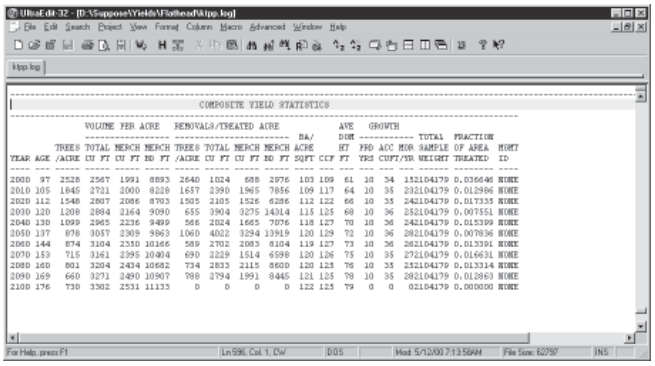


Figure 6—Targeted resources table.

management policy objective. Note that the *Priority* column is ordered sequentially from left to right then down in terms of descending stand age. The *Credit* column equates to the selected stands' harvested board foot volume multiplied by the number of acres within the stand. If only part of the stand was needed to meet the exact ASQ goal, then the remaining stand acres would be carried to the next time period. Split stands are denoted by a series of two asterisks in the *Select* column within the Targeted Resources table.

The second important PPE table to review is the *Composite Yield Statistics Table* (fig. 7). Average removal volume per acre is displayed. *Total Sample Weight* [acres] and *Fraction of Area Treated* are also presented. Multiplying these terms together will render the targeted volume goal.



COMPOSITE YIELD STATISTICS

YEAR	AGE	VOLUME PER ACRE TREES /ACRE	TOTAL CU FT	MERCH CU FT	MERCH BD FT	REMOVALS/TREATED ACRE TREES /ACRE	TOTAL CU FT	MERCH CU FT	MERCH BD FT	BA/ ACRE SQFT	SDI CCF	AVE HT FT	GROWTH PRD YRS	TOTAL ACC CUFT/YR	FRACTION MOR WEIGHT	SAMPLE OF AREA TREATED	HSRT ID
2000	97	2528	2567	1991	8893	2640	1024	688	2976	103	109	61	10	34	152104179	0.036646	NONE
2010	105	1845	2721	2000	8228	1617	2390	1965	7886	109	117	64	10	35	232104179	0.012986	NONE
2020	112	1548	2807	2086	8703	1505	2105	1526	6286	112	122	66	10	35	242104179	0.017335	NONE
2030	120	1208	2884	2164	9090	655	3904	3275	14314	115	125	68	10	36	252104179	0.007551	NONE
2040	130	1099	2965	2236	9499	566	2024	1665	7076	118	127	70	10	36	242104179	0.015399	NONE
2050	137	878	3057	2309	9863	1060	4022	3294	13919	120	129	72	10	36	282104179	0.007836	NONE
2060	144	874	3104	2350	10166	589	2702	2083	8104	119	127	73	10	36	262104179	0.013391	NONE
2070	153	715	3161	2395	10404	690	2229	1514	6598	120	126	75	10	35	272104179	0.016631	NONE
2080	160	801	3204	2434	10682	734	2833	2115	8608	120	125	76	10	35	252104179	0.013314	NONE
2090	169	660	3271	2490	10907	788	3794	1991	8445	121	125	78	10	35	282104179	0.012863	NONE
2100	176	730	3302	2531	11133	0	0	0	0	122	125	79	0	0	02104179	0.000000	NONE

Figure 7—Composite yield statistics table.

Summary

By using the labelling capabilities and Parallel Processing Extension of the Forest Vegetation Simulator, a comprehensive analysis of a resource supply problem was addressed. These tools were used to prepare reports showing trends in forest stocking as impacted by changes in growth, harvest, and mortality. Figure 8 displays the projected outcome relative to board foot volume over the next 50 years. Live tree stocking showed an ever-increasing accumulation as a result of forest growth outpacing harvest and mortality components.

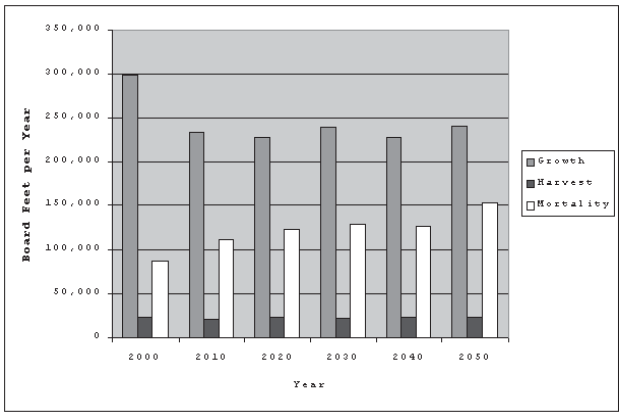


Figure 8—Flathead National Forest, board foot volume trends.

Acknowledgments

The complexities of the Flathead National Forest example could not have been fully developed without the input and oversight provided by Doug Berglund, Forest Silviculturist, Flathead National Forest. Doug's consummate knowledge of local history, ecology, and silviculture proved invaluable. Barry Bollenbacher, Northern Region Silviculturist, and George Lightner (retired), Northern Region Inventory Specialist, provided preliminary support data and direction.

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Session 4. Model Development

Incorporating Soil Parent Material into Prognosis

Robert E. Froese
Andrew P. Robinson

Abstract—The Prognosis large-tree basal area increment model is being adapted to include soil parent material (lithology) as a new predictor variable. In this paper, the critical issue of how to aggregate diverse geologic units into a set that is meaningful for growth model prediction is examined. We fit the model in a pilot study to compare subjective (concept-based) and objective (data-based) approaches to aggregation. When compared using Akaike's Information Criterion, the best models were those using data-based approaches. Concept-based approaches produced groupings that are least useful for modelling, and data-based approaches produced groupings that were least meaningful biologically and geologically. Poor data distribution and a narrow data set are likely causes of the discouraging result.

Soil properties have an important and well-recognized influence on tree and forest dynamics. Soils are reservoirs of both water and the mineral nutrients that are required by plants. The properties of soil are substantially defined by the properties of the parent material – usually bedrock – from which soils are derived. Over the past decade a number of studies have revealed empirical evidence of a cause/effect relationship between soil parent rock, soil properties, and forest dynamics. The Intermountain Forest Tree Nutrition Cooperative (IFTNC) has identified a number of interactions between fertilizer type, soil parent rock, forest growth, and mortality using an extensive set of forest fertilization trials (for example, Hayek and others 1999; Garrison and Moore 1998; Mika and Moore 1990). Soil parent rock has also been related to mortality and basal area increment (Shen and others 2001, 2000) in models closely related to those used in the Prognosis Model (Wykoff and others 1982). These studies suggest inclusion of soil parent rock may be a useful operational revision to Prognosis.

Lithology is the branch of geology concerned with the study of the properties of rock. This paper presents an overview of issues involved in using the lithology of soil parent rock as a predictor, and a pilot study that involved incorporating lithology into the Prognosis large-tree basal area increment model.

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Link Between Lithology and Tree Growth

Five factors define soil attributes: time, climate, biota, topography, and parent material (see for example Buol and others 1989). Parent material is important because the mineralogy of parent rock defines the potential supply of most mineral nutrients used by plants, with nitrogen being the most notable of several exceptions (Garrison and Moore 1998). The physical properties of parent material are also important because they define rock weatherability. In turn, weatherability affects the rate of nutrient release as well as physical properties of soil particles that affect nutrient and moisture holding capacity.

Classification systems are used to categorize the expected particle size and nutrient status of a soil derived from a given parent material. Results for a relatively simple classification developed by the Intermountain Forest Tree Nutrition Cooperative (IFTNC) are presented in table 1. Though granites have moderate mineral nutrient contents, they weather to sandy soils, which have poor moisture and nutrient holding capacity, and thus produce soils of medium to low fertility. In contrast, basalts weather to soils that are richer in clay minerals and produce soils with high nutrient holding capacity (Buol and others 1989). Metamorphosed sedimentary rocks (metasediments) weather to soils with low nutrient holding capacity and low nutrient content, producing soils of generally poor fertility (Garrison and Moore 1998). Thus, soil parent material may be a useful general predictor of the inherent fertility of soils.

Unfortunately, precisely identifying soil parent material at a given location is problematic. Parent material may be field sampled, but this is inefficient at operational scales and is perhaps impossible where soils are developed from complex mixtures of parent material, such as glacial till, fluvial deposits, or loess. Imputing parent material using geologic maps of bedrock lithology is a practical solution, though again, where soils are not developed *in situ* but rather from transported materials, underlying bedrock is obviously not representative of soil parent material. For these and other reasons, the use of bedrock lithology map data is not straightforward.

Using Lithology

Technical difficulties complicate geological mapping. For example, vegetation, water, surficial deposits, and soil development complicate the identification of underlying lithology. Surficial deposits, such as loess, glacial till, or alluvium, may be deep, making identification of underlying rock diffi-

Table 1—Expected soil nutrient status with respect to characteristics of different parent rock types and subclasses common to the Inland Empire. After Garrison and Moore (1998). Used with permission.

Lithology	Potassium status	Expected soil particle size	Expected soil nutrient status
Igneous			
Plutonic (granites)	medium	coarse – sandy	medium to low
Volcanic (basalts)	good	fine – clayey	high
Metamorphic			
Schists	medium	fine – silty	medium to low
Gneisses	poor	coarse – sandy	medium to low
Metasediments	poor	variable	low
Mixed			
Glacial till	medium	variable	variable
Loess	medium to poor	fine – silty	medium to high
Sedimentary			
Shales	medium to poor	fine – clayey	medium to low
Sandstones	medium to poor	variable	variable
Carbonates	poor	variable	poor

cult. In some situations, bedrock lithology maps show surficial deposits themselves as the lithologic unit. Objective and absolute standards for classification are difficult even when bedrock is visible, because the composition, age, and process of formation of rocks may be extremely variable.

Geologic maps, and specifically maps of bedrock lithology, can be based on different classification schemes that reflect the biases of the mapping geologist or differences in emphasis that relate to intended use of the resulting data. For example, rocks may be classified based on their geochemistry, their petrography, resistance to weathering, or on the process that formed the rock; the latter are the familiar "igneous," "sedimentary," and "metamorphic" processes. Thus, geologists commonly provide detailed descriptions that include various degrees of all these characteristics. The objective, perspective, and bias of the mapmaker are not necessarily clear but have a significant impact on the maps produced.

Systems of classification that are meaningful to geologists are likely suboptimal for modelling forest growth. Interpreting and redefining a geological system to make it useful is challenging for geologists, who are unfamiliar with the language and science of forest growth, and conversely for modellers and physiologists who are unfamiliar with the language and science of geology. For example, how is a "metamorphosed, siliciclastic sedimentary rock" related to potassium available to trees at a given forest plot? Descriptive geological classifications need to be reduced to a set of lithologic classes that are simple enough that they can be understood and analysed by modellers but retain as much information as possible so the effect of the information can be explored. Merging geology and forestry is a challenge in interdisciplinary science.

Research on the effects of lithology on forest dynamics has employed inconsistent approaches, as little precedent exists. Results have nonetheless demonstrated clear and statistically significant influences of parent material on forest dynamics that appear to be the consequence of nutrient supply (for example Shen and others 2000; Garrison and Moore 1998; Hamilton 1998). These results were achieved using relatively simple systems of lithologic classification, suggesting that further study may reveal opportunities for improvement. Possibilities may be to reduce:

1. Inconsistency – geologic units were aggregated into types sometimes defined by parent material attributes, and sometimes by soil properties (for example Hamilton 1998).
2. Generality – two to five qualitative classes were used to define lithology (for example Shen and others 2000) or soil nutrient status (for example Garrison and Moore 1998).
3. Uncertainty – hypotheses about causal factors may be tested by examination against a more extensive data set.

A greater understanding of functional relationships between stand dynamics and lithology would guide efficient classification schemes, bolster the credibility of model products, and guide extrapolation to conditions outside of the range of the data used in model development (for example Hamilton 1990) by increasing biological and physical credibility (Rykiel 1996).

Why Not Use Soils?

Soil properties associated with lithology would ideally be obtained directly from soil maps. Unfortunately, high-quality soils data for Northern Rocky Mountain forestlands are inconsistently available. The Natural Resources Conservation Service Soil Survey Geographic Database (SSURGO) at present covers little of the National Forest area in northern Idaho and north-western Montana. Because most data suitable for fitting Prognosis growth equations in the Northern Rocky Mountains are obtained from National Forests, using SSURGO data would be impossible. Using soil maps would also involve many of the same difficulties that apply to lithology, including the need to aggregate to a manageable set of classes and the possibility that a classification scheme

deemed optimal for soil scientists is substantially suboptimal for modelling tree growth. Indeed, studies of the relationship between soils and forest productivity are not rare in the literature, and despite extensive analytical effort generally produce weak or poorly generalizable results (see Monserud and others 1990 or Kayahara 1989 for an extensive review).

Pilot Study

The objectives were to fit the Prognosis large tree basal area increment model, using lithology as a new predictor, and explore ways to aggregate the large set of lithology units present in the preliminary map into a smaller set that would be appropriate for applying the model in management. We hypothesized that aggregation would improve model fit and reveal patterns in the data that were geologically and biologically meaningful. This hypothesis was tested in two ways. Aggregated units were compared for consistency across species and against *a priori* hierarchies of geologic similarity suggested by first principles expectation of soil properties. Final models fit using different aggregation methodologies were also tested for quality of fit using Akaike Information Criterion (AIC), which is a model-independent metric of quality fit. This exercise used a digital lithology map generated by the U.S. Geological Survey (USGS), which was merged with the database of forest plots.

Aggregation Methodologies

Developing objective criteria for aggregating across classification variables is not a new problem in forestry. Most literature concerns growth modelling in tropical forests, where an often-overwhelming number of tree species necessitates the reduction into fewer groups for purely technical reasons (for example, Alder and others 2000; Kohler and Huth 1998; Leech and others 1991; Vanclay 1991). Aggregation methodologies generally follow one of two approaches: subjective (concept-based) or objective (data-based). Concept-based grouping may be either based entirely on *a priori* beliefs about function or combined with statistical techniques that suggest initial groupings (Alder and others 2000; Kohler and Huth 1998; Leech and others 1991). A common theme to each of these three examples is that they allow or require a predetermined number of classes to be set as an initial step in the methodology.

Data-based grouping emphasizes the use of statistical techniques to objectively elucidate structure in the classification variable (for example, Vanclay 1991; Meldahl and others 1985; Wykoff and others 1982). Wykoff and others (1982) aggregated diverse ecosystem units into similar sets based on "statistical similarity," defined as groups where none of the estimated coefficients that are grouped into a class differs from any other at the 50 percent level of significance. Wykoff's technique attempts to aggregate only intercept effects, fit uniquely by group, rather than the entire model. Vanclay (1991) introduced arguably the most objective methodology. Classes were sorted by decreasing order of data set size, and whole model F-tests conducted recursively *sensu* Leech and others (1991) to identify "founding classes" that were statistically different from all others. Then remaining classes were grouped with the most similar founding members, based on minimizing the increase in residual sums of squares.

Data and Methodology

Forest Plots

Data from the USDA Forest Service Region 1 permanent plot program were available at the time of the pilot study. This program is a network of plot clusters installed in treated stands across National Forests in Region 1, which includes central and northern Idaho as well as Montana portions of the overall study area. Plot establishment began in the early 1980s, with a target measurement cycle of 5 years; thus, up to three remeasurements were available on some plots. Measurements in a given stand comprise three or more plot clusters installed in treated areas, paired with a single control cluster in an untreated area. Three measurement plots are included in each cluster. Region 1 is in the process of cleaning and certifying the permanent plot database, and clean data were only available for the Idaho Panhandle and Flathead National Forests, which restricted the geographic extent of the exercise. Only data for the four species most abundant in the database were used in the analysis: Douglas-fir (*Pseudotsuga menziesii*), grand fir (*Abies grandis*), western larch (*Larix occidentalis*), and lodgepole pine (*Pinus contorta*).

Lithology

The USGS preliminary lithology map covered the northern Idaho portions of the Bonners Ferry, Sandpoint, Coeur d'Alene, St. Maries, Thompson Falls, and Wallace 1-by-2 degree quadrangles. The total coverage was approximately 60 percent of the entire study area. Lithologic diversity within the map was extensive, including 784 unique lithologic units and nearly 37,000 individual polygons. Permanent plot locations were intersected with the USGS digital lithology map to impute lithology at plot locations.

Model

The Prognosis large tree basal area model formulation described by Wykoff (1990, 1986) was the base model used in the analysis. This model already uses the Wykoff t-test matrix algorithm to aggregate habitat type and location effects on the model intercept and as interactions with some predictors. Because the objectives of this study were to explore aggregation techniques themselves and reveal patterns in the dataset related to lithology, a modified version of the model was specified to focus on these questions. This version, in which mean annual precipitation was substituted for habitat and location, was used principally in the analysis. The Wykoff (1990) formulation was subsequently fit, applying aggregation techniques to lithology only, to examine whether using the modified version affected the results. In the modified model, mean annual precipitation is a continuous variable and was imputed at each plot from 2 km digital precipitation grids. Precipitation and lithology

were introduced simply as linear terms and not as interactions with any other variables.

Aggregation Schemes

Six aggregation schemes were tested:

1. Null — the model is fit without separate intercepts, effectively combining the effect of all lithology classes in the intercept.
2. Full — the model is fit with separate intercepts for all lithology classes.
3. Shen — set of five classes (granite, basalt, metasediment, sediment, mixed) from Shen and others (2000).
4. IFTNC — the USGS classes are interpreted following table 1 and placed into classes "good," "medium," and "poor."
5. Wykoff and others (1982) t-test matrix.
6. Vanclay (1991) paired F-test method.

Schemes 1 through 4 were implemented by introducing a class variable in standard linear regression functions in S-Plus, Version 6. The effect is to estimate parallel functions with separate intercepts for the class variables. The final two schemes were implemented by writing S-Plus scripts that coded their respective algorithms.

Results

Over 45,000 individual tree observations were available for model fitting after processing to generate the variables used in the model. However, since up to three successive measurements were made in some cases, only 124 unique stands were represented in the data (table 2). The sample of stands was distributed unevenly across the 14 lithology classes. In terms of the three broad geologic types: eight were granitic (6 percent), 78 were metamorphic (63 percent), and the remaining 38 were fluvial (31 percent). Nine of the 14 classes (64 percent) were represented by seven or fewer stands; three classes were represented by a single stand. The four species most prevalent in the data set were used for analysis (table 2).

Of the six aggregation methods, all but the Vanclay and Wykoff methods were completely determined *a priori* and were by definition constant across species. The Shen and IFTNC systems show some correspondence (table 3), mostly because of their simplicity. For example, metasedimentary types are all rated "poor" in the IFTNC system. However, the data contained only two IFTNC types; no units classified as "good" were present. The Wykoff approach, which tended to produce groups with only two or rarely three members, produced more classes than Vanclay method (tables 3, 4). Aggregated groups of up to five members were produced with the Vanclay method. Results from both the Wykoff and Vanclay algorithms were inconsistent across species, especially in comparison to the other aggregation methods. Consider the metasedimentary types, which are grouped together in both the Shen and IFTNC systems. In the Wykoff approach, none of the five metasedimentary types were grouped for any species, with the exception of two classes aggregated for grand fir. Results were only marginally more consistent using the Vanclay method. The same two classes were aggregated for grand fir, and three of five classes aggregated for lodgepole pine. Otherwise, few patterns are apparent. Notably, every set aggregated under the Wykoff system was also aggregated under the Vanclay system with one exception, though not *vice versa*.

Comparing models by AIC showed that generally a greater the number of classes resulted in a better fit (table 5). Only a minor improvement resulted from using any of the aggregation schemes compared to using all classes. The lowest AIC, and therefore presumably best model, was that developed with the Vanclay approach for Douglas-fir and grand fir, and the Wykoff approach for lodgepole pine and western larch.

Table 2—Summary of parent material classes from USGS lithology map by stand and tree species in the fitting data.

USGS mapped dominant lithology	Domlith code	No. stands	No. trees			
			DF[1]	GF	L	LP
glacial sediments[2]	glac1	7	325	84	923	1531
glaciofluvial	glac2	21	436	10	1588	4104
granitoid	gran2	6	365	231	180	497
granodiorite	gran3	2	329	0	46	7
meta-claystone	meta1	1	28	4	22	2
metamorphosed siliciclastic sedimentary rocks	meta11	14	772	695	470	180
meta-mudrock or "shale" (>50% silt and clay)	meta3	17	1146	599	687	1125
metamorphosed carbonate/siliciclastic sedimentary	meta7	4	191	24	396	150
metamorphosed siliciclastic/carbonate sedimentary	meta8	29	2774	1703	963	1144
mixed metamorphic/igneous plutonic	mixe3	1	12	0	286	181
natural unconsolidated sediments	natu	14	857	545	1328	130
older alluvium	olde	1	14	237	0	0
semi-pelitic rocks	semi	3	83	116	41	43
unconsolidated sediments	unco	4	22	164	0	518
	totals	124	7354	4412	6930	9612

[1] DF = Douglas-fir; GF = grand fir; L = western larch; LP = lodgepole pine.
[2] Though the class "glacial sediments" and some others here are strictly geomorphologic and not lithologic descriptors, they are the descriptive terms assigned to the bedrock lithology polygon by the USGS and are used accordingly.

Table 3—Results of aggregating classes using the Shen, IFTNC and Wykoff methods. Units with the same name or number are grouped together.

Domlith code	Shen	IFTNC	DF[1]	GF	L	LP
glac1	mixed	medium	1	1	1	1
glac2	mixed	medium	2	2	2	2
gran2	granite	medium	3	3	3	3
gran3	granite	medium	4		1	4
meta1	metased	poor	1	4	4	5
meta11	metased	poor	5	5	5	6
meta3	metased	poor	2	5	6	3
meta7	metased	poor	6	3	7	2
meta8	metased	poor	7	6	8	7
mixe3	granite	medium	8		9	5
natu	mixed	medium	9	7	10	3
olde	mixed	medium	6	8		
semi	metased	poor	4	8	11	8
unco	mixed	medium	6	5		4

[1]DF = Douglas-fir; GF = grand fir; L = western larch; LP = lodgepole pine.

Table 4—Results of aggregating classes using the Shen, IFTNC, and Vanclay methods. Units with the same name or number are grouped together.

Domlith code	Shen	IFTNC	DF[1]	GF	L	LP
glac1	mixed	medium	3	5	1	1
glac2	mixed	medium	1	4	1	1
gran2	granite	medium	2	3	5	3
gran3	granite	medium	2		3	4
meta1	metased	poor	3	5	5	3
meta11	metased	poor	2	2	1	3
meta3	metased	poor	1	2	3	3
meta7	metased	poor	4	3	5	1
meta8	metased	poor	1	1	2	2
mixe3	granite	medium	3		4	3
natu	mixed	medium	1	3	1	3
olde	mixed	medium	4	4		
semi	metased	poor	2	4	5	2
unco	mixed	medium	4	2		4

[1]DF = Douglas-fir; GF = grand fir; L = western larch; LP = lodgepole pine.

Table 5—Akaike Information Criterion values, by species, for models fit using different aggregation methodologies.

Model	DF[1]	GF	L	LP
base	16320.1	10039.4	15505.8	22101.4
all	15934.1	9759.7	15084.2	21437.0
Shen	16076.1	9977.7	15378.7	21767.6
IFTNC	16143.4	9975.9	15407.8	21871.0
Vanclay	15920.5	9751.8	15094.8	21431.1
Wykoff	15924.7	9752.4	15082.2	21427.7

[1]DF = Douglas-fir; GF = grand fir; L = western larch; LP = lodgepole pine.

Similar results are produced when the Wykoff (1990) base model is used instead of the modified model, which substitutes precipitation for habitat type and location. Overall, when the Wykoff (1990) base model is used, AIC values are 1 to 3 percent lower than under the modified model, but the relative ranking of aggregation methodologies is nearly identical. In either case, within and across species few patterns are apparent in the grouping of lithology classes by the Vanclay or Wykoff methods, and little correspondence is found between the final result for both methods using either base model.

Discussion

Data-based and concept-based approaches to aggregating classification variables have different strengths. Objective statistical techniques may reduce the potential for bias as well help elucidate the correct interpretation of the functional relationship between class variables and the modelled system. This is most useful when little is known about the relationship in advance. Yet when knowledge about function is available, schemes that incorporate knowledge may be superior to statistical techniques that produce some hierarchies that are an artifact of random data patterns (Vanclay 1991).

Our goal was to test the hypothesis that biologically meaningful patterns could be discerned. The results are not encouraging. This is principally because data-based techniques have suggested groupings that are not biologically sensible, and because groupings that are biologically or geologically sensible were not useful in modelling. If lithology is in fact not related to tree growth, or our interpretation of what is biologically sensible is inappropriate, this result is not surprising. Nonetheless, the analysis was limited by a data set that may not contain a sufficient breadth of information to discern meaningful relationships. A larger data set would include more lithologic diversity, and independent data would permit a more extensive evaluation.

Data structure is a better explanation for the results than causal links between lithology groupings and tree growth for this data set. Any signs of model improvement through the addition of lithology may be due more to overfitting than a true increase in explanatory power. This is evidenced by the chaotic aggregation results from the data-based techniques, which are at odds with even the simplest conceptual expectations, and inconsistent results across species, aggregation method, and underlying base model formulation. Lithology may be acting as a proxy for unmeasured site values, given the poor data distribution across lithology classes, in some cases with a class represented by a single site. Again, model development and testing using a broader data set is necessary.

The results do offer some insights into the tradeoffs between aggregation methodologies. The Wykoff and Vanclay data-based techniques were able to identify similar data patterns, albeit only within single species. AIC comparisons suggest that the two techniques produce models of similar quality. However, the Wykoff technique allows for the final decision to aggregate to be made subjectively, which may be desirable especially where some *a priori* knowledge is available to guide modelling. Vanclay's technique, which was

initially proposed for modelling of tropical species, would have an advantage where the number of groups was overwhelming or where little information is available in advance that could guide subjective decisionmaking.

A key objective of the pilot study was to produce some results that could guide and refine future work, and to this end the study has been useful. Clearly a broader data set with more lithologic diversity is needed. Lithologic units were also simplistic; greater diversity should include descriptions and information that are useful for linking lithology conceptually to soil properties and tree growth.

Acknowledgments

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FVSBGC: A Dual Resolution Hybrid Model with Physiological and Biometrical Growth Engines

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Abstract—This paper describes the physiological model, Stand-BGC, and how it was linked to the Forest Vegetation Simulator (FVS) base code as a system extension. Using a set of Stand-BGC keywords, a user can invoke the extension in an FVS simulation and grow a stand using the physiological growth engine. A daily climate file and information on soil depth and texture must be provided. Understory vegetation can be input via keywords or by running the Cover extension. When the Stand-BGC extension is running, all vegetation is grown so that grass and shrubs directly impact tree growth. Regardless of the growth engine selected, standard FVS formatted output is produced. The Stand-BGC extension also generates various reports containing elements of the water and carbon balance calculations at tree and stand levels at daily and yearly time intervals. The Stand-BGC extension may be roughly calibrated to FVS through user-controlled multipliers on annual precipitation and canopy photosynthesis. After calibrating Stand-BGC so that predicted top height after 30 years matched that from FVS, the two growth engines produced similar tree and stand attributes. The daily and yearly tree and stand level physiological variables produced should be useful in describing ecosystem function and for driving other models requiring higher resolution and climate sensitive inputs. Results suggest that more sophisticated communication between the two types of models is possible.

Ecosystem management, by definition, requires information on ecosystem processes. Generally, the current suite of mensurational models in common use by forest management organizations are not constructed to provide such information. Models such as the Forest Vegetation Simulator (FVS) simulate tree and stand dynamics through statistical correlation of the results of underlying processes that operate at higher temporal and spatial resolutions. These underlying processes are driven by factors not relevant at the resolution of such a biometrical model. Thus, our forest management models are insensitive to climate and other site variables at the resolutions needed to assess ecosystem functions.

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In the past decade or so, physiological models, such as Stand-BGC (Milner and Coble 1995), have been developed that explicitly represent some of these underlying ecosystem processes at the higher resolutions needed. There is, of course, still plenty of empiricism; it just exists at a higher level of resolution in the hierarchical system. However, with this higher resolution comes the increased difficulty of simulating reliable system behavior at the resolutions useful to forest management. The underlying processes modeled are still approximations, and the complex linkages within and between scales are not well understood. For many forest management needs, it is perhaps a truism that a physiological model will never be able to achieve the prediction accuracy of a well-defined, biometrical model fit to adequate data. Moreover, physiological models are generally designed neither to process the kinds of data collected in forest inventories nor to simulate the activities that need to be analyzed in forest management.

The challenge then is to combine the two types of models into one system that contains the strengths of both types of models. The work described in this paper is an attempt to achieve such a linkage between FVS and Stand-BGC.

Stand-BGC Description

Stand-BGC (Milner and Coble 1995) is an individual entity, distance independent, version of the whole stand physiological model, Forest-BGC (Running and Coughlan 1988). The term “entity” is used because grasses and shrubs are input and grown, as whole stand entities, right along with individual tree entities. As with Forest-BGC, Stand-BGC is a climate-driven, carbon and water balance model that operates at a daily resolution for basic production processes and at an annual resolution for carbon allocation. Unlike Forest-BGC, Stand-BGC scales the “big leaf” level physiology to individual entity subcanopies rather than to the whole stand. Combined with stand structural information, the resulting interacting subcanopies provide the mechanism for competition for site resources among entities. Details of the basic physiological modeling are contained in papers by Running and Gower (1991) and Running and Hunt (1993) and will not be repeated here.

Like FVS, Stand-BGC was designed to process tree lists from standard forest inventories. In addition to standard tree measurements such as height, diameter, and crown ratio, cover and canopy depth of understory vegetation, by lifeform or species, should be provided. A daily climate file

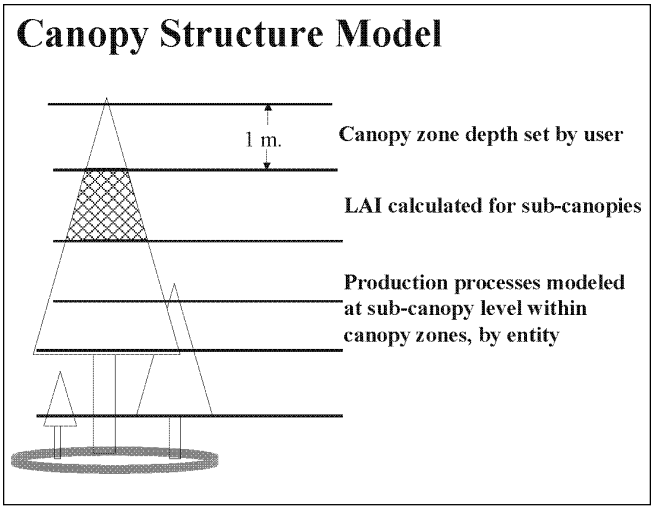

Figure 1—Schematic showing how stand canopy structure is abstracted. Individual tree crowns are right circular cones. Crowns for per hectare grass and shrub entities are cylinders. Foliar biomass is assumed to be uniformly distributed in the crown volume.

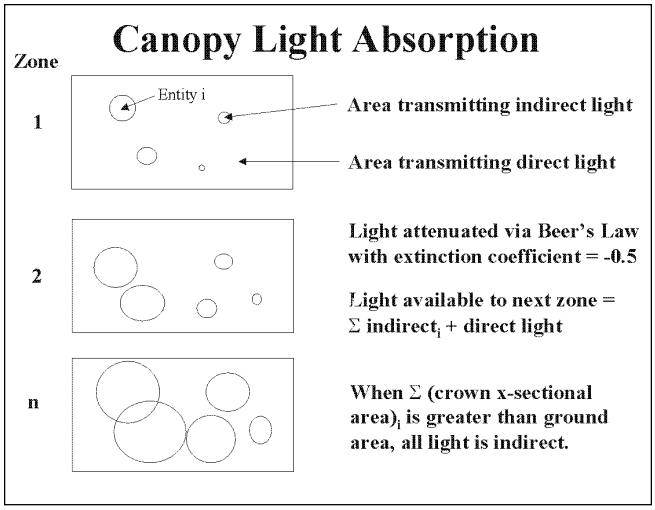

Figure 2—The light absorption model in Stand-BGC. A Beer's Law calculation provides the solar radiation that drives photosynthesis and transpiration at the subcanopy level.

containing maximum and minimum temperatures, relative humidity, solar insolation, and atmospheric transmissivity must be supplied. Soil depth and texture must also be supplied. A default set of physiological parameters is provided that may be altered by the user.

Stand dynamics result from competition for site resources (light and water) among entities. The differential access to these resources arises from how water and light are modeled and from assumptions as to how different lifeforms acquire each resource. Based on the input vegetation list, foliar biomass equations, and assumptions about the geometry of entity crowns, leaf area index for any subcanopy of an entity can be calculated. The vertical position of any subcanopy, relative to those of its neighbors is also known (fig. 1). Either a fixed distance (user defined), or one defined by entity tops and crown bases, is used to define the subcanopy layers through which light will pass. Individual entities then absorb light according to a subcanopy's LAI based on a Beer's Law formulation (fig. 2). The presence and amount of leaf area in canopy zones above a particular entity directly affect its access to the light resource. Thus, there is shading within and between canopies.

Entities access water according to their rooting depth and the size of their "water bucket" (fig. 3). The latter is proportional to the amount of leaf area an entity supports. Precipitation events provide water to the topsoil layer first. If and when the top layer's water holding capacity is exceeded, water moves to the lower soil layer. If both layers are filled, the excess leaves the site as overland flow. Entity subcanopies transpire from bottom to top, sequentially removing water from the entity's water bucket. Small trees and understory vegetation are limited to the top soil layer of their water buckets, while large trees tap water in either layer according to which has the least negative water potential. At the end of each day, a site water balance is calculated for each soil layer, and all water buckets equilibrate to the site water potential. Thus, large trees dominate the site water balance. Small trees compete with understory vegetation for water in the top layer until they become "large," at which time they access water in the lower soil layer. Competition intensifies when droughty conditions exist. Different "leaf-on" and "leaf-off" dates, transpiration rate parameters, and stomatal conductance parameters also influence realized competition.

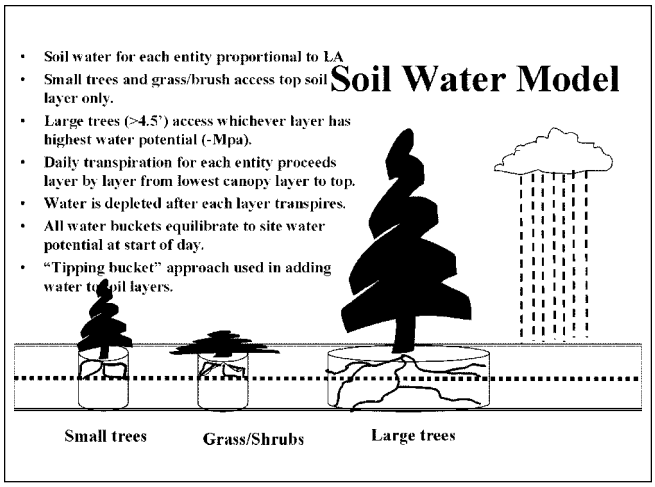

Figure 3—The water access model in Stand-BGC. Large trees (greater than 2 m in height) can access water in either soil layer. Small trees and herbaceous vegetation are restricted to water in the top layer.

At the end of each year, a carbon balance is calculated for each entity, and carbon in excess of respiration and turnover is allocated to leaf, stem (including branches), and roots using the approach described by Running and Gower (1995). Leaves and roots receive their allocation first, based on accumulated moisture stress during the year and some constraining allometric ratios. Whatever is left over is allocated to stems. In dry years, more carbon is allocated to roots and less to leaves.

Following carbon allocation, entity dimensions are updated. For trees this means converting the stem carbon allocation to diameter and height growth. After converting carbon mass increment to wood volume increment, a volume equation and a height/diameter equation are used to change height and diameter (fig. 4). For understory entities, percent canopy cover and canopy depth are updated by inverting the appropriate biomass equations. When site resources are plentiful, entities have carbon in excess of turnover and maintenance respiration costs and growth occurs. When total stand leaf area approaches site capacity (hydrologic equilibrium), competition for resources intensifies. Those entities of lesser social status cannot access sufficient resources to balance turnover and respiration, and their leaf area declines. Mortality ultimately occurs when leaf area goes to zero. Currently, an entity dies and is removed from the projection when respiration costs exceed net canopy photosynthesis for more than 3 years successive.

Output from Stand-BGC currently includes an updated entity list annually along with attributes of the carbon and water balance calculations at entity and stand levels at daily and annual intervals.

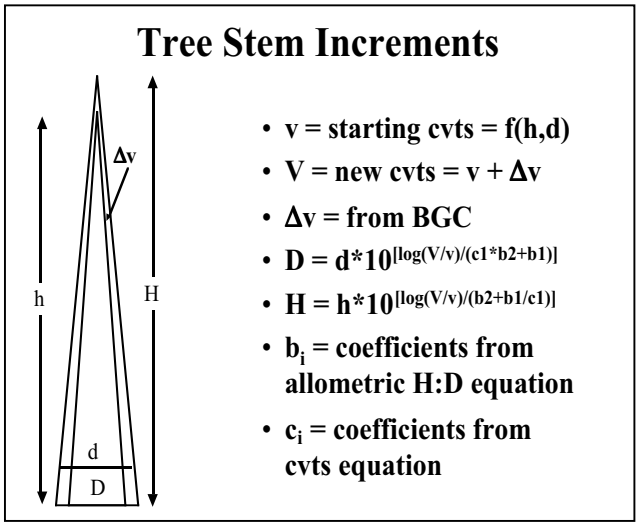

Figure 4—Procedure for updating tree height and diameter from the volume increment predicted by Stand-BGC.

Model Linkage

We linked Stand-BGC to FVS as a system extension to the base FVS code (Milner and others 2002; McMahan and others 2002). Thus, all variants can access the Stand-BGC extension. Users invoke and control the extension through a set of FVS keywords. The linkage is illustrated in figure 5. When a user invokes Stand-BGC as part of an FVS run, FVS initializes Stand-BGC with its tree list at the start of the projection. Each model then grows the tree list forward independently: FVS at about 10-year growth steps, Stand-BGC at daily and yearly time steps. Stand-BGC increments are aggregated to the cycle length specified for the FVS projection. At each FVS cycle boundary, the models can exchange growth increments, mortality, and change in crown ratio. If the user has specified, via keyword, that FVS should use the Stand-BGC increments, the FVS tree list is updated with these increments. Otherwise the tree list is updated with FVS increments. Any scheduled FVS management activities are implemented and the updated tree list, which also contains any new trees from the FVS Regeneration Model, is passed from FVS to Stand-BGC. Each model generates its standard suite of reports and the next cycle begins.

If the user has specified that Stand-BGC increments are to be used in FVS, only the new trees from FVS are processed into the carbon pools needed by Stand-BGC. The end of cycle carbon pools for the trees remaining after any thinnings in FVS are already present in Stand-BGC. Thus, the Stand-BGC output is identical to that from a stand-alone Stand-BGC projection of the initial tree list. The standard FVS reports show stand dynamics and growth and yield information as usual; the trees have just been grown using the climate-driven physiological growth engine.

If the user decides to use the FVS increments, the FVS output is unaffected by Stand-BGC. Stand-BGC is completely reinitialized at the start of each FVS cycle, and the

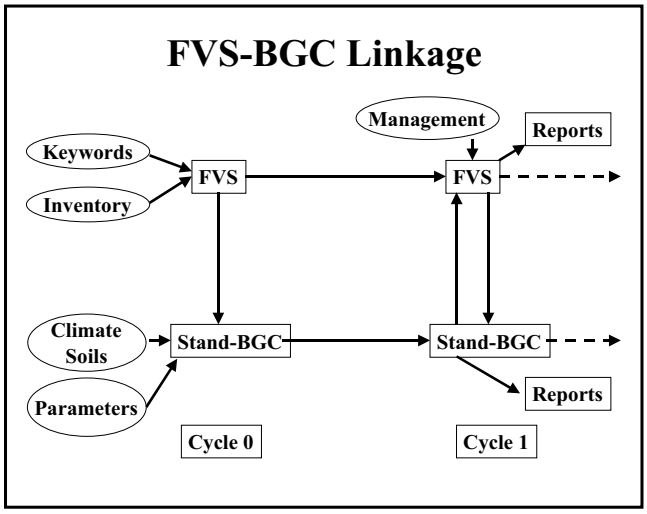

Figure 5—Schematic of the linkage between Stand-BGC and FVS. FVS initializes Stand-BGC at the start of a simulation and at FVS cycle boundaries. The user may choose to have growth and mortality predicted by FVS or Stand-BGC.

end-of-cycle Stand-BGC output just provides a suite of physiological variables for that FVS cycle.

An Example

An FVS tree list was prepared from plot data in an even-aged lodgepole pine stand in western Montana. The stand had the following characteristics:

— QMD = 7.4 inches
— TPA = 302
— BA/acre = 90 square feet
— Top height = 45 feet
— Slope = 15 percent, aspect = NE, elevation = 3800 feet
— Habitat type = PSME/PHMA
— Grass cover = 30 percent
— Soil was a sandy loam, 1 meter deep

A 30-year climate file was prepared from a nearby valley bottom weather station and extrapolated to the site using the MT-CLIM climate model (Nemani 1988). The stand was projected forward for 30 years with and without the Stand-BGC growth increments and mortality so the two models could be compared. All Stand-BGC parameters were the defaults. The model was calibrated to FVS by setting a multiplier on net canopy photosynthesis so that top height from Stand-BGC matched that from FVS after 30 years. For these runs, the multiplier reduced photosynthesis by 10 percent. The Stand-BGC keywords for the simulation were as follows:

Keyword	Explanation
BGCIN	Signals the start of Stand-BGC keywords and invokes the Stand-BGC growth engine. Matched with an END keyword.
BGCGROW	Indicates that Stand-BGC increments are to replace FVS increments when growing trees.
VEGOPT 2	The keyword signals how understory vegetation is to be entered. A '1' means output from the COVER extension will be used. A '2' means vegetation data will be entered in a supplemental record.
UNDERVEG	Signals the start of vegetation data.
G gr 1.0 30	G = grass life form, gr = species label, 1.0 = grass canopy depth, 30 = percent cover of grass.
ENDENT	Signals the end of vegetation data.
END	Signals the end of Stand-BGC keywords.

The summary yield tables from FVS, with and without the Stand-BGC increments, for the 30-year projection of the unthinned stand, are quite similar (table 1). The most noticeable difference is in the amount and pattern of predicted mortality. FVS killed a few more trees, with the mortality occurring in a gradual pattern; Stand-BGC killed fewer trees but all in the same period.

A variety of physiological variables are produced by Stand-BGC so that a user can view the underlying processes. For example, tables 2 and 3 show annual estimates of photosynthesis, respiration, and transpiration at stand and entity levels, respectively. Other tables (not shown) are produced that give these variables at daily resolutions, show light absorption by canopy layer, provide details of the daily stand and tree level water balance calculations, give estimates of mortality, and show updated entity lists.

Table 1—Summary statistics from FVSBGC using FVS vs. Stand-BGC growth increments.

Summary statistics when using FVS Increments					
Year	TPA	BA/ac	QMD	Top Ht	CVTS/ac
1984	302	90	7.4	45	1853
1994	285	111	8.5	50	2517
2004	269	132	9.5	57	3272
2014	251	148	10.4	61	3977
Summary statistics when using Stand-BGC Increment					
Year	TPA	BA/ac	QMD	Top Ht	CVTS/ac
1984	302	90	7.4	45	1853
1994	302	119	8.5	52	2807
2004	302	135	9.1	56	3437
2014	267	145	10	61	4051

Discussion

Assuming that FVS provided a reliable forecast over the 30-year period, the fact that Stand-BGC can, with minimal calibration, produce similar results, suggests that the underlying physiological processes may be reliably modeled as

Table 2—Annual stand level processes from Stand-BGC

Annual stand-level output from Stand-BGC									
FVS Cycle	Year	Psn (KgC/ha)	Trans (m3/ha)	Mresp (KgC/ha)	Gresp (KgC/ha)	Grass LAI	Tree LAI	Total LAI	Stem C (tC/ha)
1	0	0	0	0	0	0.21	6.9	7.1	42.9
1	1	11843	1882	2997	3358	0.19	6.7	6.9	45.0
1	2	11604	1997	3063	3217	0.17	6.8	6.9	48.2
1	3	8318	1378	3055	2325	0.16	6.1	6.2	50.0
1	4	9831	1482	2921	2783	0.14	6.6	6.8	51.6
1	5	10820	1806	2788	3013	0.13	7.1	7.2	53.9
1	6	9088	1463	2780	2486	0.14	6.8	6.9	56.0
1	7	14271	2551	2978	4076	0.17	8.5	8.6	58.9
1	8	10876	1575	3411	3024	0.15	7.8	8.0	61.7
1	9	12628	1745	3454	3553	0.13	8.4	8.6	64.2
1	10	16429	2558	3219	4768	0.13	9.7	9.9	68.5

Table 3—Annual entity level processes from Stand-BGC

Annual Entity level output from Stand-BGC											
FVS Cyde	Year	Entity	SP	Psn (KgC)	Transp (m3)	Mresp (KgC)	Gresp (KgC)	Leaf (KgC)	Stem (KgC)	Root (KgC)	Turnover (KgC)
1	0	1	Lpp	0.0	0.0	0.0	0.0	3.0	43.6	3.0	0.0
1	0	2	Lpp	0.0	0.0	0.0	0.0	1.7	23.2	1.7	0.0
1	0	3	Lpp	0.0	0.0	0.0	0.0	5.2	95.4	5.2	0.0
1	0	53	gr	0.0	0.0	0.0	0.0	85.3	0.0	85.3	0.0
1	1	1	Lpp	12.5	1.8	3.0	3.5	2.9	45.8	3.5	3.3
1	1	2	Lpp	6.9	0.9	1.9	1.9	1.6	24.4	1.9	1.8
1	1	3	Lpp	21.8	3.0	5.1	6.2	5.1	99.2	6.2	5.8
1	1	53	gr	163.9	95.0	315.8	0.0	76.7	0.0	42.6	51.2
1	10	1	Lpp	16.5	2.3	3.5	4.7	4.0	68.3	2.9	3.3
1	10	2	Lpp	6.9	0.8	2.0	1.9	1.7	33.2	1.2	1.4
1	10	3	Lpp	29.0	3.8	5.8	8.4	7.2	139.7	5.2	5.9
1	10	53	gr	94.1	39.7	45.0	28.1	53.6	0.0	11.3	17.2

well. While significant work is needed to establish this reliability for the Stand-BGC model, the possibilities are clear. Such a linked model can provide a means for analyzing impacts of climatic variation on forest growth and yield, provide variables at resolutions perhaps more suitable for driving pest models, and provide insights into the mechanisms of stand responses to thinning treatments.

The way in which FVS and Stand-BGC were linked in this study is quite simple; tree lists and predicted increments are merely passed back and forth. A more exciting approach would be to have each of the two models contribute to one combined forecast. The complete suite of state variables for each model is available to the other at FVS cycle boundaries. Thus, one can envision communication between models ranging from creating weighted averages of some predicted states (such as basal area increment) to alteration of underlying model parameters. For example, the strong dimensional relationships in FVS could be used to calibrate or constrain carbon allocation fractions and leaf turnover rates in Stand-BGC. Alternatively, the climate sensitive rates of photosynthesis, respiration, and water stress could be used to modify FVS mortality parameters.

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Eco-Physiology Approach to Projecting Tree Stress and Vigor in FVS

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Abstract—Tree stress and vigor affect, and are affected by, damage agents such as insects and pathogens. Stand density and tree growth rates serve as indicators of stress and vigor, but drought events and other disturbances are also important components of stress and vigor status. Site factors must also be considered when relating stand density to stress. In this paper, the FVS-BGC hybrid model has been used to analyze tree and stand vigor at different time scales, under a number of hypothetical management, climate, and site scenarios for lodgepole pine stands in the Central Rocky Mountains. Results suggest a quantifiable relationship between stand density, soil moisture, and tree vigor that can be projected using the FVS-BGC model. Example simulations using FVS-BGC relates stand density, site, and precipitation with a stem growth/leaf area vigor index. The timing of simulated moisture stress within a year appears to be correlated with the mountain pine beetle flight period. Results related to stand basal area appear to agree with management guideline to lower mountain pine beetle hazards. This approach may be useful in enhancing FVS insect and pathogen extensions and has the potential to better explain the limiting factors to growth for different sites and stand structures.

Consideration of insect and pathogen effects on stand projections is a component of the Forest Vegetation Simulator (FVS) system (Wykoff and others 1982). Tree stress and vigor affect, and are affected by, damage agents such as insects and pathogens, so direct estimates of these biological conditions could improve FVS projections. We use the term "stress" to refer to conditions that inhibit normal tree functioning, and "vigor" to generally refer to the efficiency with which a tree or stand is utilizing its resources.

Stress factors, such as limited soil moisture, affect basic physiological processes such as photosynthesis and allocation. Although these processes can be difficult to track individually, the net effects of these processes can be described in terms of growth efficiency, or vigor. In this study, we analyze the relationships between two stress factors—soil water availability and competition—and tree vigor. We represent vigor in terms of an index proposed by Waring and others (1980). Soil moisture availability is directly simulated; competition is expressed in terms of stand density (as basal area per acre).

Pine bark beetles are important forest mortality agents that appear to be sensitive to vigor conditions. It has long been held that tree "vigor" is an important factor in pine-bark beetle interactions (Eaton 1941; Johnson 1951). Moisture conditions are often limiting in pine forests and are thus a factor in determining tree and stand vigor (Berryman 1976). Stand moisture conditions are the result of site conditions including soil texture and depth, and of interplant competition, damage from other agents, and climate including variation in precipitation. Forest entomologists have developed semiempirical stand hazard rating systems for tree-vigor sensitive insects such as pine bark beetles. The systems primarily use measures of basal area, trees per area, or both, to represent the vigor status. Other factors, such as tree diameter or phloem thickness, have been included to represent suitable beetle habitat once the tree is successfully attacked. The problem with these systems is that they poorly account for variation in site and climate conditions, and not at all for annual variation in weather (Amman and Anhold 1989). More data-intensive rating systems include phloem thickness and changes in relative growth rates, based on ring measurements. This captures some of the variation in weather factors, but even these cannot be easily used to project future conditions because empirical growth projection systems, such as FVS, use average, multiyear time steps that ignore within- and between-year variability.

Tree growth is generally assumed to be directly correlated to photosynthetic production. However, not all of the fixed carbon is used for growing stems, roots, and leaves. In some trees, one important use is to produce oleoresin compounds (pitch), which are used by the tree to seal wounds and defend against insect attacks. The toxic, sticky resin produced by the tree can flow out through holes produced by bark beetles, and kill the beetles. It can also play a role in limiting the spread of beetle-introduced fungi through the phloem.

In pine trees, resin is produced under two conditions. It may be *preformed* in resin canals in the phloem, or it may be *induced* as a response to wounding. There is evidence that production of preformed resin may occur during times of moderate moisture stress (Lorio 1986, 1993; Lorio and Sommers 1986; Wilkens and others 1998), and that induced resin is more available during times when high levels of carbohydrates are moving through the phloem to the roots (Herms and Mattson 1992), in times of low moisture stress. In times of high moisture stress, little or no photosynthesis takes place, and the tree must rely on whatever preformed resin was produced earlier. The preformed resin reserves

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are limited and will be exhausted if the tree is attacked by a large number of beetles. The relationship of tree vigor and resin defenses has been used to relate tree vigor to mountain pine beetle attacks (Waring and Pitman 1985).

In recent years, a number of tree physiology growth models have been developed that simulate photosynthesis processes (Battaglia and Sands 1998). Some of these models provide outputs that correlate with tree vigor status and defensive resin production. Stand-BGC (Milner and Coble 1995) is a process-based model that has been designed to simulate the allocation of total stand photosynthate back to individual trees. FVS-BGC (Milner and others, these proceedings; McMahan and others 2002) is an adaptation of the Stand-BGC model designed to function as an extension of the Forest Vegetation Simulator (FVS) system (Wykoff and others 1982). FVS-BGC links the process-based modeling approach from Stand-BGC to the FVS empirical growth approach, and uses the management options in FVS to simulate stand manipulations.

The FVS-BGC extension provides a suite of carbon- and water-cycle output files at the tree and stand levels, at both daily and yearly time steps, as well as standard FVS stand tables derived from the process model. The inputs to FVS-BGC include the primary factors that determine tree and stand vigor (namely, site and climate), and the outputs correspond to observable indicators of stress and vigor status. We have used the FVS-BGC model to demonstrate its usefulness for analyses of stand and tree vigor as it relates to pine bark beetles.

Methods

FVS-BGC requires two sets of inputs: those required for a standard FVS simulation; and BGC specific inputs, which include climate files, soils data, and physiology parameters. The simulation was performed on a lodgepole pine stand, from the White River National Forest, in central Colorado. The initial stand, chosen to be typical of the area, had these characteristics:

Basal area:	174 ft^2/acre	[≈ 40 m^2 / ha]
Trees per acre:	534	[≈ 216 / ha]
Q.M.D.:	7.7 inches	[≈ 19.6 cm]
Mean top height:	71 ft	[≈ 21.6 m]

FVS thinning keywords were used to create five additional levels of stand density. Stands were created having basal areas of 80, 100, 120, 140, and 160 ft^2/acre. These stands were created (using FVS keyword THINDBH) by removing a constant proportion from every tree record in the tree list; consequently, the stand's diameter distribution structure was not altered.

A single year's daily climate input from Vail, CO, was used as input. The year chosen had a total annual precipitation close to the 20-year mean for that site (μ=22.0; σ = 4.5 inches); it also had similar monthly means, hence the intraannual distribution of moisture was similar to patterns under which the stand developed.

The MTCLIM model (Hungerford and others 1989) was used to adjust the weather data for the elevation of the stand. Seven separate weather input files were created representing a range of dry to wet conditions. These files were created by scaling each daily precipitation event by a constant so that the year's total precipitation would sum to 60, 75, 90, 100,110, 125, or 140 percent of the long-term average annual precipitation. (This range captures most of the observed variability, and represents approximately two standard deviations on either side of the mean annual precipitation.) The simulations were run for 3 years each. All simulations used the average precipitation file in the first year, followed by 2 years of one of the proportionally adjusted precipitation files. Soil data were obtained from a forest soil survey.

Results

Within-Year Stress

Figure 1 displays the relationship between daily precipitation and simulated soil water potential for one of the modeled combinations of stand density and precipitation during the summer months. Before July 1, soils in this area generally have high water availability (less negative water potentials) from snowmelt. The simulated drying process results from evapotranspiration exceeding precipitation.

Figure 2 displays the simulated soil water potential for three of the modeled precipitation levels during the summer months, for the 120 ft^2/acre stand. Mountain pine beetles (MPB; *Dendroctonus ponderosae*, Hopkins) in this area primarily emerge and attack sometime between early July and early September, with the attack period generally concentrated in the middle of the that time. Actual MPB flight times can vary year to year and can occur over small time intervals. Note that the amount of time this stand is under moisture stress varies significantly during the normal beetle attack period depending upon the amount of precipitation. The possible temporal correspondence of MPB flight to the period of moisture stress might influence the successfulness of MPB attacks.

Figure 3 displays the simulated soil water potential for three of the modeled stand density levels, all simulated using the average (100 percent) precipitation level throughout the simulation. This range of stand densities bracket the

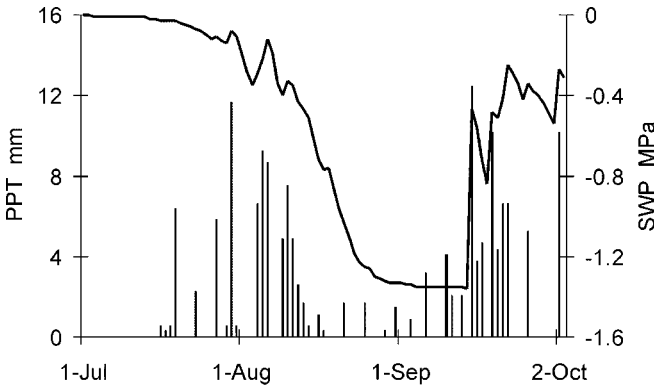

Figure 1—Daily precipitation (PPT, in millimeters [bars]) and simulated soil water potential (SWP, in megapascals [line]) for July through September for an "average" precipitation year.

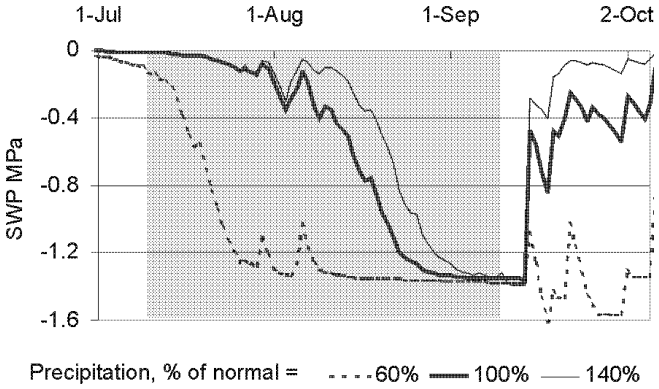

Figure 2—Soil water potentials in year 3 for the 120 ft²/acre basal area stand under three precipitation regimes. Increasing simulated precipitation delayed the onset date of moisture stress; decreasing simulated precipitation quickened the onset of moisture stress. The period over which the mountain pine beetles are known to fly in this area is shaded.

levels that are regarded as having low to high risk for beetle infestation. Again, note that the amount of time this stand is under moisture stress varies significantly for this range of stand densities.

Annual-Level Vigor

Waring and colleagues (Waring and others 1980; Larsson and others 1983; Mitchell and others 1983; Waring and Pitman 1985) performed a series of studies involving pines and mountain pine beetle susceptibility that were based on the assumption that photosynthate allocation is hierarchical. They proposed that allocation to defensive oleoresins was lower in the hierarchy than either leaf or stem growth. They produced a vigor index (Waring and others 1980) that they defined as:

$$\frac{grams/year\ of\ stemwood\ produced}{m^2\ leaf\ area\ (projected)}$$

The Waring vigor index (WVI) was based on the premise that the ratio of stem growth to leaf area was indicative of the amount of photosynthate available for oleoresin production.

As applied in field studies by Waring and others, this value used stemwood production estimated from diameter increment, and leaf area estimated from sapwood area. In FVS-BGC, stemwood growth and leaf area are available as simulation outputs, so we can estimate the WVI with the model.

A field study (Waring and Pitman 1985) related the estimated WVI of lodgepole pine trees on an Oregon site to mountain pine beetle attacks. The study showed a distinct threshold at about 100 grams of stemwood production per m^2 of leaf area. Trees below this level suffered many attacks; with a positive linear relationship between the WVI below this level and the number of attacks it took to kill the tree. Above this level, few trees were attacked, none successfully.

Figure 4 shows WVI values for individual trees from FVS-BGC simulations for two stand densities, at average precipitation levels, of our example lodgepole stand. In these simulation scenarios, trees in the less dense stand fix more net carbon per unit of leaf area than trees in denser stand. The 80 ft^2/acre represent the thinning density recommended for this area to lower mountain pine beetle hazard (Angwin and others 1996); 180 ft^2/acre for this stand structure would be considered to be at high risk. Note that most of the trees in the 80 ft^2/acre stand fall above the 100 WVI level, and all of the trees in the 180 ft^2/acre stand are below it.

The six levels of stand densities and the seven levels of precipitation were simulated for all 42 combinations, and the stand level WVIs calculated. Figure 5 shows the results of WVI values when plotted, and isopleths estimated, to

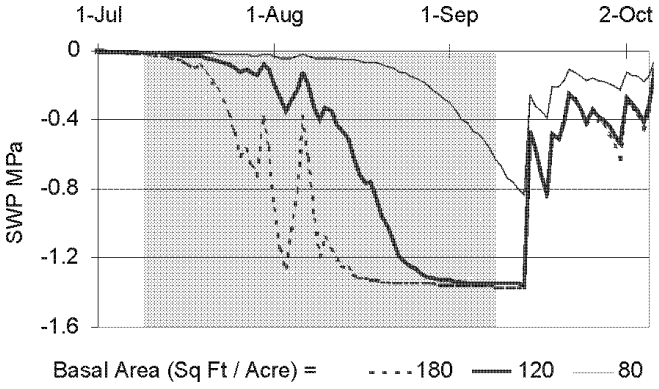

Figure 3—Soil water potentials in year 3 for stands of differing densities during an "average" precipitation year. Decreasing stand density delayed the onset of moisture stress; increasing stand density quickened the onset of moisture stress. Compare with figure 2.

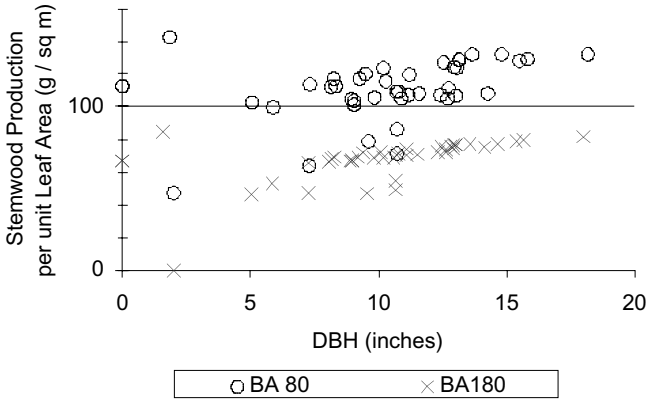

Figure 4—Simulated Waring vigor index values for individual trees from two stands with different stand basal areas (BA). These values are from year 3 of a simulation using the average precipitation for a consecutive 3 years. Note the "threshold" Waring vigor index at 100 g/m^2.

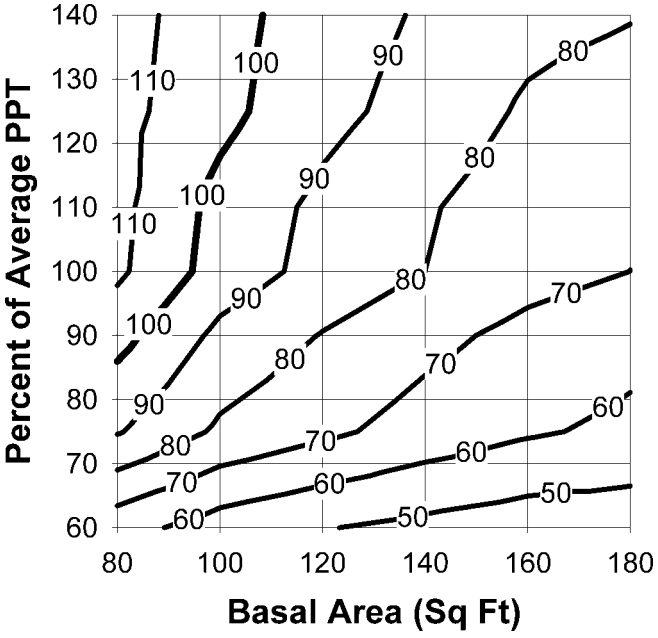

Figure 5—Waring vigor index isopleths by stand density and precipitation for a given site and stand structure. Isopleths connect lines of equal vigor and were generated using SigmaPlot®, from vigor index estimates from 42 simulations (six stand densities times seven precipitation regimes).

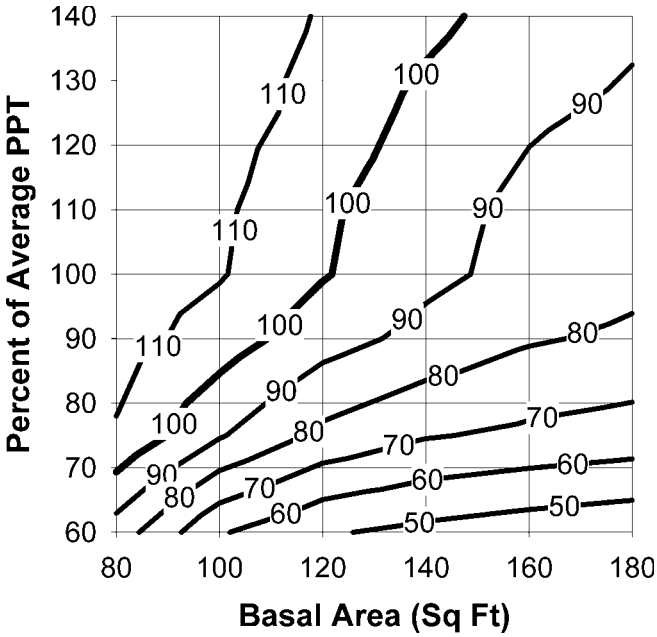

Figure 6—Vigor isopleths generated from 42 simulations that used the same stands and climate files used in the previous example, but simulated on a different site, one having deeper soil with higher total available water. Compared with figure 5, isopleths have shifted to the right and down, indicating generally higher Waring vigor indices for any given moisture/density combination.

show lines of equal vigor conditions. For this site and stand structure, the 100 g/m^2 WVI level corresponds, under average precipitation conditions, to about 92 ft^2/acre basal area. One should not consider the 100 g/m^2 WVI level as being a well-defined threshold because it is based on estimates of the independent variables and the study has not been replicated. These simulation results, however, suggest that the 100 g/m^2 value does correspond to local guidelines where stand conditions would be considered on the border of being at risk.

The soil conditions used for these simulations represent one of two major soil types found in the area from which the example stand was taken. A second soil type in the area, which is deeper and has a different texture, provides more available water to plants. As a way of simulating the effects of varying site qualities, we ran a second set of the same 42 combinations of stand densities and precipitation levels using the second soil type as FVS-BGC input. The results are displayed in figure 6. Note that for average precipitation conditions, the 100 g/m^2 WVI level corresponds to a stand density of approximately 125 ft^2/acre basal area in this better soil.

Conclusions

The physical and biological outputs from the FVS-BGC model can be compared to measurable values obtained from field studies. This creates the potential for validation studies that directly compare simulated results and measured values for the same stand conditions. The simulation results produced by these examples are consistent with the findings of other studies and with local management guidelines. If further testing confirms that the model has the ability to reliably represent stress and vigor conditions for forest stands, the model's outputs may be used to supplement base FVS information and enhance insect and pathogen models. The ability to separate the contributions of site components to both growth and vigor may allow the development of more biologically insightful hazard rating systems. Use of a BGC-based vigor rating system from within FVS also has the potential to improve current FVS insect impact extensions, especially the Mountain Pine Beetle model and the Westwide Pine Beetle model.

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Stand-Level Scaling of a Single-Tree, Distance-Independent, Diameter-Growth Model: Interim Calibration of Prognosis for the Southeastern Interior of British Columbia

Abdel Azim Zumrawi
Albert R. Stage
Barry Snowdon

Abstract—The main feature of the 1998 release of Prognosis^{BC} is an interim calibration of its large-tree diameter-growth model. The calibration is based on the development of multiplier functions that predict the ratio between growth rates inherent in the northern Idaho variant of the Prognosis Model (now called the Forest Vegetation Simulator in the United States) and those rates observed in long-term permanent sample plots (PSP) in the Nelson, Kamloops and Cariboo forest regions of British Columbia, Canada. The self-calibration feature of the Prognosis Model was used to generate the calibration statistics. These statistics were then modelled as a function of variables whose effects were hypothesized to change as the model range is expanded northward. This paper discusses the methodology and presents the results of this stand-level calibration of an individual-tree, diameter-growth model.

The Forest Vegetation Simulator (FVS) (Stage 1973; Wykoff and others 1982) — FVS is a new name for the Prognosis Model — is a single-tree, distance-independent model of forest-stand dynamics. The model also provides linkage to other submodels of various components of the ecosystem such as root disease and understory development. The architecture of the model is such that the model is applicable to a wide range of timber types and stand conditions. During execution of the model, growth measured in the current inventory can be used to scale its projections, providing a smooth link between past experience and the future projections. This feature also provides a convenient means to extend the range of model applicability.

The British Columbia (B.C.) Ministry of Forests in Canada is currently adapting the northern Idaho (NI) variant of FVS to the Southeastern Interior of British Columbia. This variant of the model was selected as a basis because of its geographic proximity and its use of classes of potential vegetation or habitat types (Daubenmire and Daubenmire 1968) as part of its index of productivity.

An initial approach to extending the model northward was to map the B.C. Biogeoclimatic Ecosystem Classification (BEC) classes (Meidinger and Pojar 1991) onto the Daubenmire habitat types represented in the northern Idaho variant (McKenzie 1991; Sargent and McKenzie 1997).

BEC units represent groups of ecosystems under the influence of the same regional climate. Zones are divided into subzones (actually the subzones are the basic units and aggregate to zones). The notation used is ZONEab, where ZONE is abbreviation of the zone (ICH, IDF...and so forth) and "a" and "b" are two letters that define the subzone based on precipitation and temperature, respectively. The codes for "a" could be x (very dry), d (dry), m (moist), w (wet), or v (very wet). The codes for "b" could be h (hot), w (warm), m(mild), k (cool), c (cold), and v (very cold). A subzone may further be divided into variants (a geographic location identifier) indicated by a number that follows the zone and subzone, for example, ICHmw2 (the Schuswap moist warm Interior Cedar-Hemlock variant). A subzone or variant is divided into Site Series (01, 02…and so forth). Site Series group ecosystems within a subzone or variant by environmental properties (soil moisture and nutrient regimes) and potential climax vegetation. The 01 is the zonal (typical) series of the variant. Site Series with numbers less than 4 (for example, 02 and 03) are (generally) drier and poorer. Site Series with numbers greater than or equal to 4 (04, 05,06…and so forth) generally occur on wetter, richer sites. However, the soil moisture or nutrient regime of a given series relative to the zonal (01) may vary from variant to variant.

The prevailing BEC zones in Southeastern B.C. that were included in this study are the Engelmann Spruce-Subalpine Fir (ESSF), the Interior Cedar Hemlock (ICH), the Interior Douglas-fir (IDF), the Montane Spruce (MS), and the Ponderosa Pine (PP). This approach of mapping the BEC units to habitat types permitted B.C. analysts to evaluate the potential usefulness of the Prognosis architecture in their decisionmaking context.

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The longer term objective is to have a variant of Prognosis for Interior British Columbia that is based entirely on local data. However, that objective may require more specific data than are presently available. In the interim, useful projections seem possible with a model that uses our limited B.C. data to adjust for the major ecological differences between northern Idaho and Southeastern B.C. This adaptation consists of a series of steps, ordered by the sensitivity of the model to our ecological differences. Each step provides an interim model with improved representation of B.C. forests:

1. Convert the NI variant from Imperial units to metric units of measure including the B.C. static tree-volume equations (Robinson 1997).
2. Modify the large-tree diameter-increment component to recognize BEC classes, and determine appropriate scaling factors using diameter-increment data from B.C. permanent sample plots (PSP's). The methods used in this step are the primary feature of this report and are the basis for the 1998 release of Prognosis^{BC}.
3. Modify the individual-tree mortality model to agree with B.C. PSP data.
4. Modify the large-tree height-increment model to use the BEC classes in place of NI habitat types.
5. Construct a height-increment submodel for small trees (less than 12.5cm.).
6. Construct a submodel for regeneration.

Steps 3, 4, 5, and 6 are in process and are expected to form the basis for a future release of Prognosis^{BC} in early 2002. Calibration of the diameter-increment submodel was the first step in modifying the dynamic (growth and mortality) aspects of the northern Idaho variant. This paper presents the interim calibration of the diameter-increment submodel for the Southern Interior of British Columbia.

Background

In the northern Idaho (NI) variant of the Forest Vegetation Simulator (FVS), the overall model behavior is sensitive to the diameter-growth component for trees larger than 12.5 cm. This sensitivity is a consequence of the model's use of diameter at breast height (d.b.h.) and diameter increment in the prediction of changes in other tree attributes (height growth, mortality, and crown length). The NI variant of Prognosis is thus predominantly a diameter-driven growth-and-yield model as opposed to height-driven models that use a potential height-growth based on site index. Therefore, we started the calibration of FVS to the Southern Interior of British Columbia with the diameter-increment model. The diameter-increment model predicts 10-year diameter increment in trees greater than 12.5 cm in d.b.h. The model uses tree and stand attributes, site and location variables to predict the change in inside-bark d.b.h. The model modifies this prediction for trees less than 25 cm to provide a smooth transition between the large-tree estimates and the diameter-increment estimates derived from height increment for trees less than 12.5 cm.

The form of the diameter-increment model (Wykoff 1986) is as follows:

$$Ln(DDS) = HAB + LOC + b_1*SL*\cos(ASP) + b_2*SL*\sin(ASP) + b_3*SL + b_4*SL^2 + b_5*EL + b_6*EL^2 + b_7*\ln(DBH) + b_8*CR + b_9*CR^2 + b_{10}*(BAL/100) + b_{11}*BAL/(DBH+1) + b_{12}*DBH^2 + b_{13}*(CCF/100) \quad \text{(Eq. 1)}$$

Where:

Ln(DDS) = Natural log of 10-year change in squared inside-bark diameter
HAB = Constant term that is dependent on habitat type
LOC = Constant term that is dependent on location
SL = Stand slope ratio
ASP = Stand aspect (degrees)
EL = Stand elevation (hundreds of feet)
CCF = Stand crown competition factor
CR = ratio of crown length to total tree height
DBH = diameter at breast height
BAL = Stand basal area in trees larger than the subject tree
b_1,.., b_{13} = Species-specific regression coefficients

The regression coefficients in the NI variant of FVS, at the time the model was adopted for calibration in B.C., were given in Wykoff (1986).

Data

Permanent sample plots (PSP) have been established throughout the operable land base in B.C. (B.C. Forest Productivity Council Minimum Standards Manual 1995). The PSPs used in the calibration were selected from the Nelson, Kamloops, and the Cariboo forest regions based on the following criteria:

- The PSP has been measured at least twice.
- The plot has been ecologically classified to the site series using the Biogeoclimatic Ecological Classification system.
- The plot Biogeoclimatic Ecological Classification at the site-series level has been mapped to a corresponding northern Idaho habitat type.
- Measurement periods were excluded if the plots were disturbed or partially cut between any successive measurements.
- Only measurement periods of 9, 10, or 11 years were selected. This was intended to minimize the effects of interpolating to a 10-year growth cycle.

Repeated measurements on the selected plots were used to provide the initial tree and stand conditions and a 10-year diameter increment. The distribution of PSP data used in the interim calibration by forest region is given in tables 1 and 2.

In addition to the tree-list data, a keyword list was also prepared for each sample plot. The tree list and keyword list were used to project the stand between successive measurements. For the purpose of these calibration projections, the plot elevation, slope and aspect were set to the average conditions in the northern Idaho data used to develop the variant. This substitution results in a reduced model where the aspect, slope and elevation terms become part of the model constant terms (equation 1).

The plot site series from the British Columbia Biogeoclimatic Ecological Classification (BEC) were mapped to nearest corresponding NI habitat type. The mapping of the BEC site series in the Nelson and Kamloops forest

Table 1—PSP distribution by BEC site series, number of plots and average number of trees in the plot in the Kamloops and Cariboo forest region.

	Site series				
Subzone/variant	**03**	**04**	**01**	**05**	**06**
ICHmk1	7 (65)	4 (42)			
ICHmw2	n/m	1 (14)	47 (43)	2 (21)	
ICHmw3	No Data	n/m	24 (40)		
IDFdk1	n/m	17 (53)	18 (53)		
IDFdk2	20 (50)	n/m	37 (66)		
IDFdk3	n/m	6 (54)	32 (53)	n/m	11 (49)
IDFdm1	n/m	2 (55)	1 (24)		
IDFmw1	n/m	3 (62)			
IDFxh1	n/m	2 (53)	8 (63)		
IDFxh2	n/m	n/m	n/m	4 (74)	2 (78)
MSdm1	n/f	5 (27)			
PPxh2	3 (27)				

n/m = Site series not mapped to a corresponding habitat type.
n/f = Site series not forested

Table 2—PSP distribution by BEC site series, number of plots and average number of trees in the plot in the Nelson forest region.

	Site series					
Subzone/variant	**02**	**03**	**04**	**01**	**05**	**07**
ESSFdk	n/m	n/m	9 (48)	11 (29)		
ESSFwc4	4 (49)	3 (78)	n/m	n/m		
ESSFwm	No Data	3 (38)	1 (29)	9 (29)		
ICHdw	n/m	n/m	No Data	45 (44)		
ICHmk1	n/m	30 (57)	15 (55)	25 (71)	2 (65)	
ICHmw1	n/m	n/m	n/m	1 (110)		
ICHmw2	n/f	82 (61)	69 (41)	22 (36)	2 (45)	
ICHmw3	n/m	2 (43)	6 (26)	6 (25)	8 (30)	1 (26)
ICHwk1	n/f	n/m	1 (31)	No Data		
IDFdm1	n/f	n/m	12 (32)	25 (30)		
IDFdm2	n/f	n/m	13 (48)	43 (62)		
MSdk	n/f	5 (51)	49 (83)	15 (43)		
MSdm1	No Data	No Data	2 (23)	No Data		
PPdh2	n/f	n/m	n/m	5 (59)		

n/m = Site series not mapped to a corresponding habitat type.
n/f = Site series not forested.

regions of B.C. to the corresponding northern Idaho habitat types is given in tables 3 and 4. The tables show the habitat-type codes used in FVS. For more details on the habitat types represented by these codes, see Wykoff and others (1982).

Calibration Statistics

Wykoff and others (1982) gave a brief description of the FVS model selfcalibration process. The calibration process scales growth predictions of each species to match the input growth data from the PSP repeated measures. Calibration statistics represent the magnitude of the scaling factor needed such that the plot totals of the model-based growth estimates will equal the totals as measured on the plot. The adjustment includes an empirical-Bayes-based averaging of the estimates from the a priori, imbedded-increment model and the a posteriori stand sample of increments. The version of FVS used in this study reports the unadjusted values of the calibration statistics. Newer versions of FVS now report the modified calibration statistics.

The diameter-increment scale factors are expressed as a multiplier to the change in squared diameter and are in effect multipliers of the tree-basal-area increment. The calibration statistics were computed for each projected-growth-measurement period.

Table 3—Mapping of the BEC site series to habitat types in the Nelson forest region.

	Site series					
Subzone/variant	**03**	**04**	**01**	**05**	**05**	**07**
			FVS Habitat Type Codes			
PPdh1			PIPO/AGSP			
PPdh2			PIPO/AGSP			
IDFdm1		PSME/CARU	PSME/VACA	ABLA/VACA		
IDFdm2			PSME/VACA			
IDFxh1		PSME/CARU	PSME/CARU			PSME/SYAL
ICHdw		THPL/OPHO	TSHE/CLUN			
ICHmw2		TSHE/CLUN	TSHE/CLUN	THPL/OPHO	THPL/OPHO	
ICHmw3	PSME/VACA		TSHE/CLUN			THPL/OPHO
ICHmk1	PSME/VACA	ABLA/VACA				
ICHwk1				THPL/OPHO		
ICHvk1			THPL/OPHO			
MSdm1		PSME/VACA				
ESSFdc1	ABLA/VASC					

Table 4—Mapping of the BEC site series to habitat types in the Kamloops forest region.

	Site series					
Subzone/variant	**03**	**04**	**01**	**05**	**05**	**07**
			FVS Habitat Type Codes			
PPxh1		PIPO/AGSP	PIPO/AGSP		PSME/SYAL	PSME/SYAL
PPxh2	PIPO/AGSP					
IDFxh1		PSME/CARU	PSME/CARU			
IDFxh2				PSME/CARU	PSME/CARU	
IDFdk1		PSME/CARU	PSME/CARU			
IDFdk2	PSME/CARU		PSME/VACA			
IDFdk3			PSME/CARU			
IDFdm1		PSME/CARU	PSME/CARU	THPL/ATFI		
IDFmw1		PSME/VACA				
ICHmw2		TSHE/CLUN	TSHE/CLUN	THPL/OPHO	THPL/OPHO	
ICHmw3	PSME/VACA		TSHE/CLUN			THPL/OPHO
ICHwk1				THPL/OPHO		
ICHmk1	PSME/VACA	ABLA/VACA				
ICHvk1			THPL/OPHO			
MSdm1		PSME/VACA				
Msxk				PSME/CARU		
ESSFdc1	ABLA/VASC					

Calibration Methods

The next step models the calibration statistics obtained for each plot. Effects of stand elevation, slope, and aspect on tree growth are expected to change as the model's geographical scope is expanded northward. Setting the plot elevation, aspect, and slope to the average NI conditions during the calibration runs allowed us to examine the correlation between the model-generated calibration statistics and the actual elevation, aspect, and slope of the plot. The stand stocking, expressed as CCF, was also chosen as a potential predictor variable. The inclusion of CCF in a regression model to predict plot-level calibration statistics provides a stand-level adjustment to the species-specific CCF regression coefficients in the original NI model.

Mapping of the BEC units to corresponding NI habitat types was not a one-to-one mapping. It was a subjective process based on the ecologist's best knowledge of the vegetation characteristics of the BEC unit and the habitat type. Differences between the two systems of classification could result in more than one habitat type as a possible match to a given BEC site series (McKenzie 1991; Sargent and McKenzie 1997), so that two or more site series are mapped to the same habitat type. The inclusion of the BEC site series as a predictor variable is expected to explain that source of variation in the calibration statistics that may be due to differences between a BEC site series and the habitat type to which it had been mapped.

The regression model of plot-level FVS-generated calibration statistics as a function of stand aspect, slope, elevation, BEC site series, and CCF is:

$$Ln(Scale) = SITE + c_1*SL*\sin(ASP) + c_2*SL*\cos(ASP) + c_3*SL + c_4*EL + c_5*EL^2 + c_6*(CCF/100) \quad \text{(Eq 2)}$$

Where:

Scale = Prognosis-generated plot-level scale factor for 10-year change in squared diameter

SITE = Constant term that is dependent on the BEC site series

C_1 to C_6 are species-specific regression coefficients.

All other variables appear in equation (1) and are defined there.

The natural-log transformation of the dependent variable was selected to have a model that is consistent with the original NI model (equation 1). The growth multiplier becomes an additive term on the log scale. In this formulation, the CCF coefficient C_6 in equation (2) becomes a stand level adjustment to the original CCF term (b_{13}) of equation (1). The aspect, slope and elevation terms with coefficients C_1 to C_5 in equation (2) are in effect adjustments to the constant term that resulted from the use of the average NI aspect, slope, and elevation conditions in the model runs that generated the scale factors. The model in equation (2) was fit to each of 10 coniferous species included in the original model. Of the 11 species covered in the NI version, only mountain hemlock was not included in the analysis due to lack of PSP data. A list of the tree species included in the analysis is given in table 5.

Results and Discussion

The fit statistics for equation (2) are shown in table 6. The adjusted R^2 values ranged from 0.10 for hemlock and western white pine to 0.56 for subalpine fir. Note that low R^2 values indicate species for which the NI model required little change. Standard errors of the estimate ranged from 0.29 to 0.46 on the log scale. For Douglas-fir, for example, the standard error on the log scale is 0.36, which results in a lower and upper one-standard deviation of 0.70 and 1.43, respectively, or 30 and 43 percent error.

Table 5—Tree species included in the large-tree diameter-growth model calibration.

Common name	Code	Scientific name
Western white pine	Pw	*Pinus monticola*
Western larch	Lw	*Larix occidentalis*
Douglas-fir	Fd	*Pseudotsuga menziesii*
Western hemlock	Hw	*Tsuga heterophylla*
Western redcedar	Cw	*Thuja plicata*
Lodgepole pine	Pl	*Pinus contorta*
Engelmann spruce	Se	*Picea engelmannii*
Grand fir	Bg	*Abies grandis*
Subalpine fir	Bl	*Abies lasiocarpa*
Ponderosa pine	Pp	*Pinus ponderosa*

Table 6—Fit statistics for equation (2).

Species	No. of plots (N)	Adjusted R^2	Standard error of estimate
Douglas-fir	1130	0.20	0.3562
Lodgepole pine	779	0.26	0.2995
Western larch	592	0.20	0.4614
Western redcedar	541	0.14	0.4033
Western hemlock	368	0.10	0.3509
Western white pine	209	0.10	0.3616
Engelmann spruce	167	0.20	0.4033
Subalpine fir/Grand fir	73	0.56	0.3779
Ponderosa pine	58	0.38	0.4441

Least squares estimates of the regression coefficients of equation (2) are presented in tables 7 and 8. The negative significant CCF coefficients (C_6) for Douglas-fir and lodgepole pine indicate that the two species are more negatively affected by stand density in Southeastern B.C. than in the northern Idaho variant of Prognosis. The positive effect of elevation on growth is offset by a significant EL^2 term for the species that occur in a wide range of elevation, indicating that an optimum elevation does exist for these species. The magnitude of the EL^2 coefficient is higher for the two species that occur mostly in the higher elevations of the Englemann Spruce Subalpine Fir (ESSF) zone, namely spruce and subalpine fir. For all other species, C_5 of equation (2) is not significantly different from zero.

Constant terms for site series are given in table 7. These coefficients represent site differences as well as an adjustment for any possible mapping mismatch between the site series and the NI habitat type deemed most appropriate. Because of this confounding effect, the coefficients for a given species cannot be interpreted to indicate site differences between the different site series for that species. We could add the intercept given for the root habitat type to the new intercept for each BEC class. However, as the intercept also includes the mean times regression coefficient for each of the other variables in the model, its interpretation as relative productivity is still clouded.

For each species, residual analysis by BEC site series showed that there were no significant biases in the predicted scale factors across the site series.

The large-tree diameter-growth model implemented in the current release of Prognosis^{BC} is a combination of equation (1), in which aspect slope and elevation were fixed to the average of these conditions in NI, and equation (2). Preliminary verifications of the model's performance (Temesgen and Lemay 1999) indicated no serious bias in the overall behavior of the model. Furthermore, and because diameter growth is an important predictor of height growth, Temesgen and LeMay (1999) found that the large-tree height model performed well in the site series where the diameter model was calibrated.

Table 7—Species-specific coefficients in the calibration function for the large-tree, diameter-increment model (equation 2).

Variable	Species	PW	LW	FD	HW	CW	PL	SE	BL/BG	PY
Overall constant		–1.20012	0.03164	–0.33768	–0.53158	0.30382	–0.57696	–1.46710	–0.65511	–2.01572
Sl.Cos(ASP)	C1			0.00083			–0.08531			–1.11471
SL.Sin(ASP)	C2								–0.74662	
SL	C3							–0.82000		
EL	C4	0.01724		0.01048	0.04685		0.01065	0.07223	0.07129	0.06151
EL^2	C5				–0.00068			–0.00090	–0.00099	
CCF	C6			–0.07463			–0.16348			

Table 8—Species-specific, BEC constant terms in the calibration function for the large-tree, diameter-increment model (equation 2). The shaded cell(s) indicate the site series or group of site series for which the constant term applies.

BEC variant	Site series 2	Constant
Western white pine		
ICH		0.97080
mw2		0.55088
mw3		0.54472
		1.57930
Western larch		
ICH		—0.24679
		—0.11546
mk1		—0.45001
IDF		0.16060
dm2		—0.53506
		—0.83091
mw1		—0.28032
MS		—0.47719
		—0.13477
Douglas-fir		
ICH		0.22398
mk1		0.15358
mw2		0.26506
		0.12485
mw3		0.52539
		0.37126
		0.16271
wk1		0.29088
IDF		0.13588
dk2		0.28110
dk3		—0.17949
		—0.73119
		—0.18901
dm1		0.31994
		0.11163
dm2		0.14139
mw1		0.35498
xh1		—0.20460
xh2		
MS		0.22099
Grand fir		
ESSF		—0.68074
wm1		0.26881
ICH		—1.32980
mk1		—0.99113
mw2		—1.08111
mw3		—0.74432
MS		—0.49646

BEC variant	Site series 2	Constant
Western hemlock		
		—0.33966
		—0.32891
		—0.38468
		—0.35852
		—0.34059
		—0.33842
Western redcedar		
		—0.67998
		—0.53091
		—0.24884
		—0.45763
mw3		—0.94850
		—0.26425
		—0.36550
		—0.74451
		—0.50328
		—0.85966
		—0.93040
Lodgepole pine		
		0.14517
		0.21038
		0.10317
		0.24878
		—0.29809
		—0.44302
		—0.53275
		—0.38840
		—0.31680
Engelmann spruce		
		0.26510
		0.72027
		0.30629
mk1		—0.21132
Subalpine fir		
		—0.68074
		0.26881
ICH		—1.32980
		—0.99113
mw2		—1.08110
mw3		—0.77432
		—0.49646
Ponderosa pine		
IDF		—0.44823
xh1		—0.41938
xh2		—0.68892

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Diameter Growth Models for Inventory Applications

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Abstract—Distant-independent, individual-tree, diameter growth models were constructed to update information for forest inventory plots measured in previous years. The models are nonlinear in the parameters and were calibrated using weighted nonlinear least squares techniques and forest inventory plot data. Analyses of residuals indicated that model predictions compare favorably to another regional diameter growth model and may be considered unbiased for their intended application. In addition, the models provide for estimation of model prediction uncertainties and may be easily recalibrated. The final model calibrations were by species within each of three ecological provinces in the North Central United States.

The U.S. Renewable Forest and Rangeland Resources Planning Act of 1978 requires that the Forest Service, an agency of the U.S. Department of Agriculture (USDA), conduct inventories of the nation's forest land to determine its extent and condition and the volume of standing timber, timber growth, and timber removals. The U.S. Agricultural Research Extension and Education Reform Act of 1998 further requires that in conducting these inventories, the Forest Service measure a proportion of the plots in each State annually. In response, the Forest Inventory and Analysis (FIA) program of the Forest Service has initiated the Enhanced FIA program that features a systematic sampling design with plots assigned to panels and individual panels selected for measurement on a rotating basis.

One objective of the FIA program at the North Central Research Station (NCRS), USDA Forest Service, has been to establish the capability of annually producing standard inventory estimates. Three approaches to calculating annual estimates using inventory data collected under the Enhanced FIA program have been proposed (McRoberts 1999). The simplest approach is to use the data from the most recently measured panel of plots. Although the resulting estimates would reflect current conditions, their low precision may be unacceptable for some variables because of the small sample size. A second approach is to use the most recent plot measurements for each panel, regardless of the date, and then employ a moving average estimator. The advantage of this approach is that precision is increased because data for all plots are used for estimation; the disadvantage is that the estimates reflect a moving average of conditions over past years and may lag current conditions in the presence of temporal trends. A third approach is to update to the current year data for plots measured in previous years and then base estimates on the data for all plots. If the updating procedure is sufficiently unbiased and precise, this approach provides nearly the same precision as using all plots but without the adverse effects of using out-of-date information.

Two models are currently available for predicting individual tree survival and growth in the North Central region of the United States: STEMS (Belcher and others 1982), and two variants of the Forest Vegetation Simulation (FVS). The FVS variant for the Lakes States (Bush and Brand 1995) and the variant for the Central States (Bush 1995) both use the TWIGS models (Miner and other 1998), which, in turn are based on the STEMS models. For over a decade, the FIA program at NCRS has used the STEMS (Belcher and others 1982) survival and diameter growth models for updating inventory plot information. A decision to construct new models was motivated by several limitations in the STEMS models:

1. Calibration data for the STEMS models were collected primarily from long-term research plots in selected locations and may not represent forest conditions across the North Central region as do FIA plots.
2. The mathematical form of the STEMS models includes a potential growth component that is difficult and cumbersome to calibrate, primarily because potential growth is unobservable.
3. The STEMS diameter growth models were calibrated using a two-step process in which a subset of the model parameters were estimated first and then held constant while the other parameters were estimated, a procedure that would be difficult to defend statistically today.
4. The STEMS calibrations did not use weighted regression, did not estimate model parameter covariances, and did not retain estimates of residual variances, thus precluding estimation of the precision of model predictions.

The discussion that follows outlines and reviews progress to date by FIA scientists at NCRS in constructing new individual tree, distant independent, diameter growth models for updating inventory plot information.

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Methods

Data

The models were calibrated using inventory data for trees with diameter-at-breast height (d.b.h.) (4.5 ft. above ground) greater than 5 inches for all ownership categories on lands capable of producing 20 ft^3/ac/yr of industrial wood (FIA timberland). For States in the North Central inventory region and some adjacent States, plot data were obtained for two consecutive periodic inventories: Illinois - 1985, 1998; Indiana - 1986, 1998; Iowa - 1974, 1990; Kansas - 1981, 1994; Kentucky -1974, 1987; Michigan - 1980, 1993; Minnesota - 1977, 1990; Missouri - 1972, 1989; Nebraska - 1983, 1994; North Dakota - 1980, 1994; Ohio - 1978, 1990; South Dakota - 1980, 1995; Tennessee - 1989, 1996; and Wisconsin - 1983, 1996. Data for a random selection of 75 percent of plots were assigned to a model calibration data set; the remaining data were assigned to a model validation data set and were excluded from use for initial model calibration.

Calibration analyses focused on the suite of plot- and tree-level variables identified in preliminary analyses reported by Holdaway (2000) and Lessard (2000a,b). Plot-level variables included latitude (LAT) and longitude (LON) of the plot center, plot basal area (BA), and physiographic class (PC). PC is a measure of site soil and water conditions that affect tree growth and is coded as follows: 3-xeric; 4-xeromesic; 5-mesic; 6-hydromesic; 7-hydric; and 8-bottomland (NCRS 1998). Tree-level variables included observed average annual d.b.h. growth, which was calculated as the ratio of the difference in d.b.h. measurements for the two inventories and the number of growing seasons between measurements and was used as a surrogate for observed annual d.b.h. growth. For the purpose of consistency in notation and model expression, DBH and ΔDBH are used to denote variables quantifying d.b.h and annual change or growth in d.b.h., respectively.

Other tree-level variables included crown ratio (CR), plot basal area in trees larger than the subject tree (BAL), and crown class (CC) at the time of the initial inventory. CC is a measure of a tree's dominance in relation to adjacent trees in the same stand and is coded as follows: 1-open grown; 2-dominant; 3-codominant; 4-intermediate; and 5-overtopped (NCRS 1998). BA and BAL are calculated as the sum of cross-sectional areas of live tree boles at breast height, are scaled to a per unit area basis, and when used to calibrate the models were calculated as the average value for the two inventories. Although current BA and BAL would be used as the value of these predictor variables when applying the models, average BA and BAL over the rather long (12 to 17 years) inventory remeasurement interval for the calibration data better reflect the growing conditions over the entire interval than do BA and BAL at the initial inventory. The values of CC and PC are categorical, but their coding is ordered with respect to their expected effects on growth, and they were treated as continuous predictor variables in the model formulation.

Although calibration data were selected from plots with no disturbance or minimal disturbance over the measurement interval, some plots had substantial mortality or harvesting before the measurement interval. Nevertheless, this disturbance is expected to have little impact on model prediction bias because predictor variables such as plot basal area partially account for disturbance and because the proportion of extensively disturbed plots was small.

Annual Forest Inventory System Models

The diameter growth models constructed for updating FIA plot information are designated the Annual Forest Inventory System (AFIS) models. Their mathematical form consists of the product of two components, an average component that predicts average ΔDBH with respect to DBH for the calibration area, and a modifier component that adjusts ΔDBH predictions in accordance with local plot and tree conditions. The average component is based on a two-parameter gamma function with a constant multiplier and uses DBH as the predictor variable. The modifier component consists of the product of exponential factors of which each expresses a multiplicative effect on growth predictions in terms of departures from the mean over the calibration area for a single predictor variable. The mathematical form of the AFIS growth models is

$$E(\Delta DBH) = Ave(DBH)Mod(X) \quad [1]$$

where E(.) denotes statistical expectation, ΔDBH is annual d.b.h. growth, and X represents the set of selected predictor variables. Further,

$$Ave(DBH) = \beta_1 \exp(\beta_2 DBH) DBH^{\beta_3} \quad [2]$$

and

$$Mod(X) = \exp[\beta_4(X_4 - \gamma_4)]\exp[\beta_5(X_5 - \gamma_5)]\ldots\exp[\beta_p(X_p - \gamma_p)]$$

$$= \exp\left[\sum_{j=4}^{p} \beta_j \left(x_j - \gamma_j\right)\right] \quad [3]$$

where the Xs are predictor variables, the γs are constants representing mean values for the associated predictor variables over the calibration area, the βs are parameters to be estimated, and p is the number of model parameters. After substituting [2] and [3] into [1], mathematically expanding the resulting expression, and combining constants where possible, the AFIS growth model form may be expressed as,

$$E(\Delta DBH) = \beta_1 \exp(\beta_2 DBH) DBH^{\beta_3} \exp\left(\sum_{j=4}^{p} \beta_j X_j\right) \quad [4]$$

where the βs are still parameters to be estimated, although not the same parameters as for [3]. The mathematical form of the d.b.h. growth models is generally similar to the forms used by STEMS and by Wykoff (1990) for modeling basal area increment in northern Idaho.

Analyses

Three sets of analyses were performed to evaluate the AFIS models: (1) the AFIS and STEMS model predictions were compared; (2) the AFIS models were calibrated by species for three ecological provinces in the North Central United States, and an analysis of the residuals was conducted; and (3) the utility of the AFIS models for updating FIA plot information was evaluated.

AFIS/STEMS Comparisons—The objectives of the first set of analyses were to compare both the forms and calibrations

of the STEMS and AFIS models using their predictions for trees on a subset of a plots in northeastern Minnesota (Holdaway 2000, Lessard 2000a,b, McRoberts 2000).

These analyses were conducted early in the model construction process and used the mathematical form of the models as expressed in [1], [2], and [3]. Variables were selected for inclusion in the model using the criterion, C, proposed by Linhart and Zucchini (1986),

$$C=SS_e + 2p*MS_e, \quad [5]$$

where p is the number of model parameters, and SS_e and MS_e are the sum of squared residuals and mean square residual, respectively. This criterion simultaneously accounts for unexplained residual variability and the number of model parameters. Models with lower values of C are judged to provide better fits to data. The final set of predictor variables considered for inclusion in the models was restricted to DBH, CR, BAL, BA, CC, PC, LAT, and LON. If the estimate of a parameter corresponding to a variable included zero in its asymptotic 95 percent confidence interval, the parameter estimate was set to zero in the model, effectively excluding any effect of the predictor variable.

Heterogeneity of residual variance was accommodated by weighting each observation by the inverse of the estimated residual standard deviation, $\hat{\sigma}_{res}$, which was adequately described by,

$$E\left[\ln\left(\hat{\sigma}_{res}\right)\right] = \alpha_1 + \alpha_2 \ln\left(\Delta\hat{DBH}\right) \quad [6]$$

where E(.) denotes statistical expectation, $\Delta\hat{DBH}$ is predicted diameter growth from the models, and the αs are parameters to be estimated (McRoberts and others 2000).

To compare the form of the STEMS models to the form of the AFIS models, the STEMS models were first recalibrated using FIA data. Because of the complexity and time-consuming nature of this task, the recalibration was restricted to four commonly occurring species in northeastern Minnesota: two conifers, red pine and balsam fir, and two hardwoods, quaking aspen and paper birch. The recalibrated STEMS models were designated the STEMS-FIA models and were calibrated with data for 37,550 trees on 2,434 plots. The analyses consisted of three-way comparisons of the ΔDBH predictions on the selected plots using the existing STEMS models, the STEMS-FIA models, and the AFIS models. The comparisons were based on median residuals and correlations, r^2, between observed and predicted ΔDBH.

AFIS Model Calibrations for Ecosystem Provinces—The AFIS models were calibrated for each of the three largest ecosystem provinces defined by Bailey that occur in the North Central region: (1) Province 212, Laurentian mixed forest, characterized as a transitional zone between the boreal and broadleaf deciduous forests; (2) Province 222, Eastern broadleaf forest (continental), characterized by dominance of broadleaf deciduous species favoring drought-resistant oak-hickory associations; and (3) Province 251, Prairie parkland (temperate), characterized by intermingled prairie, groves, and strips of deciduous species (Bailey 1995) (fig. 1).

The model fitting, verification, and validation procedures were similar to those for the first analyses and as reported by Lessard and others (2001) with two exceptions: first, [4] was used as the mathematical form of the model rather than [1], [2], and [3], and second, the parameters were tested for statistical significance using an F test based on the extra sum of squares principle (Ratkowsky 1983). Validation analyses were conducted using the independent validation data sets and consisted of analyses of standardized residuals, ε, calculated as,

$$\varepsilon = \frac{\Delta DBH - \Delta\hat{DBH}}{\hat{\sigma}_{res}} \quad [7]$$

where ΔDBH is observed average annual d.b.h. growth, $\Delta\hat{DBH}$ is the corresponding model prediction, and $\hat{\sigma}_{res}$ is the estimate of residual standard deviation obtained from [6]. The standardized residuals were analyzed by evaluating their distributions by species within ecosystem provinces for the validation data sets. Following the validation analyses, the calibration and validation data were pooled to form final calibration data sets, the models were calibrated again, and the residuals were evaluated using the same procedures.

Updating—The AFIS models were evaluated with respect to bias and precision for updating data for FIA plots measured in previous years. Because this task required additional analyses to estimate the uncertainty in model parameters for each species, the evaluations were restricted to data for Province 212 plots that included only trees of the four species, red pine, jack pine, quaking aspen, and balsam fir.

An annualized 11-year database of plot and tree variables was constructed using data for the selected inventory plots. The year of first inventory measurement for each plot was designated year 0, growth for individual trees was distributed equally over the observed remeasurement intervals,

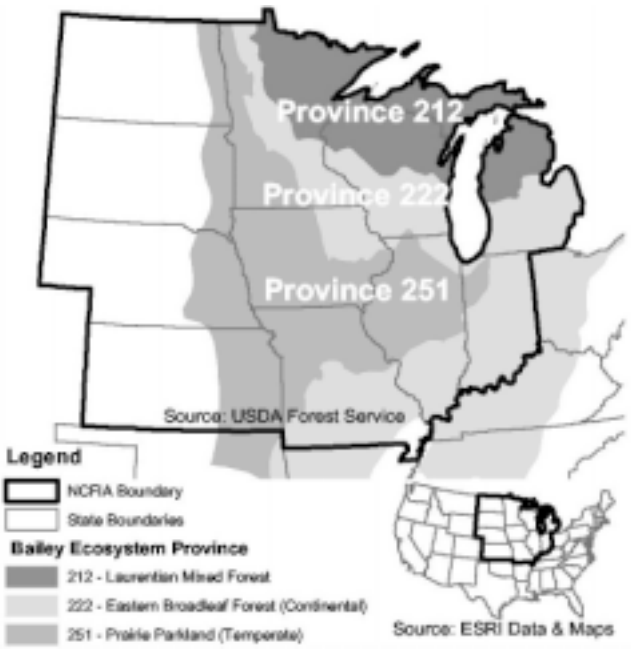

Figure 1—Ecosystem provinces for the North Central region of the United States.

and years of mortality, harvest, and in-growth for individual trees were randomly selected using a uniform distribution over the remeasurement intervals. The resulting annual database included data for 2,900 trees on 185 plots for years 0 to 10. Details regarding construction of the annualized database are documented in McRoberts (2001).

Monte Carlo simulations were used to obtain estimates of uncertainty for model parameter estimates, annual mean plot BA estimates, and annual inventory estimates of mean plot BA and the standard error of the mean. Before the simulations could be implemented, uncertainty had to be quantified for all the relevant components. Measurement error and sampling variability in predictor variables were ignored and assumed to be negligible. Estimates of residual variability were obtained from [6] as by-products of calibrating the models.

Model parameter covariances reflect uncertainty in the parameter estimates and must be included as a component of total uncertainty whenever the precision of model predictions is to be estimated. When the models are relatively simple (for example, linear), parameter covariance estimates may be easily calculated using analytical methods. However, when the models are complex and nonlinear, then Monte Carlo simulations are appropriate for reliably estimating these covariances. Distributions of model parameter estimates from which covariances may be derived were obtained using a three-step Monte Carlo procedure:

1. Simulated d.b.h. growth observations were calculated as the sums of two components: first, ΔDBH predictions obtained using the models with the original parameter estimates and observations of the predictor variables, and second, simulated residuals randomly selected from a Gaussian distribution with zero mean and standard deviations obtained from [6].

2. Model parameter estimates were obtained by fitting the models to data sets consisting of the simulated ΔDBH observations obtained from step 1 and the observed values of the predictor variables.

3. Simulated distributions of model parameter estimates were obtained via 250 repetitions of steps 1 and 2.

Estimates of the uncertainty in ΔDBH predictions and in estimates of derived BA variables were obtained using Monte Carlo simulations. The simulation approach was designed to mimic the sampling procedures of the Enhanced FIA program. The selected plots were ordered with respect to their plot numbers for each State and distributed among five equal-sized panels by systematically assigning every fifth plot to the same panel. Because FIA plot numbers had been assigned sequentially on the basis of their geographic locations, the panel assignments approximated the systematic, interpenetrating feature of the sampling design. Annual inventory estimates of mean plot BA and the standard error of the mean were calculated with three methods: (1) the SAMPLE20 estimates were based on measurements for plots in the current year's 20 percent panel; (2) the MOVING estimates were based on the most recent measurements for all plots; and (3) the UPDATE estimates were based on measurements for plots in the current year's 20 percent panel of plots and updated data obtained using the AFIS growth models for plots in the four panels measured in previous years.

Annual estimates of mean plot BA and the standard error of the mean were obtained using a four-step Monte Carlo procedure:

1. Year 0:
   a. Measurement of all plots was simulated by selecting the year 0 values of DBH, CR, CC, PC, LAT, and LON from the annualized database.
   b. Simulated values of BA and BAL were obtained from the simulated d.b.h. observations by calculating BA for each plot and BAL for each tree on each plot; mean plot BA and the standard error of the mean were calculated and recorded.
   c. A set of model parameter estimates for each species was randomly selected without replacement from the simulated distributions previously constructed.

2. Subsequent years:
   a. For panels selected for measurement, plot field measurement was simulated by replacing values for each tree with values from the annualized database for the appropriate year.
   b. For panels not selected for measurement, an updated value of DBH for each tree was calculated as the sum of previous year's DBH, predicted ΔDBH, and a simulated residual randomly selected from a Gaussian distribution with zero mean and standard deviation obtained from [6].
   c. BA was calculated for each plot, and BAL was calculated for each tree on each plot; mean plot BA and the standard error of the mean were calculated and recorded for all three methods.

3. Step 2 was repeated 10 times to obtain estimates for years 1 through 10.

4. Steps 1 through 3 were repeated 250 times to obtain distributions of mean plot BA and the standard error of the mean for each method for each year.

The standards of comparison for evaluating bias and the contribution of uncertainty in model predictions to the uncertainty in estimates of mean plot BA were the annual estimates of mean plot BA and the standard errors of the means calculated from the annualized database values. For comparison purposes, the latter estimates represent a current year sample of the entire area of interest and are regarded as being without measurement error. These estimates use 100 percent of the sample plots and are designated the SAMPLE100 estimates.

Bias and uncertainty in the annual inventory estimates of mean plot BA and standard errors of the means were evaluated using the medians of the distributions of simulated estimates. Comparisons of median estimates of mean plot BA for the SAMPLE20, MOVING, and UPDATE methods to the annual SAMPLE100 estimates of mean plot BA provide the bias check. Comparisons of the medians of distributions of estimates of the standard error of mean plot BA for the UPDATE method with the SAMPLE100 estimates reveals the effects of uncertainty in model predictions on annual inventory estimates of mean plot BA.

Results

AFIS/STEMS Comparisons

The distributions of residuals for the STEMS, STEMS-FIA, and AFIS predictions were not substantially different (table 1). Median residuals for all species were less in absolute value than 0.015 inch. Values of r^2 were also comparable for the three models, although values for the AFIS models were largest for three of four species, while values for the STEMS models were smallest for three of four species.

Ecosystem Province Models

The distributions of standardized residuals were consistently slightly skewed with longer tails in the positive direction and with slightly negative medians. These results are attributed to the combination of a lower bound, $\Delta DBH=0$, for observed average annual d.b.h. growth and the lack of an analytical (not a physiological) upper bound for average annual d.b.h. growth. In no case, however, was this skewness considered severe enough to affect the robustness of least squares techniques to slight violations of the normality assumption.

The analyses of residuals focused on median and mean residuals for the validation and final calibration data sets. Standards of 0.20 inch for absolute values of medians and 0.05 inch for absolute values of means were arbitrarily selected. The analyses sought to identify any species group with residual statistics that consistently failed to satisfy these standards for reasons that could not be attributed to small sample sizes or skewness in the distributions as previously discussed. For Province 212, absolute values of mean residuals were less than 0.05 inch for 17 of 25 species groups for the validation analyses and for all 25 species groups for the final calibration analyses. Only yellow birch exhibited any consistent failures, although the mean residual for the final calibration data set was less than 0.01 inch For Province 222, absolute values of mean residuals were less than 0.05 inch for the validation data sets for only 10 of 26 species groups, a result attributed primarily to small validation sample sizes. For the final calibration data sets, absolute values of mean residuals were less than 0.01 inch for all species groups. For Province 251, absolute values of mean residuals were less than 0.05 inch for five of nine species groups for the validation data sets. These results are partially attributed to overall small sample sizes and the necessity of pooling data over larger geographic areas. Absolute values of mean residuals were less than 0.01 inch for all species groups for the final calibration data sets. Parameter estimates by species within ecosystem provinces are reported by McRoberts and others (submitted).

Updating

The 250 simulations were deemed adequate based on the observation that coefficients of variation for estimates had stabilized by 100 to 150 simulations and were virtually unchanged for the final 50 simulations. Bias in the annual inventory estimates of mean plot BA was evaluated by comparing the medians of the distributions of the SAMPLE20, MOVING, and UPDATE estimates to the SAMPLE100 estimates (fig. 2). The medians of the SAMPLE20 estimates deviated considerably from the SAMPLE100 estimates due to the SAMPLE20 small sample size, while the medians of the MOVING estimates exhibited consistent bias due to the trend in the SAMPLE100 estimates. The medians of the distributions of the UPDATE estimates tracked the SAMPLE100 estimates quite closely, a result confirmed by the failure of the Wilcoxon Signed Ranks test to detect

Table 1—STEMS versus AFIS comparisons for validation data sets.

Species	Model	No. trees*	Median residual	r^2
Red pine	STEMS	501	0.004	0.480
	STEMS-FIA	496	–0.002	0.462
	AFIS	496	0.005	0.469
Balsam fir	STEMS	1,924	–0.012	0.201
	STEMS-FIA	1,922	–0.012	0.324
	AFIS	1,922	–0.010	0.363
Quaking aspen	STEMS	5,348	–0.005	0.133
	STEMS-FIA	5,345	–0.001	0.197
	AFIS	5,345	–0.009	0.228
Paper birch	STEMS	1,708	–0.005	0.066
	STEMS-FIA	1,704	–0.006	0.123
	AFIS	1,704	–0.005	0.144

*The number of trees represents only the 25 percent of the data randomly selected for the validation data sets; slight differences in number of trees by model for a particular species reflects analyses of residuals conducted at different times.

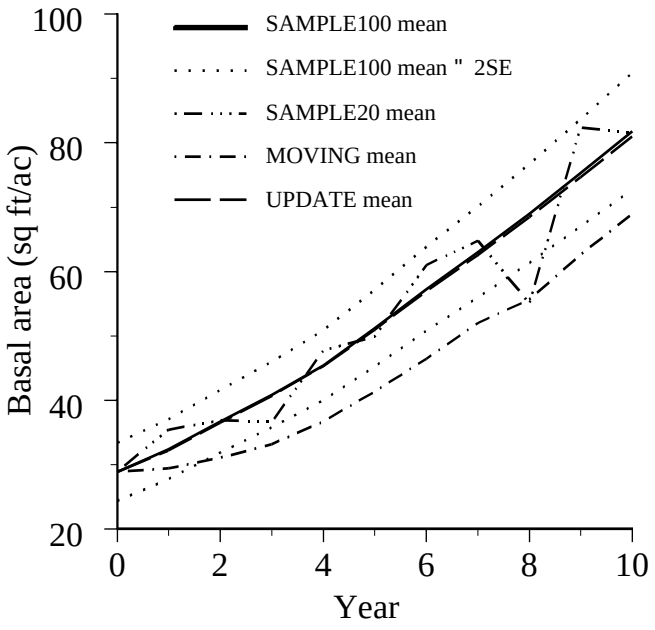

Figure 2—Annual inventory estimates of mean plot basal area.

statistically significant differences (α=0.05). The medians of the distributions of the UPDATE estimates of the standard errors of the means were only slightly larger than the SAMPLE100 estimates, indicating that uncertainty in model predictions of d.b.h. growth has only a slight negative impact on the uncertainty of annual inventory estimates of mean plot BA. This result is attributed primarily to the observation that variability among plots is much greater than model prediction uncertainty.

Summary

The AFIS models were constructed to update information for FIA plots measured in previous years. Predictions using the AFIS and STEMS models were comparable, but the AFIS models remedy the noted limitations in the STEMS models. Based on the general observation that average annual d.b.h. growth for the North Central region is approximately 0.1 inch and that time intervals between inventories for the calibration and validation data ranged between 12 and 17 years, the small mean and median residuals obtained with the AFIS models indicate that they may be regarded as unbiased for updating d.b.h. for trees measured in previous years. In addition, annual inventory estimates of mean plot BA obtained using the AFIS models to update information for plots measured in previous years were superior to estimates using only the current year's panel of data and estimates using a five-panel moving average. Finally, the AFIS models may be easily recalibrated as new data becomes available or as regional growth conditions change due to climatic changes, management practices, or forest succession.

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Assessing Sampling Uncertainty in FVS Projections Using a Bootstrap Resampling Method

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S. Hummel

Abstract—The Forest Vegetation Simulator (FVS) lets users project changes in forest stands associated with different initial conditions and silvicultural treatments. Our objective is to develop tools that help model users estimate the precision of FVS projections. A technique called bootstrap resampling (bootstrapping) allows us to approximate the sampling distribution of any variable simulated by FVS. To use the technique, the original FVS tree list is sampled repeatedly, with replacement, to build hundreds of bootstrapped tree lists. These bootstrapped tree lists are then used to make several hundred FVS projections. Each projection is thus based on a resample of the original tree list. The resulting empirical distribution provides information on the sampling uncertainty associated with the original tree list, which is important for making statistical inferences about FVS model outcome. This paper introduces a new bootstrapping program (FVSBoot) and describes its purpose and potential value.

"…The oldest and simplest device for misleading folks is the barefaced lie. A method that is nearly as effective and far more subtle is to report a sample estimate without any indication of its reliability…" (Freese 1967)

The Forest Vegetation Simulator (FVS) (previously known as the Prognosis Model for Stand Development; Wykoff and others 1982), lets model users project forest stand development through time. To use the FVS model information about the initial condition of a stand must first be formatted into a tree list. A tree list typically is created from a sample of forest conditions (stand exam or forest inventory) and is the basis for projecting the development of vegetation in FVS. Hence, at least two potential sources of uncertainty exist in FVS projections and should concern anyone who uses either the model or its results. The sources of uncertainty are (1) variation in the parameters and model forms that build the simulation and 2) variation in the sample data used to create tree lists.

The FVS model is generally considered deterministic rather than stochastic (Hamilton 1991). It is important to remember that a single realization from a single FVS projection is only one of several possible outcomes for the simulated development of that tree list. To explore "stochastic" (or "random") variation, the FVS user should make several projections (also referred to as "runs" or "simulations"), each of which has the same simulation file tree list but a new random number seed. Model outcomes generated this way can be summarized and analyzed; descriptive statistics include the computation of upper and lower bounds on 95 percent (α=0.05) of the FVS outcomes. We define the interval between these bounds as the FVS prediction interval (FVSPI). FVS users have been able to compute FVSPI to characterize uncertainty associated with variation in parameters and models forms for several years.

The Issue

Results from FVS projections are, in our opinion, too often reported without disclosing distributions of predicted outcomes or associated statistics. At issue is the ability to interpret the precision of FVS simulations.

FVSPI is already available to users via the RANNSEED keyword (Van Dyck 2000). There are several reasons why FVSPI is not often reported, many of which relate to computational intensity. One obvious reason is simply the cost of making a large number of projections. This was especially true prior to the 1990s when FVS users had to pay by the run on time-share systems. Another reason is the time associated with making large numbers of projections on old computers. However, the improved power in desktop systems has made fast and cheap computing possible, and thus these reasons are no longer insurmountable. Users can now easily report FVSPI and simple summary statistics such as the mean and standard deviation.

A different matter altogether is the challenge of reporting distributions that include sampling uncertainty in FVS projections. It hasn't been possible to compute the effects of sampling uncertainty because classical statistical methods are not available to make inferences about FVS projections. A variance estimator is not available for the results of simulation. Our objective is to develop tools that characterize sampling uncertainty in FVS projections so that users can easily report this important component of variation.

Bootstrapping

Technological advances helped to resolve the problems of time and money in making multiple FVS projections, and we felt technology could also help us to tackle the problem of assessing sampling uncertainty in FVS projections. Indeed,

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a technique called bootstrap sampling ("bootstrapping") allows us to empirically approximate the sampling distribution of any statistic for which we want to make inferences and thus avoid the lack of a variance estimator. In essence, bootstrapping is data-based simulation. The statistical theory underlying bootstrap sampling dates to the 1930s but the computer capacity necessary to apply it to problems such as ours has only recently become widely available. Bootstrapping allows us to substitute computational power for theoretical analysis (Efron 1982).

Starting in the 1970s, Efron introduced bootstrapping as a generalized, computer-based method for estimating standard error for any parameter estimate of interest (Efron 1979 and 1982; Efron and Tibshirani 1993). Since then, a flood of statistical research and reports on practical applications using bootstrapping has been published. The bootstrap method has gained popularity among scientists working with complex problems where estimating standard error and confidence intervals is difficult, inaccurate, or impossible using classical statistical methods. Because of the generalized nature of bootstrapping, it has been applied to a wide range of statistical applications for estimating error rates (Chernick 1999). These include discriminate analysis, multiple, logistic, and nonlinear regression analysis, and complex surveys. It has also been applied in a variety of disciplines, including psychology, all the major physical sciences, economics, medicine, and engineering. Our goal was to apply bootstrapping techniques to FVS simulations. We set three specific tasks:

1. Develop a method using bootstrap sampling techniques for assessing uncertainty in FVS projections caused by variation in input (tree list) data.

2. Create a module compatible with Suppose (Crookston 1997) and FVS to implement the method.

3. Illustrate the method using tree lists from the Gotchen Late Successional Reserve study on the Gifford Pinchot National Forest in Washington State.

Methods and Results

For the first task, we take our original sample of the stand (n) and replace the unknown population characteristics with the known empirical distribution derived from repeatedly resampling $\boldsymbol{n}$ (Chernick 1999). Because n comprises multiple plots (that FVS pools to create a tree list), by resampling with replacement we "reshuffle" the combination of plots that create the FVS tree list for that stand. There are just two steps required:

- Generate a new sample of stand conditions by sampling the original plots with replacement to create a bootstrap sample, also of size n.
- Compute a bootstrap mean (Θ^*) from the bootstrap sample for any FVS attribute.

By repeating this process k times, we generate a Monte Carlo approximation of the distribution of Θ^*. The standard deviation of this Monte Carlo approximation is the bootstrap estimate of the true standard deviation for the population.

For the second task, we wrote a program (FVSBoot) to implement the process described above within FVS and Suppose. Output from the bootstrap program includes intervals around a set of FVS predictions. One interval available as FVSBoot output is based on variation from the parameters and model forms of FVS (FVSPI). For example, we made 201 FVS projections of stand 1022144 (using the original tree list and random number seed plus an additional 200 projections seeding new random numbers). Figure 1

```
Stand ID      = 1022144
    Management ID = NONE

    Model output data from FVS SUMMARY Table = Cycle( 3), BA


    FVS-PI mean               =      129.56

    Number of FVS runs        =         200
    Standard Deviation        =        1.30
    Median                    =      130.00
    Max                       =      133.00
    Min                       =      126.00
    Range                     =        7.00


 Frequency distribution for (  201 ) samples for "Cycle( 3), BA" from FVS.

 Interval  Midpoints   Counts
 --------  ---------  ---+------------------------------------------------------------
     1      126.50    12 |IIIIIIIIIIII
     2      127.50    25 |IIIIIIIIIIIIIIIIIIIIIIIII
     3      128.50    64 |IIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIII
     4      129.50    51 |IIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIII
     5      130.50    37 |IIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIII
     6      131.50    10 |IIIIIIIIII
     7      132.50     2 |II
 --------  ---------  ---+------------------------------------------------------------
```

Figure 1—FVSBoot output of basal area (BA) for stand 1022144 at year 30 based on the same initial tree list projected 200 times with a new random number each time.

illustrates how the FVSBoot program displays FVSPI output for square feet of basal area per acre (BA) after the third cycle (Cycle (3)) for stand 1022144. It shows that the FVSPI mean for BA is 129.56, and the standard deviation is 1.30. The frequency distribution reveals that the midpoint value in 64 of 201 counts was 128.50. Another interval available from FVSBoot is based on variation in the sample data used to create tree lists. We refer to it as the sampling error prediction interval (SEPI). For comparison with FVSPI, figure 2 illustrates how the FVSBoot program displays SEPI

```
Data from FVS Model:  SUMMARY STATISTICS.

   Stand ID      = 1022144
   Management ID = NONE

 FVS Variable           =  Cycle( 3), BA

  FVS-PI
    Mean                =      129.56
    Number of samples   =         201
    Standard Deviation  =       1.295

  SEPI:
    Number of samples   =         500
    Mean                =      131.87
    Standard Deviation  =       14.00
    Bootstrap Median    =      132.00
    Max outcome         =      175.00
    Min outcome         =       93.00
    Range of outcomes   =       82.00

BOOTSTRAP SAMPLING ERROR PREDICTION INTERVALS

    Variable             Mean    Percent  Lower    Upper
 ----------------      --------   -----  -------- --------
 Cycle( 3), BA          129.56     68    118.00    146.00
                                   80    114.00    150.00
                                   90    109.00    157.00
                                   95    105.00    162.00
                                   99     99.00    173.00
 ------------------------------------------------------------

 Frequency distribution for (  500 ) bootstrap samples for "Cycle( 3), BA" from FVS.

 Interval  Midpoints   Counts
 --------  ---------  ---+------------------------------------------------------------
     1       95.05     2 |II
     2       99.15     3 |III
     3      103.25     9 |IIIIIIIII
     4      107.35    13 |IIIIIIIIIIII
     5      111.45    20 |IIIIIIIIIIIIIIIIIII
     6      115.55    31 |IIIIIIIIIIIIIIIIIIIIIIIIIIII
     7      119.65    44 |IIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIII
     8      123.75    40 |IIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIII
     9      127.85    50 |IIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIII
    10      131.95    83 |IIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIII
    11      136.05    54 |IIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIII
    12      140.15    43 |IIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIII
    13      144.25    31 |IIIIIIIIIIIIIIIIIIIIIIIIIII
    14      148.35    31 |IIIIIIIIIIIIIIIIIIIIIIIIIII
    15      152.45    17 |IIIIIIIIIIIIIIIII
    16      156.55     9 |IIIIIIIII
    17      160.65    12 |IIIIIIIIIII
    18      164.75     4 |IIII
    19      168.85     2 |II
    20      172.95     2 |II
 --------  ---------  ---+------------------------------------------------------------
```

Figure 2—FVSBoot output of the mean basal area for stand 1022144 at year 30 based on 500 bootstrapped tree lists projected 500 times.

output for BA after the third cycle (Cycle (3)) for stand 1022144. In this example, the SEPI mean is the mean predicted value basal area per acre (BA) from 500 FVS runs made with 500 bootstrapped samples. The SEPI mean is 131.87, and the standard deviation is 14.00. The 95 percent SEPI for BA ranges from 105-162 ft^2 per acre. Except in rare cases, the SEPI interval also includes the variation in the parameters and model forms of FVS. This is because in FVS the sequence of random numbers changes with very small changes in the tree list. Bootstrapping implies changes in the tree list sufficient to generate new random number seeds in FVS over multiple time intervals. For this reason the FVSPI is also reported with the SEPI statistics in the FVSBoot output. In figure 2, the FVSPI summary statistics are based on 201 projections, as described for figure 1.

For the third task, we pilot-tested FVSBoot using stand exam data from the Gifford Pinchot National Forest. We created 200 bootstrap samples for each tree list, ran the East Cascades variant of FVS for 50 years, and evaluated the projected values for variation in quadratic mean diameter. Details, results, and potential implications for two tree lists are reported in Hummel and others (this proceedings).

Summary

The FVSBoot program offers model users a tool that can strengthen both the analysis of potential treatment effects on stand development and the design of forest inventories.

If users rely on only one FVS projection of a tree list to characterize stand development, then other outcomes possible from different combinations of sample data or from other sequences of random events are not considered. We think it is useful to characterize "extreme" outcomes as well as "average" projected outcomes for FVS variables of interest because analyses that consider the likelihood of different outcomes are more informative than analyses that do not. The value of this additional information will depend on the real or perceived risk associated with rare events. In addition to strengthening FVS analysis for management planning, FVSBoot creates the possibility for computer-based experiments. By generating intervals around FVS output, it is possible to determine whether differences among treatments on projected stand development are statistically significant. Further, it provides a way to investigate assumptions about the distribution of populations and patterns of variation through time.

Another promising area for using FVSBoot is in the evaluation of sample design. We could, for example, characterize the standard deviation from presampling and then calculate the desired number of samples for a given level of acceptable error. We could also ask whether within-stratum variation is greater or less than that among strata to test the value of different stratification methods.

FVSBoot does not cover all potential sources of variation (climate change, for example), nor does it answer whether statistically significant differences are, in fact, biologically significant. Despite these shortcomings, we offer FVSBoot as a new tool that can provide information about important components of uncertainty in FVS model projections.

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Comparing Methods for Modelling Tree Mortality

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Abstract—Our goal is to compare different methods for estimating the parameters of individual tree mortality models. We examine general methods including maximum likelihood and weighted nonlinear regression, and a few specialized methods including Proc LOGISTIC in *SAS*, and an implementation of the Walker-Duncan algorithm. For fixed period lengths, almost all methods for fitting the logistic mortality model should work. The LOGISTIC procedure in *SAS* is quite robust and the easiest to use. For unequal period lengths, either a weighted nonlinear least squares or a maximum likelihood formulation is needed to specify the annualized logistic mortality model: NLIN(wtLS) and NLIN(LOSS) in *SAS*. Of course, other statistical packages that mimic these procedures should give the same results.

Introduction

Mortality remains one of the least understood yet important components of growth and yield estimation (Hamilton 1986). Great success in modeling mortality is rare, perhaps because the focus is on modeling the occurrence of rare events. Realistically, mortality modelers mostly hope to capture the average rate of mortality and relate it to a few reliable and measurable size or site characteristics (Keister 1972; Hamilton and Edwards 1976; Monserud 1976; Hamilton 1994; Monserud and Sterba 1999).

A few preliminary observations provide some context, several of which conspire to increase the difficulty of mortality modeling in forestry. First, mortality is a discrete, rare event. A common rule of thumb for both temperate and boreal forests is that roughly 0.5 to 1.5 percent of the trees are expected to die in a given year (background mortality). It therefore follows that a large sample is needed to observe enough occurrences of mortality for modeling the process adequately. Using this rule of thumb, we expect that a sample of 10,000 trees/yr (or 2000 trees/5 yrs) would be needed to observe approximately 50 to 150 deaths, which is a relatively small sample of the event of interest. Second, observations of the same individual tree at two points in time are necessary to observe the survival or mortality status of a tree; this requires remeasured permanent plots. Estimates of the date of death from temporary plots are notoriously unreliable and should not be used. Third, we usually do not know tree age, so we cannot use Survival Analysis methods (Allison 1995) that have been successful in medical research. Furthermore, remeasured tree survival data are usually both left and right censored (Allison 1995; Meeker 1998): we only know that some of the trees died sometime during the sampling interval, and the others failed to die. Fourth, it is not uncommon to have widely varying period lengths, which precludes the proper use of some estimation programs that assume equal period lengths, such as Proc LOGISTIC in *SAS* (SAS Version 8.1 is a product of the SAS Institute, Cary, NC 27513).

Simulator architecture determines how mortality must be calculated and simulated. Mortality is *discrete* in a spatial simulator such as *TASS* (Mitchell 1975) or *FOREST* (Ek and Monserud 1974), with the tree either completely dead or alive. This mortality process is stochastic. Furthermore, the costs of misclassification are not equal in spatial models. Misclassifying a live tree as dead can never be corrected, but misclassifying a dead tree as live can be corrected in the future. Mortality can be *continuous* in a nonspatial simulator such as *FVS* (Stage 1973; Wykoff and others 1982; Hamilton 1994; Teck and others 1997) or *ORGANON* (Hann and others 1997), with the mortality rate smoothly reducing the number of trees each sample tree represents. Therefore, it is much easier to predict mortality rates over large areas with nonspatial models.

Our goal here is to compare several methods for estimating the parameters of individual tree mortality models. Note that our objective is not to find the best mortality model for a given data set. We will examine several methods: maximum likelihood, weighted nonlinear regression, and a few specialized programs (Proc LOGISTIC in *SAS*, and the Walker-Duncan algorithm of Hamilton 1974). Our motivation is that all too often authors do not provide enough details on methods to reproduce results. Although our immediate context is modeling in the *FVS* environment, our results apply to any other forest simulation system.

We have a few caveats. We will not address:

- Correlation of trees within a plot. They will have the same stand density, and they could all be exposed to the same unobserved mortality agent.
- Plot size effects on model parameters (see Stage and Wykoff 1998).
- Simultaneous fitting of mortality and the growth equations (Hasenauer and others 1998; Cao 2000)

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The Algebra of Mortality

Because a tree can only die once, mortality is not a Markov process. Survival is, however. This property requires that all algebra be mediated in terms of survival, not mortality. The probabilities of survival (P_s) and mortality (P_m) are connected by the standard identity:

$$\text{Survival} = 1 - \text{Mortality: } P_s = 1 - P_m$$

We must use the compound interest formula to convert survival to other period lengths:

$$\text{1-year: } P_{s_1} = 1 - P_{m_1}$$

$$\text{n-year: } P_{s_n} = P_{s_1} P_{s_1} P_{s_1} \ldots P_{s_1} = (P_{s_1})^n = (1 - P_{m_1})^n \quad (\textit{The Markov property})$$

$$\text{1-year: } P_{m_1} = 1 - P_{s_n}^{1/n} = 1 - (1 - P_{m_n})^{1/n}$$

Statistical Considerations

The modeling of tree mortality requires fundamentally different statistical methods than those used for most of the other components of forest growth models. This is because the dependent variable is dichotomous rather than continuous: 0 or 1 (live or dead). It then follows that the variance is Binomial and is not constant: Var = $P(1–P) = P_m P_s$. Maximum Likelihood (ML) methods are the proper estimation procedure. The likelihood of a sample of observations is the joint probability of that sample (Mendenhall and Shaeffer 1973). The ML estimation problem is to find the values of the unknown parameters that maximize this likelihood, which is a product of individual probabilities. The log of this product is used instead because it is a monotonically increasing function of the Likelihood and is much easier to differentiate and maximize (Mendenhall and Shaeffer 1973). Although seemingly complicated, ML estimates are quite intuitive. They have the desirable properties of consistency, asymptotic unbiasedness, and efficiency. The independence of the observations is an underlying assumption, which is violated if there are correlations between trees on the same permanent plot, resulting in the underestimation of confidence intervals for parameters. We do not examine the independence assumption.

A seminal paper by Grizzle and others (1969) demonstrated that Weighted Least Squares (with the weight $\propto 1/\text{var}$) could be an equally appropriate estimation method for categorical data analysis (Agresti 1990). The method is widely available and is asymptotically equivalent to maximum likelihood (Agresti 1990). Fisher's Discriminant Analysis also works but quickly becomes unwieldy as the problem becomes increasingly multivariate.

To model the probability of mortality (or survival), all that is needed is a flexible function bounded by 0 and 1. The Logistic equation is most often used, although any sigmoid or cumulative distribution function would work. The logistic for the probability of survival (P_s) is:

$$P_s = \frac{1}{1+e^{b'X}} = \frac{1}{1+e^{b_0+b_1x_1+b_2x_2+\ldots}}$$

where X is a vector of independent variables, and $b'X$ is a linear combination of the n parameters b_i and the x_i independent variables. Invoking the identity $P_s = 1 - P_m$ and some algebraic manipulation leaves us with the closely related logistic form for the probability of mortality (P_m):

$$P_m = \frac{e^{b'X}}{1+e^{b'X}}$$

The inverse transform has a long history (McCullagh and Nelder 1983):

$$\log(P_m/(1-P_m)) = b'X$$

It is recognizable as the "logit" or the "log odds ratio." This equation provides the link between the unconstrained function $b'X$ and the logistic probability prediction, which is bounded by [0,1].

In the foregoing, P_m and P_s are interchangeable. The function to model P_m could be used equally well to model P_s; the only difference is that the signs in the coefficient vector b would be reversed. This amounts to switching the 0-1 coding on the dependent variable.

We always want to know how good the model is. Usual measures of residual variation (R^2) are useless for dichotomous variables. It does not matter how close a predictor is to 0 or 1 as long as it can accurately estimate expectations. We will simply use the sum of the log likelihoods, with the standard factor of –2 that results from maximizing the logarithmic linearization; we will label this –2LL. A closely related statistic for model comparison is Akaike's Information Criterion (AIC). It penalizes –2LL by the number of parameters in the model (Chatfield 1996). The Chi-square statistic is also appropriate, with the calculation based on dividing important predictor variables into classes. Hosmer and Lemeshow (2000) discuss these and other statistics.

Methods

We concentrate on a comparison of several methods for estimating parameters with a fixed logistic model. Five fitting techniques are described:

1. Logit Model for Proportions { REG } — This model, also referred to as the linear logistic model, is ascribed to several authors in the 1940s and 1950s (McCullagh and Nelder 1983). It requires that the data be grouped into classes of X values. Within each class, the predictions are identical for all observations. The observed proportion in each class should be between zero and one, and the expected numbers of events and nonevents in each class should be at least five. The procedure is to transform the independent variable by computing its logit and then regressing that transformation against X.

2. Least squares { NLIN (LS) } — Unweighted least squares minimizes the sums of squared errors, where the error is calculated as $\varepsilon = Y - P_m$, where Y equals one for mortality and zero otherwise, and P_m is the predicted probability of mortality. Because of the logistic link function, P_m is not a linear function of the parameters. Therefore, nonlinear regression is needed.

3. Walker-Duncan {RISK } — The Walker-Duncan algorithm (Walker and Duncan 1967) is a sequential approach to weighted least squares that was developed in an era of limited computer resources. It is claimed to be asymptotically equivalent to the maximum likelihood fit of the logistic

model. This routine was coded by Hamilton (1974) in the RISK program and extended to deal with variable period-length data.

4. Weighted Least Squares {NLIN (wtLS), LOGISTIC } — Weighted least squares minimizes the weighted sums of error squared, using weights that are inversely proportional to the estimated variance: Var = *P(1-P)*. McCullaugh and Nelder (1983) show that the minimization of this weighted sums of squares produces the maximum likelihood solution. That proof assumes that the link function is linear in the parameters, which is not true for the variable length period regressions to be discussed later. Nonetheless, in every test regression that we have examined, the weighted least squares method does produce the ML solution, a result supported by Agresti (1990). The weighting is iterative because the weights depend on the parameter vector *b*, which is being estimated. The iterative weighting can prevent some fitting techniques from fully converging. A conservative strategy is to hold the weights constant while iterating toward a least squares solution, then resetting the weights and proceeding to further rounds of minimization. Most LOGISTIC programs use iteratively reweighed least squares to obtain the ML solution.

5. Maximum Likelihood { NLIN (LOSS) } — Maximum likelihood solutions can be derived directly by iterating the model parameters until the likelihood is maximized, or equivalently until the negative log likelihood is minimized. This is done by writing the LL function shown in the appendix and incorporating that computation into an optimizer. The *SAS* procedure NLIN and equivalent procedures in other statistical packages can perform the optimization. In NLIN, the keyword _LOSS_ defines the objective criteria.

The above programs are all procedures within *SAS*, except for RISK, which was developed by Hamilton (1974). We use the notation "LS" to indicate the least squares objective function normally employed in nonlinear regression. The notation "LOSS" indicates where we employ an explicitly defined loss function.

Data Sets

Four data sets are used to illustrate various regression methods. The data sets are referred to as data A, B, C, and D; they are summarized or listed in their entirety in tables 1 through 4, respectively. Data sets A and B offer simple examples suitable for event estimation (tables 1 and 2); period length is not involved. Data set C is real data (64,121 observations) from young unthinned plantations of Douglas-fir in coastal Washington, Oregon, and British Columbia (summary in table 3). The growth rates in those data are from regressions of change in DBH versus initial DBH fit to the data one plot and one growth period at a time. Growth periods are from 1 to 4 years. Data set D is a simulated data set, which also has variable period lengths (table 4). It consists of four 0.5 acre plots, each with 10 arbitrary selected tree sizes, arbitrary frequencies, and arbitrary growth rates. The mortality was simulated for all trees in all years using the ML regression fit to data set C. Because data set D was selected to have high densities and long periods, the predicted mortality rates are high, allowing us to better see the differences due to the various fitting methods. As with data set C, the growth rates are best thought of as having been predicted by a diameter growth function.

Table 1—Data set A - categorized data distributed as an example for the RISK program.

Y	X_1	X_2
0	1	2
1	2	1
1	1	2
1	2	2
0	1	2
0	1	1
0	2	1
0	2	1
1	2	2
1	2	2
1	2	2
1	2	1
1	1	2
0	2	1
1	1	1
1	2	2
1	2	2
1	1	2
1	2	1
1	1	2
1	1	2
1	2	2
1	1	1
0	2	2
0	2	2
1	2	1
1	1	1
0	1	1
1	1	2
0	1	1
1	1	2
0	2	1
1	1	1
1	1	2
0	2	2
0	1	1
0	2	1
1	1	1
1	2	1
1	1	1

An alternative formulation of the same data set shows N observation on each line, with NY1 of them indicating an event (Y=1):

X_1	X_2	N	NY1
1	1	10	6
1	2	10	8
2	1	10	5
2	2	10	7

Table 2—Data set B. A simple data set illustrating low-probability events. The data set is shown in its classed formulation. It could also be shown as 100 observations, with 11 observations having Y = 1 and 89 observations having Y = 0. All models using these data use the expanded form (100 observations) unless stated otherwise.

X_1	N	NY1
0.0	10	3
0.1	10	1
0.2	10	2
0.3	10	1
0.4	10	1
0.5	10	2
0.6	10	0
0.7	10	0
0.9	10	1
1.0	10	0

Table 3—Summary of data set C, remeasurement data from fixed-area plots in young Douglas-fir plantations. The data set contains 64,121 observations.

Variable	Mean	Minimum	Maximum
DBH (in)	4	0	14
Height (ft)	22	2	74
BA (ft^2/ac)	62	3	172
Age	14	5	22
Period length (years)	3.4	1	4
Mortality proportion	0.014		

Results

Fitting with Fixed Period Length

The examples presented use techniques that are suitable for predicting mortality in a period of fixed length, where all of the data are from remeasurement periods of that same length. In these circumstances, the length of the period does not enter into the prediction process.

Data set A is used to illustrate the fitting of a simple logistic regression. Code for three methods is shown in the appendix. Coefficients and -2 LL's are in table 5; predictions for all X values are in table 6. RISK, REG, and LOGISTIC solutions all have nearly identical likelihoods, even though there are minor differences in the coefficients. RISK predicts there will be 25.90 events, whereas the other methods have prediction closer to the observed 26 events; this offers a hint that the RISK solution may not be the true maximum likelihood solution. The results from RISK may vary a bit if the order of observations is changed. The conclusion is that for classed data, with event (or nonevent) expectations as low as 2, all of the fitting methods produce results that are statistically indistinguishable from one another.

Data set B (table 2) is another simple data set. It is included here to show some lower probability events, as are typical in mortality data sets. Code is presented for four regression procedures in the appendix. Unweighted least squares is implemented with NLIN (LS); weighted least squares is implemented by NLIN (wtLS) and LOGISTIC; direct maximum likelihood is implemented with NLIN (LOSS). In the NLIN(wtLS) code, note how the iterative reweighting is implemented in two passes: first, an unweighted regression returns preliminary estimates of event probabilities; second, a weighted regression then uses the earlier estimated probabilities in assigning weights. The solutions are nearly identical for all methods (table 7). The trivial differences in -2LL are due to incomplete convergence for NLIN(LOSS) and to the fundamental consideration that NLIN(LS) is not using the theoretically correct weighting.

Fitting with Variable Period Length

One complication in mortality modeling is unequal period lengths. In the Algebra subsection, we saw how the compound interest formula (Markov property) can bring mortality or survival rates for any period length to an annual basis. It is important to have this flexibility to simulate any reasonable period length. However, not all estimation procedures allow for variable period lengths. The LOGISTIC procedure in *SAS* is a case in point. Beyond the mechanical difficulties of fitting, there may be serious differences between how the regression predictions are applied to the data set, and how they will be made within a simulator.

Data set C has variable period lengths of 1 to 4 years (table 3). An annual mortality model is fit for these data. The independent variables generally take on values as assigned at the start of the growth period. One variant on the regression process uses midpoint values for the independent variables, a technique that is useful for building annual simulators from multiyear data (Hyink and other 1985). The linear combination used in the Logit is:

$$b'X = b_0 + b_1 DBH + b_2 BAL/BA + b_3 BA$$

where BA is the total basal area per acre, and BAL is the basal area of larger trees. Although these variables were a good set of predictors for this particular data set, they are not a recommended set for other applications.

The procedures applied to data set C include RISK, LOGISTIC, and NLIN(LOSS). The latter procedure is run once with start-of-period X values and once with midpoint values. Results are in table 8. The results from NLIN(LOSS) are the best (the lowest -2LL), and RISK is the poorest. Surprisingly, the LOGISTIC results are almost the best, even though they rely on a statistically incorrect model. In this application, each period of YIP years is treated as YIP independent observations, one of which may result in mortality. For situations where mortality rates are very low (as in data set C), the LOGISTIC procedure can produce good estimates of parameters. However, all the fit statistics (including -2LL) and confidence intervals returned by the LOGISTIC regression program are incorrect. The NLIN (LOSS) regression using midpoint values is significantly poorer than those using start-of-period values. The use of midpoint values was expected to be an improvement; the lack of improvement might indicate a deficiency in our choice of independent

Table 4—Data set D. Simulated data set based on models from data set C.

PLOT	SIZE	YIP	DBH	DBHRATE	NTREES	GROUP	BAL	BA	TPA	NSURV	BA_FINAL	TPAFINAL
1	0.5	8	2.8	0.80	40	1	1.710	17.191	800	37	220.410	688
1	0.5	8	2.6	0.78	40	2	4.896	17.191	800	35	220.410	688
1	0.5	8	2.4	0.76	40	3	7.627	17.191	800	35	220.410	688
1	0.5	8	2.2	0.74	40	4	9.940	17.191	800	36	220.410	688
1	0.5	8	2.0	0.72	40	5	11.868	17.191	800	36	220.410	688
1	0.5	8	1.8	0.70	40	6	13.448	17.191	800	33	220.410	688
1	0.5	8	1.6	0.68	40	7	14.713	17.191	800	37	220.410	688
1	0.5	8	1.4	0.64	40	8	15.699	17.191	800	35	220.410	688
1	0.5	8	1.2	0.62	40	9	16.441	17.191	800	31	220.410	688
1	0.5	8	1.0	0.60	40	10	16.973	17.191	800	29	220.410	688
2	0.5	12	2.8	0.80	40	1	1.710	17.191	800	34	296.201	456
2	0.5	12	2.6	0.78	40	2	4.896	17.191	800	29	296.201	456
2	0.5	12	2.4	0.76	40	3	7.627	17.191	800	27	296.201	456
2	0.5	12	2.2	0.74	40	4	9.940	17.191	800	31	296.201	456
2	0.5	12	2.0	0.72	40	5	11.868	17.191	800	30	296.201	456
2	0.5	12	1.8	0.70	40	6	13.448	17.191	800	26	296.201	456
2	0.5	12	1.6	0.68	40	7	14.713	17.191	800	22	296.201	456
2	0.5	12	1.4	0.64	40	8	15.699	17.191	800	12	296.201	456
2	0.5	12	1.2	0.62	40	9	16.441	17.191	800	8	296.201	456
2	0.5	12	1.0	0.60	40	10	16.973	17.191	800	9	296.201	456
3	0.5	8	7.8	0.50	30	1	9.955	156.883	600	24	283.609	434
3	0.5	8	7.6	0.50	30	2	29.361	156.883	600	24	283.609	434
3	0.5	8	7.4	0.50	30	3	47.772	156.883	600	20	283.609	434
3	0.5	8	7.2	0.50	30	4	65.214	156.883	600	22	283.609	434
3	0.5	8	7.0	0.50	30	5	81.714	156.883	600	23	283.609	434
3	0.5	8	6.8	0.50	30	6	97.298	156.883	600	22	283.609	434
3	0.5	8	6.6	0.50	30	7	111.991	156.883	600	24	283.609	434
3	0.5	8	6.4	0.50	30	8	125.821	156.883	600	17	283.609	434
3	0.5	8	6.2	0.50	30	9	138.813	156.883	600	21	283.609	434
3	0.5	8	6.0	0.50	30	10	150.993	156.883	600	20	283.609	434
4	0.5	12	7.8	0.50	30	1	9.955	156.883	600	20	326.410	356
4	0.5	12	7.6	0.50	30	2	29.361	156.883	600	23	326.410	356
4	0.5	12	7.4	0.50	30	3	47.772	156.883	600	15	326.410	356
4	0.5	12	7.2	0.50	30	4	65.214	156.883	600	20	326.410	356
4	0.5	12	7.0	0.50	30	5	81.714	156.883	600	18	326.410	356
4	0.5	12	6.8	0.50	30	6	97.298	156.883	600	18	326.410	356
4	0.5	12	6.6	0.50	30	7	111.991	156.883	600	17	326.410	356
4	0.5	12	6.4	0.50	30	8	125.821	156.883	600	16	326.410	356
4	0.5	12	6.2	0.50	30	9	138.813	156.883	600	14	326.410	356
4	0.5	12	6.0	0.50	30	10	150.993	156.883	600	17	326.410	356

Variables for data set D

Plot	An arbitrarily assigned plot number
Size	Plot size in acres
YIP	Years in the period
DBH	Initial diameter (inches)
DBHRATE	DBH growth rate (in/yr)
NTREES	Initial number of trees of this size.
GROUP	Sequence number assigned to a group of trees of same size.
BAL	Initial basal area of larger trees (including half of current group)
BA	Initial basal area (sq. ft/ac)
TPA	Initial trees per acre
NSURV	Number of surviving trees at end of growth period
BA_FINAL	Final basal area for the plot (sq. ft/ac)
TPAFINAL	Final trees per acre.

Table 5—Regression results, data set A.

Regression	b_0	b_1	b_2	–2LL
LOGISTIC	–.011508	–.462517	.908641	49.558
REG	–.002985	–.47223	.91406	49.558
RISK	.0530757	–.494347	.889641	49.562

Table 6—Predictions from three methods for the probability of an event using data set A.

X_1	X_2	N	NY1/N	P (RISK)	P (LOGISTIC)	P (REG)
1	1	10	.6	.61025	.60698	.60798
1	2	10	.8	.79216	.79302	.79461
2	1	10	.5	.48851	.49302	.49166
2	2	10	.7	.69924	.70698	.70696
Wt'd Sum		40	26	25.90	26.00	26.01

Table7—Regression results, data set B.

Regression	b_0	b_1	–2LL
LOGISTIC	–1.1115	–2.6602	64.3675
NLIN(LS)	–1.1219	–2.6270	64.3682
NLIN(wtLS)	–1.1120	–2.6586	64.3675
NLIN (LOSS)	–1.1219	–2.6270	64.3682

Table 8—Regression results, data set C.

Regression	b_0	b_1	b_2	b_3	–2LL
LOGISTIC[1]	–3.2956	–.9826	–1.5666	0.0410	8049
NLIN(LOSS)	–3.4217	–1.0068	–1.38	0.0425	8047
NLIN(LOSS) – Midpoint	–2.3943	–1.1032	–2.3609	0.0423	8068
RISK	–3.1513	–.90577	–1.6717	0.0391	8096

[1]The regression reports –2LL as 10363, based on an inflated number of observations.

variables. The RISK procedure shows the poorest -2LL value, possibly indicative of convergence problems.

Data set D is an artificial data set of four plots, each with 10 tree sizes. Four variations of the same model are examined: a Compound survival model, a Midpoint model, an Interpolated model, and a Simulation model. The differences between the models arise from different assumptions for calculating the same X variables. The Compound model uses the initial values of X's for each survival prediction, so a compound interest formula for survival is appropriate. The Midpoint model uses the average of starting and ending values for the independent variables and applies the same compound survival formula as for the previous method. The Interpolated model uses different X values for each year in the growth period; these are from linear interpolation. For both the midpoint and interpolated models, BAL/BA is not updated from the start of the period because doing so would require information on tree mortality. The Simulation model uses different X values for each year; these are iteratively recomputed based on predicted survival (for example, the computation of each year's BAL is dependent on the predicted mortality in earlier years). The NLIN (LOSS) procedure is used for fitting in all four cases. The Midpoint model, the Interpolated Model, and the Simulation model all take advantage of knowing something about DBH growth rates or end-of-period values. If the DBH growth rates are in fact predictions from a growth model, their use does not invalidate the independence of the X values. The use of the end-of-period basal area by the Midpoint and Interpolated models is a not a statistically valid procedure, but may still produce good results (Hyink and others 1985).

The Compound survival model for data set D uses the same code as given in the appendix under the heading: "C - NLIN(LOSS)". This is a reasonable approach for data where the period lengths are similar. With period lengths in the data of 8 and 12 years, this model could reasonably be applied to a 10-year period. The Midpoint model uses the same code as indicated for "C - NLIN (LOSS), Midpoint X values." The Interpolated X model uses linear interpolation code shown in the appendix. Code for the Simulation model is specific to this problem and relies upon a particular data structure (see appendix).

Results of fitting data set D are in table 9, where two values are shown for -2LL, the "fit" value as reported by the regression program and the "true" value that would be obtained within the context of an annual simulation. The Compound model would not be applied within an annual simulation, nor can it be evaluated for the 10-year steps where it is likely to be applied. Thus, its true -2LL is unknown. The best fit is expected to be from the Simulation model. Here the mortality predictions within the regression are identical to those made within the simulator, and a

Table 9—Regression results, data set D. The NLIN (LOSS) procedure is used for fitting in all four cases. Two values of –2LL are shown: those from the fitting routine, and the "true" –2LL values that would be obtained by using the coefficient solutions in an annual growth simulation.

Model	b_0	b_1	b_2	b_3	–2LL (fit)	–2LL(true)
Compound[1]	0.1956	–1.6602	–2.1140	.058730	1606	
Midpoint[2]	–2.5369	–1.4604	–2.3461	.063074	1550	1596
Interpolated X[3]	–4.9798	–.9577	–1.4003	.04970	1538	1544
Simulation[4]	–2.9387	–1.0529	–1.7037	.0437	1538	1538

[1]Predicted annual survival rate is compounded for YIP years; X's are initial values. Suitable for 10-yr step.
[2]Annual model relying on midpoint X values. Reported –2LL =1550
[3]Annual model relying on annually interpolated X values.
[4]Annual model, with iteratively simulated annual X variables.

maximum likelihood solution is chosen; we do not address any interaction with maximum density constraints that *FVS* may employ. The Interpolated X method has a -2LL value that is almost as good; the Midpoint model is considerably poorer. A partial explanation for the interpolated X method being so good, is that a linear DBH growth model is assumed; a nonlinear model would not interpolate as well. Another result, not shown in the table, is the total number of mortality trees that would be predicted by an annual simulation. The observed mortality was 433 trees. The predicted mortality for the Midpoint, Interpolated X, and Simulation model fits were 518, 474, and 459, respectively. There is a tendency to overpredict mortality. Normally that might be indicative of model misspecification. Here there is the additional possibility that the simulation that created the data set was somehow defective.

Summary

Fitting a fixed-period length mortality model is straightforward. The model should directly predict the probability of survival (or mortality) for the entire period, without any requirement to compound the survival rate. Any of the methods presented here should be adequate for this task, with the exception that the Logit model for proportions should not be used unless the data are easily summarized into cells with a constant mortality rate. We offer this Logit model for proportions for historical completeness, not as a viable general alternative. The LOGISTIC regression procedure is the most robust. It is the easiest to apply, should not have convergence problems for typical data sets, and should normally be the preferred methodology. Each tree is one observation, and weighting is not used. Weighted least squares, NLIN(wtLS), should also be problem-free but is a bit more work. NLIN(LOSS) is the maximum likelihood option. It should provide good solutions, although convergence may slow as the number of parameters increases. RISK is a product of its time: a clever approximation to maximum likelihood when mainframe computer resources were limited. A FORTRAN compiler is required if model transformations cannot be done beforehand in an external data structure. Finally, a fixed-length survival model can be formulated as a direct prediction, as we have done here, or it could be formulated as a compound annual survival model for a fixed-length application. The appropriate methodology for fitting the latter formulation would be the same as for a variable-period length model, using initial X values.

For variable-length periods, the first decision is whether the model will be used in an annual simulation or in a simulation with a fixed step size of greater than 1 year. For the fixed step size, the data should be limited to growth periods of approximately that duration. The appropriate regression model is the Compound model in table 9, or the equivalent NLIN(LOSS) regression in table 8. For an annual simulation model, the best fit is assured with the Simulation model in table 9. In a real fitting exercise, the assumed DBH growth rates would be replaced by predicted growth rates (Cao 2000). As alternatives to a full Simulation model, reasonable approximations may be achieved with Interpolated X's or Midpoint X's. It is impossible to know in advance whether one of these approximate methods will be adequate. Due to the difficulty in programming the full simulation method, the use of midpoint X's may be the preferred method for model screening, and the use of interpolated X's may be adequate for final fitting. If the Midpoint or Interpolated X model is used, the Simulation model should be used to verify that the total predicted mortality is close to the observed total. This verification may be part of the validation of a completed growth simulator. Regardless of the formulation of the X's, the actual fitting method should be either NLIN (wtLS) or NLIN(LOSS).

In the foregoing, NLIN(wtLS) and NLIN(LOSS) are presented as having similar capabilities; in general, they both produce the ML solution. For the *SAS* system, NLIN(wtLS) seems to have better convergence properties than the NLIN(LOSS). For other statistical packages, this observation may not hold.

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Appendix

Code for selected regression examples, by data set (A, B, C, D).

A - LOGISTIC

Proc LOGISTIC for data set A (40 observations)

```
PROC LOGISTIC ORDER=INTERNAL DESCENDING;
  MODEL Y = X1 X2 ;
```

A - REG

Logit Model for proportions, using classed formulation of data set A

```
Data Step
  P = NY1 / N ;
  LOGITY = LOG(P/(1-P)) ;

PROC REG;
MODEL LOGITY = X1 X2;
WEIGHT N ;
```

A - RISK

Control lines for running data set A (40 records) with the RISK program.

```
TEST PROBLEM 1
            1              1       3       40          8
                        9999       3        5.0
     4
00000
(4F2.0)
 PROB XONE XTWO
000010000200003
```

B- LOGISTIC

```
PROC LOGISTIC ORDER=INTERNAL DESCENDING;
  MODEL Y= X1;
  OUTPUT OUT=fileout P = PRED;

PROC TABULATE;
  CLASS X1;
  VAR Y PRED;
  TABLE X1 ALL, SUM*( Y PRED);
```

B - LOGISTIC (for classed data set of 11 records)

```
PROC LOGISTIC;
  MODEL NY1 / N = X1;
```

B - NLIN (LS)

```
PROC NLIN ;
  PARMS B0 = -.5 B1 = -2 ;
  LOGIT = B0 + B1 * X1;
  Yhat = EXP(LOGIT) / (1 + exp(LOGIT)) ;
  MODEL Y = YHAT;
```

B- NLIN (wtLS)

```
PROC NLIN ;
  PARMS B0 = -.5 B1 = -2 ;
  LOGIT = B0 + B1 * X1;
  Yhat = EXP(LOGIT) / (1 + exp(LOGIT)) ;
  MODEL Y = YHAT;
  OUTPUT OUT=File2 P=Pred1 ;

PROC NLIN data=File2;
  PARMS B0 = -.5 B1 = -2 ;
  LOGIT = B0 + B1 * X1;
  Yhat = EXP(LOGIT) / (1 + exp(LOGIT)) ;
  VAR = Pred1 * (1-PRED1);
  _WEIGHT_ = 1/VAR ;
  MODEL Y = YHAT;
  OUTPUT OUT=File3 P=Pred2 ;
```

And optionally, one more iteration

B - NLIN(LOSS)

```
PROC NLIN ;
  PARMS B0 = -.5 B1 = -2 ;
  LOGIT = B0 + B1 * X1;
  Yhat = EXP(LOGIT) / (1 + exp(LOGIT)) ;
  IF Y = 1 then N2LLIKE = -2*LOG(Yhat);
           else N2LLIKE = -2*LOG(1-Yhat);
_LOSS_ = N2LLIKE;
MODEL Y = YHAT;
OUTPUT OUT=Filename P = PredY;
```

C - LOGISTIC

```
PROC LOGISTIC ORDER=INTERNAL ;
  MODEL MORT/YIP = DBH BAL_BA BA ;
```

note: YIP = years in period.
MORT=1 if tree dies, else 0.
BAL_BA = BAL / BA

C - NLIN(LOSS).

```
PROC NLIN METHOD=DUD MAXITER=130;
  PARMS
    B0 = -3 B1 = -1 B2 = -1 B3 =0.05 ;

  LOGIT = B0 + B1 *DBH + B2 * BAL_BA + B3*BA;
  P_annual = exp(LOGIT) / (1 + exp(LOGIT) );
  P_surv = ( 1 - P_annual)**YIP;
  P_mort = 1 - P_surv ;
  IF MORT = 1 then N2LLIKE = -2*log(P_mort);
              else N2LLIKE =-2*log(1 - P_mort) ;
  _LOSS_ = N2LLIKE;
  MODEL MORT = P_mort;
  OUTPUT OUT=OUTF P=Pmort;
```

The above does not converge satisfactorily. It was followed up by several regressions with B1 fixed at various values, including B1 = -1.38, and improved initial guesses for the other parameters.

note: YIP = years in period.
MORT=1 if tree dies, else 0.
BAL_BA = BAL / BA

C - NLIN (LOSS), Midpoint X values.

Same as the above code, but preceded by a data step redefining the independent variables:

```
BAL_BA unchanged
F = (YIP/2 -0.5)/YIP ;
BA = BA + F*(BAfinal - BA) ;
DBH = DBH + F * (DBHgrown - DBH)
```

where BA_{final} is the basal area at the end of the period, and DBH_{grown} is from a by-plot regression of ending DBH (for the surviving trees) versus the initial DBH.

C - RISK

```
RISK with SMC data for DF
        1.          1.        4.      64121.      15.         0.       0.
        0.   999999.         5.          20.
  8
  0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0
(8F9.5)
  A0BAL/B    BA   DBH   MORT   1     1     step
  1      2      3     4      5      6     7      8
```

Note: This is the control file that was actually used. The resultant coefficients are in a different order than is shown in our results (Table 8).

D - Interpolated X.

```
Data Step
  BAL_BA=BAL/BA;

  DO I=1 to NSURV;
  MORT=0;
  OUTPUT;
  END;

  NDEAD = NTREES-NSURV;
  if NDEAD> 0 then DO I=1 to NDEAD;
                        MORT=1;
                        OUTPUT;
                        END;

PROC NLIN METHOD=DUD ;
  PARMS B0 =-3 B1=-1 B2 =-1 B3=.04;

PER_SURV = 1.0 ;
Label PER_SURV='Pr{Surv for Period}';

  DO I = 1 to YIP;
    BAi = BA + (I-1)/YIP * (BA_FINAL-BA);
    DBHi = DBH + (I-1) * DBHRATE ;
    F = B0 + B2* BAL_BA + B3*BAi + B1*DBHi;
    P_mort = exp(F) / (1 + exp(F) );
    P_surv = ( 1 - P_mort);
    PER_SURV = PER_SURV * P_SURV;
  END;

PER_MORT = 1.0-PER_SURV;
IF MORT = 1 then N2LLIKE = -2*log(PER_mort);
             else N2LLIKE =-2*log(PER_SURV) ;

_LOSS_ = N2LLIKE;
MODEL MORT = PER_mort;
OUTPUT OUT=OUTF P=Pmort;
```

D - simulation model

```
*          Collapse to one record per plot;
DATA A;
  SET [original data]; by PLOT;
  ARRAY     VDBH{10}      DBH1-DBH10 ;
  ARRAY     VRATE{10}     RATE1-RATE10;
  ARRAY     VN{10}        N1-N10;
  ARRAY     VTPA{10}      TPA1-TPA10;
  ARRAY     VNSURV{10}    NSURV1-NSURV10;
  ARRAY     VBAL{10}      BAL1-BAL10;

   VDBH{GROUP}      = DBH;
   VRATE{GROUP}     = DBHRATE;
   VN{GROUP}        = NTREES;
   VTPA{GROUP}      = NTREES/SIZE ;
   VNSURV{GROUP}    = NSURV;
   VBAL{GROUP}      = BAL ;

  DEATHS = (TPA-TPAFINAL)*SIZE;

  if LAST.PLOT then output;

  RETAIN DBH1-DBH10
         RATE1-RATE10
         N1-N10
         TPA1-TPA10
         NSURV1-NSURV10
         BAL1-BAL10 ;

KEEP PLOT SIZE YIP TPA BA DEATHS
         DBH1-DBH10
         RATE1-RATE10
         N1-N10
         TPA1-TPA10
         NSURV1-NSURV10
         BAL1-BAL10;

PROC NLIN METHOD=DUD ;
  PARMS B0 =-3 B1=-1 B2 =-1 B3=.04;

ARRAY   VDBH{10}      DBH1-DBH10;
ARRAY   VRATE{10}     RATE1-RATE10;
ARRAY   VN{10}        N1-N10;
ARRAY   VTPA{10}      TPA1-TPA10;
ARRAY   VNSURV{10}    NSURV1-NSURV10;
ARRAY   VBAL{10}      BAL1-BAL10;
ARRAY   GDBH{10}      GDBH1-GDBH10;
ARRAY   GTPA{10}      GTPA1-GTPA10;
ARRAY   GBAL{10}      GBAL1-GBAL10;

  *         START-UP before growth;
  DO I=1 to 10;
         GDBH{I}=VDBH{I};
         GTPA{I}=VTPA{I};
         GBAL{I}=VBAL{I};
  END;
  GBA = BA;

DO   IYEAR = 1 to YIP;

BASUM=0;
DO I = 1 to 10;
  F = B0 + B2* GBAL{I}/GBA + B3*GBA + B1*GDBH{I};
  P_mort = exp(F) / (1 + exp(F) );
  P_surv = ( 1 - P_mort);
  GTPA{I} = GTPA{I} * P_SURV;
  GDBH{I} = GDBH{I} + VRATE{I};
  BAgroup = GTPA{I} * 0.005454154 *GDBH{I}*GDBH{I};
  GBAL{I} = BASUM + BAGROUP/2;
  BAsum = BAsum + BAgroup ;
END;
  GBA= BAsum;
END;

*          Evaluate all the losses;
  N2LLIKE=0;
  PRDeaths = 0;
  DO I = 1 to 10;
  PR_SURV = GTPA{I}/VTPA{I} ;
  PR_MORT = 1-PR_SURV;
  PrDEATHS = PRDEATHS + VN{I} * PR_MORT;

  CNT_DEAD = VN{I} - VNSURV{I};
  CNT_LIVE = VNSURV{I};

  THISLOSS = CNT_DEAD * ( - 2*log(PR_MORT))
               +CNT_LIVE * (- 2* log(PR_SURV)) ;
  N2LLIKE = N2LLIKE + THISLOSS;
  END;
  _LOSS_ = N2LLIKE;
  MODEL DEATHS = PRDEATHS;
  ID GTPA1-GTPA10;
  OUTPUT OUT=OUTF P=Pred;
PROC PRINT;
```

Spatial Statistical Model for the Spread of Dwarf Mistletoe Within and Between Stands

Donald C.E. Robinson
Brian W. Geils
John A. Muir

Abstract—Dwarf mistletoes affect the growth and survival of many conifer species in North America. Interactions between the host and pathogen influence spread, intensification, and stand development. These interactions are especially complex in stands with several tree species, multiple storys, and irregular patterns of tree distribution. For such stands, we developed a model of mistletoe dynamics linked to FVS. The model simulates the development and dispersal of mistletoe seeds and describes infection distribution by dwarf mistletoe rating (DMR). The stand-level model includes several important features such as the spatial arrangement of trees, the spatial autocorrelation of trees with similar amounts of mistletoe infection, the dynamics of seed flight, the effect of crowns intercepting and inhibiting infection spread, and the light environment that strongly affects the life history of dwarf mistletoes. Model input requirements are modest: at a minimum, only an FVS tree list that includes DMR is required. Users may either enter parameters for the patterns of tree distribution and mistletoe patchiness or accept default values. User-determined values can be computed from many standard survey designs or set from experience with similar situations. Default values represent many typical stands. Simulations based on data from uneven-aged ponderosa pine and coastal western hemlock stands show reasonable projections of stand-level changes in mistletoe incidence and severity over several decades, and plausible responses to silvicultural management scenarios. Recent work is also described that provides a theoretical basis for simulating spread between stands. This between-stand model is currently being implemented using the Parallel Processing Extension to FVS.

Dwarf mistletoes (*Arceuthobium*) are among the most widespread and serious conifer pathogens in western North American forests. Up to half of lodgepole pine and Douglas-fir forests and over one-third of ponderosa pine forests in the Central and Southern Rockies are affected by dwarf mistletoe (Hawksworth and Scharpf 1984). Infection by mistletoe reduces growth, survival, and reproductive potential of many commercially important tree species, resulting in estimated losses of more than 11 million m^3 per year of merchantable timber in the United States (Drummond 1982). Development of silvicultural prescriptions to control the tree-to-tree spread of mistletoes within stands has been the subject of extensive research efforts for many years (Van Sickle and Wegwitz 1978; Hawksworth and others 1987; Hawksworth and Johnson 1989). The goal of these prescriptions has been to limit the intensification of already established infections and to reduce the potential to spread to uninfested trees. Spread across stand discontinuities is also recognized as an important factor when designing spatial cutblock patterns in variable retention silviculture.

While control of mistletoe can sometimes be achieved silviculturally, planning cost-effective treatments must be done within the larger context of landscape- and stand-level management planning. Increased use of forest growth and yield models to assist forest managers in planning silvicultural operations and their expected consequences on economic returns have created a need for accurate prediction of the dynamics of dwarf mistletoe response to stand-level management, and the ability to accommodate nonclearcutting practices. Our objectives were to: (1) develop a model of the mistletoe infection dynamics that can be used to assess stand-level silvicultural activities for mistletoe management; and (2) extend the conceptual model to accommodate the simulation of spread across stand discontinuities.

Dwarf Mistletoe Spread and Intensification

Two aspects of the life history of dwarf mistletoe are critical for predicting mistletoe spread and intensification: first, the mechanics of seed dispersal, and second, the establishment, incubation, and reproduction of mistletoe plants on their hosts. Generally, there is a unique relationship between the host tree species and its associated dwarf mistletoe species, and seeds will not successfully infect a tree of another species. Dwarf mistletoes are dioecious plants that reproduce only from seeds borne on shoots. Seed dispersal begins when a mature fruit explosively discharges its seed in ballistic flight. Unlike other mistletoes, which are primarily dispersed by birds, the dwarf mistletoes rely almost exclusively on ballistic spread. Birds and mammals are important for the rare, long-distance dissemination of seeds to new infection centers.

The physical process of dispersal brings the mistletoe seed to the location where it establishes a new infection. The incubation period of newly established plants varies greatly but is typically 3 to 4 years (Hawksworth and Wiens 1996).

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Generally, 1 to 2 years then elapse from shoot appearance to initial flowering. Individual plants may persist for many decades. Because they rely upon the host for nutrition and because reproductive success does not require annual seed production, mistletoes can persist without aerial shoots, as latent infections. Little is known of the physiological mechanisms regulating shoot production, but it appears that shoot production and flowering are suppressed in the low light and nutrition environment of shaded lower crowns (Shaw and Weiss 2000). Opening the canopy by removing surrounding trees, as is often done to thin or regenerate a stand, commonly results in a proliferation of mistletoe shoots on the residual trees.

Ballistic dispersal and parasitism are critical to mistletoe population dynamics. Ballistic dispersal is effective for short-range dissemination only, and parasitism requires a living host. Consequently, mistletoe plants are found clustered within trees, and infected trees are clustered into infested groups. The spatial pattern of mistletoe populations therefore operates across a range of scales: the tree, neighborhood, and stand. The average level of infection is usually described by an index of the amount of host crown affected: the dwarf mistletoe rating (DMR) system (Hawksworth 1977). Each crown third is rated 0 if it is apparently not infected, 1 if less than half is infected, or 2 if more than half is infected. The DMR system allows infection to be quantified in various ways: by crown thirds, for the whole tree, or by averaging across a collection of trees, for a group or stand of trees.

We define *spread* as the establishment of mistletoe infection in previously uninfected trees, and *intensification* as the establishment of new mistletoe infections within infected trees. Spread and intensification are influenced by the same factors and are complementary aspects of the same process. Dispersal is primarily affected by the physical configuration of the tree: crown density and distribution; and by stand species composition. Establishment, incubation, and reproduction are determined by weather, genetic, and other biological factors.

The Model

A number of dwarf mistletoe models have been developed to assist forest managers in planning silvicultural operations and estimating effects on yield. These models range from projecting whole-stand impacts (for example, Myers and others 1971, Edminster and others 1991) to the explicit simulation of the effects of the spatial arrangement of trees (for example, Strand and Roth 1976, Bloomberg and Smith 1982).

The model described in this paper simulates dwarf mistletoe spread and intensification at an intermediate spatial resolution in which the transmission of dwarf mistletoe is the outcome of spatial relationships between infected and uninfected trees. In the model, height and canopy relationships are *explicit* and stem location relationships are *statistical*, based on the spatial distribution of trees at the 14-m scale of ballistic spread. Those parts of the model that are explicitly spatial operate at a 2-m resolution. The model operates on an annual time step and is able to simulate infection dynamics in patchy multispecies, multistoried stands. It does not simulate long-distance transmission of mistletoe and is restricted to spread from ballistic seed flight. It is linked to the Dwarf Mistletoe Impact Modelling system (DMIM; Hawksworth and others 1995), an extension to the FVS model (Stage 1973; Wykoff and others 1982). Dwarf mistletoe impacts, reduced diameter increment, and reduced survival for severely infected trees, are modelled using the DMIM system.

Model users are provided with the means to parameterize the model. The detailed model structure and user-control are fully documented in Robinson and others (1994) and in Hawksworth and others (1995). Modelling behavior studies are described in Robinson and others (2000) and in Robinson and Geils (in preparation). The main features of the model are summarized below.

Life History

In the simplest case, new infections progress from an immature through an incubation stage and finally produce an active (flowering) adult that contributes to the DMR classification. The passage from immature to incubation status is modeled with a default delay of 4 years. Passage to the reproductive stage depends on the amount of light available in the crown third. If light decreases to the point that an active infection cannot be sustained, the infection regresses to a nonflowering suppressed state. These life-history dynamics and stages are summarized in figure 1. Light plays an important role in most of the transitions between life history stages and takes the form of a height-dependent extinction curve. As described below, this curve is dynamically generated using a simulated stem map and a model of the canopy.

Light and Opacity

The presence or absence of light is critical to the maturation of incubating infections and to the activation or suppression of mature flowering plants. The model uses the concept of stand-average opacity to simulate the reduction of light by foliage, branches, and stems. In doing so, it is able to estimate the proportion of incident light at different heights above the ground, and by the same mechanism account for the interception of seeds in ballistic flight. Stands may be made up of trees of different species, height, crown shape, length, and foliage opacity. To account for this complexity, stand-average opacity is computed by Monte Carlo simulation. At the beginning of each time step, a 1-ha stand simulation is made. Each tree is represented in proportion to its density in the stand. Beginning at the ground and extending upward in 2-m steps, the structure of each layer is simulated with simplified circular discs of canopy, each representing the crown diameter of trees at that height. Canopy geometry is computed by the COVER model (Moeur 1985) (fig. 2). After simulating all the stem locations, the stand-average opacity at each height is a function of the amount of space unoccupied by canopy, combined with the canopy opacity of the space occupied by foliage. Stand-average opacity is then used to reduce the amount of light

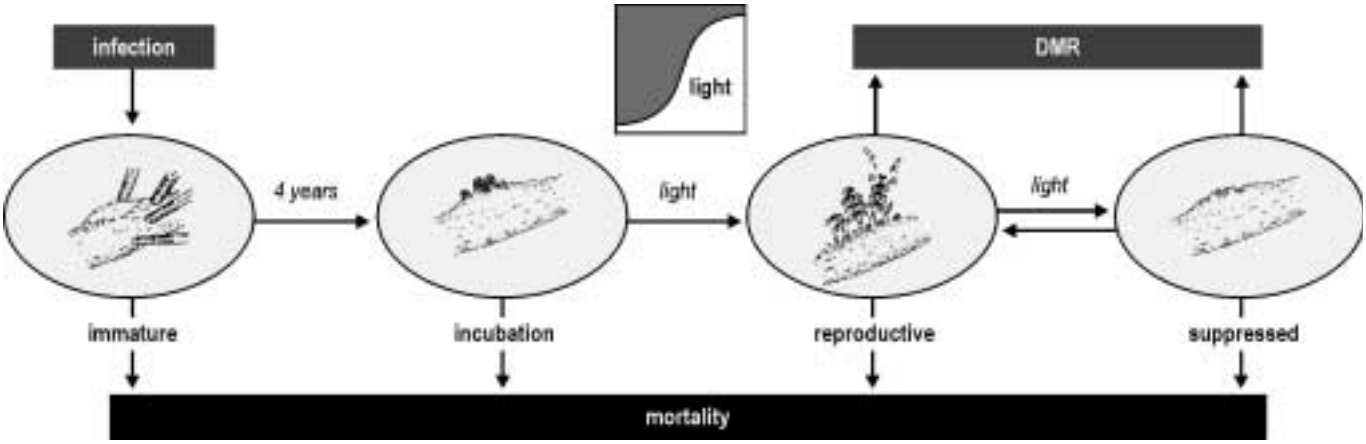

Figure 1—The model simplifies dwarf mistletoe life history into four stages. Light drives the progress of incubating infections to reproductively active individuals, and to and from the suppressed pool.

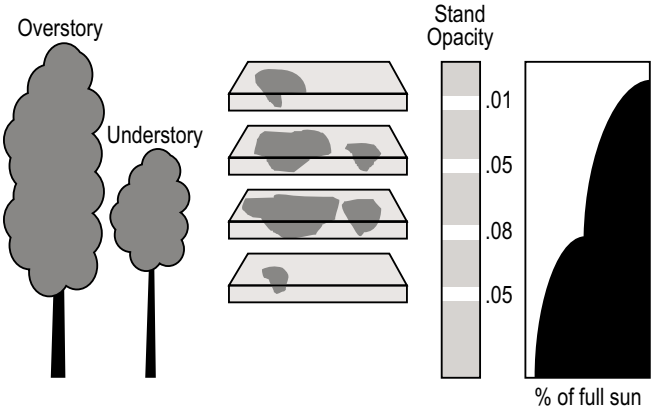

Figure 2—An estimate of stand-average opacity is made by simulating the crown diameter at each height in the stand. Light penetrating the stand from above is blocked by crowns, and less light is available at lower heights (right panel). The ability of crowns to block light varies with stem density and by species. For example, pines allow more light to pass than western hemlock.

transmitted from the top of the stand to the ground. Because light extinction is cumulative, a decay curve results.

Stem Clumpiness

Seeds spread ballistically from a source tree to a target tree. For an infection to be transmitted successfully, two trees must have compatible heights and be in the same neighborhood. The local neighborhood of each target tree can be regular, random, or clumped. As the left part of figure 3 shows, the model simulates stem spacing by placing a target tree at the center of a bulls-eye, surrounded by 2 m rings. Source trees are then selected and simulated as if they were located in each of the concentric rings. Placing a target at the center of a bulls-eye with source trees at discrete distances allows the infection field of each source tree to overlap the canopy of the target, simulating the dynamics of spread.

For each of the concentric rings, the expected number of stems is the average stem density of the whole stand multiplied by the area in the ring. A ring is defined by its inner and outer radius, r_i and r_o. The distribution for an inner disc with radius r_i (the r_i disc) is derived first, giving the probability of sampling $x=0,1,2,3...$ trees in the inner disc. The same method is followed for the larger r_o disc, as shown in figure 3. The expected distribution of trees in the ring is then defined by the distribution of trees found in disc r_o that are not already in disc r_i. The distribution is generated by counting all the combinations of tree numbers on the two discs that would give rise to an observation of a particular number of trees in the ring (equation 1). In equation 1, the probability generating function, P, can be binomial, poisson, or negative binomial. The upper tail of the distribution drops

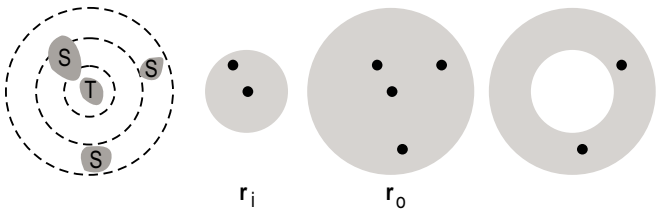

Figure 3—At left, source trees, S, surrounding each target tree, T, are selected based on an underlying spatial clumping function (for example, binomial). Samples in each ring are based on the conditional distribution functions produced by overlapping inside and outside discs, r_i and r_o. The example shows one possible way in which a ring with two source trees could be simulated from samples from inside and outside discs. Actual positions around the disc are not necessary for the simulation.

off rapidly, and in practice the summation over j and k usually converges with fewer than 20 terms.

$$P(x=n \mid r_i, r_o) = \frac{\sum_{j=o}^{\infty} P(x=j \mid r_o)\, P(x=j-n \mid r_i)}{\sum_{k=o}^{\infty}\sum_{j=k}^{\infty} P(x=j \mid r_o)\, P(x=j-k \mid r_i)}; n>0 \qquad [1]$$

The denominator term scales the probability distribution. This scaling is necessary because the two disc samples are not independent. The r_i disc lies completely inside the r_o disc, and therefore some tree counts are impossible. For example, if a sample of size 3 is observed in the inner disc r_i, a sample of 2 or fewer can never be observed in the outer disc r_o. The double summation in the denominator adjusts the distribution so that the probabilities over all sample sizes sum to one.

Infection Patchiness

In addition to creating a local neighborhood around each target tree, the model simulates positive autocorrelation among infection classes, resulting in patches of infection. The autocorrelation results in an increased likelihood that trees of similar DMR are neighbors compared to trees of unlike DMR. The stem-mapped Log Cabin plot shown in Dixon and Hawksworth (1979) and the Wind River site (Shaw and others 2000) both give good examples of such patches. Although the existence of patches is well documented, modelling their explicit arrangement is not reasonable for a nonspatial growth model. We have therefore modelled the autocorrelation structure of DMR with a simple function (equation 2), an exponential decay curve driven by the magnitude of DMR difference between a target and its potential neighbors. Equation 2 gives a modified density estimate, ρ'_i, for each DMR class, i, surrounding a target tree of DMR t.

$$\rho'_i = \rho_i e^{\alpha \mid t-i \mid} \frac{\sum_{j=0}^{6} \rho_j}{\sum_{j=0}^{6} \rho_j e^{\alpha \mid t-j \mid}} \qquad [2]$$

This difference-driven weighting assigns greater density to neighboring source trees with DMR similar to the DMR of the target tree, and less density to trees with unlike DMR. It allows the local DMR to vary in different target tree neighborhoods, while maintaining the observed stand-average DMR. To preserve stand-level statistics, reducing the likelihood of finding a source tree having a different DMR class implies a corresponding increase in the density of similar-DMR sources in other neighborhoods. Equation 2 preserves this symmetric property of target-source differences in DMR: trees "taken away" from one neighborhood are "put back" in another neighborhood, so that the stand density of each DMR class is preserved. These properties are illustrated in table 1 (setting $\alpha = -0.5$).

The term can be estimated from stem-mapped data by comparing the density of each source DMR class observed around each target DMR tree. Predictions made by equation 2 are compared against observed stem map densities, generating a range of χ^2 over a range of values for α. Minimizing χ^2 then gives the best choice of α. Results from an analysis of six sites (four from a long-term study in the Grand Canyon National Park; one from Fort Valley, and one from the Wind River site; J.J. Smith, personal communication) are shown in table 2. Three of the sites have repeated measures but show no consistent change in α over time. The mean of all 28 observations is $\alpha = -0.103$ (SD = 0.075).

Ballistic Seed Dispersal

Because of physical constraints on seed flight, infection is usually transmitted laterally and downward from an infection source. An infection in a higher tree will usually expose a lower neighbor to infection, but not the reverse. The model uses encoded and simplified ballistic seed trajectories based on the following characteristics: 24 m s^{-1} initial velocity (Hinds and Hawksworth 1965); 7.5 m s^{-1} terminal velocity (Hawksworth 1959); uniform random angle of discharge; and aerodynamic drag represented as a quadratic function of velocity. These assumptions produce the dispersal pattern shown in figure 4. The 14-m lateral limit is consistent with field observations (for example, Hawksworth 1961).

Table 1—An example of spatial autocorrelation setting $\alpha = -0.5$ The left side of the table shows the stand-average density of each DMR class. Rows of the right table show the neighborhood density of source trees around each target DMR class (columns). In each case, the overall stand density is preserved. Weighted sums by neighborhood density (right-most column) show that the stand-average DMR densities are also preserved.

DMR	Stand avg. density	Source DMR	Target DMR class 0	1	2	3	4	5	6	Wtd. density
0	45	0	80	47	29	21	17	15	13	45
1	25	1	27	43	26	20	16	14	12	25
2	32	2	21	33	56	41	33	29	25	32
3	17	3	7	11	18	36	29	26	22	17
4	12	4	3	5	8	16	34	30	26	12
5	3	5	0	1	1	2	5	12	11	3
6	5	6	0	1	1	2	5	12	29	5
Total	139	Total	139	139	139	139	139	139	139	

Table 2—Observed values of α, the autocorrelation parameter, at six sites.

	Stand					
Year	GC11	GC12	GC22	GC06	Ft. Valley	Wind R
1950		–0.13	–0.07			
1952				0.06		
1955		–0.12	–0.06	0.00		
1961		–0.15	–0.08	–0.01		
1966		–0.14	–0.07	–0.03		
1970		–0.15	–0.03	–0.04		
1979		–0.16				
1982		–0.20	–0.07	–0.10		
1986		–0.25				
1988				–0.13		
1990		–0.27	–0.02	–0.14		
1997	–0.07	–0.18			–0.12	–0.15

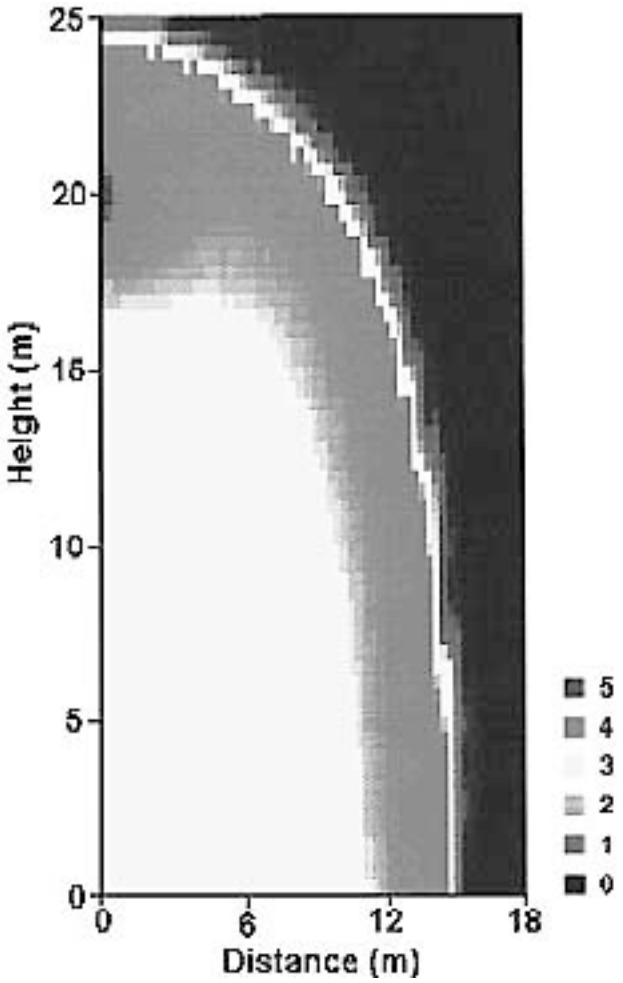

Figure 4—The aerodynamic simulation of ballistic flight produces a field of trajectories. The maximum lateral discharge is about 14 m, and the maximum rise above the point of discharge (20 m in the figure) is about 6 m. Discharge is heaviest near the outer margin of the discharge envelope. The scale is log-transformed relative seed density.

Examples of Model Behavior

Grand Canyon —Ponderosa Pine

In 1950, Frank Hawksworth initiated a study of dwarf mistletoe control in several fixed area plots of moisture-limited ponderosa pine on the south rim of the Grand Canyon. We used data from plot GC12, an untreated 4-ha fixed area plot that was stem-mapped and monitored for its tree and mistletoe characteristics (tree condition, dbh, height, DMR). Stand examinations were made in 1950, 1955, 1961, 1966, 1970, 1979, 1982, 1986, 1990, and 1997. The oldest trees are currently about 250 years. Ingrowth had been minimal for most of the period. Stand basal area of original trees declined from 11.5 m^2 ha^{-1} in 1950 to 5.3 m^2 ha^{-1} in 1990. (The most recent 1997 inventory was not included in this analysis and includes the recent ingrowth.)

We carried out numerous model simulations with these data to examine the model's sensitivity to opacity, clumping, and patchiness, comparing those runs to the empirical observations. The results in figure 5 show the influence of α, which controls the patchiness of infections. When α = –2.50, infection patches are tightly focused, resulting in high mortality, limited spread to uninfected trees, and declining stand DMR. Conversely, with α = 0.0 the infections are evenly spread throughout the stand, resulting in extensive spread. When α = –0.30 the predicted stand DMR follows the inventory estimates quite closely. The mean estimate over the 50-year period is α = –0.18 (see table 2).

Vancouver Island—Western Hemlock

Through the courtesy of Weyerhaeuser Canada Ltd., we were provided with a number of 1-ha inventories from Vancouver Island, B.C. The stands are predominantly western hemlock and range from dwarf mistletoe-free to moderately infested. To study response to management, we selected a young, lightly infected stand (age = 53 years in 1987; SI = 24 m; QMD = 15 cm; BA = 44 m^2 ha^{-1}; stand DMR = 1.2). The stand was initially understocked. An initial planting was therefore simulated, to give a target stocking level of 1,200 stems ha^{-1}.

The simulations follow a block design, with two retention scenarios and three regeneration scenarios. Shelterwood harvests left 15 and 25 percent of the basal area following an entry at age 100. Three regeneration scenarios were simulated: (1) no manual planting following entry; (2) planted using the original species mixture following entry; and (3) planted using an 80:20 hemlock:cedar mix following entry. In all three scenarios a small amount of simulated natural regeneration was added in each cycle. At the time of stand entry, 15 percent mortality was applied to the advanced regeneration, and natural regeneration was cancelled in the planted stands for 20 years. Finally, the residual overstory was removed 20 years after the stand entry, allowing the regenerating stand to continue growing. Some results of these simulations are shown in figure 6. The figure shows two measures of infection: stand DMR in the upper panels and infected trees/ha in the lower panels.

In each of the simulations, the first entry is responsible for a dramatic decline in DMR and in the number of infected

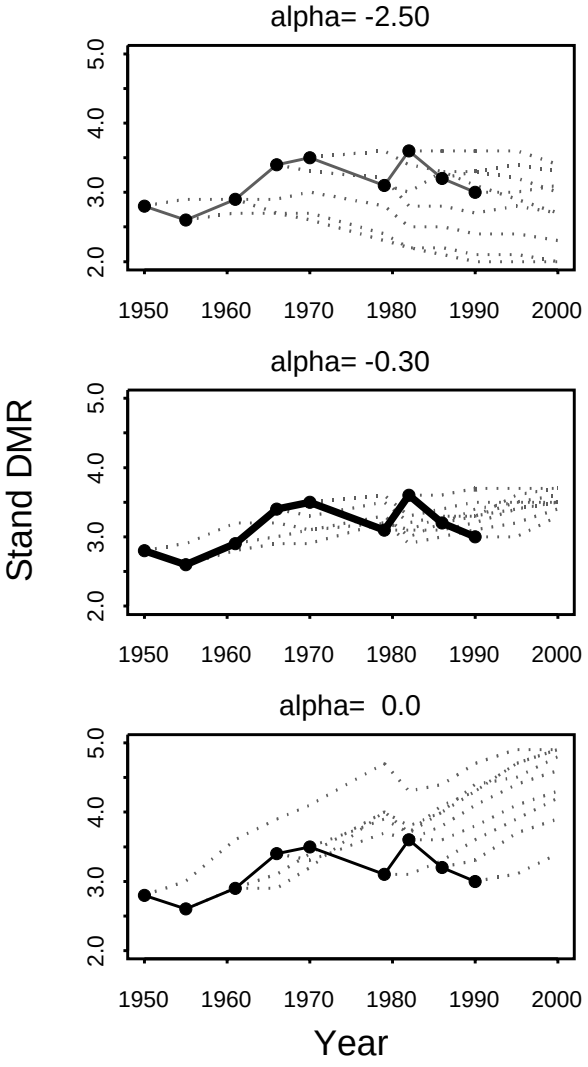

Figure 5—Sensitivity to the choice of the autocorrelation parameter, α (see equation 2) is shown in simulations from the GC12 plot. The heavy line in each pane shows the inventory-based estimate of stand DMR over time. Lighter lines show the model projection of DMR, starting at each inventory date. See text for further interpretation.

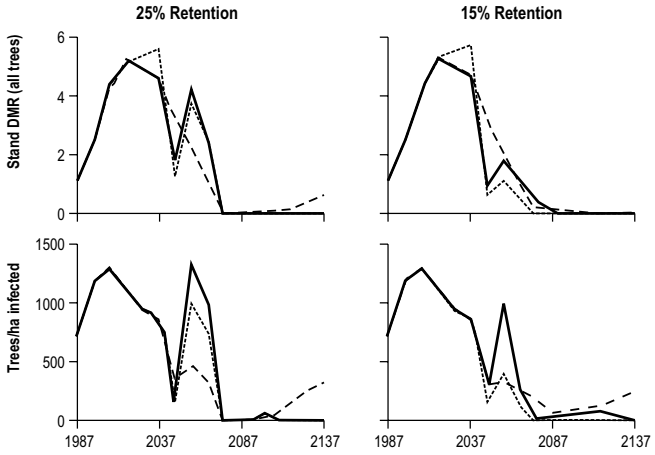

Figure 6—The model's sensitivity to management actions are shown in simulations from the Vancouver Island plot: variable levels of retention, different regeneration scenarios, and different species mixtures. The representation of overstory and understory relationships is responsible in large measure for this sensitivity. See text for further interpretation. Dashed line — unplanted following entry; solid line — planted with original mixture following entry; dotted line — planted with cedar mixture following entry. See text for additional details.

trees. The decline is less precipitous in the unplanted scenario for two reasons. First, the scenario continues to regenerate in the period after the first entry and therefore carries more mistletoe infection in the advanced regenerating trees. Second, the two planting scenarios "dilute" stand DMR with large numbers of initially uninfected seedlings. After thinning, infection levels and DMR both rebound as the infection is transferred from the residual overstory to the new understory trees. As expected, the 25 percent retention scenarios always transmit more mistletoe because they contain almost twice as many overstory trees as the 15 percent scenario. Likewise, regeneration scenarios that incorporate western redcedar all result in lower transmission success. This reduction is achieved through the physical blocking of seeds and because the infection measures are based on summing over both western redcedar (which is never infected) and western hemlock.

The success of the postentry mistletoe flush is transient in most of the simulations and is nearly always quenched by the subsequent second entry removal of the residual overstory. The young regenerating stands appear to "outrun" the new infestation because they are adding sufficient height annually so that they outgrow and then suppress the more slowly advancing mistletoe. In some scenarios — notably the unplanted — the infection is successfully transferred to the next generation because of its greater incidence in the more abundant advanced regeneration.

Spread Across Boundaries

To meet habitat conservation goals, group retention harvesting systems are being considered in some harvest plans (Bill Beese, Weyerhaeuser Canada Ltd., Nanaimo, B.C.; personal communication). In these scenarios, retained patches containing dwarf mistletoe have the potential to spread across patch boundaries and into young regrowing areas. The need to understand and project the future state of these regrowing stands motivated us to adapt the spatial statistical framework to accommodate spread across boundaries. As figure 7 shows, the first step in extending the existing framework is to superimpose a boundary line across the local neighborhood of target trees. Conceptually, the stand structure of the adjacent stand then contributes any dwarf mistletoe influence onto trees in the index stand.

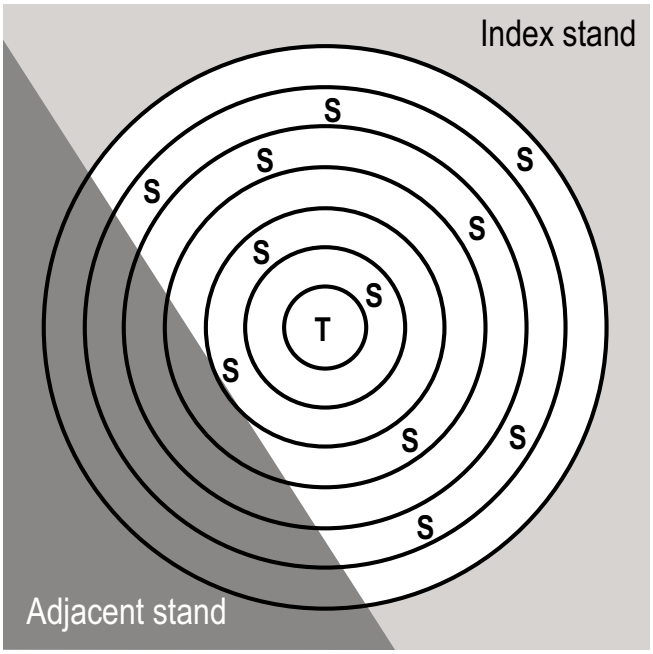

Figure 7—Between-stand spread is simulated using the same framework as the single-stand model, superimposing a boundary across the local neighborhood of the target tree, T. Source trees (S) and stand structure of the adjacent stand then contribute to the spread of DM onto trees in the index stand.

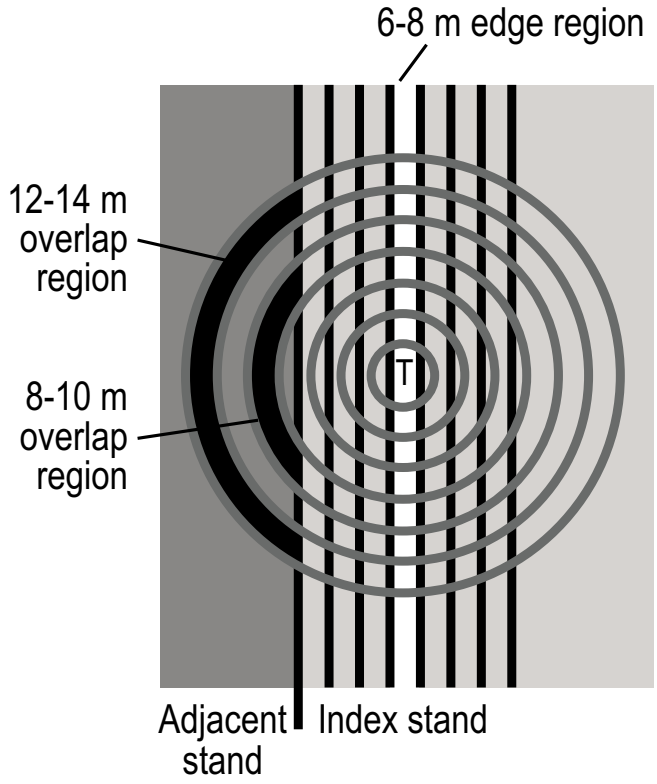

Figure 8—In this example, the likelihood that a target tree, T, lies within 6 to 8 m of the adjacent stand depends upon the proportion of stand area in that edge region. The amount of area found in ring samples in the adjacent stand (for example, the 8 to 10 m overlap region) depends on the amount of overlap of the target tree neighborhood. DM present in source trees found in the adjacent stand can then be included for the target tree.

Figure 8 shows a target tree, T, adjacent to a stand boundary. The likelihood of finding a tree in this location depends on the proportion of the stand area within a given "edge band." If a target lies in a band, the influence of source trees in the adjacent stand then depends on the amount of overlap into the adjacent stand. These relationships are being modelled using the programming infrastructure of the Parallel Processing Extension (PPE: Crookston and Stage 1991), combined with a map preprocessing step using spatial numerical integration to derive the measures of relative and absolute area in edge bands and in adjacent stands.

Conclusions

A spatial statistical model was developed to represent several important features of the life history and distribution of dwarf mistletoe in complex stands—namely, mistletoe latency and mortality, stem clumpiness, and infection patchiness. Several example situations demonstrate that parameter estimation is not an impediment to use and that projections produce reasonable results that are useful for assessing management alternatives within infested stands. The spatial statistical framework has been extended to a slightly larger scale and is able to model the spread of dwarf mistletoe across stand or treatment discontinuities.

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Session 5. FVS in Modeling Systems

An Intelligent Information System for Forest Management: NED/FVS Integration

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Abstract—An Intelligent Information System (IIS) is viewed as composed of a unified knowledge base, database, and model base. This allows an IIS to provide responses to user queries regardless of whether the query process involves a data retrieval, an inference, a computational method, a problem solving module, or some combination of these. NED-2 is a full-featured intelligent information system for the sustainable management of forestlands. It is designed to help managers plan for wildlife, ecology, water, and landscape objectives as well as timber production. FVS is one of the integrated decision support model components in NED-2. We provide the FVS simulation agent and "wrapper" that permit communication between FVS and NED-2. We are developing a meta-knowledge base. Simulation agents can use it to set up and execute external simulation models. This paper will briefly describe the NED decision process, the NED-2 architecture, and discuss the design issues explaining the integration of NED-2 and FVS.

Owners and managers of forestlands in the United States are being challenged as never before to produce an increasingly complex set of benefits as a variety of costs increase. Getting the most money from your forestland through timber harvesting is by itself a challenging goal. But a growing number of landowners want much more than money from their forestlands. They may want to create or maintain certain desirable ecological conditions such as a grove of "old growth forest" or a scenic, parklike environment. They may want to restore portions of their property to more natural conditions to enhance the habitat for many creatures well into the future. Knowing that one is being a good steward of the land may also be part of the rewards of forestland ownership. And many landowners have said for years that they are more concerned with enhancing wildlife habitat, increasing bird population diversity, or protecting rare and endangered species than they are with high returns from timber harvesting. Landowners want to manage their forestlands for more and more goods, services, and environmental conditions than ever before. However, providing for these increasingly complex benefits often increases management costs and the cost of ownership.

Researchers at the USDA Forest Service, Northeastern and Southern Research Stations, in cooperation with many collaborators, have been developing a computer software system called the NED decision support system. This system is designed to help forestry consultants and their private landowner clients develop goals, assess current and potential conditions, provide a way to study and select from different scenarios, and produce management plans for their forest properties.

In this paper, we will briefly describe the NED decision process, the NED-2 architecture, and how we have used the theory of Intelligent Information Systems (IIS) to link FVS into the NED-2 DSS.

The NED Decision Support Process

The purpose of modern forest management is to achieve diverse goals selected by the landowner. This perspective is critical and central to the NED Decision Process. It cannot be overemphasized that without goals, reasoned management cannot be practiced.

Surprisingly, identifying and choosing a good set of goals is the most difficult part of the entire decision process. A difficult part about choosing suitable goals is that you have to be able to tell whether you have achieved them or not. For example, one of the goals for the Deer Hill case study in South Carolina was to focus on producing *Wild Turkey Habitat*. Well, you can't just walk into the forest, pull out your *Wild Turkey Habitat* measurement gauge, swing it around, and get a reading on it. There is, of course, no such gauge and that is because *Wild Turkey Habitat* is an abstract concept that unifies many factors about the birds and their needs. So how do we measure it? Well, first we have to further define what we mean by *Wild Turkey Habitat*. We talked with turkey management experts and decided that

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we needed three things for good turkey populations: (1) a favorable landscape pattern, (2) forestland with all sizes of trees represented, and (3) turkey food. That list certainly helps, but we are still not able to go out and measure any one of these three things. So what do we do? We define what we mean by each of the three subdivisions. A favorable landscape pattern for turkey is defined as: (1) parklike, open forests that cover at least 80 percent of the area, (2) scattered small fields that make up more than 10 percent of the area, (3) parklike large hardwood forests that are present near small fields, and (4) parklike large pine forests that cover at least 10 percent of the area. So now, finally, we have something we can measure in our forests. By going through this process, we create a list of goals in sequence with immeasurable but valuable top level goals at one end and measurable conditions that define the top level goals at the other end of the hierarchy.

Having defined our goals, we next need to learn about our property. Many landowners do not possess an inventory of the trees on their land and have only a general idea of the mix of vegetation, soil, and topographic features. Obtaining an inventory is an expensive proposition yet a cost that must be paid prior to the beginning of serious efforts to establish a cost effective management program. Knowing this, the NED Team developed a relatively inexpensive and yet quite complete inventory procedure that provides good estimates of the large trees, the smaller trees, shrubs, and herbs, and allows for a rapid assessment of wildlife habitat conditions using measures such as the presence or absence of dead standing and dead fallen trees. We look for perches for birds, whether moss, ferns, or grasses cover the ground, whether there is permanent water available for all creatures and especially salamanders and turtles, and so on. Although we look for many things, we have designed a process that takes approximately a half hour per forest stand.

Given the set of goals and an understanding of the current forest conditions, we can turn our attention to figuring out what we might do to our land (if anything) so that it better achieves the goals. We want to create a small number of different strategies for managing our land while satisfying the goals. These strategies are called management scenarios. Each is a different road to get to the same place. In sustainable forest management there is rarely a single, best road to follow to achieve a given set of goals. What we can realistically do is design several different ways (roads) to get to our goals and then compare them. At each cycle through this process, we learn more about our own values and goals, about our land, and about the things we can do with it. For Deer Hill, we designed three management scenarios (fig. 1):

1. **A Timber Only scenario:** maximum profit from timber operations consistent only with best management practices for sustainable timber management and the CRP requirements. Wildlife is not specifically addressed, and no revenue from wildlife operations is expected. All open areas will be planted to loblolly pine. The pine-hardwood stands will be commercially chipped and converted to loblolly pine plantations as soon as feasible. Loblolly pine plantations will have two thinnings (age 10 to 12 and 20 to 25) and a final harvest at age 30 to 40. And the plantation size class distribution will be spread out to get a more even flow of income.

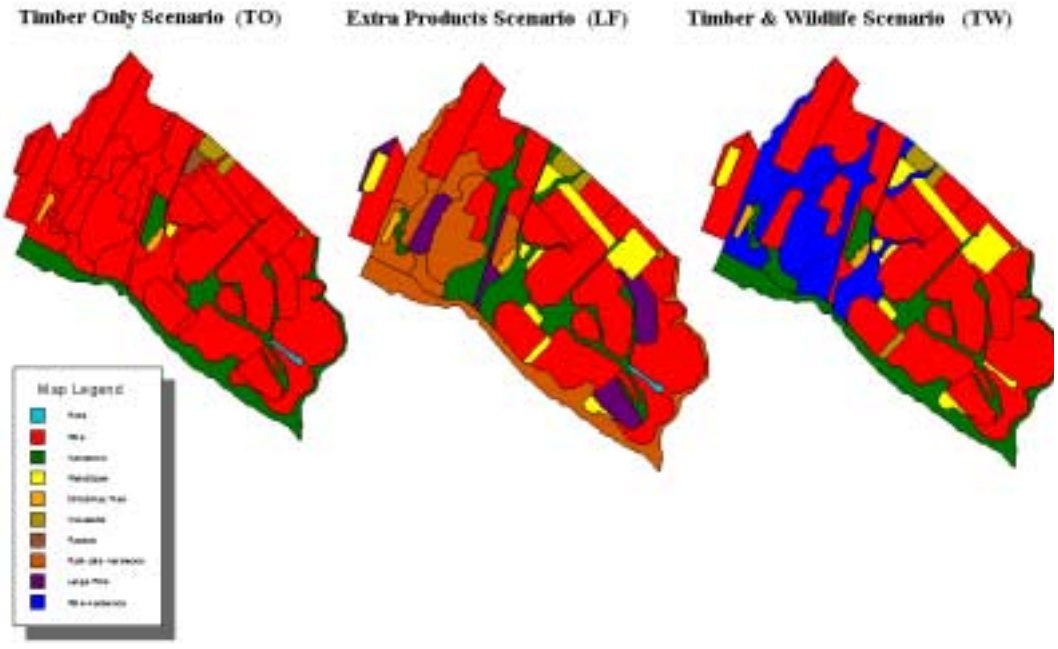

Figure 1—Computer models allow the forest manager to predict the results of different management options

2. **A Timber and Extra Products scenario:** maximum profit from nontimber, nonextractive human use of the land. Leave 400 acres of existing pine plantations alone and continue to manage for maximum timber. Take 100 acres of pine plantation and manage for big pine over long rotations. The pine-hardwood stands will be turned into park savannahs with large hardwood trees spread out over a 30 by 30 foot grid. Islands of regenerating hardwoods will be created in these open forests. Wildlife food plots will be established in all open fields, and the wildlife row-crop planting (corn) will continue. Many different camping, nature education, hunting, and other sporting activities will be developed as income producing activities.

3. **A Timber and Hunting scenario:** maximum profit from timber and hunting operations. Leave all pine plantations as they are and manage for maximum production. Rent hunting rights to highest bidder. Thin pine-hardwood and hardwood stands to promote acorn production. Keep open fields open and food plots productive.

Having developed the three management scenarios for Deer Hill, we had to pretend to carry each of them out over our 40-year time frame and then compare them to each other. We did this by using a forest growth forecasting software package called the Forest Vegetation Simulator (FVS). FVS was created and is maintained by the USDA Forest Service, Forest Management Service Center in Fort Collins, CO. This system covers all forest types in the entire United States. It is, however, fairly complicated to use and requires at least 1 week training before users feel comfortable with the software. NED integrates FVS but only for regions east of the Mississippi. FVS is available on the Internet for downloading, free of charge, at www.fs.fed.us/fmsc/fvs.

We are almost at the end of the NED decision process now. To recap: We set our goals; learned about the current condition of our property; figured out some alternative ways we could manage our land; and projected those alternatives over a 40-year time horizon to get an estimate of how each forest is likely to look 40 years in the future. Now we can go back to our goals, find our measurable conditions, and evaluate them against each of our simulated future forests (fig. 2). For example, in the *Wild Turkey Habitat* goal, we needed parklike hardwood forests with large trees near small fields. By evaluating the three simulated scenarios, we can determine that only the **Timber and Extra Products** scenario (#2) will provide us with that condition. Mass producing oak forests, on the other hand, are found in both the **Timber and Extra Products** scenario (#2) and the **Timber and Hunting** scenario (#3). Comparisons were continued for each of the measured conditions. It is then a relatively simple matter to rate each scenario against each measurement condition and then determine which scenario does best in satisfying the top-level goals.

We usually learn a lot from this process. We may find that a goal that we selected at the beginning turns out to be unrealistic. We learn this because no matter what we do in any scenario, we simply cannot achieve this particular goal given the resources we are willing to spend and the time we are willing to commit. We then may wish to change our goals or maybe see if we can achieve them in 60 years instead of 40 and thus leave a legacy for our grandchildren. We may also discover through discussions some other ways to manage our property, thus creating another alternative scenario. Such changes are OK, because now it is inexpensive to play "what-if" games with the NED software; to look at different

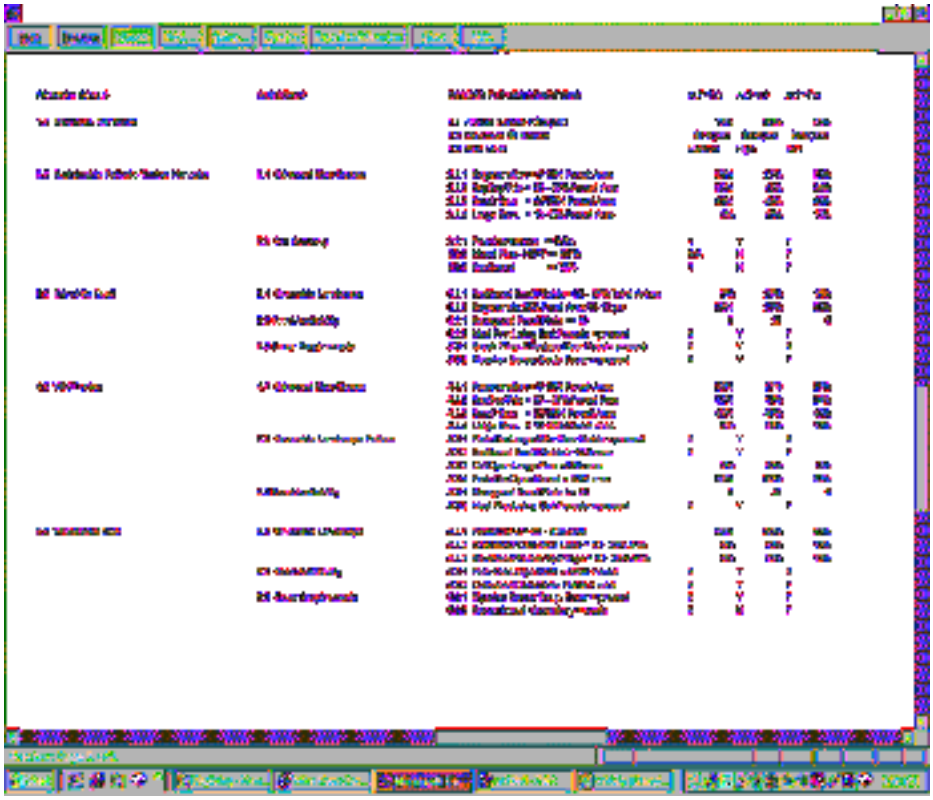

Figure 2—By comparing the outcomes of different management scenarios, you can choose the right management plan to meet your goals.

futures and different goals until we are comfortable with our "final decision." This final decision is of course to be used, but it is only tentative. It is likely that next year or the year after, we as well as our world will have changed enough that our "final decision" may be outdated. But because we have done our homework, know our land, and have increased our understanding, we can go through the NED process again quickly and efficiently.

We have described the NED decision process. This process is currently being field tested in case studies with real users. The NED-2 decision support system is being developed to automate the NED decision process and make it as efficient and easy to implement as possible. Next, we will provide a brief overview of Intelligent Information Systems theory, a description of the NED-2 architecture, and then discuss the implementation issues about how we integrated FVS into the NED Intelligent Information System.

Intelligent Information Systems and the NED-2 Architecture

We view an Intelligent Information System (IIS) as composed of a unified knowledge base, database, and model base. This allows an IIS to provide responses to user queries regardless of whether the query process involves a data retrieval, an inference, a computational method, a problem solving module, or some combination of these (Potter and others 2000). The integration of information sources, whether local or remote, should be transparent to the user. That means after getting user queries, the system itself decides which source(s) need to be accessed.

To add new functionality to a software system, one approach is to integrate additional autonomous, heterogeneous information sources. Because each source is designed to perform a particular task using its own data model, we might need to deal with these issues. First, the data format of the information source may need to be translated to communicate with the other sources. Second, the information source that is developed in a different programming environment should be invoked by appropriate control codes. We might also need to consider how to perform transparent processing so that the users would just focus on their queries without having to consider where the results could be gotten. There are many existing approaches that provide intelligent integration of information, such as a federated database approach (Sheth and Larson 1990), a hierarchical mediator approach (Papakonstatniou and others 1996), a description-logic-based approach (Levy and others 1996), or an ontology-based approach (Cheung and Cheng 1996). Instead of designing and building NED-2 based on a monolithic and predefined solution, we approach the development by creating a loosely organized system that consists of smaller components. Each smaller component performs its own functions within the larger problem-solving framework. Essentially, every component is an external heterogeneous information source composed of an intelligent agent, its associated knowledge base, and whatever source it accesses. By consulting the knowledge base, an external model management agent knows when and how to perform its tasks. Therefore, the use of intelligent agents and knowledge bases makes integration of heterogeneous information sources easier and more flexible.

NED-2 is a blackboard system with semiautonomous intelligent agents. Its blackboard integrates a Microsoft Access database and a set of Prolog clauses. Inventory data and other information are stored in the database. NED-2 includes a user interface, databases, simulators, knowledge bases, hypertext documents, geographical information systems, and visualization tools. Simulators and other external modules are integrated into NED-2 via their intelligent agents (fig. 3).

In an agent-based blackboard system, each agent makes a contribution to the problem-solving process. Agents communicate with each other through a blackboard. Tasks that need to be done are posted to the blackboard. Agents also post most of the intermediate results of their activities to the blackboard. Agents watch the blackboard continually. The information on the blackboard will prompt an agent to do some work. If an agent performs some task listed on the blackboard, it will erase that task from the task list. An agent may place a report that the task has been performed on the blackboard after it completes the task. If an agent begins a task, then discovers that something needs to be done that is beyond its capability, it can put the new task on the blackboard and wait until another agent performs it before completing its original task.

In NED-2, Prolog, a high-level logic programming language, provides the primary implementation platform for agents, knowledge bases, and inference engines. The user interface is implemented in Microsoft Visual C++. The databases are implemented in Microsoft Access. To perform its tasks, an agent may need to retrieve and update the core data on the blackboard. The Prodata LPA Prolog interface (http://www.lpa.co.uk/ind_pro.htm) is used to implement the database access. The Prodata interface provides a tight coupling between LPA Prolog for Windows and all Database Management Systems (DBMSs) that support a sufficient level of Open Database Connectivity (ODBC) compliance to be used with Microsoft ODBC 2. Prodata allows database tables to be accessed from Prolog as though they existed

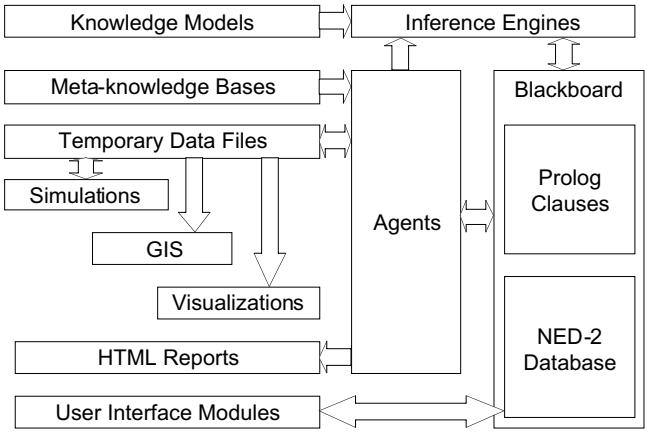

Figure 3—The NED-2 architecture

within Prolog's environment as unit ground clauses (facts). All routine database functions — such as creating tables or updating/retrieving records — may be achieved via normal Structured Query Language (SQL) commands. When an agent needs to get something from the blackboard or put something onto the blackboard, it calls a particular predicate designed to retrieve or update information. If information is already present as facts on the blackboard, it is easy to be accessed or changed. However, if information is stored in the core database, a Prodata SQL query will be constructed to select, update, add, or delete the data values in the database.

The FVS Agents, Wrappers and Meta-Knowledge Bases

The first growth and yield models integrated with NED-2 are the Northeastern and Southern variants of FVS (Teck and others 1997). Simulation agents are designed to set up and call these growth and yield models. The NED user develops management plans using a drag-and-drop scheduling screen (fig. 4). Treatments are selected and dropped onto individual stands. Management plans are stored in the core database. A set of default treatment parameters and user-specified treatment parameters are stored in the core database also. A set of rules is included in the simulation knowledge base. According to these rules, a simulation agent for an external model will determine all the conditions that must be satisfied for the model to function. For example, FVS needs stand information such as stand year of origin, site index species, site index, and basal area. If a condition is not satisfied, the agent will go to the blackboard to see if the message it needs is there. If not, the agent will post a request on the blackboard. Eventually the required message will be posted. Once all conditions are satisfied, the agent will run the external model. Currently the FVS agent needs to invoke the FVS wrapper in order to access FVS. The FVS wrapper creates the FVS key file and FVS tree data file, runs FVS, and then converts the FVS simulation results and inserts them back into the NED-2 database (fig. 5).

Figure 4—The NED management plan screen.

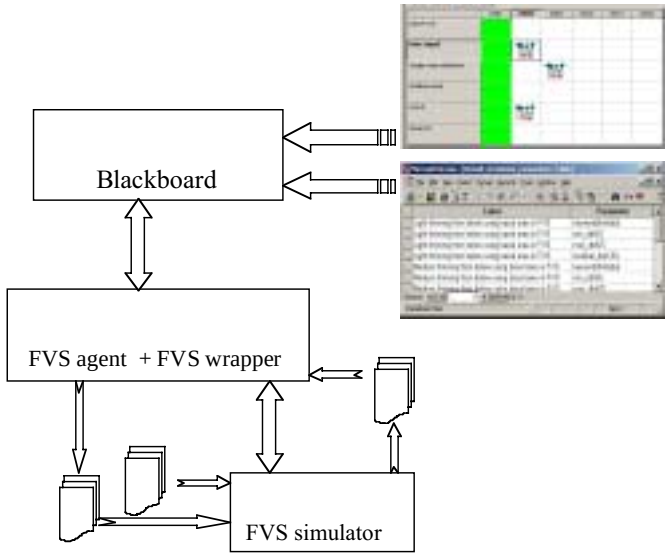

Figure 5—NED/FVS integration.

The FVS Agents

There are two agents related to FVS: the baseline agent and the FVS simulation agent. The baseline agent generates data of the baseline year if necessary (when inventory data are collected in a previous year from the specified baseline year). The baseline agent gets the baseline year value from the blackboard and then checks every stand in the specific management unit under consideration. If the last inventory year for a stand is the baseline year, the baseline agent does not need to take any action. However, if the inventory year is different from the baseline year, the baseline agent will set up a request for the FVS wrapper to run FVS in order to generate the data for the baseline year.

The primary functions of the FVS simulation agent are to retrieve the user's treatment plan and manage the FVS run via the wrapper. A treatment plan includes which stands will be simulated, how long the simulation will run, how to implement the treatment, and when to treat the stand. The FVS simulation agent gets the treatment parameters from the blackboard, then requests the FVS wrapper to simulate the plan.

In addition to these primary functions, there are other functions such as determining which variant to use for FVS and in some cases which region within a variant. If this information is not available on the blackboard, the FVS agent will put a request on the blackboard and the variant agent will respond to this request. Currently, the variant agent is responsible for providing the proper FVS variant information via a graphical interface. It is designed to allow the user to select an appropriate FVS variant (and region). We plan to incorporate a knowledge base into the variant agent that would suggest a variant to the user based on known conditions (such as knowing the State where the stand is located; that is, if the stand is in Vermont, it is likely that the northeastern variant would be utilized). If the user

chooses a variant that is not consistent with the user's inventory data, the agent will issue a warning window to the user to allow an alternate variant to be selected or a warning override. Once the variant is decided, the agent will post appropriate messages on the blackboard.

The FVS Wrapper

In intelligent information systems, a wrapper is an important component. Usually, information sources are heterogeneous (and sometimes distributed). They could (1) be multimedia (video, sound, images, and text), (2) be stored in diverse formats (databases, flat files, or Internet sites), (3) have different data meanings across sources (for example, grade point average might be based on a 4.0 system in one database and a 10.0 system in another), (4) differ in temporal and spatial dimension, and/or (5) be application programs. By building wrappers "around" the heterogeneous information sources, we can communicate with them easily. The function of a wrapper should be to accept the caller's queries and data, convert them into the target-source format, and then pass them on to the target-source for execution. After execution, the results are captured by the wrapper that will transfer them into the format of the caller.

NED-2 is written in LPA Prolog and Microsoft Visual C++. Agents, the callers, are written in Prolog. FVS is written in FORTRAN. We provide an FVS wrapper that permits communication between FVS and agents, and is also written in Prolog. Because the input and output of FVS consists of only plain text files, and NED stores all the data in a Microsoft Access database, the FVS wrapper needs to transfer the data between these two formats.

The FVS wrapper includes three main modules: the MDB to FVS module, the FVS to MDB module, and the NED calculation module. It (1) accesses related stand data in the NED-2 database to create FVS keyword and stand files, (2) runs FVS, (3) converts the FVS simulation results and inserts the results back into the NED-2 database, and (4) runs the NED calculation module to calculate simulation results at the stand level.

MDB to FVS Module —This module takes the stand data, plot data, and tree data from the blackboard and creates a keyword file (*.key) and a set of FVS tree data files (*.fvs).

One of the FVS input files is the keyword file. In NED-2, we completely by-pass the SUPPOSE interface that allows direct FVS users to specify treatments and treatment parameters when running FVS. The values that are included in the keyword file can be retrieved from the NED-2 database and treatment plan.

For keyword related thinning, the parameters will be decided by the treatment plan. The MDB to FVS module takes the plan and then retrieves the corresponding thinning parameter from the treatment parameter database. For example, if the treatment plan is "light thinning from below using basal area in FVS in 2010," and the default values for light-thinning are residual_ba(120), min_dbh(1), and max_dbh(7) in the treatment parameter database, the keyword thinBBA will look like "ThinBBA 2010 120 1 1 7 0 999".

FVS to MDB Module—After running FVS, we have results of the simulation. They are saved in a tree list file (*.trl). This module takes the tree list file as input and inserts appropriate data back to the NED-2 database. The FVS to MDB module selects each line in the tree list file. It checks if the data record for this tree is duplicated. If it is, the record is ignored and processing continues with the next tree record. If it is not, the module gets the values of tree ID, tree species code, tree diameter at breast height, and tree stems per acre. These items are converted to
the NED-2 database format and sent back to the NED-2 database.

NED-2 Calculation Module—The function of this module is to run the NEDCalc.dll. In NED-2, trees are identified by the stand, cluster, and plot that they belong to. Tree data are stored in the overstory and understory tables according to d.b.h. To facilitate the retrieval from the NED-2 database, the FVS wrapper runs the NED calculation module before calling the MDB to FVS module. The NED-2 calculation module then runs several routines that will create a "pseudo_stand" combining all trees in a cluster into one "pseudo_plot". After running the FVS to MDB module, the FVS wrapper calls the NED-2 calculation module again. This time the NEDcalc.dll shuffles the simulation results into the overstory and understory tables, and then computes the other tree data at both the tree level and stand level.

Meta-Knowledge Bases

To make the simulation agents more intelligent, we are creating a meta-knowledge base for simulation agents. Meta-knowledge is knowledge about knowledge. Different simulators require different formats for input data and generate output data differently. Wrappers can provide data translation. But on the one hand, for each specific simulator, we have to build a corresponding wrapper in order to set up and run the simulator. On the other hand, these simulator wrappers include some common procedural knowledge. Therefore, it is desirable to develop a meta-knowledge base. Simulation agents will use this meta-knowledge base to know when and how to use a knowledge source. For example, by consulting the meta-knowledge base, the simulation agents will know how to convert NED-2 data into the format FVS can accept, how to set up control codes for FVS, and how to convert output from the FVS format back into the NED-2 format. So all procedural knowledge for running simulators will be provided by the simulation agent, and specific knowledge needed to run individual simulators will be stored in the meta-knowledge bases.

Conclusions

We have described the FVS integration process for NED-2. Our blackboard architecture based on intelligent agents makes integration of information sources easy, fast, and more powerful. Our future work is to build more intelligent simulation agents. Other simulation models, such as Silvah (Marquis and Ernst 1992), will be integrated in NED-2. Simulation agents will consult meta-knowledge to know when and how to access related sources (FVS, Silvah, or

other integrated simulators). NED-2 will be able to respond to high level queries, such as "Show me how Stand 10 will look in 25 years if I remove all hardwoods under 6 inches in diameter today." The simulation agent will reformat the original user query and run an appropriate growth and yield model according to the meta-knowledge base. This allows seamless database, knowledge base, and model base interaction that is transparent to the user. The point is to increase the intelligence of the software to reduce the complexity that the user has to overcome. For further information on NED, please visit NED Web site at http://www.fs.fed.us/ne/burlington/ned.

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Use of the Forest Vegetation Simulator in Determining Optimal Forest Rotation Settings for Abandoned Mined Lands in Appalachia

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Gary D. Kronrad
Ching-Hsun Huang
Don Vandendriesche

Abstract—Approximately 1 million acres of abandoned mined lands exist in the Appalachian coal region. Reclamation and afforestation of these sites may be conducted if it is profitable or if losses can be minimized. Calculating profitability requires a determination of the optimal thinning and harvesting schedule that maximizes financial return. The Forest Vegetation Simulator was used to determine the best management regime by simulating stand growth for northern red oak (*Quercus rubra*). Soil expectation value, calculated with real alternative rates of return ranging from 0.0 to 12.5 percent, was used as the investment criterion. Results indicate that when reclamation costs are low, afforestation can be profitable only when a landowner's real alternative rate of return is 0.0 percent and one thinning is conducted with a final harvest age of 100, at 2.5 percent with two thinnings and a final harvest age of 100, and at 5.0 percent with one thinning and a final harvest at 80 years. Afforestation can be profitable with high reclamation costs only when the alternative rate of return is 0.0 percent and one thinning is conducted with a final harvest at age 100, and at 2.5 percent with two thinnings and a final harvest age of 100.

Appalachia and Abandoned Mined Lands

The Appalachian coal region of the Eastern United States extends from Pennsylvania to Alabama. Of this region, according to the Office of Surface Mining (OSM) (USDI-OSM 2000), there are approximately 1 million acres of land classified as abandoned mined lands (AML) (fig. 1). AML sites are inadequately reclaimed mine sites occurring before passage of the 1977 Surface and Mining Control and Reclamation Act (SMCRA); no Federal or State laws exist that require any further reclamation responsibility to any company or individual (USDI-OSM 2002).

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The many problems associated with Appalachian AML sites range from dangerous highwalls causing landslides to underground mine fires causing the release of smoke, haze, heat, or hazardous gases. In an effort to combat the problems present on these lands, OSM has set up the following five AML reclamation priority levels:

- Priority 1—the protection of public health, safety, general welfare, and property from extreme danger of adverse affects of past mining practices.

Figure 1—Abandoned mined lands within Appalachia.

- Priority 2—the protection of public health, safety, general welfare, and property from adverse affects of past mining practices.
- Priority 3—the restoration of land and water resources and the environment previously degraded by adverse effects of past mining practices including measures for the conservation and development of soil, water, woodland, fish, wildlife, recreation resources, and agricultural productivity.
- Priority 4—the protection, repair, replacement, construction, or enhancements of public facilities such as utilities, roads, recreation, and conservation facilities adversely affected by past mining practices.
- Priority 5—the development of publicly owned land adversely affected by mining practices including land acquired for recreation and historic purposes, conservation, and reclamation and open spaces (USDI-OSM 2002).

The correction of these problems can be costly, in some cases more than $100,000 per acre. Therefore, OSM has become interested in developing environmentally sound least-cost reclamation methods. Planting trees can be a perfect reclamation tool to achieve this goal for several reasons. First, the Appalachian region has the largest contiguous, temperate hardwood forest in the world (Smith 1995), so restoration with trees can create a landscape that is closer to the premined state. Reclamation with trees can also increase environmental benefits to the surrounding communities by increasing soil pedogenetic processes, enhancing recreational opportunities, and creating more wildlife habitat. Another reason why trees can be presented as a perfect reclamation tool is their ability to withstand pH levels lower than that of other vegetation (Vogel 1981). Trees can also provide landowners with cyclical revenues from forest product sales and effectively reduce the overall cost of reclamation. As a result, economic stimulus can be created within surrounding communities.

Methods

Reclamation and afforestation of AML sites at a least cost requires the determination of the optimal forest rotation setting that maximizes financial return. This study was designed to determine the optimal thinning and harvesting schedules for northern red oak (*Quercus rubra*), one of the major commercial tree species within this region, on AML sites in Appalachia. The Forest Vegetation Simulator (FVS) was used to simulate stand growth data on diameter, height, and volume, for stands from establishment to final harvest. FVS, in conjunction with the Keyword Iteration Navigator (KIN) (an FVS preprocessor that allows a user to input minimum, maximum, and increment values for any one keyword), was combined with an economic program to calculate cash flow tables, net present worths (NPW), and soil expectation values (SEV). This dynamic program was developed to simultaneously determine the financially optimal timing and intensity for thinning(s) and the financially optimal rotation age for northern red oak.

Site index 80 (base age 50) land was examined in this pilot study. The maximum rotation age was set at age 100 with a choice of zero, one, two, or three thinnings during the rotation. The method used for thinnings was a percent of basal area removal from below. The first thinning could not be conducted until the stand was at least 30 years of age. The minimum years between thinnings, or between a thinning and final harvest, could not be less than 15 years. For all of the dynamic computer runs, a "thinning and final harvest" regime would be considered to be operable only if (1) each thinning or final harvest yielded a minimum of 10 cords (960 ft^3), (2) each thinning or final harvest yielded a minimum of 1,500 Doyle board feet (1995 Scribner board feet), or (3) each thinning or final harvest yielded a minimum combination of 5 cords (480 ft^3) and 750 Doyle board feet (997 Scribner board feet). A minimum of 80 residual trees was required after each thinning operation. Four thinning intensities, 25, 30, 35, and 40 percent basal area removal from below, were conducted for each possible thinning regime.

Six real alternative rates of return (ARR) were chosen for the economic analyses: 0.0, 2.5, 5.0, 7.5, 10.0, and 12.5 percent. The annual real price increase of sawtimber and pulpwood were assumed to be 2.5 and 2.0 percent, respectively. The price of sawtimber was assumed to be $255 per 1,000 Doyle board feet ($191.25 per 1,000 Scribner board feet), and pulpwood was priced at $9.00 per cord ($0.09375 per ft^3). The cost for marking and administering a pulpwood or sawtimber sale was assumed to be 10.0 percent of the gross sale. Two sets of establishment costs were used in these analyses. The first set was for the case when little to no reclamation was conducted, and a cost of $225 per acre for seedlings and planting was used. The second set of establishment costs included a $1,100 per acre reclamation cost used to correct erosion and pH problems, and a $225 per acre cost for seedlings and planting. It was assumed that the environmental engineering problems associated with some abandoned mined lands have been corrected, and these lands are ready for forestry practices.

Economic Approach

SEV was used as the efficiency criteria to select the most profitable thinning and harvesting schedule. SEV is the NPW of bare forestland for timber production over a perpetual series of rotations. NPW is the sum of the discounted revenues minus the sum of the discounted costs of a project (Gregory 1987). SEV is used to compare forest investments of different rotation lengths. For each real ARR, the management regime with the highest SEV was chosen as the optimal forest rotation setting.

Results

A total of 144,066 thinning and harvesting combinations, NPWs, and SEVs were calculated. The optimal forest rotation settings that maximize SEV for each real ARR are presented in table 1, and the NPWs for each real ARR with low reclamation costs and high reclamation costs are presented in tables 2 and 3, respectively. All monetary values are presented on a per acre basis.

Table 1—Optimal forest rotation settings that maximize soil expectation value for northern red oak site index 80 (base age 50).

Real alternative rate of return	Thinning year(s)	Thinning[b]	Final harvest year
percent		*percent*	
0.0	51	25	100
2.5	47-82[a]	30	100
5.0	59	25	80
7.5	41	40	74
10.0	40-55	40	70
12.5	40-55	40	70

[a]First number indicates first thinning year; second number indicates second thinning year.
[b]Basal area removed from below during thinning(s).

Table 2—Net present worth of the optimal forest rotation settings for northern red oak site index 80 (base age 50) with low reclamation costs.

Real alternative rate of return	Net present worth
percent	*dollars per acre*
0.0	70,470
2.5	6,108
5.0	448
7.5	–110
10.0	–206
12.5	–219

Table 3—Net present worth of the optimal forest rotation settings for northern red oak site index 80 (base age 50) with high reclamation costs.

Real alternative rate of return	Net present worth
percent	*dollars per acre*
0.0	69,370
2.5	5,008
5.0	–652
7.5	–1,210
10.0	–1,301
12.5	–1,319

0.0 Percent Real ARR

The optimal forest rotation setting when the landowner's ARR is 0.0 percent requires that a thinning should be conducted at stand age 51, removing 25 percent of the basal area from below, and the final harvest should be conducted at age 100 (table 1). This optimal management regime would generate an NPW of $70,470 per acre when reclamation costs are low (table 2) and an NPW of $69,370 per acre when reclamation costs are high (table 3). These NPW values indicate that the landowner who followed this management regime, over one rotation, would earn 0.0 percent on every dollar invested plus $70,470 per acre if reclamation costs are low, or 0.0 percent plus $69,370 per acre if the reclamation costs are high.

2.5 Percent Real ARR

For landowner's who have a real ARR of 2.5 percent, the optimal thinning and harvesting schedule requires the first thinning at age 47 and the second thinning at age 82. At each thinning, 30 percent of the basal area should be removed. The final harvest should be conducted at age 100. The NPWs for this thinning and harvesting schedule are $6,108 per acre with low reclamation costs and $5,008 per acre with high reclamation costs.

5.0 Percent Real ARR

For landowners who have real alternative rates of return of 5.0 percent, the optimal thinning and harvesting schedule requires that 25 percent of the basal area should be removed at age 59, and a final harvest should be conducted at stand age 80. With low reclamation costs, the NPW for the optimal forest rotation setting is $448 per acre. If reclamation costs are high, the NPW would be –$652 per acre.

7.5 Percent Real ARR

If a landowner's real ARR is 7.5 percent, the optimal thinning and harvesting schedule requires that a thinning should be conducted at age 41, in which 40 percent of the basal area should be removed. The final harvest should be conducted at age 74. This optimal schedule would generate an NPW of –$110 per acre when reclamation costs are low, and an NPW of –$1,210 per acre when reclamation costs are high.

10.0 Percent Real ARR

If a landowner has a real ARR of 10.0 percent, the optimal forest rotation setting shows that the first thinning should be conducted at stand age 40, a second thinning at age 55 (removing 40 percent of the basal area during thinnings), and a final harvest at age 70. This thinning and harvesting schedule would yield an NPW of –$206 per acre when reclamation costs are low, and an NPW of –$1,301 per acre when reclamation costs are high.

12.5 Percent Real ARR

When 12.5 percent is the landowner's real ARR, the optimal thinning and harvesting schedule is the same as the 10.0 percent ARR; a first thinning is conducted at age 40 and a second thinning at age 55. At each thinning, 40 percent of the basal area should be removed. The final harvest should be at stand age 70. The NPWs for this thinning and harvesting schedule are –$219 per acre for low reclamation costs and –$1,319 per acre for high reclamation costs.

Conclusions

The profitability of reclaiming and afforesting AML sites is highly dependent on the landowner's real ARR and the site's productivity, or site index. The use of the optimal forest rotation setting methodology allows a landowner to answer the two basic questions in any profit-maximizing forestry related project: (1) How should I manage my stand, and (2) How profitable will it be? Results indicate that reclaiming and afforesting AML with northern red oak can be a profitable investment when a landowner's real ARR is 0.0 or 2.5 percent, regardless of reclamation costs, or 5 percent when reclamation costs are low. Although there is a net loss in profit when higher ARRs are used, the positive externalities generated from reclaiming these sites may exceed the negative environmental effects present on these AML sites.

Every site has specific reclamation needs. Successful reclamation and afforestation requires a thorough understanding of critical species-site relationships. Future analyses will investigate the potential of reclaiming AML sites with northern red oak and white oak (*Quercus alba*) for site indices ranging from 40 to 80 (base age 50) across the Appalachian coal region.

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Linking Tools of Forest and Wildlife Managers: Wildlife Habitat Evaluation Using the Landscape Management System

Kevin R. Ceder
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Abstract—Natural resource managers are increasingly being asked to consider values outside their fields. This is especially evident with regards to wildlife habitat changes caused by forest management activities. Forest managers are being asked to balance both wildlife habitat and forest product outputs from the forest. Our approach of implementing a Habitat Evaluation Procedure as a module of the Landscape Management System is an example of how forest growth and yield models can be integrated with existing wildlife models to expand the forest manager's tool set. The Landscape Management System uses the Forest Vegetation Simulator to simulate forest growth and changes caused by silvicultural activities on the Satsop Forest ownership, located in southwestern Washington State. The Habitat Evaluation Procedure module then calculates Habitat Suitability Indexes and Habitat Units for Cooper's hawk (*Accipiter Cooperii*), pileated woodpecker (*Drycopus pileatus*), southern red-backed vole (*Clethrionomys gapperi*), and spotted towhee (*Pipilo erythrophthalmus*) from the resulting projected forest inventories. The result is a tool that allows forest managers to assess changes in wildlife habitat caused by potential forest management at the stand and ownership levels. Because the Landscape Management System produces summaries of a variety of forest outputs, both tabular and visual, the results can then be used in analyses of existing and proposed forest management plans. On a stand-by-stand basis, multiple silvicultural pathways can be tested to assess which pathways meet varying desired habitat and forest product outputs. Through the use of stand and ownership level simulations and analyses of multiple target outputs, forest managers and decisionmakers are able to better understand output tradeoffs at the landscape and watershed levels.

The public has become increasingly concerned over the past three decades about potential negative effects on wildlife caused by development and other modifications of wildlife habitat. Conversion of naturally regenerated forests to intensively managed plantations for timber production has raised concerns about habitat for species that are associated with these forest structures at the present time and in the future. While planning current and future forest management activities, forest managers are being asked to address how management will affect forest systems in the coming decades.

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As concern grows and more species are studied, many of these species become candidates for special consideration ranging from a "species of concern" at the State level, such as the pileated woodpecker (*Dryocopus pileatus*) in Washington State, to "threatened" or "endangered," such as the northern spotted owl (*Strix occidentalis caurina*) in the Pacific Northwest, the red-cockaded woodpecker (*Picoides borealis*) in the Southeast, and the Kirtland's warbler (*Dendroica kirtlandii*) in the Lake States region, at both the State and Federal levels. Listing of these species resulted in regulatory constraints on forest management. Changes in Federal forest management in the Pacific Northwest under the Northwest Forest Plan to protect old forest habitat and the spotted owl exemplify the regulatory constraints. Harvest on Pacific Northwest National Forests has virtually stopped.

Technology has increased greatly during this time as well. Computing power has greatly increased, and forest growth and yield models, such as the Forest Vegetation Simulator (FVS), have been developed to predict forest growth and development though time. Using these tools, forest managers can estimate potential harvest volumes and tree sizes in the future. From initial forest inventory data and simulated future data, managers create forest management plans based on criteria such as allowable harvest volume or stand structures, now and in the future, calculated from stand attributes such as tree species, sizes, and volumes. As demands on forests change, managers must estimate effects on other forest outputs such as wildlife habitat. Using a simulation system that includes wildlife habitat models, it may be possible for managers and other interested parties to gain insight into how current forest management may affect future forest outputs and ensure forests are managed in a sustainable manner.

This study implements a Habitat Evaluation Procedure (HEP; USDI 1980a) within the Landscape Management System (LMS) for two reasons: first, to develop tools to support analysis of new management alternatives for Satsop Forest. Any analysis must be consistent with the original Satsop Forest HEP (Curt Leigh personal communication) to ensure comparable results. The original Satsop Forest HEP was performed on Satsop Forest, formerly the Satsop Nuclear Site, to assess losses of wildlife habitats caused by construction of two nuclear power plants and to analyze management plans to mitigate for lost habitats. Second, because Habitat Suitability Index (HSI) models and the HEP use, primarily, tree-based measures, the HEP is used in this study to demonstrate linking wildlife habitat models with forest growth models within a forest simulation system.

Background

Several methods have been used to assess changes in quality and quantity of wildlife habitat caused by forest management and disturbances. These have included HSI models implemented within a GIS, optimization systems, population density models, and the HEP. Kliskey and others (1999) used GIS-based HSI models for woodland caribou (*Rangifer tarandus*) and pine marten (*Martes americana*) in the North Columbia Mountains of British Columbia, Canada. This study examined changes in habitat quality and quantity for both species as well as harvested volume under four simulated forest management scenarios to assess amounts of habitat generated by each scenario, tradeoffs of habitats among species for each scenario, and tradeoffs between habitat quantity and harvested volume. Moore and others (2000) used an optimization technique, which employed a "genetic algorithm," to optimize harvest scheduling on a simulated landscape based on bird populations derived from population models for hypothetical species. Beavers and Hof (1999) took a different approach by spatially optimizing the amount of edge habitat to maintain populations of both edge and interior habitat species. Hansen and others (1995) constructed population density response models for 16 species of birds in the Central Oregon Cascades that used densities of trees in specific diameter classes to estimate population densities. With these models several silvicultural pathways were simulated with the ZELIG growth model (Urban 1992) and the outputs were used to estimate the resulting population densities. The HEP is a methodology used to assess impacts to wildlife habitats caused by projects such as power plant construction where wildlife habitat is used as "currency" in an accounting system. Initially developed in the 1970s, this system is still in use today.

Study Location

Satsop Forest encompasses roughly 1,400 acres south of the Chehalis River in southwestern Washington State (fig. 1) owned by the Grays Harbor Public Development Authority (PDA). About 840 acres are forested, and 220 acres are in grassy meadows, shrubs, or riparian areas and not included in timber management analysis. The remaining 340 acres are part of the developed infrastructure of the Satsop Development Park. Elevation is relatively constant at 250 feet, and forest productivity is moderate to high (56 percent of the forest is Site Class II, Site Index 115 to 135 feet (King 1966)). Stands range from pure conifer to pure hardwood, but most are complex mixtures of Douglas-fir (*Pseudotsuga menziesii*), big leaf maple (*Acer macrophyllum*), western hemlock (*Tsuga heterophylla*), red alder (*Alnus rubra*), and western redcedar (*Thuja plicata*). Most of the area is covered by forest 5 to 10 years old; forests greater than 120 years are present in small proportion on the site (Marzluff and others 2002).

Currently, Satsop Forest management is dictated by a wildlife mitigation agreement. This agreement was put in place to mitigate for wildlife habitat losses caused by the partial construction of Washington Public Power Supply System's Nuclear Plants No. 3 and No. 5. Even though this agreement was created prior to the PDA's acquisition of the land, it is still in force, providing management prescriptions through the year 2040.

The PDA's management objectives for Satsop Forest extend beyond strictly the creation and enhancement of wildlife habitat (Jim Walls, personal communication). There is a desire to create a demonstration forest where alternative silvicultural practices that create both wildlife habitat and income can be showcased to other landowners with the primary focus being nonindustrial private forest (NIPF) owners. Income is important because the trees on forestland are often an investment for the owner.

Original Satsop Forest HEP (WPPSS 1994)

Performing the original HEP on Satsop Forest involved several steps. First a vegetation cover type inventory of the area was undertaken using aerial photographs with associated criteria (percent canopy closure, percent conifer/deciduous, average d.b.h., average height, total trees per acre, trees per acre greater than 21 inches d.b.h., and number of canopy layers) used to determine cover types. Next, a set of species for the analysis was selected, followed by Habitat Suitability Index (HSI) model selections and a habitat attribute inventory. Several potential management scenarios were then drafted for the area, with forest cover type changes estimated. Habitat Suitability Index values were then calculated for each cover type that was expected to be found on Satsop Forest at specific future target years. For each target year, cover type acreages, HSI, and Habitat Unit (HU) values for each species were calculated. For the life of each

Figure 1—Location of Satsop Forest in southwestern Washington.

alternative, Annual Average Habitat Unit (AAHU) values were calculated to estimate average available habitat quantities. AAHU values were compared between alternatives to select the "preferred" management alternative.

We found 21 cover types on Satsop Forest including "Developed" and "Barren" ground that are not considered as wildlife habitat. There are three riparian cover types as well as ponds, grass, and brush. Nonriparian forested areas that can be managed fit into 13 cover type classifications.

Five species and associated HSI models were selected for the HEP analysis: Cooper's hawk (*Accipiter cooperii*; USDI 1980b), southern red-backed vole (*Clethrionomys gapperi*; Allen 1983), pileated woodpecker (*Dryocopus pileatus*; Schroeder 1983), spotted towhee (*Pipilo erythrophthalmus*; USDI 1978), and black-tailed deer (*Odocoileus hemionus columbianus*; WDFW 1991). Each species was chosen for a specific reason (WPPSS 1994). Cooper's hawks tend to prefer hardwood and mixed conifer-hardwood forests in both upland and riparian habitats. Southern red-backed voles were chosen to represent small forest rodents. They prefer mature and older forest structures and are a prey species for forest raptors and owls. Pileated woodpeckers were selected to represent cavity nesters. They are the largest of the woodpeckers and require larger snags than other cavity nesters; and they are listed as a Washington State "species of concern." If habitat exists for pileated woodpeckers, it is assumed that smaller cavity users such as nuthatches, flying squirrels, and bats will have habitat as well. Spotted towhees prefer open structures with dense shrub layers, such as brush lands and young forests. Black-tailed deer use multiple habitats and are of concern to the public and wildlife management agencies as a game species.

All HSI models chosen for the Satsop Forest HEP require tree-based measures, such as canopy closure, overstory d.b.h., and number of trees with d.b.h. greater than 21 inches per acre, and all the HSI models, except the Cooper's hawk, also require non-tree-based measures, such as downfall litter, downed logs per acre, and grass cover. All attributes were inventoried on Satsop Forest in 1991 and used in the original HEP analysis. Based on average habitat attribute values for each cover type, HSI values were calculated for each species for each cover type on Satsop Forest. Cover type acreages were calculated for all the target years based on estimated forest changes caused by growth and potential management alternatives. These acreages were used with the HSI values to calculate HU values and AAHU values for each species. Changes in AAHU values between alternatives were used as the deciding factor in selecting the preferred mitigation alternative for the mitigation agreement.

Landscape Management System

The Landscape Management System (LMS) is an integrated forest management simulation and decision analysis software package developed as a cooperative effort between the Silviculture Laboratory, College of Forest Resources, University of Washington, and the USDA Forest Service (McCarter and others 1998). LMS is an evolving application designed to assist in stand and landscape ecosystem analyses by coordinating the processes of forest growth and management simulations, tabular data summarization, and stand and landscape visualization. Implemented as a Microsoft Windows™ application, many separate programs integrate these tasks. These programs include forest growth models, harvest simulation programs, and data summary programs, as well as stand and landscape level visualization software.

Underlying data for LMS are consolidated into a landscape portfolio. These data include forest inventory data (stand-by-stand tree list); stand level data (such as site index and age), and topographic data (slope aspect and elevation), as well as geographic information system (GIS) data in the form of a digital terrain model (DTM), ESRI (Environmental Systems Research Institute, Inc., Redlands, CA) shapefiles of stand boundaries, and other features such as streams and roads. This assemblage of data is then used by LMS to simulate, analyze, and communicate the effects of forest management on the landscape.

Summary output tables from LMS range from standard inventory tables, to stand structural stages, to harvested and standing volumes. All tables are summaries of current and projected inventories for analyses of predicted future conditions and forest outputs. The large array of tables allows analyses of proposed forest management from many perspectives.

Habitat Evaluation Procedure (HEP) Implementation within LMS

Given the similarities between HSI model input data and LMS output data and the modular, integrative nature of LMS, implementation of an HEP was a process of codifying the graphical HSI models and cover typing rules and creating the computer programs needed to read LMS output files, generate model input data, perform cover typing and HSI calculations, and create HEP output files. This was done using the Python programming language (URL: http://python.org). The LMS implementation of the Satsop HEP consists of cover typing and four of the five original HSI models. Because of the spatial nature of the black-tailed deer model and the lack of spatial metrics in LMS output, it cannot be implemented directly in LMS.

HSI Model Implementation

HSI models contain several component variables that contribute to the total habitat suitability for a species. Each component variable has its own graphical relationship between that habitat attribute and that attribute's contribution to the overall HSI value. Each of these component HSI's varies from 0.0 to 1.0. When each component HSI has been estimated, an overall HSI is determined by geometric averages or minimum values, depending on the relative importance of attributes to the particular species. The HSI model for Cooper's hawk (fig. 2) is an example of the graphical model.

To be used in a computerized simulation system, HSI models must be converted into piecewise equations. An

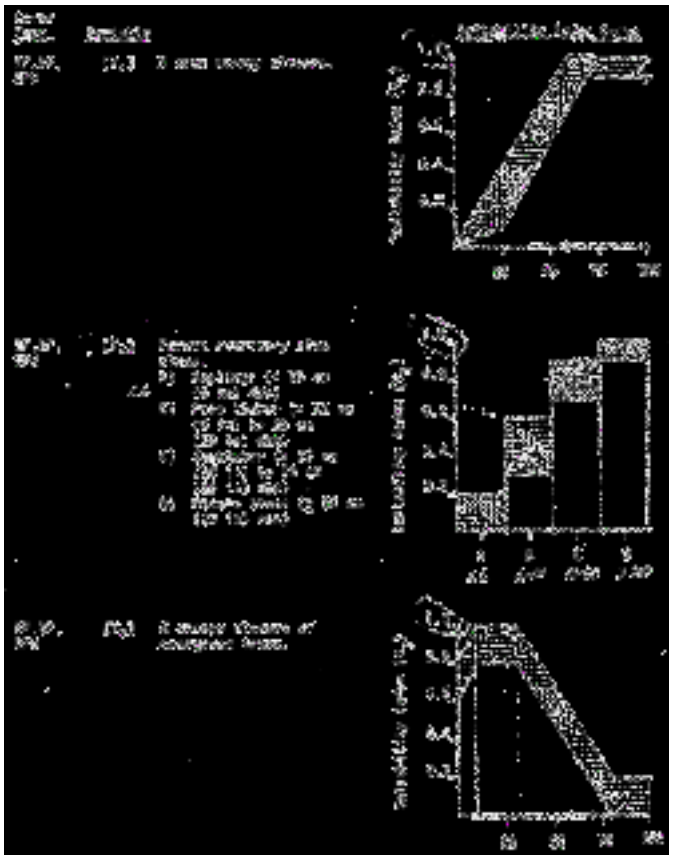

Figure 2—Cooper's hawk Habitat Suitability Model from USDI (1980b)

example of this are the equations for the Cooper's hawk HSI model as implemented in the Satsop HEP module of LMS:

Variable 1 (V1) – % Canopy closure
Input – % Canopy closure (CC)
V1 = 1/60 * CC, where CC ≤ 60
V1 = 1, where CC > 60

Variable 2 (V2) – Overstory size class
Input – Average DBH (ADBH)
V2 = 0.2, where ADBH ≤ 6
V2 = 0.6, where 6 < ADBH ≤ 10
V2 = 0.9, where 10 < ADBH ≤ 20
V2 = 1, where ADBH > 20

Variable 3 (V3) – % Conifer canopy closure
Input – % Conifer canopy closure (CCC)
V3 = 0.8 + 0.2/10 * CCC, where CCC ≤ 10
V3 = 1, where 10 < CCC ≤ 30
V3 = 1 – 0.8/50 * (CCC – 30), where 30 < CCC ≤ 80
V3 = 0.2, where CCC > 80

HSI = Lesser of: $(V1 * V2)^{1/2}$ or V3

Cover Type Rule Implementation

Generating the algorithm to perform the cover typing required writing a series of "if" statements based on the rules in table 1. Within each "if" is a series of "and" statements to test all criteria required for each cover type. If all criteria are satisfied, the stand is assigned that cover type. If any one criterion is not satisfied, the algorithm moves to the next cover type. The process continues until the stand satisfies all criteria for a cover type or ends in the catchall "Brush" cover type.

HEP Input Data Generation

Cover types and HSI model implemented within LMS require LMS generated data. These data come from two sources: (1) Tree-based measures (total canopy closure, conifer canopy closure, percent conifer/deciduous, dominant height, average d.b.h., overstory d.b.h., trees per acre, trees per acre with d.b.h. greater than 21 inches, and canopy layers) are calculated from initial and simulated future tree lists. (2) Non-tree-based data (downfall litter, grass cover, stumps per acre, logs per acre, snags per acre with d.b.h. greater than 21 inches, average d.b.h. of snags with d.b.h. greater than 21 inches, total ground cover, and a Shrub Suitability Index) are taken from a lookup table based on the cover type of the stand.

Calculation of tree-based data is performed using algorithms within LMS plus implementations of the canopy closure equation published by Crookston and Stage (1999) and the canopy layers algorithm published by Baker and Wilson (2000). All tree based measures are calculated then stored for use by the cover typing and HSI calculation algorithms.

Extracting the non-tree-based measures from the lookup table is done after the stand has been assigned a cover type. Within the lookup table there are habitat attribute values, from the 1991 habitat attribute inventory, presented as cover type averages. The non-tree-based data extraction algorithm reads the cover type of a stand then retrieves the non-tree-based values and stores them to be used by HSI calculation algorithms.

After all HSI model inputs have been generated, HSI calculations are performed for each species chosen for the analysis. The results are relative measures, on a 0.0 to 1.0 scale, of habitat suitability for each stand for each species. Habitat suitability is analogous to habitat quality. Estimating the amount of potential available habitat is done by multiplying the HSI value by the acreage of the stand resulting in HU values. HU values are a relative measure of available habitat where a value of 50 may be 50 acres of optimal habitat, with HSI of 1.0, or 500 acres of poor habitat, with an HSI value of 0.1. HU values can then be summed across the entire landscape to get a relative measure of available habitat for the species used in the analysis. Estimating the amount of habitat available over the life of the simulation is done with Average Annual Habitat Units (AAHU).

Table 1—Timbered cover type thresholds for Satsop Forest from the original HEP.

Cover type	Description	Canopy closure	Percent conifer	Percent deciduous	TPA	TPA >21" d.b.h.	Avg. d.b.h.	Avg. height	Canopy layers
		- - - - - - - - - - *Percent* - - - - - - - - - -					*Inches*	*ft*	
C4	Conifer late-successional	>70	>75			20	≥21	>40	3
C4T	Conifer late-successional, thinned	<70	>75				≥21	>40	
C3	Mature conifer	>70	>75				12-21		
C3T	Mature conifer, thinned	<70	>75				12-21		
C2	Conifer pole/sapling	>50	>75				4-12		
C1	Early-successional conifer	>50	>75		≥150		1-4		
M3	Mature mixed	>70	<75	<75			12-21	>40	
M2	Mixed pole/sapling	>50	<75	<75			4-12		
M1	Early-successional mixed	>50	<75	<75			1-4		
H3	Mature deciduous	>50		>75			12-21	>40	
H2	Deciduous pole/sapling	>50		>75			4-12		
H1	Early-successional deciduous	>50		>75			1-4		
B	Brush	<50							

Satsop Forest HEP Output Tables

Output tables from the HEP analysis performed by LMS are designed to be compatible with the tables used in the original Satsop Forest HEP. In addition, there are other summary tables and tables formatted to be imported into ESRI ArcView for mapping of cover types and habitat suitabi1ty values. Four cover type output tables are available: cover type designation for each stand for each year of the simulation with acreage for each stand; summary of acreage in each cover type for each year of the simulation; cover type by stand for each year of the simulation and the acreage summary; and a table to be imported into ESRI ArcView. Seven habitat-related output tables are available: HSI, HU, By Species, HSI Summary, AAHU, All HEP tables, and an HSI table to be imported into ESRI ArcView for mapping habitat suitability. This suite of tables will allow the analysts and managers to answer many questions regarding habitat suitability and availability.

Validation

To assess the performance of the models implemented in LMS, it was necessary to use data, both tree-based and non-tree-based, from the original HEP to calculate HSI values for the four species. When compared with the HSI values calculated during the original HEP, differences range from –0.009 to 0.001. A paired t-test on the differences between HSI values reported in the original HEP and those calculated with LMS using data from the original HEP was performed using the statistical analysis software package SPSS 10.0. Mean differences range from 0.000 – 0.001 with all 95 percent confidence intervals containing 0.0 (fig. 3). Results from the Cooper's hawk HSI model, using the original HEP data, could not be analyzed using the t-test because the model predicted the exact HSI values that were reported in the original HEP analysis. The resulting mean difference of 0.0 with a standard error of the mean of 0.0 does not allow the paired t-test to be used. Because all 95 percent confidence intervals contain 0.0, the models predict as well as the original HSI models at the 0.05 level.

Given these results it can be said that the HSI models, as implemented in LMS, predicted HSI values as well as the original HSI models and using updated forest inventory data summarized on a per stand basis made no significant difference in HSI values for each cover type.

Applications of the Satsop Forest HEP Using LMS

LMS with the HEP module is currently being used to develop potential management alternatives for Satsop Forest that will be used in wildlife mitigation agreement renegotiations. Development of management alternatives involves two processes: stand-level analyses and landscape-level analyses. These analyses allow the manager to examine tradeoffs between habitat values and other

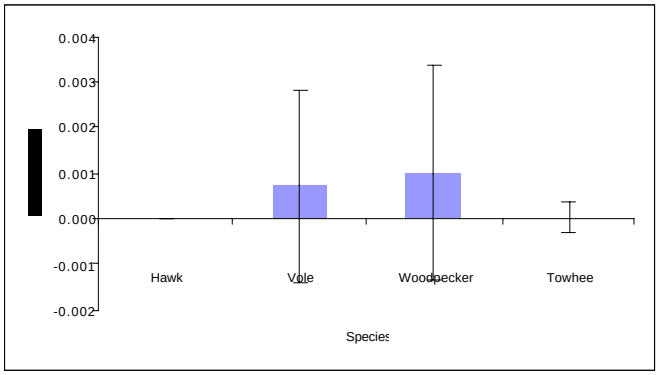

Figure 3—Mean difference between HSI values reported in original HEP and values calculated by LMS using original HEP data, with 95 percent confidence intervals.

outputs from many stand-level silvicultural pathways and landscape level management plans. Performing stand-level analyses allows planners and managers to screen potential silvicultural pathways based on habitat quality, potential harvest volume, or other criteria. Preferred pathways are assigned to specific stands to create a landscape-level management plan. Landscape-level analyses of the management plan assess potential consequences of applying the plan on the landscape.

Management of Satsop Forest is constrained by the requirements of a wildlife mitigation agreement. Any alternative management plans must meet the habitat levels of the current management plan. Screening potential alternative silvicultural pathways was done with four stands: two 10-year-old stands, with 435 t.p.a. and 1350 t.p.a, and two 90-year-old stands, open stand with a single canopy layer and dense stand with multiple canopy layers. Thirty pathways were simulated using the young stands, and 21 pathways were simulated using the older stands. Many of the pathways were taken from previous studies that assessed the effect of timber harvesting on habitats or populations in other areas of the Pacific Northwest (CCEM 1993; DeBell and Curtis 1993; McComb and others 1993; Hansen and others 1995; Carey and others 1996; Barbour and others 1997). Based on the results of these simulations, the pathways that produced the highest habitat levels for individual species or highest harvest volume, regardless of habitat provided, were selected. Examples of the pathways that produce the highest levels of habitat and harvest volume are shown in table 2. It should be noted that different pathways provided different amounts of habitat or harvest volume. If a land manager is to balance providing habitat for many species and produce harvest volume, one silvicultural pathway cannot be applied on all acres of a landscape. Designing landscape level plans from simulated pathway results can be done with a spreadsheet known as "the Toggle Program" (Johnson 2001) that allows managers to assess tradeoffs between many objectives by apportioning different amounts of the landscape acreage to different pathways.

Landscape-level management alternatives are analyzed to assess consequences of applying the management plan on the landscape. Questions such as "How much habitat is available?" and "How much timber volume is being harvested?" can be answered for the entire landscape. Tradeoffs between average harvest volume and average available habitat for each species can be assessed for the life of the management plan (table 3). Flows of habitat can be examined as well (fig. 4). Flows of habitat are important to avoid "boom-and-bust" cycles of habitat and species populations. AAHU values do not address potential changes in habitat availability over the life of the management plan.

Advantages of Integrating HEP and LMS

Implementing the HEP calculations in LMS provided several advantages. First, because an empirical growth model is used, all assumptions are held constant for all forest

Table 2—HSI and harvest volume (m.b.f.) values and top five pathways for individual pathway simulations using young dense stand.

	Hawk	Vole	Woodpecker	Towhee	Harvest volume
Max	0.614	0.968	0.651	0.078	260
Min	0.200	0.580	0.112	0.012	0
Average	0.383	0.863	0.486	0.024	96
Top five pathways					
	Barbour15-150	Barbour30-250	YSTD-Light	Hansen0-40	Hansen0-80
	Barbour30-150HL	YSTD-Light	BarbourNT	CC40_PCT	McComb_CC
	Barbour30-75	BarbourNT	Hansen0-120	CC60_PCT_CT	CC80_PCT_2CT
	Barbour15-75	Hansen0-120	Barbour30-250	Hansen0-80	CC40_PCT
	Barbour30-150	CareyBDPS	0_NA	CC80_PCT_2CT	Hansen0-40

Table 3—Comparison of annual harvested volumes (mbf/yr) to percent changes in wildlife habitat over an 80-year simulation (bold = maximum, *italics = minimum*).

	Annual harvest	Cooper's hawk		Southern red-backed vole		Pileated woodpecker		Spotted towhee	
		2038	2078	2038	2078	2038	2078	2038	2078
	mbf/yr	*Percent*							
1. No Action	*0.0*	**–10**	**–19**	65	75	93	112	*–80*	*–86*
2. 45-yr rotation	**914.4**	*–71*	*–71*	47	*56*	*–22*	*–20*	**–45**	**–47**
3. Moderate enhancement	47.1	**–10**	**–19**	65	75	**98**	112	*–80*	*–86*
4. Intensive enhancement	478.4	–53	–60	**116**	**146**	90	135	–70	*–86*
5. Mixed management	337.5	–31	–35	*32*	67	39	58	–65	–77

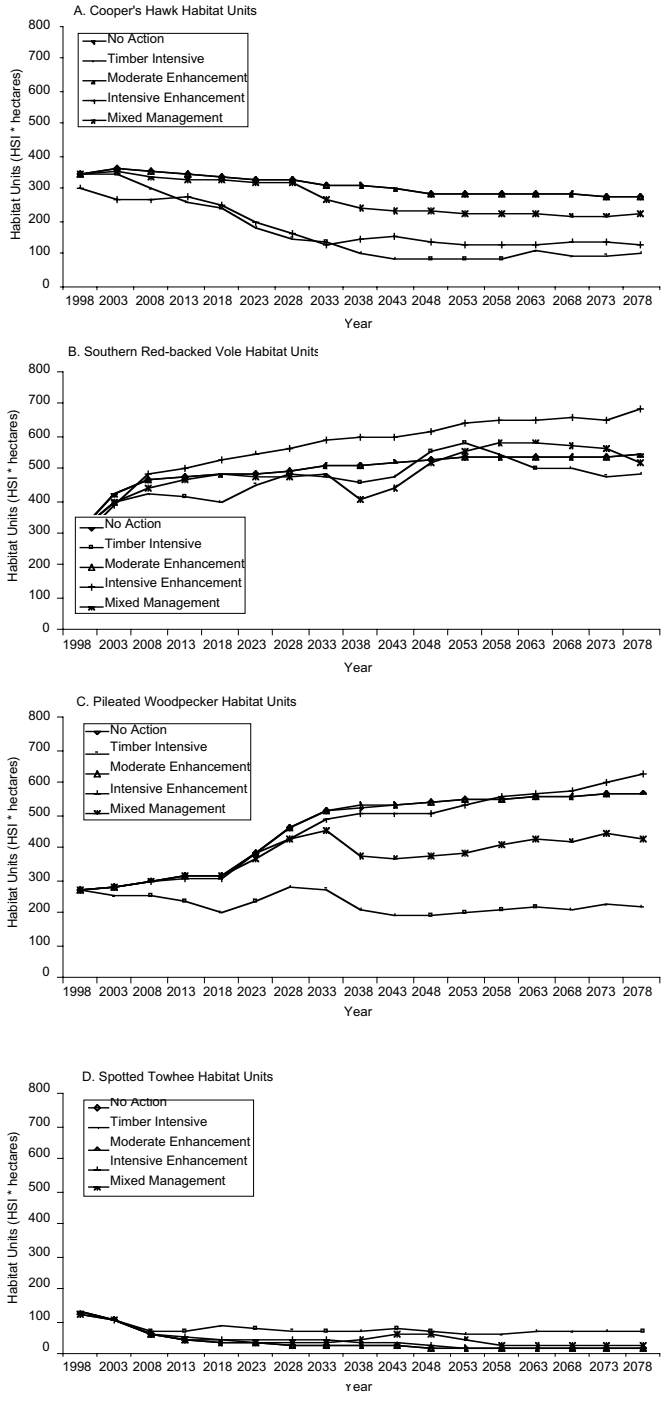

Figure 4—Flows of habitat for four species under five management alternatives

growth simulations, allowing alternatives to be compared without bias. Also, with the HSI models hard-coded into the Satsop HEP module, any bias in HSI model application is held constant as well.

Using stand-by-stand forest inventory, compared to cover type averages, allows the variability within each cover type to be included in the analysis. Cover type classification rules allow a wide range of tree sizes and canopy closures within each cover type. Selecting only cover type average attribute values, instead of stand-level forest inventory data, may neglect variability and result in lower habitat quality estimations.

The most significant advantage of automating these calculations in LMS is the ability to develop and analyze many alternatives quickly. Both landscape level and stand level simulations can be made to assess and communicate the effects of proposed management regimes. Working at the stand level, several alternative silvicultural pathways can be compared to assess potential benefits. Using hypothesis-testing framework, pathways can be selected that may closely meet management goals in the present and the future, before they are applied on forest landscapes.

Many other analyses are available to the user of LMS. More analysis tables are included with LMS that are created by programs within LMS, which summarize the current and projected future inventories in different ways. Tables created in this process have been developed to answer questions relating not only to levels of habitat and volumes but also other forestry measures such as inventory tables and stand summary tables and other measures such as carbon sequestration and stand structures.

Other assessments include landscape-level and stand-level visualizations using the Stand Visualization System and EnVision programs (developed by Robert McGaughey, Research Forester, USDA Forest Service, Pacific Northwest Research Station, University of Washington, Seattle, WA) that are included with LMS. These visualizations are especially important when some parties involved in planning have backgrounds other than forestry and therefore do not understand standard forestry metrics such as volume, tree sizes, and stand structures, allowing managers to communicate forest changes caused by forest management activities.

Limitations of Integrating HEP and LMS

This approach also has several limitations. A primary limitation is the HSI models themselves. All models used in this study are knowledge-based (expert opinion) models designed for the entire ranges of the Cooper's hawk, pileated woodpecker, southern red-backed vole, and spotted towhee. The primary weakness of these models is lack of validation and local calibration. None of the HSI models used were validated using data to assess their performance prior to use in the original Satsop Forest HEP. Results from the HSI models and HEP may not actually reflect actual habitat use for the species in southwestern Washington without validation and calibration to local habitat uses.

Because understory, snag, and downed wood data are needed for calculating HSI values for all models used in this study, with the exception of Cooper's hawk, the applicability of these models is limited to the Satsop Forest ownership. Applying these models elsewhere would require collection of the appropriate understory, snag, and downed wood data, and calculations of average values based on cover types classified by the cover type classification algorithm.

Understory relationships in Pacific Northwest forests have been studied in great depth. Studies have focused on developing relationships between overstory and understory structure and composition, as well as responses of the

understory to disturbances, including harvesting, in old growth, mature, and young forests (Halpern and Spies 1995; Bailey and others 1998; Van Pelt and Franklin 2000). Relationships have been developed into models for other regions of the Pacific Northwest (McPherson 1992; Klinka and others 1996; Mitchell and Popovich 1997), but none were found for southwestern Washington. Forest inventory that is limited to tree measures will have little success in estimating wildlife habitat using the Satsop Forest HEP module of LMS because both the spotted towhee and southern red-backed vole require understory metrics as well as tree metrics. Development of understory models for other regions demonstrates that it can be done, and building models for western Washington would increase the applicability of the models to other areas of the region.

Snags and downed wood are important habitat attributes for pileated woodpecker and southern red-backed vole models. A snag and downed wood model is scheduled to be included in future versions of LMS. Application of this model will allow the models to estimate habitat with variability of snags and downed wood within each cover type included. It is hoped that including snag and downed wood in the models will increase their sensitivity and accuracy.

Spatial arrangement and size of habitat patches are important for some species. Pileated woodpeckers need a home range of up to 600 acres (Schroeder 1983). In the case of Satsop Forest, with an average polygon (habitat patch) size of 5.2 acres, the ability to arrange harvest activities, in such a way that minimum home range requirements are met, is through iterative applications of silvicultural pathways to various stands. After an initial management plan simulation, there may be 600 acres of pileated woodpecker habitat, but it may be arranged in a series of small patches that are not of use for the woodpeckers. This is less of a concern for a species with a small home range such as the southern red-backed vole with a home range size of up to approximately 3.5 acres (Allen 1983).

Conclusion

This study provide the conceptual process of linking forest growth models with wildlife habitat models within a simulation system that brings many advantages over the old process of separate habitat and forest growth simulations but also many limitations. Given the limitations of the HEP within LMS and the variability between growth model outputs and actual tree and stand growth, this system should be used in an adaptive management context. Ensuring stands are developing on the desired trajectory will require managers to revisit the results after several years to verify that silvicultural pathways are providing the desired results. If the silvicultural pathways are not producing the desired results, silvicultural pathways and assessment tools can be adjusted to produce the needed forest outputs.

HSI models used in this study, which are limited by their lack of verification and validation, do not provide estimates of actual species populations, only measures of potential habitat quality and quantity. Thus, if population estimates are required, managers will need to perform field surveys to determine if animals are actually using the habitats that are expected to exist on the landscape. If species are using habitats different from the model's predictions, the models may be modified using the monitoring data to predict habitat suitability indices better. Alternatively, if the models are found to be completely inadequate and better models are constructed, these models can be implemented within LMS to expand and refine the wildlife habitat analysis capabilities of LMS.

Even with the limitations of the HEP within LMS, using this type of simulation system in a gaming context will allow people to gain valuable insights into tradeoffs of various forest outputs under many potential forest management plans with all assumptions being held constant for all analyses. Even though results of the models may only be an abstract representation of reality, relative differences between the outputs of compared silvicultural pathways can be examined. Comparing these differences for a large array of management objectives between many alternatives developed using LMS will help to avoid unintended consequences of forest management plans.

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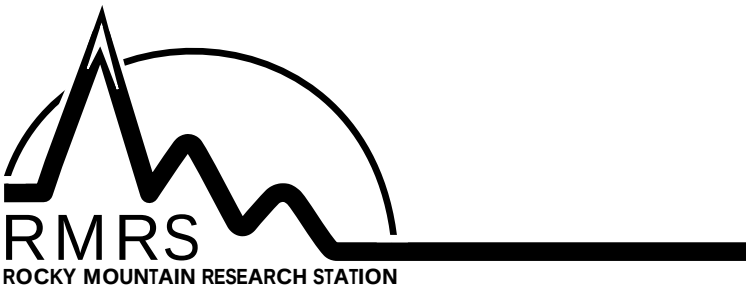

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