Simulation Tools for Forest Health Analysis: An Application in the Red River Watershed, Idaho

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Abstract—*Software tools for landscape analyses—including FVS model extensions, and a number of FVS-related pre- and post-processing "tools"—are presented, using an analysis in the Red River Watershed, Nez Perce National Forest as an example. We present (1) a discussion of pre-simulation data analysis; (2) the Physiographic Information Extraction System (PIES), a tool that can improve the quality of stand level input-data prior to its use in FVS simulations; and (3) tools for output-data spatial analysis, including the Event Monitor ArcView Project (FVS-EMAP), the Westwide Pine Beetle Model mapping tools, and EnVision.*

Introduction

The focus of public lands forest management has recently shifted from emphasizing stand management to protecting and restoring ecosystems. Landscape level 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. Numerous computational tools—simulation models, such as the Forest Vegetation Simulator (Dixon 2003); GIS software, such as ArcView and ARCGIS; data recorders; database and spreadsheet software—are now readily available to land managers and their staffs. These technological tools can assist managers by providing realistic projections about what future conditions might be like under different management alternatives. They can also provide powerful and efficient interfaces that vastly improve our ability to understand natural processes and conditions.

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). The PPE permits the simulation of stands altogether (in parallel) through simulated time—instead of serially (one stand after another). In FVS, parallel processing facilitates not only the simulation of landscape-scale managerial decision-making (for example, the scheduling of thinning treatments), but also the modeling of landscape-scale ecological processes, such as pest contagion and fire behavior. The Westwide Pine Beetle Model (FHTET, in press) is an FVS extension that takes advantage of the parallel processing capabilities of FVS by simulating, on an annual time step, between- and within-stand bark beetle contagion and bark beetle-induced tree mortality.

Though landscape-scale analyses of forest management projects are important and often necessary, applications of FVS to landscape analyses are often hindered by incomplete inventory coverage of the landscape. Statistical imputation programs and procedures are available to facilitate the "populating" of landscapes with tree list data that can then be processed by simulation models. One example is the Most Similar Neighbor (MSN) imputation program of Crookston and others (2002). Such statistical imputations greatly improve our ability to meaningfully simulate whole landscapes into the future. Although we did not use the MSN program, per se, in the Red River watershed analysis, we mention it here because (1) imputing tree data to polygons for landscape analyses can be a very worthwhile undertaking, (2) MSN is a good tool to do such imputations, and (3) it provides context for our description of the Physiographic Information Extraction Tool, a software program we developed as part of this landscape analysis project.

This paper describes processes involved and tools used in a landscape-scale analysis of forest conditions in the Red River Watershed (Nez Perce National Forest, Idaho; fig. 1). The project arose from local observations of increased tree mortality from mountain pine beetle (*Dendroctonus ponderosae*) and western root disease (*Phellinus weirii*), and associated increased fire risk in the Red River watershed. In April 2002, the Red River Ecosystem Analysis at the Watershed Scale (EAWS) Team, the Regional Forest Health Protection office, and the Forest Health Technology Enterprise Team developed a strategy to use simulation modeling to assist with the evaluation of current and potential future watershed conditions. The strategy was refined over the next few months, and completed within the year. This paper describes some of the procedures we used in the Red River analysis, and outlines, in more general terms, types of landscape-level ecological questions to which these tools can be applied.

The Red River project utilized a number of software tools. All of these tools are readily available through the internet. Proprietary software—ESRI's ArcView and ARCGIS software packages, and Microsoft's Access database and Excel spreadsheet software—while available at a cost to the general public, are available to all USDA Forest Service personnel as part of their standard computing environment.

Some software tools used in the Red River Analysis include:

- The Physiographic Information Extraction System (PIES)
- The base model Forest Vegetation Simulator (FVS)
- The Parallel Processing Extension to FVS
- The FVS Event Monitor
- The Structural Stage Model (an FVS extension)
- The WWPB Model (an FVS extension)
- The Western Root Disease Model (an FVS extension)
- The FVS Event Monitor ArcView Project (FVS-EMAP)
- Two WWPB Model ArcView-based mapping tools

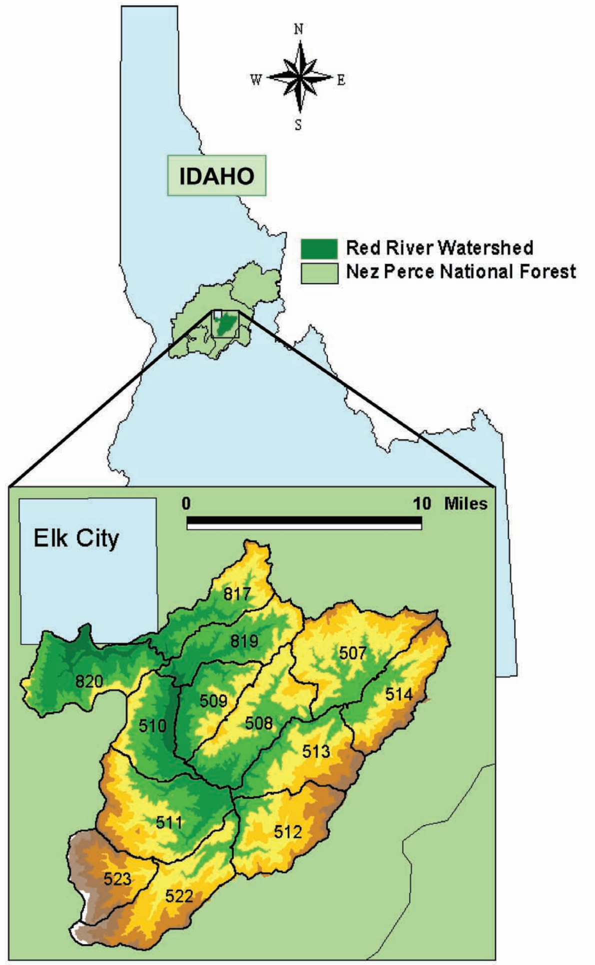

Figure 1. The management compartments of the Red River watershed. At the south end is compartment 522, depicted in subsequent figures.

Overview of the Red River Analysis Area

The Red River watershed is located in the Red River Ranger District of the Nez Perce National Forest, Idaho (fig. 1). It consists of all or part of thirteen management compartments, comprising approximately 103,000 acres (41,722 hectares). The biophysical classification of stands is represented predominantly by five habitat type groups (Applegate and others 1993; table 1). Tree species are predominantly lodgepole pine, grand fir, subalpine fir, Douglas-fir, and Engelmann spruce, with smaller amounts of western larch, western redcedar, and ponderosa pine. Several stands have had management actions performed on them since inventory. For the FVS simulations, no management was simulated because quantitative data (about removal or residual amounts) were not readily available.

Lodgepole pine stands in the watershed experienced significant mountain pine beetle (MPB, *Dendroctonus ponderosae*) activity in the decade leading up to this analysis. The most recent MPB outbreak commenced in the late 1990s, though significant MPB-induced mortality occurred at smaller spatial scales within the watershed during early 1990s (Randall and Wulff 2002). An earlier outbreak occurred in the mid 1980s, giving rise to much of the 1980s-era management and inventory activity. Additionally, laminated root disease (*Phellinus weirii*) is prevalent in the landscape. A primary objective of the study was to estimate potential future effects of these two disturbance agents on tree mortality, stand structure, and fuel loading.

Pre-simulation Processes

Gathering Data/Analyzing Current Conditions

We assembled numerous forms of data to help us characterize the landscape, including: stand exams, aerial photo-interpretation (PI) data, aerial detection surveys (for MPB), and tabular data characterizing stand-level

Table 1. Red River watershed stratification criteria. A stratum is a unique combination of one class from each of the four categories: habitat type group, forest type, size class, and percent canopy cover. Classes are defined by the Red River Ranger District's 1986 photo-interpreted GIS data-layer.

	Habitat Type Group (HTG)
HTG number	**Definition**
1	Warm and Dry PIPO or PSME/grass types
2	Moderately warm and dry PSME and dry ABGR types
3	Moderately warm and moderately dry PSME or ABGR types
4	Moderately warm and moist ABGR, Asaria, and Clintonia types
7	Cool and Moist Clintonia and Menziesia types
8	Cool and wet *Calamagrostis canadensis*, Equisetum, Galium, and Streptopus
9	Cool and moderately dry cooler ABLA and PICO types
	Forest Type
Class	**Definition: Plurality of overstory is composed of:**
1	*Pinus ponderosa* and/or *Pseudotsuga menziesii*
2	*Pinus contorta*
3	*Picea engelmannii* and/or *Abies lasiocarpa*
4	Mixed species
	Size Class
Class	**Definition: Stand QMD is:**
1	0-5”
2	5-9”
3	9-14”
4	>14”
	Percent Canopy Cover Class
Class	**Definition: Total Stand %Canopy Cover is:**
0	0-10%
1	10-40%
2	40-70%
3	70-100%

disturbance and management histories. Satellite data (heavily relied upon by MSN) were not readily available. Of the 3955 stands in the watershed, 1723 were inventoried at least once between 1981 and 1996. Essentially all of the stands were photo-interpreted in 1986 and again in 1996.

Using the 1986 PI data layer as a basis, we stratified the landscape by habitat type group, forest type, size class, and percent canopy cover. Within each of these four categories are PI-defined classes (table 1). Each unique combination of the classes, one from each of the four categories, represents a stratum; every stand falls into a stratum. For example, one stratum represents stands classed into HTG 3; forest type: lodgepole pine; size class: small sawtimber; percent canopy cover: 70-100 percent. The Red River watershed, as PId in 1986, comprised 216 strata.

The classification of the stands in the landscape into strata served two purposes. First, it guided our populating of stands with stand exam (tree data) for the modeling exercise (discussed in next section). Additionally, it provided a means by which to analyze current and historical conditions. For example, comparisons among 1986 and 1996 PI data layers, yearly aerial detection surveys (throughout the 1990s), and stand exam data (throughout the 1980s and 90s) can provide insight as to where conditions have recently changed, where future data collection might need to be concentrated, what portions of a landscape might be susceptible to MPB (or fire, or other agents), and where potential managerial problems might exist. Although our pre-simulation analysis did not specifically probe into these types of “current conditions” analyses, these types of geo-processing techniques can be extremely useful to address questions such as these. For our purposes, these pre-simulation analyses served primarily to guide our simulation model-building.

Imputing Tree Data to Non-inventoried Stands

To predict future landscape conditions using FVS, we needed to (1) establish a point in time to begin the simulations, and (2) describe the landscape at that point in time (that is, provide the model with appropriate tree data). We used 1986 as our simulation start year for a number of reasons, two of which are: (1) it is year around which most of the stand inventories were conducted, and (2) it is a year for which there exists a complete photo-interpreted vegetation classification data layer, spatially resolved at the stand-level.

After the stands were stratified (as described above), a representative stand exam from each stratum was chosen as a surrogate for the remaining un-inventoried stands in that stratum. (Methodologies behind how we chose a representative stand exam will not be presented here.) In cases where a stratum contained no inventoried stand, tree data from an inventoried stand in a similar stratum was used. We acknowledge that there are numerous methods available to populate the landscape. The MSN is one example of a (potentially) more rigorous approach. The method we implemented, although simple, is effective. Our imputation procedure resulted in a landscape fully "populated" with tree data. An extensive sensitivity analysis showed that the level of "accuracy" achieved by our imputation was sufficient to address the types of landscape scale questions that this project was attempting to answer.

Improving Imputations with PIES

Input data used by FVS typically consists of two "types" of data: individual tree measurements ("tree records", "tree data"), and stand-level physiographic information (slope, elevation, aspect, etc). Tree records represent the tree data that will be projected by the model. Stand level data consist of variables used in various ways by FVS. For example, tree diameter-growth rates in FVS utilize slope, aspect, elevation, and (in many variants) habitat type. Fire intensity in the Fire and Fuels Extension to FVS (Reinhardt and Crookston 2003) is strongly influenced by slope. Elevation can be a strong controlling variable on simulated beetle dynamics in the WWPB Model.

Typical imputation procedures (including MSN) often result in an imputed stand inheriting stand level data along with its surrogate tree data. In some cases, the inheritance of site data from a surrogate stand will contribute significant errors to model predictions because the inherited site factors are significantly different from those of the imputed stand. As GIS applications are becoming more sophisticated, imputing accurate physiographic data into simulations is becoming easier.

The Physiographic Information Extraction System (PIES) is a simple program that greatly improves the quality of physiographic data made available to FVS. The PIES utility writes GIS-extracted physiographic data into FVS-ready stand list files. (A stand list file is the data structure used by FVS to read in stand-level data.).

The PIES utility consists of two programs, one operating within a customized ArcView 3.x project (FVS-EMAP, discussed later); the other a simple FORTRAN-based program operating in Windows DOS. The utility requires both a polygonal layer delineating stand boundaries, and a raster-based elevation data layer (for example, a DEM). The PIES utility allows FVS users to extract up to five different physiographic data elements from their GIS: slope, aspect, elevation, habitat type, and area. The extracted stand-level physiographic data are then appropriately inserted into a stand list file (SLF). For imputed stands—heretofore non-existent in the SLF—PIES will create new SLF records. This new record will contain appropriate "pointers" to the imputed stand's surrogate tree data, as well as containing the imputed stand's GIS-extracted physiographic data. The PIES utility thus accomplishes two important functions for landscape analyses. It facilitates the creation of a complete-landscape stand list file. Secondly, it inserts into a stand list file physiographic information that is potentially more accurate than what would otherwise be available to FVS. The end result of our imputation procedures was an FVS-ready stand list file composed of records representing all 3955 stands of the Red River watershed.

Simulation Set-up

The Forest Vegetation Simulator (Dixon 2003; Van Dyck 2001) is a keyword driven model. Keywords are the means by which users provide instructions to the model. The keyword sets we developed for this landscape analysis involved many of FVS' numerous extensions. We present here a very cursory overview of the procedures we employed and extensions used. Further details about these simulations are provided in McMahan and Smith 2003.

The WWPB Model was used to simulate the effects of MPB in the landscape. We used aerial detection survey (ADS) data to guide our initialization of beginning-of-simulation beetle "population" levels. Specifically, the 1986 ADS provided estimates of trees per acre beetle killed, acres beetle-infested, and numbers of stands infested. We constructed the model's "beetle history" file—used to initialize beginning-of-simulation beetle conditions—to reflect the ADS-estimated conditions. Construction of keywords simulating environmental "stress events", used to initiate simulated outbreaks, was guided by historical climate data (using a Palmer Drought Severity Index) and expert opinion about typical temporal trajectories of MPB outbreaks. Lodgepole pine is the most abundant host to MPB in the landscape, with smaller amounts of ponderosa pine.

The Western Root Disease Model (Frankel 1998) was used to simulate the effects of laminated root disease (LRD, *Phellinus weirii*) in the landscape. Keyword sets parameterizing its behavior were developed by local pathologists. All tree species were modeled as potential hosts to LRD. Keyword sets were habitat type-group specific.

The Structural Stage Model (Crookston and Stage 1999)—an FVS extension—was invoked in order to calculate variables needed by a mountain pine beetle hazard rating (Randall and Tensmeyer 2000). The hazard rating was translated into FVS Event Monitor (Crookston 1990) "code" and included in the simulation. By having FVS calculate stand-level MPB hazard over simulated time, we provide a means by which to evaluate (1) the imputation procedure, (2) current conditions, (3) model behavior, and (4) the hazard rating system itself. These evaluations are accomplished via comparing the hazard rating estimates with aerial detection survey data, PI data, and model predictions of beetle-induced tree mortality.

We conducted a number of simulations ("runs"), including a "no pest" run, runs including both pest models simultaneously, and runs simulating each pest by itself. Because the focus of this paper is to demonstrate spatial analysis software, we present only a very brief description of numerical results.

Simulation Results

All simulations, including the base-model "no pest" run, predicted high levels of tree mortality. Tree mortality in the no-pest run represents density-dependent and/or "background" mortality, occurring mostly in small trees. Runs simulating LRD predicted high tree mortality rates throughout most forest types, in all but the smallest size-classed stands, and occurred predominantly in the first decade of the simulation. Runs simulating effects of MPB predicted high rates of mortality in the largest pine trees, concentrated in the larger size-classed stands, in the two pine forest types. Runs simulating both MPB and LRD experienced only slightly more mortality than did either of the single-agent runs alone (because there is much overlap in the trees killed by the two models.

Simulated MPB-induced mortality (in terms of basal area per acre) was highest in the pole-size-classed stands of the lodgepole pine forest type. At the landscape scale, MPB-induced mortality rates remained relatively low for the first decade of the simulation (1986-1996). A landscape-wide "outbreak" occurred during the simulation in the late 1990's continuing to about 2006. Some stands, however, experienced high rates of MPB-induced mortality early in the simulation.

The Red River watershed, as projected into the future by FVS, is a mosaic of stand conditions. Spatial analysis of this mosaic can lead us to a better understanding of the conditions. In the images presented in the following discussion, we focus attention on one compartment—522—to simplify the presentation.

Spatial Analysis of Simulation Output

Standard base-model FVS output data consists of tabular data representing stand-level estimates of tree growth and mortality, stand density, wood production, etc. Concatenating output from multiple stand runs provides landscape-level estimates of these metrics. Although such analysis provides useful information regarding means and ranges of output variables across the landscape, it is lacking in spatial evaluation.

Numerous software tools are now available to assist FVS users to spatially analyze simulation output. These include the FVS Event Monitor ArcView Project (FVS-EMAP, McMahan and others 2002), the WWPB Model Annual and Cycle Mapping Tools (AMT and CMT; FHTET), and EnVision (USDA Forest Service, Pacific Northwest Research Station).

The FVS Event Monitor ArcView Project (FVS-EMAP)

The Event Monitor (Crookston 1990) is part of FVS that allows users to schedule "activities" during a simulation. One type of activity that a user can schedule is the computation of various user-defined output variables over simulated time. For example, a user could enter into the simulation mathematical expressions, using stand-level metrics, to calculate a stand-level hazard rating. After processing, FVS makes available these output variables in a separate comma-delimited text file (indexed by stand number and simulation year).

The FVS-EMAP (McMahan and others 2002) facilitates the "joining" of these user-defined stand-level output variables to maps in ArcView. Figure 2 presents an example FVS-EMAP-generated map portraying a MPB stand hazard rating for compartment 522 in simulated-year 2001. The hazard rating was calculated within FVS by supplying the Event Monitor mathematical expressions representing the hazard rating algorithms of Randall and Tensmeyer (2000). Results show large contiguous areas of "moderate" hazard, and scattered areas of high hazard. Evaluation of the specific location of these high hazard areas, in context of the surrounding landscape, can provide a land manager with useful information—for example where control measures might be more effective or more important.

The use of FVS-EMAP requires that a user has an ArcView-based shapefile containing a polygonal layer defining stand boundaries, along with polygonal identifiers corresponding to the FVS stand identifiers. Using FVS-EMAP, one can efficiently produce time-series map

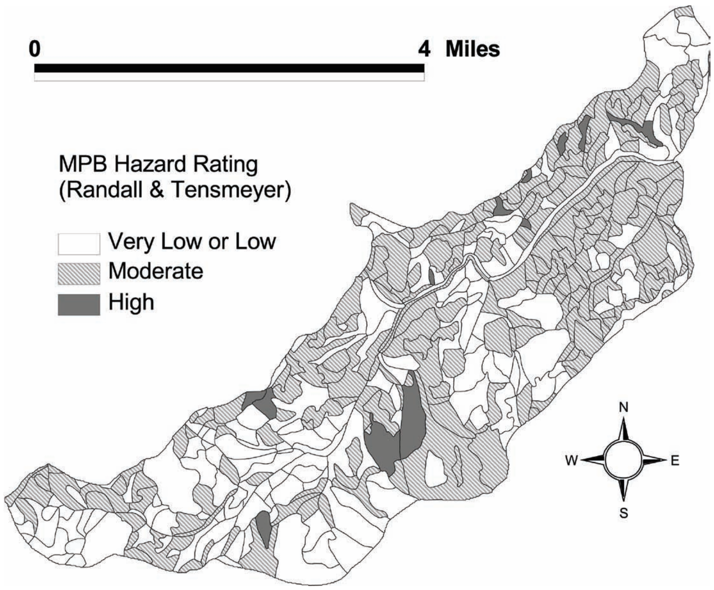

Figure 2. MBP hazard rating in simulation-year 1996. Map was produced using FVS-EMAP, using the Randall and Tensmeyer (2000) hazard rating system calculated within FVS via the Event Monitor. Results are from the run that simulated effects of MPB.

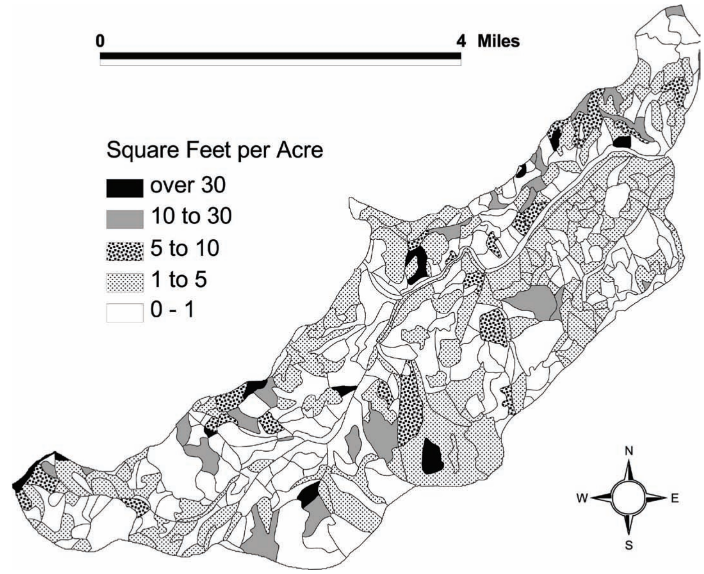

Figure 3. Simulated MPB-induced basal area mortality during the pre-epidemic period 1991-1995. Map was produced using the Westwide Pine Beetle Model Cycle Mapping Tool, using model results from the run invoking the WWPB Model (without the WRD Model).

displays of FVS model projections of any of the user-defined output variables. Once these data are joined to a GIS, numerous spatial statistical analyses can be performed. For example, habitat scores could be calculated via the Event Monitor, brought into ArcView via FVS-EMAP, and then spatial metrics such as habitat edge, connectivity, or fragmentation could be elucidated. Moreover, numerous other ArcView-based extensions—such as the Spatial Analyst, and the (freeware) Patch Analyst (Elke and others 1999)—could be used in conjunction with this application to help evaluate spatial data.

The WWPB Model Mapping Tools

The WWPB Model produces number of different output files containing data characterizing the simulated landscape. The WWPB Model mapping tools—the annual mapping tool (AMT) and the cycle mapping tool (CMT)—work very much like FVS-EMAP. The CMT reads FVS/WWPB Model output data from two WWPB Model output files written at FVS cycle boundaries and joins those data to an ArcView-based shapefile. ("Cycles" are FVS's time-units of projection, typically five or ten years.) The AMT reads and joins data from a WWPB Model output file that is written every projection year (within cycles). Maps produced using these tools can be useful for analyzing potential bark beetle behavior and effects across a landscape.

Figure 3, produced using the CMT, depicts simulated MPB-induced basal area mortality over the period 1991-1995, prior to the simulated landscape-wide epidemic. It shows that while most of the area is experiencing low "endemic" levels of simulated MPB, a number of stands (in black) have experienced high rates of mortality. Thus we see that what constitutes an "outbreak" is, to a large degree, scale-dependent. That is, the simulated landscape as a whole has not yet experienced an epidemic, but some individual stands have experienced epidemic levels of mortality. With these WWPB Model mapping tools, one can quickly produce time-series maps of simulated landscapes, facilitating the analysis of spatial trajectories of simulated outbreaks. Note that some of stands experiencing the highest rates of mortality during 1991-1995 have a relatively low MPB hazard rating in 1996 (fig. 2) because, by then, a large proportion of the host basal area in those stands has already been consumed by MPB.

EnVision

EnVision (USDA Forest Service, Pacific Northwest Research Station) is a landscape visualization tool that can produce realistic images of landscapes from grid-based elevational GIS data (used to build topographic terrain) and FVS output data (used to render vegetation) (fig. 4). This powerful program enables portrayals of viewsheds from virtually any defined point in space, and at different time steps. Further, because of its ability to utilize FVS-simulated tree data output, it enables rapid viewshed assessments of hypothetical management scenarios, or other simulation scenarios—for example,

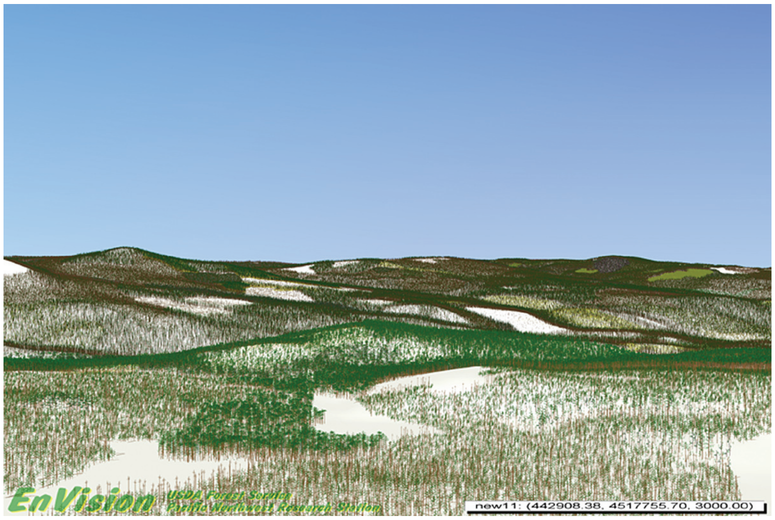

Figure 4. Landscape image produced using EnVision. Rendered tree data are from FVS-produced output tree data. Terrain data are from a raster-based elevational GIS. (Note: This image is not from the Red River watershed.).

post-wildfire. Such demonstrations are extremely useful for communicating scenarios to the public.

Discussion

Landscape analyses can be conducted at different levels of complexity (Smith and others 2002). For public lands managers, landscape analyses often need to be more complex than a mere accounting of landscape-level means or ranges (of condition classes, for example). Indeed, land managers are often interested in spatial distribution patterns across a landscape, including various "emergent properties" of such patterns, such as connectivity, fragmentation, and configuration (of condition classes, for example).

The Forest Vegetation Simulator is a powerful and continually evolving set of tools able to simulate a variety of ecological processes. While historically it was developed as a stand level analysis tool, the FVS—together with various pre-and post-processing tools and extension—is increasingly becoming a tool for landscape-scale analyses.

The tools presented here—PIES, the WWPB Model and associated mapping tools, FVS-EMAP, and EnVision—facilitate the process of "landscape analysis" by providing interfaces between geographic databases and the simulation model FVS. Such interfacing can vastly improve the efficiency with which managers and analysts can examine current and projected data.

In addition to the tools presented here, there exist other FVS extensions that further improve the capabilities of FVS as a landscape analysis tool. The Database (DB) extension to FVS (Crookston and Gammell 2004) greatly facilitates data handling at both the input and output "ends" of processing. The DB extension is now fully integrated into all FVS variants. Also, the linkage between the Parallel Processing Extension (PPE) and the Fire and Fuels Extension (FFE) has been recently completed. Although this linkage does not yet—by itself—permit the simulation of stand-to-stand fire contagion, the PPE-FFE linkage will certainly lead to vast progress in the realm of landscape-scale fire and fuels analyses.

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