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The forest vegetation simulator: A review of its structure, content, and applications

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Abstract

The Forest Vegetation Simulator (FVS) is a distance-independent, individual-tree forest growth model widely used in the United States to support management decisionmaking. Stands are the basic projection unit, but the spatial scope can be many thousands of stands. The temporal scope is several hundred years at a resolution of 5–10 years. Projections start with a summary of current conditions evident in the input inventory data. FVS contains a self-calibration feature that uses measured growth rates to modify predictions for local conditions. Component models predict the growth and mortality of individual trees, and extensions to the base model represent disturbance agents including insects, pathogens, and fire. The component models differ depending on the geographic region represented by regionally specific model variants. The differences are due to data availability and the applicability of existing models. The model supports specification of management rules in the input, such as thinning if density is too high. The rules can be extended to represent other factors. For example, the effect of climate change on stand development by entering rules that specify how growth and mortality will change in response to changing climate.

Applications range from development of silvicultural prescription for single stands to landscape and large regional assessments. Key issues addressed with FVS include forest development, wildlife habitat, pest outbreaks, and fuels management. The predictions are used to gain insights into how forested environments will respond to alternative management actions. Broad-scale forest management policies have been studied with FVS.

For the 30 years since the model was initially introduced, the development team has anticipated and provided needed enhancements and maintained a commitment to working with and training users. The

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existence of an adequate user interface and the continued use of the original programming language are often overlooked factors for the success of this model.

Future work will focus on improving FVS by adopting recent biometric techniques and including new information linking geomorphology to mortality and growth. Extending the model to more closely represent biophysical processes and adapting the model so that it is more relevant to management questions related to predicted climate change are also foci. Providing ways to dynamically link FVS to other models is our current strategy for providing major new capabilities.

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1. Introduction

The Forest Vegetation Simulator (FVS, Wykoff et al., 1982; Dixon, 2002) is used extensively throughout the United States in a variety of ways to support contemporary forest management decisionmaking. FVS began as the Prognosis Model for Stand Development (Stage, 1973). Stage's original intent was to predict stand dynamics in the mixed forests of the inland mountains of northern Idaho and western Montana – places where insects, pathogens, and fires are key disturbances influencing forest successional processes. Although the ability to forecast growth and yield was as key then as it is today, that need did not entirely drive the modeling effort. The model is best understood in the context of predicting stand dynamics and succession using techniques that produce sound forest development estimates for alternative management prescriptions. To avoid overpredicting yields when disturbances occur, FVS was designed to provide linkages to models that represent disturbance-causing agents.

Although forest growth and yield forecasts have been in use in the United States since about 1900 (Burkhart, 1990), most were for single species, even-aged conifer stands in narrowly defined geographic areas. The need for the models clearly existed, and they proliferated throughout the country, rapidly increasing in number from about the year 1960 through 1990. This period coincided with computer advancements, widespread data collection efforts, improved analytical methods, and the passage of important federal resource management laws in the United States. Forest growth and yield models became important to addressing requirements of these laws. However, surveys of available models revealed a scarcity of models for mixed species, uneven-aged, and hardwood stands in most areas of the country (Farrar, 1979; Teck et al., 1987; Trimble and Shriner, 1981; among others).

Research efforts expanded the scientific knowledge about forest growth and yield, but these efforts did not produce a uniform application and delivery process needed for rapid and expanded use of the research by the National Forest managers. In about 1980, the lack of national direction and coordination was identified as a potentially serious limitation to addressing analyses required by law. After looking at available models and their structures, the Prognosis Model was chosen as a common modeling platform in the United States Department of Agriculture, Forest Service. Soon thereafter it was renamed the Forest Vegetation Simulator or FVS.

This paper includes an overview of FVS structure, a description of the component models, and a review of applications to demonstrate the relevancy, scope, and utility of FVS in addressing contemporary forest management issues. We identify other key factors that led to this model's more than 30 years of use, and comment on model limitations and outline our future work.

2. Structure of FVS

FVS belongs in the distance-independent, individual-tree class of models (Munro, 1974). Other general model types are whole stand, diameter class, or gap process models. Although FVS is a distance-independent individual-tree stand growth model, in some cases it has been made semi-distance-independent by statistically representing spatial variability within stands (Stage and Wykoff, 1998). Stands are the basic unit of management, and projections are dependent on interactions among trees within stands.

The key state variables for each tree are density, species, diameter, height, crown ratio, diameter growth, and height growth. Key variables for each sample point, or plot, include slope, aspect, elevation, density, and a measure of site potential. The same information is available at the stand level. In addition, the model computes the percentile rank in the distribution of tree basal areas both among trees growing at the same plot and again among all trees in the stand.

Model flow is as follows:

For all stands

Initialization

Read Input Data

Calibrate

Report initial conditions

For all cycles

Check events, schedule activities

Simulate harvests, thinning, and pruning

Check events, schedule activities

Predict typical growth

Predict typical mortality

For each year within cycle

Predict insect and disease dynamics and simulate related management actions

Predict fire and fuels dynamics and simulate related management actions

End year within cycle loop

Apply insect- and disease-caused damage, modify typical growth and mortality rates as needed.

Apply fire effects

Update tree variables for growth and mortality

Simulate regeneration establishment

Update crown ratio

Report projected conditions

End cycle loop

End stand loop

FVS starts by reading inventory data and site information. A self-calibration process automatically adjusts the internal growth models to match the growth rates evident in the input data. The output report includes a summary of the current stand conditions, sampling statistics, and calibration results.

Time steps, or growth cycles, are generally between 5 and 10 years long, and the total projection is between a few years and several hundred years. The first step in a cycle is to call the Event Monitor (Crookston, 1990; Crookston and Stage, 1989) to schedule activities that are dependent on the value of state variables. For example, a rule can be placed in the input command file to thin the stand when density exceeds a user-specified threshold. The rules can be involved. For example, some input files contain several hundred lines of rules representing many management regimes, and commands used to modify the FVS predictions can also be included and are sometimes used to represent damage by pests or other agents. The Event Monitor also provides a way for users to create new output variables as functions of state variables normally carried by FVS. An example application of this capability is to compute user-defined habitat suitability indices.

Almost any kind of harvest can be simulated. Details such as specifying how much of the crown of trees is left on site and how much is removed can be included. These details are needed to simulate fire because fire is dependent on fuels, and fluxes in fuels partly depend on harvest practices.

Postharvest conditions might invoke changes in the way growth and mortality are computed. For example, a harvest resulting in a major disturbance might trigger scheduling site preparation and planting trees—activities simulated by the regeneration establishment component of FVS. Thus, rules are checked a second time, just after harvests are simulated.

Typical growth and mortality rates are those devoid of major disturbance agents or diseases. They are predicted as functions of postremoval densities and conditions.

Extensions to the FVS model have been written that represent insects, pathogens, and fire (Table 1). These models usually run as closely coupled subroutines to the base FVS program. They modify the typical growth and mortality estimates as necessary to represent losses caused by these agents. The extensions are called in a loop that is incremented once per year within a cycle. While this approach allows extensions to interact with each other at 1-year time steps, current extensions interact on cycle boundaries instead.

The assumption that stands grow independently of each other can be relaxed using the Parallel Processing Extension (PPE, Crookston and Stage, 1991). The PPE simulates the growth of thousands of stands in parallel through time allowing the model to dynamically represent the interactions of stands in a landscape. It can also be used to calculate efficient harvest schedules. The logical flow in the PPE includes a loop over stands within the loop over cycles listed above. After the insect, pathogen, and fire models are run, the individual tree records are updated by adding growth increments and subtracting mortality. If conditions warrant, regeneration is added. Finally, change in crown ratio is computed, stand level statistics are summarized, reports are written, and another cycle begins.

Table 1

FVS extensions represent disturbance agents and provide additional capabilities to the base model

Extension	What is represented	Key references
Western root disease model	<i>Phellinus weirii</i> <i>Armillaria</i> spp. <i>Heterobasidion annosum</i>	Frankel (1998)
Douglas-fir beetle impact model	<i>Dendroctonus pseudotsugae</i>	Marsden et al. (1994)
Douglas-fir tussock moth outbreak model	<i>Orgyia pseudotsugata</i>	Monserud and Crookston (1982)
Dwarf mistletoe impact model	<i>Arceuthobium</i> spp.	Hawksworth et al. (1995)
Mountain pine beetle	<i>Dendroctonus ponderosae</i>	Crookston et al. (1978), Cole and McGregor (1983)
Mountain pine beetle hazard rating system	<i>Dendroctonus ponderosae</i>	McMahan and Smith (2002)
Southern pine beetle	<i>Dendroctonus frontalis</i>	Courter et al. (2002)
Spruce beetle risk rating	<i>Dendroctonus rufipennis</i>	FHTET (2002)
Western spruce budworm model	<i>Choristoneura occidentalis</i>	Crookston et al. (1990)
White pine blister rust	<i>Cronartium ribicola</i>	McDonald et al., in preparation
Biogeochemical physiology growth model	Northern Rocky Mountain tree species	Milner et al. (2002), McMahan et al. (2002)
Canopy and shrubs extension	Northern Rocky Mountain shrubs (limited coverage)	Moeur (1985)
Fire and fuels extension (FFE-FVS)	Snags, down wood, fire, and fire effects.	Reinhardt and Crookston (2003)
The parallel processing extension (PPE)	Interactions of stands in a landscape	Crookston and Stage (1991)

3. Component models and modeling techniques

Geographically specific versions of FVS are called *variants*. Twenty-two FVS variants have been developed for the forested areas of the United States and for part of British Columbia, Canada. The methods used to predict growth and mortality are different among them. When building a variant, compromises are made so that model builders can use available component models and data. Where these component models are lacking, coefficients are estimated using available data and existing scientifically documented techniques. The FVS structure accommodates a wide variety of modeling techniques for each component model. A summary of Dixon's (2002) detailed review is presented below.

Stand development is simulated by predicting changes in the dimensions of the trees that compose the stand. FVS uses two strategies to predict tree growth. For large trees, diameter increment is predicted first, and then height growth is predicted as a function of diameter increment and other variables. For small trees, height growth is predicted first, and the diameter increment is predicted as a function of height growth and other variables.

3.1. Large-tree growth – diameter increment driven

The first and most important prediction is large-tree diameter increment. All facets of predicted large-tree development are dependent in part on diameter or diameter increment.

The behavior of the FVS as a whole is strongly influenced by the behavior of the diameter increment model and the subsequent use of diameter at breast height (*DBH*) and diameter increment in the prediction of other tree attributes.

In most variants, diameter increment is predicted periodic change in squared inside-bark diameter (*dds*, Stage, 1973; Cole and Stage, 1972; Wykoff, 1990). The trend in $\ln(dds)$ relative to $\ln(DBH)$ is linear, and the residuals on this scale have a nearly homogeneous variance.

Site factors are included in the *dds* model in two general ways. The effects of habitat type and location are included in the model by varying intercepts. Slope and aspect are included as a continuous circular effect (Stage, 1976), with the addition of a slope-squared term that allows optimum growth to occur at other than infinite or level slopes. The optimal aspect varies by species, but most grow better on south-facing moderate slopes. In North America, the growing season is longer on the warmer southern exposures, and moderate slopes tend to be well drained with adequate soil. Elevation is also transformed so that an optimum is possible – it usually occurs at an elevation that is in the middle of the range for a species.

The increment model predicts that trees with large crowns and trees in dominant crown positions grow more rapidly than subordinate trees with smaller crowns. As stand density increases, the growth rates of all trees decrease. Stand density and the distribution of trees among species tree sizes can be changed by management actions. If smaller stems are removed, the diameter increment of the residual trees increases in proportion to the reduction in stand density. If larger trees are removed, residual trees will respond with faster growth rates because they have an improved position in the canopy.

At any point in time within a stand, the largest diameter increment attained by any tree of a given species is likely to be attained by the largest tree of the species. The growth rate of a suppressed tree culminates at a smaller diameter than does the growth rate of a dominant tree. In a relatively even-aged stand, culmination of all trees of a species will occur at about the same time. As a result, the relationship between diameter increment and diameter is monotonic or sigmoid increasing, with the slope of the relationship dependent on stand density.

In some variants, the height increment of large trees is driven largely by the diameter increment using equations similar to Stage's (1975) model, which is based on the allometric relationship between height and diameter. In variants that are based on the TWIGS models (Miner et al., 1988; Hilt and Teck, 1989; Meldahl and Bolton, 1989), potential height growth is predicted and then modified according to stand conditions and tree characteristics. A third approach, used in the variant based on GENGYM (Edminster et al., 1991), blends portions of each of these techniques. An even-aged estimate of height growth is obtained from a potential site index curve and modified based on stand and tree attributes. An uneven-aged estimate of height growth is made from a regression equation based on tree and stand parameters. The two estimates are averaged using a weighting function based the range in tree ages in the stand, total stand basal area, and an individual tree's percentile rank in the basal area distribution. While the Stage method is the most direct estimate of height increment, all methods yield satisfactory predictions and show a similar sensitivity to changing stand conditions, tree vigor, and a tree's social position within a stand.

3.2. Small-tree growth – height increment driven

Height growth for small trees is a driving developmental force as trees compete for light and vertical growing space. Because of this, the small-tree portion of FVS is a height-growth driven model; height growth is estimated first, and then diameter growth is predicted from height growth. Equations used to predict small-tree height increment vary by species and variant. However, they are usually dependent on factors such as site characteristics, stand density, social position, and crown ratio.

Having two independent models to predict height growth – the one for small trees, and the diameter-increment driven model used for large trees – results in a discontinuity in the predicted height growth rates when the tree *DBH* is near the dividing point between small and large trees. This problem is resolved by predicting height increment with both models and computing a weighted average.

Examining the composite behavior of the model reveals that the height increment curve increases rapidly to a maximum at 7.6–12.7 cm *DBH* and then gradually decreases, much in the fashion of the classical increment curve (Assman, 1970). The effect of increasing density is to decrease height increment. In the large-tree model, this is accomplished indirectly through the diameter increment term. In the small-tree model, there is a direct effect using crown competition factor (*CCF*, Krajicek et al., 1961) as a measure of density. *CCF* is independent of site quality and stand age and is suitable in all stand structures. It estimates the growing area available to the average tree in the stand in relation to the maximum area it could use if it were open grown. In an undisturbed even-aged stand, the height and diameter increment models work together to produce increasingly flattened height–diameter curves over time.

Small-tree diameter increment is predicted as the difference between the beginning and end of cycle diameters, adjusted for bark ratio. These diameters are estimated from a species-specific height–diameter function using the beginning and end of cycle heights, respectively.

3.3. Mortality

Mortality predictions are intended to reflect background or typical mortality rates. Increases in mortality from insects, pathogens, and fire are accounted for in the various extensions. Mortality from other causes, such as logging damage, animal damage, or wind events, can be simulated by the user by specifying FVS commands. Mortality is applied in an FVS projection by reducing the trees per unit area representation of each tree record in the stand. The three types of mortality models used in FVS are presented below.

3.3.1. Prognosis-type mortality model

The Prognosis-type mortality model (Hamilton, 1986; Wykoff, 1986) is used in variants where enough inventory data suitable for developing the equations were available. In this model, mortality is predicted using two independent equations and then combined using a weighting function.

First, a logistic equation is used to predict annual mortality rate as a function of habitat type, species, diameter, diameter increment, estimated diameter increment, stand basal area, and relative diameter. The estimated annual mortality rate is then multiplied by a factor

based on Reineke's (1933) stand density index (*SDI*) that accounts for expected differences in mortality rates on different habitat types and National Forests. *SDI* is the number of trees per acre that a stand would have at a standard average *DBH*. It is a valuable parameter for describing crowding as it is generally independent of stand age and site quality.

The second equation is based on the theory that as basal area approaches the maximum for a site, mortality rates increase. Hamilton (1990) describes this procedure, along with five other concepts, that underpin the logic used to extend the logistic model to cover a broad range of sites and densities – situations not represented by the data used to calibrate the model's first equation.

The combined mortality model predicts relatively high mortality rates for small trees when they are relatively numerous in the stand. The mortality rates predicted for large trees are unaffected by the number of trees in the stand. As stand basal area increases, however, mortality rates for all trees increase. On the stand level, the effect of increasing density on mortality rates can be observed by comparing accretion and net total volume increment. With all other factors held constant, including time, accretion continues to increase, even at high levels of stand basal area. As stand basal area approaches the maximum for the site, however, net volume increment rapidly approaches zero.

3.3.2. *SDI-based mortality model*

SDI-based mortality model (Dixon, 1986; Johnson and Dixon, 1986) is used in variants where there were not enough inventory data suitable for developing the Prognosis-type mortality model, and no other suitable mortality model exists. When this model is used, the total number of mortality trees is determined, and then mortality is distributed to the individual tree records.

The number of mortality trees represents background and density-related mortality. Background rates are used when stand density is below 55% of maximum *SDI*. The rate itself is computed using a logistic function of *DBH*. The coefficients, including values of maximum *SDI*, are variant- and species-dependent. Density-related mortality begins when the stand *SDI* is above 55% of maximum. The rates increase as needed to ensure that the stand *SDI* does not exceed 85% of its maximum.

In general, the density-related mortality rate is partially dependent on shade tolerance of individual species. The more intolerant species have higher mortality rates than the tolerant species. The rate is also dependent on a tree's social position as measured by its rank in the basal area distribution. Trees with a lower rank (e.g., understory tree) receive heavier mortality than those with a higher rank (e.g., overstory tree). Finally, the rate is dependent on a tree's vigor as measured by crown ratio. Trees with smaller crown ratios receive higher mortality rates than trees with higher crown ratios.

3.3.3. *TWIGS-based mortality model*

Some eastern variants of FVS use mortality models developed for the TWIGS family of models (Teck and Hilt, 1990; Buchman et al., 1983; Buchman, 1983; Buchman and Lentz, 1984). Equations are variant dependent and predict survival rate rather than mortality rate. Survival rate is predicted as a function of diameter, diameter growth, basal area in larger trees, and/or site index. The survival rate is converted to a mortality rate for FVS processing.

3.4. Regeneration establishment

Two strategies are used to introduce tree regeneration into an FVS simulation. For variants that cover the Northern Rocky Mountains, a model developed by [Ferguson et al. \(1986\)](#) and later extended by [Ferguson and Carlson \(1993\)](#) is available. The model predicts the number, size, and species of trees expected to be found on a 0.0013 ha plot after a disturbance, given characteristics about the plot that include site preparation methods and the residual species composition of the surrounding area. Briefly, the model first computes the increment in the probability of a site being stocked from one time period to another. The model predicts the number of trees and the number of species that stock each plot. The probability of species occurrence is then computed and used to pick the species that will be regenerated. From these data, a number of trees of each species are added to the FVS simulation. A similar model is available for the coastal Alaska variant ([Ferguson and Johnson, 1988](#)).

The second strategy, and the most common, is that users specify the species, density, and size of expected new trees. This approach is used where a calibrated model is not available. Users have also developed Event Monitor rules for simulating regeneration processes. For them, the rules are the model, and frequently users share these rules resulting in an informal regeneration model for a given region. In some cases, the rule sets mimic the general approach used by [Ferguson et al. \(1986\)](#).

3.5. Crown ratio change

Just as with the other component models, there are several crown models used in the different FVS variants. These include the Prognosis crown model, the Weibull-based crown model, and crown models from other modeling systems. These models are discussed below.

3.5.1. Prognosis-style crown model

The crown ratio model used in the Prognosis Model was developed by [Hatch \(1980\)](#). The model predicts the log of crown ratio as a function of species, habitat type, stand basal area, crown competition factor, tree *DBH*, tree height, and the tree's percentile in the stand basal area distribution. To estimate change in crown ratio, crown ratio is predicted based on stand and tree attributes at the beginning and at the end of a cycle. The first prediction is then subtracted from the second prediction to obtain a difference. This difference is added to the actual crown ratio to effect the change.

There are some additional operational constraints on this crown model. Theoretically, crowns should just touch when *CCF* is equal to 100. It is assumed the effect of density will be negligible below this threshold. When *CCF* is less than 100, predictions made at the end of the cycle use the same *CCF* and basal area values that were used to make predictions at the start of the cycle. Thinning results in increased crown development. However, when the stand is thinned from below, a tree's basal area percentile is reduced for the residual trees, with the result that predicted crowns are smaller. To avoid this anomaly when the stand is thinned, the same percentile value is used when making predictions at both the start and the end of the cycle.

For most species, crown ratios decrease as the trees get larger. A dominant tree (as measured by basal area percentile) tends to have a larger crown ratio than a similar-sized

tree in a subordinate crown position. The effect of increasing stand density is to reduce crown ratio. However, as trees become large, the predicted changes in crown ratio become smaller.

3.5.2. Weibull-based crown model

The Weibull-based crown model (Dixon, 1985) is used in most western variants. The distribution of crown ratios within a stand is modeled to follow a Weibull distribution (Johnson and Kotz, 1970). First, the mean stand crown ratio is estimated from *SDI*. Next, parameters of the Weibull distribution are estimated from mean stand crown ratio. Finally, crown ratios for individual trees are predicted using the parameterized Weibull distribution, their rank in the diameter distribution, and a density-dependent scale factor.

Changes in crown ratios from one projection cycle to the next are found by subtracting the crown ratio predicted at the beginning of a projection cycle from one predicted at the end of a cycle. Crown ratios may increase, decrease, or stay the same depending on tree growth and changes in the stand structure. Crown ratio change is bounded to 1% per year to avoid unrealistic changes from one cycle to the next when there are dramatic changes in stand structure.

The Weibull-based crown model is responsive to changes in the tree and the surrounding stand. With thinning, the crowns lengthen; conversely, if density increases, the crowns shorten. A dominant tree (as measured by basal area percentile) tends to have a longer crown than a similar-sized tree in a subordinate crown position.

3.5.3. Crown models from other modeling systems

For some FVS variants, existing crown models from other modeling systems were embedded into the FVS framework. These include the GENGYM (Edminster et al., 1991) crown model, the TWIGS based crown models (Miner et al., 1988; Holdaway, 1986), and the BGC process-based crown model (Milner et al., 2002).

3.6. Self-calibration of component models, record tripling, and user control

A distinguishing feature of FVS is its ability to automatically calibrate internal models to reflect local deviations from the regional growth trends represented in the variant. If three or more tree records for a species have measured heights, the model parameters of the height–diameter function for that species are adjusted. If qualifying growth increment data are provided on five or more sample trees per species, parameters of the large-tree diameter increment model, the small tree height increment model, or both will also be scaled. To qualify, diameter increment observations are used from trees that were larger than a threshold *DBH* (generally 7.6 cm) at the start of the growth measurement period. Height increment observations are accepted only from trees that were less than 12.7 cm *DBH* at the end of growth period.

Random effects are incorporated into FVS projections as described by Stage (1973). A random component is assigned to the distribution of errors associated with the prediction of the logarithm of basal area increment. The effects of this variation extend in highly nonlinear ways through most of the remaining components of FVS. In ad-

dition, if relatively few sample trees represent the stand, tree records are tripled to increase the number of replications of the random effects, and this stabilizes stand parameter estimates.

Another feature is the amount of control users are given over all features and component models of FVS. Users can easily control the calibration feature, random effects, and record tripling, and can turn these features off if desired. Users can also alter growth equations using multipliers to correct any consistent model bias observed when running a landscape analysis, to extend the effective range of a variant outside the geographic area for which it was fit, or to simulate stand effects that are not specifically included in the model (e.g., fertilization effects, insect outbreaks, pathogens, and storm damage).

4. FVS applications

Contemporary applications utilizing FVS are presented in proceedings from two FVS Conferences (Teck et al., 1997; Crookston and Havis, 2002). A summary of these applications provides insight into the model's utility, relevance, and versatility in addressing forest management issues. In several cases, the linkages to processes represented externally to FVS are the key to the model's application. The ability to predict changes in species- and size-composition of forest stands is a key attribute allowing FVS to support the applications.

4.1. Large-scale habitat assessments

Management of endangered wildlife has motivated a need to assess habitat status and stability. Examples include work done by Maffei et al. (1997), who identified Oregon plant communities that can sustain northern spotted owl (*Strix occidentalis caurina*) dispersal habitat. The chief indicator variable was the percent canopy cover provided by trees larger than 28 cm DBH. The number of these larger trees needed to achieve and maintain 40 percent canopy cover was a model output, as was a bark beetle (*Dendroctonus ponderosae*) risk rating where the primary species was ponderosa pine (*Pinus ponderosa*). Later, Maffei and Tandy (2002) modeled spatial and temporal effects of management actions on spotted owl habitat. Maps showing the distribution of habitat and fire hazard were prepared for each management alternative and for up to 60 years into the future.

In California, Wilson (1997) used FVS to build 300-year yield estimates to support the spotted owl environmental impact statement for 3.5 million ha. FVS was used to update inventories that were further processed to predict several measures of volume yield plus the number of trees greater than 76 and 102 cm DBH, the number of snags greater than 76 cm DBH, the amount of submerchantable material, and a custom "stand resiliency index" developed for the analysis. Such long simulations require paying attention to how ingrowth and regeneration are modeled.

Eng (1997) assessed the potential cumulative impacts of timber harvest on habitat suitability and connectivity of late successional forest in northwestern California. The model predictions were used to classify stand structure for each stand over each decade. Structure class depended on canopy cover, tree species, and tree size.

4.2. Forest health assessments

Large-scale forest health assessments quantify how insects and pathogens will influence harvest yields, habitat status, and watershed quality. An example is the work of Goheen (1997) who predicted vegetation development and established treatment priorities in the southern Cascades, Oregon. The role insects and pathogens play in stand dynamics were included, making traditional yield predictions sensitive to processes controlled by these agents. Fourteen descriptors of vegetation, dwarf mistletoe (*Arceuthobium* spp.), and root diseases (*Phellinus weirii*, *Armillaria* spp., and *Heterobasidion annosum*) were projected.

Roberts and Weatherby (1997) developed successional pathways using FVS and its ability to represent insects and pathogens in support of a southwestern Idaho planning effort. A key output was predicted successional stage taking into account disturbances caused by Douglas-fir beetle (*D. pseudotsugae*) and western spruce budworm (*Choristoneura occidentalis*).

In Colorado, Eager and Angwin (1997) conducted a forest health assessment where the outputs included the amount of land in different size classes and those with different dwarf mistletoe ratings, plus aggregate volume over time. The roles of mistletoe and root diseases were of specific interest.

Atkins and Lundberg (2002) used FVS to conduct a hazard analysis of fire, insects, and pathogens in Montana. This was a statewide assessment of conditions and trends. Outputs included estimates of area in specific forest structure classes (based on tree size distribution) and bark beetle hazard classes (based on several custom formulas computed using the Event Monitor). Fire-related outputs include wildfire crowning and torching index classes, and land area expected to burn as surface fires, torching fires, or as active crown fires. These were predicted using the Fire and Fuels Extension to FVS (FFE-FVS, Reinhardt and Crookston, 2003).

In British Columbia a metric version FVS is known as PrognosisBC. This model was used by Robinson et al. (1997) to predict mean annual increment in an assessment of partial harvest options in root-disease infected sites in the Nelson Forest Region, in British Columbia. Greenough et al. (2002) linked PrognosisBC to the PPE and a set of environmental indicators algorithms to produce a program called Prognosis EI, where EI stands for environmental indicators. They used this program to assess disturbance scenarios in southeastern British Columbia.

4.3. Traditional forest planning

Uses of FVS directly related to large-scale forest planning often include considerations of habitat, pests, and fire. This use is so common that most examples are only reported in the planning documents. Published examples include the work of Rupe and Wisler (1997) who analyzed the economics and feasibility of alternative timber harvest methods and timing choices in support of the Black Hills National Forest, South Dakota, plan revision. Besides timber volumes, FVS was used to compute fire hazard, bark beetle risk, snag density, structure stage, age, thermal cover, and percentage of plots that were harvested.

Hummel et al. (2002) integrated FVS into an optimization scheme to produce efficient management plans for the Gotchen late successional reserve in southern Washington. Key

issues included western spruce budworm, fire risk, and northern spotted owl habitat. Outputs included predicted flame length and crowning and torching indices predicted by FFE-FVS.

Hill (1997) used the model to support the preparation of the Custer State Park, South Dakota, resource management plan. Vegetation structural class and the basal area by tree size class were key outputs. Courter et al. (2002) included the influence of southern pine beetle (*D. frontalis*), oak decline (*Quercus* spp. decline), and littleleaf disease (*Phytophthora cinnamomi*) when predicting yields used in planning efforts in the southeastern United States. Keyser and Stephens (2002) used FVS in support of the Chattahoochee-Oconee National Forest, Georgia, planning effort. Yield forecasts included effects of forest pests. Bates et al. (2002) used FVS to compute the optimal forest rotation for reclaimed Appalachian coal mines of the eastern US.

4.4. Policy and resource supply analysis

Policy analysis determines the effect of forest management policies on forest resource supplies and economics. Examples include the work of Cousar et al. (1997) who reported a policy analysis for the Sierra Nevada ecosystem in central California. The indicator variables included number of large trees, basal area, stand and harvest volume, present net value, and a fire hazard index that was based on other FVS outputs. Vandendriesche (2002) reported the use of FVS in a large-scale resource supply analysis requested by the US Senate. Reported variables included current volume, harvest volume, growth rate, mortality rate, and land area by stand structure class for now and at 10, 20, and 50 years into the future. The PPE was used in this analysis to automate the management policy scenarios. This application capitalized on the PPE's capability to build decision trees and allocate harvests among stands.

4.5. Linkage to other tools

FVS is routinely linked to other models and computer programs including databases and geographic information systems (GIS). One of the most widely used external tools is the Stand Visualization System (SVS, McGaughey, 1997) used to generate three-dimensional drawings of FVS outputs. FVS is also used as an embedded component in larger systems, notably the Integrated Forest Management System (INFORMS, USDA Forest Service, 2002), Northeast Decision Model (NED, Wang et al., 2002), SmartForest (Orland, 1997), and the Landscape Management System (LMS, McCarter and Wilson, 1998).

Examples of FVS being linked to additional tools are illustrated by work reported by Scharosch et al. (1997) who integrated FVS with a custom tool called the Ecosystem Diversity Matrix Projection System to support ecosystem management for 2.3 million ha of corporate land in west-central Idaho. Steele (1997) used FVS to provide input for an Ecosystem Diversity Matrix that allowed analysts to link terrestrial, riparian, and aquatic elements of a central Idaho ecosystem. Stage (1997) used FVS to provide structural class attributes and volume estimates to the Columbia River Basin Successional Model. The algorithm was later incorporated into the FVS program (Crookston and Stage, 1999). Ceder and Marzluff (2002) used FVS to evaluate wildlife habitat under the umbrella of LMS and Christensen et al. (2002) studied the economics of reducing fire hazards in Montana by linking FVS to a financial evaluation program (Fight and Chmelik, 1998).

4.6. Climate change

Extending FVS to represent conditions outside those in existence today is another class of applications. Stage (2002) showed how this can be done by using FVS to predict the influence of climate change on fire hazard and stand dynamics for the Flathead Indian Reservation, Montana. Options in FVS were used to modify growth and mortality rates to represent the effects of postulated climate change on accretion, mortality, regeneration, and dead wood decomposition rates.

4.7. Beyond North America

Use of FVS outside North America is rare. One example is the application of the Lake States variant to assess Amur tiger (*Panthera tigris altaica*) habitat on the Chuguevksi Leskhoz demonstration project in Russia. In this application, growth equations for similar species in the United States were applied to Russian species (e.g., Eastern white pine (*Pinus strobes*) equations are being used to simulate development of Korean pine (*P. koraiensis*)). In northern Italy, FFE-FVS has been used in combination with SVS as a teaching tool to explain the roles of fire and silviculture on stand dynamics. In Austria, the form of the growth equations and some other attributes of FVS were adopted in building a new model called PROGNAUS (PROGNosis for AUStria; Monserud et al., 1997; Sterba and Monserud, 1997).

4.8. Forestry research and teaching

Field applications of FVS, highlighted above, do not address the important role FVS plays in supporting forestry research. The model is often used as a simulation-based platform suitable for testing hypotheses about new ways to represent forest growth. Another routine, yet mostly undocumented, application of the model is to support silvicultural training and certification of professionals and application as a teaching tool in several schools of forestry.

5. Support organization and other key factors

Many good forest growth simulation models have been developed yet do not have the widespread usage of FVS. There are some additional factors significant to the widespread use of FVS.

First, the team that develops and supports FVS, also directly participates in supporting and training users. This practice, coupled with actively monitoring changing directions in forest management, allows the team to anticipate future needs. The development of the FFE-FVS is an example of how anticipation of needs leads to the timely delivery of a new extension.

Selecting Fortran (which literally means FORMula TRANslation) turned out to be a good choice in building FVS. Now, after 30 years, our reliance on the original programming language has had important payoffs. Foremost, team members have participated in code maintenance and innovation over many years. We believe that if we had changed computer lan-

guages, adopting C or C++ as many have suggested, we would have lost our key brain trust. Secondly, we never lost the time it takes to undergo a conversion to a new language. Note that excellent Fortran compilers are readily available, and the language is simple to learn and understand. Continued reliance on proven code, a dedicated and knowledgeable support staff, and a focus on user needs are often overlooked reasons for the success of this model.

A graphical user interface called Suppose (Crookston, 1997) is available that offers users a quick and versatile way of running FVS.

The source code for FVS is freely available and in the public domain. This fact was an important consideration of the models adoption in British Columbia and was considered by Robinson and Monserud (2003) in finding FVS the most adaptable model among several evaluated.

6. Limitations and future work

FVS has been in use by forest managers for more than 30 years. The summary of applications demonstrates that the structure and content of FVS is suitable for addressing a wide variety of decisions. The original Prognosis Model contended with the huge variability and disturbances present in the forests of northern Idaho and accommodated all forest types and stand conditions present there. The modeling framework that was developed has proven adaptable across the US and to other countries.

Understanding the limitations of FVS suggests future work. The following discussion describes noteworthy limitations and how we intend to address them.

Non-tree vegetation is represented in a limited way with the Canopy and Shrubs Extension, which is calibrated only for northern Idaho and western Montana. As a result, FVS is of limited use for answering range management questions or for evaluating habitat requirements that hinge on detailed predictions of non-tree vegetation. In applications that require such estimates, FVS users rely on gross relationships between tree canopy cover and the amount of non-tree vegetation expected on a given habitat. Relationships such as these are used in the FFE-FVS when predicting the amount and flux of non-tree fuels. In some cases, users rely on trends predicted by the Canopy and Shrubs Extension rather than absolute values of the outputs. The need to provide for better representation of non-tree vegetation is growing. Currently, we plan to meet this need by linking FVS to other vegetation models rather than building new components into FVS.

FVS represents the photosynthetic capability of a tree by its crown ratio, size, and social position. The base model is therefore not directly sensitive to environmental changes such as increasing temperatures, changes in rainfall, and changes in atmospheric CO₂. Work to make predictions sensitive to changing climate includes the recent introduction of an extension that contains a biogeochemical physiology growth model (Milner et al., 2002). This experimental extension is linked to one FVS variant and is still under development and refinement.

Another aspect of climate change regards that fact that trees can become maladapted to local environments if the climate changes (Rehfeldt et al., 2002). FVS is insensitive to climatic changes that can influence tree geography. We are currently conducting research to predict tree distributions from climate.

Taking advantage of recent biometric developments is another active subject area. This work includes applying Stage and Wyckoff's (1998) method to represent within-stand spatial variability in all variants. Hasenauer et al. (1998) demonstrated that simultaneous regression techniques improve model performance of individual-tree growth equations. Recent work on nitrogen fertilization lead to understanding how soil geomorphology can directly affect growth and mortality rates (Shen et al., 2001). Capitalizing on this knowledge is also on our agenda.

The FFE-FVS is used to assess the efficacy of proposed fuel management actions in reducing fire hazard. A limitation of this extension is that it is a stand-level model, not sensitive to spatially dependent fire behavior. Current work includes linking the FFE to the PPE and then building linkages to separate landscape-level fire behavior models such as FARSITE (Finney, 1998). The goal is to establish efficient schedules for treating fuels in a landscape. It will also demonstrate the concept of dynamically linking FVS to a separate model rather than adding a new major component to FVS. We expect this to be a trend in our future development.

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