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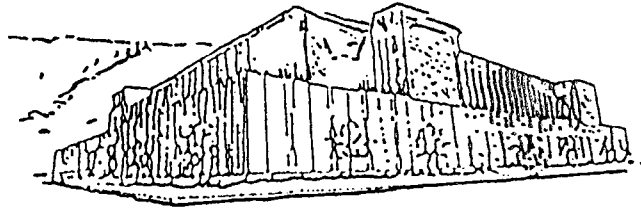
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**Growth Response of Residual Stands in Western Montana**

**And**

**FVS Model Validation Using Remeasurement Data**

by

Christopher R Schwalm

presented in partial fulfillment of the requirements


for the degree of

Master of Science

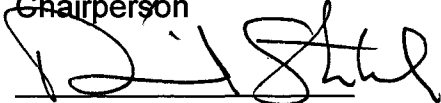
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## Abstract

Schwalm, Christopher R, M.S. October 1997

Forestry

### Growth Response of Residual Stands in Western Montana and FVS Model Validation Using Remeasurement Data

Director: Dr. Kelsey S. Milner 

Forty-two research installations were established throughout western Montana in 1984/5. Plots were all located in stands with recent harvest activity with the range of harvest intensity between 250 ft<sup>3</sup>/acre for a precommercial thin to upwards of 7000 ft<sup>3</sup>/acre for an overstory removal. Study plots were remeasured every five years with the most recent measurement occurring in 1996. Periodic annual increments of individual tree diameter and height as well as plot level accretion were then calculated. Growth rates increased after harvest activity and ranged from 0.03 to 0.3 inches per year, 0.3 to 2.8 feet per year and 20 to 140 ft<sup>3</sup>/acre/year respectively. Regeneration and ingrowth tallies were also summarized. The Forest Vegetation Simulator (FVS) model was evaluated using a part of the remeasurement data. Accretion, individual tree volume, height and diameter growth were tested for precision, bias and accuracy. FVS explained little of the variation associated with the height and diameter growth dynamics in residual stands. Individual tree and plot level accretion were better predicted. Calibration also improved model performance.

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## Introduction

The silvicultural system of selection cutting (single or group) has been practiced in the United States since the latter part of the 19<sup>th</sup> century (Guldin 1995). Indeed, many of the 'New Forestry' silvicultural practices have seen widespread use earlier in this century only to be replaced by clearcutting during the post-war period. This ebb and flow of silvicultural practices will no doubt continue as market demands and merchantability standards change as well as society's view of the forest and the resources within evolves. In western Montana as elsewhere in the United States, the fates of these 'partially cut' stands are largely 'unknown' (Oliver and Larson 1996). Stands of western conifers were repeatedly entered every 10 to 40 years. Merchantable stems were removed at each entry. Stands were successively reentered, *not* because the remaining trees grew vigorously, *but* because the species and sizes of trees considered merchantable changed (Oliver and Larson 1996). The result of these cuttings was a forest consisting of crooked, often diseased trees with little future timber value (Trimble, 1963). Short term effects of this type of partial cutting include a suppressed understory, low vigor overstory trees and increased susceptibility to insects and disease (Smith and Grant 1986; Oliver and Larson 1996). Howe (1995) also notes that genetic selection towards competitively inferior trees may also be occurring (*high grading*). Despite the above there are instances where selection cutting has been used to successfully create stands with vigorous trees of many sizes and ages. Foresters however need quantitative data upon which to base sound

management decision. The qualitative assessments of low vigor, suppressed understory and 'jumbled age classes' (Hatch 1967) need to be supplemented by growth and yield data on the residual stands.

Forestry has become a computerized profession. Models of all types project stand development, smoke plumes, fuel loads and many other phenomena. Growth and yield models are a subset of forestry models in general. Their purpose is to give the land manager information regarding future stand (or even individual tree) development. The most important growth model in western Montana and the Inland West is the Forest Vegetation Simulator (FVS). It is used by various private timber corporations as well as the Forest Service to predict stand development and volume yields. Despite its ubiquity in management its performance has not been rigorously evaluated. Specifically, how FVS predicts residual stands has not been adequately addressed in the forestry literature. Foresters confronted with such a stand are in need of information regarding the performance of FVS. As such the specific objectives of this study are to:

- 1) summarize remeasurement data collected during a 10-year period from research installations established in residual stands in western Montana;
- 2) determine how well, in terms of accuracy, precision, bias and predictive power, the Forest Vegetation Simulation model predicts growth in those residual stands; and,
- 3) Determine if the self-calibration feature of FVS improves model performance.

## Literature Review

Partial cutting has been around for a century. As the timber frontier extended westward everything was removed that had any value. The residual stands were simply re-entered as merchantability standards changed and/or logging technology improved. As virgin timber became scarce and eventually disappeared altogether this attitude changed by necessity (Chase, 1995). In the sparsely populated inland West, however, the notion that 'there's more timber just over the next hill' proved quite tenacious (Milner, personal communication). This, in part, explains the relative paucity of literature on residual stands in the inland West versus more populous and physically smaller regions of the country like the mid-Atlantic seaboard or New England and the southern Pinery. The need for different management techniques that go hand in hand with selection cutting or any type of 'partial cutting' was not judged great. The other reason for a relative dearth in publications on partial cutting in the inland West can be found in the relative productivity of the forestlands implicated. The states of Montana and Idaho along with the eastern parts of Oregon and Washington (the region generally assumed under Inland West) are, on a merchantable volume per acre basis, among the least productive timberlands in the United States (Barrett, 1995). The longer rotations necessary to produce merchantable wood have also conspired to make clearcutting the regeneration system of choice. Despite this, Schmid et al. (1991) state that partial cutting will become more desirable as it has shown some promise in reducing tree mortality caused by insect outbreaks. Selection cutting practices are also being mandated by law. Despite the relative low importance,

historically, of growth and yield data on partially cut stands, some data do exist for several species.

The proper management of ponderosa pine (*Pinus ponderosa* Lawson) depends on sound statistical knowledge of tree growth under various stand conditions and site qualities (Schmid et al. 1991). Substantial information is available of how overstocked, even-aged, immature stands respond to release. For example, Boldt and Van Deusen's (1974) study of growing stock levels (GSL, basal area in square foot after thinning to some mean tree size) in the Black Hills, periodic annual increment of basal area ranged from 1.63 to 2.61 sq. ft. per acre per year for ponderosa pine. Average diameter growth ranged from 0.10 to 0.17 inches per year. On three partially cut plots with GSL's of 60, 80 and 100 in the northern Black Hills, Schmid et al. (1991) found basal area increments ranging from 1.18 to 1.26 sq. ft. per acre per year and mean stand diameter growth ranged from 0.06 to 0.14 inches per year with GSL's of 130 to 135. Dolph et al. (1995) found diameter ponderosa pine growth rates ranging from 0.02 to 0.12 inches per year in a mixed-species stand in northern California after selective cutting. Mowat (1961) tested various methods of selective (partial) cutting on 32 remeasured plots in eastern Oregon. After 22 to 86% of growing stock was removed from stands of 'virgin' ponderosa pine, accretion for the most recent ten-year period varied between a loss of 3 to a gain of 72 cu. ft. per acre per year (assuming 5 bd. ft for 1 cu. ft of volume). In central Oregon, Barrett (1983) found that released trees required about 15 years to reach their maximum height growth rates. In his study of 4 different density levels (plots thinned to 62, 125 250 and 500 trees per acre

respectively) ponderosa pine height growth ranged from 0.6 to 1.2 ft. per year with the best growth occurring in the third 5-year period after thinning. In the same study basal area increment ranged from 1.3 to 4.0 sq. ft. per acre per year with the highest increment in the denser stands. Finally, net volume increment ranged from 20 cu. ft. per acre per year in the least dense stand to over 60 cu. ft. per acre per year in the densest stands. In northern Arizona, Ronco and Trujillo (1985) found that diameter growth was negatively correlated to stand density and that volume increment was positively correlated to stand density. Diameter growth rates for ponderosa pine ranged from 0.10 to 0.34 inches per year. Basal area and net volume increment ranged from 1.9 to 4.4 sq. ft. per acre per year and 31.0 to 86.3 cu. ft. per acre per year respectively. Here, the GSLs of 30, 60, 80, 100, 120 and 150 were used. In the Methow Valley of northern Washington state, Barrett (1981) found similar growth rates with the same GSLs. Diameter growth ranged from 0.10 to 0.30 inches per year. Basal area increment ranged from 1.4 to 3.8 sq. ft. per acre per year. Accretion ranged from 45 to 170 cu. ft. per acre per year.

Partial cutting of lodgepole pine (*Pinus contorta* Dougl.) was 'generally accepted and widely practiced' in Montana prior to 1946 (Hatch 1967). However, large-scale pulpwood cutting forced the abandonment of selective systems in favor of clearcutting. Hatch (1967) continues: 'Whether clearcutting or selective cutting was a more suitable practice from the standpoint of regeneration and ultimate yield became highly conjectural.' His 1967 study was a response to this uncertainty. Periodic annual increment on a 120 to 160 year old stand of lodgepole pine in western Montana was 16.6 gross increment and -52.8 net increment cu. ft. per



acre per year over 11 years. Hatch concludes by stating that this partial cut 'should not have been made.' The excessive mortality and 'jumbled age classes' left a stand that lacked adequate values to justify a final cut. 'Chances of a successful partial cut are determined largely by the vigor of the residual stand, by the site and by accessibility and market opportunities. Partial cutting in the lodgepole pine type should be made only for cultural benefits...' In general, in unmanaged old-growth stands, average annual volume growth ranges from 5.0 and 8.0 cu. ft. per acre per year due to large numbers of smaller trees and insect outbreaks (Alexander and Edminster 1980; Lotan and Critchfield 1990). However, annual net volume growth may be increased to 30.0 to 80.0 cu. ft. per acre per year by controlling stand density and mistletoe infection (Edminster 1978; Alexander and Edminster 1981). Lodgepole pine generally grows much faster in height than its associates (Deitschmann and Pfister 1973). Schmidt and Seidel (1988) found height growth rates ranging from ranging from 0.2 for poor vigor trees aged 15 to 25 years to 1.7 ft. per year for high vigor trees aged 10 to 15 years. Land managers should expect diameter growth rates of around 0.15 inches in unmanaged lodgepole pine stands and basal area increments of approximately 2.0 sq. ft. per acre per year ( Lotan and Critchfield 1990).

How a tree species responds to new available growing space is more complete for western larch (*Larix occidentalis* Nutt.) than other conifers in the Inland West (Schmidt and Seidel 1988). In order to maintain its vigor, larch must have a dominant position in the stand. Larch, as a shade intolerant, grows faster than any other conifer in the northern Rockies for the first century (Schmidt and

Shearer 1990). This gives larch the advantage it needs to stay in the upper strata of the canopy and hold its vigor. Many studies have compared height growth rates of larch to its associates. For example, in a managed stand larch and lodgepole pine grow at twice the rates of Douglas-fir (*Pseudotsuga menziesii* var. *glauca* [Beissn.]) and Engelmann spruce (*Picea engelmannii* Parry ex Engelm.) (Schmidt 1969; Cole and Schmidt 1986). In an unmanaged stand both larch and lodgepole grew up to four times as fast in height as western white pine, western red cedar and western hemlock (Deitschmann and Pfister 1973). Cole and Schmidt (1986) in a northwestern Montana study found height growth rates for larch ranging from 0.1 for poor vigor trees aged 15 to 25 years to 1.3 ft. per year for high vigor trees aged 10 to 15 years. Basal area increment averages 3.0 sq. ft. per acre per year for the first century in larch stands. In general, land managers can expect height growth rates of 0.8 to 1.5 ft. per year on medium to good sites in thinned pole-sized stands (Schmidt and Seidel 1988). In the second century, however, the growth rate is only about 0.3 sq. ft. per acre per year (Schmidt and Shearer 1990). Diameter growth of even-aged larch stands is significantly increased by thinning (Seidel 1971, 1975). In an Oregon stand thinned at age 33, diameter growth increased from 0.11 to 0.36 inches per year on plots (Schmidt and Seidel 1988). Seidel (1980) found diameter growth rates for larch after thinning ranged from 0.05 to 0.20 inches per year. In the same study of the 10-year growth of a 55-year-old even-aged larch stand Seidel found basal area and volume growth (accretion) rates ranging from -0.03 to 3.84 sq. ft. per acre per year and 3 to 135 cu. ft. per acre per

year respectively. Volume growth rates on the 33-year-old stand mentioned ranged from 64 to 136 cu. ft. per acre per year (Seidel 1982).

Annual growth rates for Douglas-fir following partial cutting ranged from 28.0 to 58.0 cu. ft. per acre per year (Cole and Schmidt 1986). Cole and Schmidt (1986) also found height growth rates after release for Douglas-fir ranging from 0.1 for poor vigor trees aged 15 to 25 years to 0.9 ft. per year for high vigor trees. McDonald (1976) found volume growth (accretion) of a mixed-species stand on the Challenge Experimental Forest in California with Douglas-fir as a dominant was, after being partially cut, 10.7 cu. ft. per acre per year. Diameter growth in the same study ranged from 0.24 to 0.70 inches per year on Douglas-fir. McDonald concludes that Douglas-fir was relatively insensitive to release during the study period. Coble (1991a) found a mean annual height growth rate of Douglas-fir from the Klickitat District in Washington state of 1.1 feet per year. In the same study, average annual diameter growth was 0.2 inches and individual tree volume growth was 1.45 cu. ft. per year. In another study of Douglas-fir remeasurement data from Oregon and Washington, Coble (1991b) found an average annual height growth rate of 2.1 feet per year. Average annual diameter growth was 0.29 inches per year. Average annual individual tree volume growth and plot level accretion were 1.8 cu. ft. and 145 cu. ft. per acre respectively. Hermann and Lavender (1990) report average diameter growth rates for Douglas-fir of 0.2 inches for the Inland West and accretion ranging from 20 to 140 cu. ft. per acre per year.

Knowing the broad range of grow rates for a particular stand or forest type is not enough for the land manager. The more detailed knowledge a forester has

regarding what part of the above ranges the stand in question will occupy in the future the better. Without some tool to adequately predict growth and yield, the land manager is not in a position to make enlightened decisions regarding forest husbandry. Models, such as FVS (Forest Vegetation Simulator), may provide these necessary links to the future and aid land managers in their decision-making processes. The FVS (see Appendix for a model description) model system is the most widely used growth and yield simulator in the Inland West. As residual stands become more commonplace in the management domain, FVS will be used more and more to produce growth and yield numbers and evaluate alternative stand structures. Although, FVS was calibrated with data from managed and unmanaged stands (Wykoff et al. 1982) the types of managed stands used in calibration were unlike those in the sample and those which would arise from 'partial cutting. The range of stand conditions found in the sample is not adequately represented in the data set used to derive FVS. Therefore, there is a reasonable doubt that the FVS model may 'underperform' in a residual stand environment versus the more traditional stand structures it is currently applied to. As such, the body of literature available on FVS concerns even-aged stands. This will serve as a benchmark in comparing the performance of the model here. First, though, it is necessary to review the procedures used in model validation.

Becker et al. (1984) place model validation in the following context: 'Forest managers require tools that enable them to estimate future growth trends of forest stands...' Put simply, foresters need growth models for any and every management activity. Despite the popularity of growth models, many questions

still remain as to their accuracy (Ek and Monserud 1979). Because of this forestry literature is full of various guidelines concerning model validation (Newbury and Stage 1987, Zuuring et al. 1987, Arney 1982). Most professionals agree that merely regressing observed on predicted values for a given attribute is not enough to usefully quantify a model's reliability. Particularly, Zuuring et al. (1987) state that any model validation exercise must include detailed residual analysis. If only to facilitate comparisons between other models. Finally, regardless of how a model is evaluated it must be stressed that model validity is a relative matter. The usefulness of any model must be judged in comparison with 'the mental image or other abstract model which would be used instead' (Forrester 1968).

The FVS model suite has not been extensively tested in the Inland West. Milner (1983) found the FVS model explained approximately one-half of the variability in total cubic foot volume per acre per year over a 20-year time period encountered on precommercially thinned young western larch stands in western Montana used in a replicated thinning experiment. When the model was validated over a ten-year period the model explained 66% (with actual mortality) and 74% (with predicted mortality) of the variation encountered. The above figures pertain to model runs with calibration only. Without calibration, model performance decreased 9 percentage points versus with calibration. Height increment was also evaluated, with regression of observed on predicted being done by spacing and replication. Here the amount of variability explained by the model ranged from .02% to 74%. Diameter increment was evaluated the same way and also had wide ranging values (1% to 71%). Finally, Milner (1983) found that FVS consistently

overpredicted volume growth per acre per year on 48 plots of western larch on Lolo National Forest.

## **Methods**

### ***Data Collection***

In 1985 three dozen research installations were established in western Montana (see Appendix for a list of site and topological variables). The objective of these plots was to give land managers at Champion International Corporation information about the growth dynamics of newly released trees. Plots were selected such that the sample surface of Champion lands in western Montana would be represented. In the case of this study the sample surface consisted of the range of initial stocking levels, cutting intensity and site potential found on Champion fee lands. Mean tree size, density, genetic variability and species composition were not considered during the plot placement. The majority of plots were located in 'partially cut' stands with the most recent treatment activity occurring after 1968. On no plot was there harvest activity within 5 years prior to plot establishment. Additionally, treatment selection was focused on overwood removals and single-tree selection cuts. Actual plot location was, however, subjective. Once a Forest Management Unit (an FMU is tract of contiguous land that has been delimited as a management entity primarily based on operational considerations) and then a stand had been chosen, a plot was placed and sized such that the range of conditions within the stand would be represented within the plot itself. The notion of 'representativeness' was arrived without allowing the laws

of random chance to operate. Finally, plots were placed to control for initial stocking, cutting intensity and site potential. After plot establishment, each plot was initially measured and then remeasured every five years. Approximately 3600 trees have since been stem mapped, tagged and (re)measured. A summary of measured and tallied attributes is given in Table 1 (A comprehensive data collection primer is located in the Appendix.):

**Table 1.** Summary of attributes recorded at each plot.

<b>Trees (HT &gt; 4.5')</b>	<b>Trees (HT &lt; 4.5')<sup>d</sup></b>	<b>Plot</b>
Diameter at Breast Height (in.)	Height (1/10 ft.)	Site Index (ft.) <sup>b</sup>
Height (ft.) <sup>a</sup>	Crown ratio (%)	Slope (deg.) <sup>b</sup>
Crown ratio (%)	Height Growth (1/10 ft.) <sup>b</sup>	Aspect (deg.) <sup>b</sup>
Bark Thickness (in.) <sup>ab</sup>	Species	Elevation (ft.) <sup>b</sup>
Age (yr.) <sup>ab</sup>	Damage Code	Herbaceous Cover
Height to Base of Crown (ft.) <sup>ab</sup>	Status Code	Shrub Cover <sup>d</sup>
Radial Growth (1/50 in.) <sup>ac</sup>		Regeneration Tallies <sup>d</sup>
Species		Stump Survey <sup>d</sup>
Status Code		
Damage Code		

- a) Sub-sampled by species and thirds of the diameter distribution
- b) Only measured in 1985
- c) On every tree with DBH (diameter at breast height) greater than 3.0" at the first measurement
- d) See Appendix

## **Data Analysis**

The data analysis presents growth of the residual stands at both the individual and tree level. For this purpose the following response variables were used:

- *Individual tree height growth* (feet per year). This is the tree's height at the start of the period minus the same tree's height at the end of the period divided by the time period (see below). Trees with measured heights were used as well as the off-plot height growth trees (see Data Primer).
- *Individual diameter growth* (inches per year). This is the tree's diameter at the start of the period minus the same tree's diameter at the end of the period divided by the time period. All trees used in this study have diameter measurements. Pre-harvest and at-harvest diameters were reconstructed using increment core data.
- *Plot level volume growth or increment* (cu. ft. per acre per year). This is the difference between the amount of standing volume at the start and the end of the period divided by the time period. This is a measure of gross growth on growing stock. The interim calculation of standing volume is the summation of all surviving trees' volume at any one given time. Volume equations are from Wykoff et al. (1982) as are the height-diameter relationships used to supply missing heights.
- *Basal area increment* (sq. ft. per acre per year). This is the difference between the amount of basal area at the start and the end of the period divided by the



time period. This is a measure of net change, the basal area of all trees present at a given time was used for this response variable.

Time periods used in the study center around harvest activity. Pre- and post-harvest figures are given for all response variables. Pre-harvest and at-harvest dimensions of any kind have been reconstructed using increment core data. That is, no actual measurements were taken prior to harvest for any plot. The diameter 5-years prior to harvest was computed by subtracting off diameter growth from the diameter at time of measurement. This pre-harvest diameter was then used to compute height and volume using equations from Wykoff et al. (1982). At-harvest diameter was computed using the same methods except that diameter growth was counted back only to the year of harvest.

The explanatory variables used are as follows:

- *Site index*; the height of the dominant trees at age 50 based on Milner (1993). This is generally considered a good measure of site potential or site quality which influences the amount of total biomass any one site can support and therefore influences growth patterns of trees. Site index is viewed by many foresters to reflect the combined effects of climate and various topographical variables such as aspect, slope, soil type and elevation.
- *Cutting intensity*; amount of basal area removed at harvest, both absolute and percentage. This variable serves to quantify the severity of the harvest entry and the amount of growing space released as a result of harvest. This newly available growing space is of great importance for the development of residual stands.

- *Initial stocking*; the amount of standing volume (cu. ft. per acre) immediately prior to harvest. This quantifies the amount of biomass prior to harvest which, in turn, influences the growth response potential of the residual stand.
- *Crown ratio*; an ocular estimate of a balanced live crown expressed as a percent. Crown ratio is regarded as a measure of an individual tree's vigor. Trees of high vigor are, for example, expected to outgrow a similar sized tree of the same species. Since crown ratio is based on the amount of live crown present in a given tree is also represents the tree's ability to make use newly available growing space (specifically sunlight).
- *Relative diameter*; diameter of tree over average diameter of the entire stand. This variable attempts to quantify the tree's relative position in the hierarchy of strata. For example, a tree with a relative diameter of .2 is probably suppressed whereas a tree with a relative diameter of 2.5 is most likely in the dominant stratum or overstory. The tree's relative diameter is an indication of its ability to take advantage of the newly created growing space.
- *Diameter growth*; as the response variable above. This is used as an explanatory variable for height growth. It is thought that there are certain biophysical limitations on tree growth. For example, a given height of a given species must be supported by a minimum diameter. Also, diameter growth is assumed to have an allometric relationship with height growth. FVS uses such a relationship to predict height increment (Wykoff et al. 1982).
- *Diameter*; this is diameter at breast height (DBH). Oliver and Larson (1996) mention that trees of certain species (lodgepole pine for example) lose their

ability to utilize newly available growing space after some threshold size is reached. Smaller sized trees are generally thought to have the greatest response potential.

- *Species*; the botanical classification of a particular tree specimen. Individual tree species vary in their biological response to competition, newly created growing space and response to thinning (Oliver and Larson 1996).

### ***Model Validation***

Buchman and Shifley (1983) list three areas of model testing: application environment, design and performance. While the first two are surely of import they will not be treated here. The question of how well FVS projects residual stands will be paramount. Model validation analyses address model precision, accuracy and bias. For all three aspects of model performance, the concept of residuals is important. Residuals are the difference between the actual value and its predicted counterpart. In other words, a negative residual is an overprediction and a positive residual is an underprediction. Another term often used in the same context is prediction errors. The two will be used interchangeably here. In this study precision is synonymous with the standard deviation of these residuals (Brand and Holdaway 1983) and bias refers to the mean residual. The concept of model accuracy, on the other hand, can be quantified by mean absolute residual (Milner 1983). Bias, then, concerns trends in residuals or prediction error patterns whereas accuracy is the average deviation from truth, independent of direction. Also found in the literature is one other measure of model bias arising from a regression context. Here bias means that the coefficients of a simple linear

regression (some observed attribute regressed on the same actual attribute) are statistically different from 0 for the intercept and 1 for the slope. Finally, bias can refer to trends discernable in residuals analyses.

In contrast to the data summary, the time frame used in model validation will be shorter. Only the remeasurement data will be used to evaluate FVS (1984/85 to 1996). No reconstruction (other than the use of height-diameter relationships) will be used. The attributes to be tested are accretion per acre per year and individual tree volume, height and diameter growth. All growth rates (actual and predicted for each relevant attribute) were calculated by taking the difference of the respective attributes (end minus initial value). The input tree lists used in model validation consisted of all plots that were remeasured in both 1984/5 and 1996. Starting tree lists included all trees present at the start of the period. There are two different tree lists for each plot. One tree list (*uncalibrated*) is without diameter growth data. That is, the radial increment data taken on all trees whose diameter at breast height was at least 3.0" was not part of the input tree list. In this instance the FVS model uses the default coefficients to predict diameter growth. The other tree list (*calibrated*) includes the radial growth data as diameter growth in inches for the previous 10 years. FVS uses this data to scale the diameter increment model to reflect local deviations from regional growth trends represented by the un-scaled model (Wykoff et al. 1982). Note that height increment data can also be incorporated to scale the height growth model but that calibration and the effects thereof only refer to diameter growth in this study.

After the full gamut of observed and predicted values were calculated, the observed was then regressed on the predicted values. This is a simple linear regression where the coefficient of determination is to be interpreted as the amount of variability in the actual data that is explained by the model or the model's overall predictive power. For example, with an  $R^2$  of .45, we can say that 45% of the variability encountered was explained by the model. Beyond the basic analysis, two other descriptive procedures were used. First, a residual analysis (Zuuring et al. 1987) was done. This involves graphing growth residuals (the discrepancy between actual and predicted values) over some initial condition or topographical variable (see above). For this study the following variables were used for individual tree growth rates: initial crown ratio, initial height and initial diameter. On the plot level aspect, slope, elevation, site index, crown competition factor (a measure of site utilization), stand density index (a measure of site occupancy) and initial basal area were chosen. Ideally, such a scatter would be without any pattern or homogeneously clustered about the zero reference line. This technique is also called error pattern analysis. The latter term more aptly describes what the analyst is looking for: patterns to the residuals. For example, assume that a figure of diameter growth residual over initial diameter was showed an even distribution about the zero reference line until the threshold diameter of 16" was reached. Beyond this point, all trees were overpredicted (residuals below the line). This pattern in the residuals is of interest to the land manager and model user and is rightly termed a bias. The last procedure seeks to get at model accuracy and precision. Here, mean, median prediction errors (residuals) and their standard

deviations are presented in tabular form. Smaller mean absolute prediction errors are desirable in the sense that they reflect greater degree of accuracy or closer to 'truth.' Precision is the variation associated with this average misprediction and is reflected in the standard deviations given in the results. Also, the results presented here will be compared with the few other studies where FVS has been validated. Note that although the mortality function in FVS was enabled for all projections, mortality is not addressed in this analysis. All individual tree growth rates are for the surviving trees only. Lastly, the tripling function, whereby FVS generates three tree records for each tree, and the regeneration tallies (the addition of regeneration trees to the stand) were both disabled

## **Results**

### **Data Summarization**

#### ***Individual Tree Diameter Growth***

Starting with five years prior to treatment, on through treatment itself and the three measurements, it is possible to track the growth of an individual tree through time. Two time periods will be used for comparison: Pre-harvest diameter growth (the growth based on five years prior to harvest to the actual harvest) and post-harvest (growth from harvest to 1996). Post-harvest diameter growth of all species covers a wide range of values. This variability results from overtopped specimens with low vigor to more vigorous co-dominants left after harvest being included in the sample data. Variation within each species was also marked. Average values

by diameter class of pre- and post-harvest growth rates for the same trees are given in Table 2.

Table 2. Mean survivor individual tree diameter growth rates (inches per year) and standard deviations for the four most abundant species in the sample. Pre-harvest growth rates are based on five years prior to treatment and were reconstructed using increment core data. Post-harvest values are based on harvest to 1996 interval. Values in brackets are standard deviations. Note that time since harvest varies with plot.

<b>Species</b>	<b>Diameter Class</b>	<b>Pre-harvest</b>	<b>Post-harvest</b>	<b>N</b>
Douglas-fir	0-2"	.12 (.06)	.23 (.04)	5
	2-4"	.06 (.06)	.13 (.08)	99
	4-6"	.07 (.04)	.15 (.08)	108
	6-8"	.08 (.04)	.16 (.07)	70
	8-10"	.10 (.05)	.15 (.07)	22
	10-12"	.11 (.05)	.18 (.08)	12
	12-14"	.09 (.03)	.19 (.04)	5
	14-16"	.10 (.03)	.18 (.11)	3
Lodgepole Pine	16+"	.11 (.08)	.17 (.01)	2
	0-2"	.33 (.10)	.27 (.08)	11
	2-4"	.15 (.10)	.16 (.08)	31
	4-6"	.12 (.07)	.14 (.05)	54
	6-8"	.12 (.08)	.12 (.05)	24
	8-10"	.09 (.04)	.10 (.05)	16
	10-12"	.10 (.07)	.15 (.03)	2
Ponderosa Pine	0-2"	.20 (.22)	.17 (.11)	6
	2-4"	.07 (.04)	.11 (.08)	38
	4-6"	.06 (.03)	.12 (.06)	82
	6-8"	.07 (.04)	.14 (.06)	28
	8-10"	.09 (.04)	.20 (.07)	14
	10-12"	.08 (.01)	.21 (.04)	5
	12-14"	.07 (.02)	.06 (.03)	8
Western Larch	0-2"	.28 (.05)	.28 (.05)	13
	2-4"	.10 (.09)	.17 (.07)	59
	4-6"	.08 (.04)	.15 (.06)	51
	6-8"	.07 (.05)	.11 (.06)	29
	8-10"	.11 (.06)	.13 (.06)	11
	10-12"	.12 (.08)	.14 (.08)	4
	12-14"	.12 (.07)	.15 (.09)	4
	14-16"	.09 (.05)	.07 (.05)	2

For every species and in each diameter class post-harvest growth was always greater than pre-harvest growth except for: lodgepole pine 0-2" and 6-8", ponderosa pine 0-2" and 12-14" and western larch 0-2" and 14-16" DBH classes. The increase of post-harvest diameter growth versus pre-harvest growth exhibits a pattern unique to each of the species listed. Douglas-fir exhibits a uniform response at all diameters, growth rates show approximately a twofold increase. Lodgepole pine registers only a slight response at all diameter classes, except the 10-12" where response is most pronounced. The response of ponderosa pine, on the other hand, increases as tree size increases (note the exceptions above). Finally, with western larch, response was greatest in the smaller diameter classes.

When growth rates are computed by species and crown ratio (as measured in 1984/85) a different picture emerges (Table 3). For all species, the greatest response is for the crown ratios between 45 and 70%. Only lodgepole pine shows no response in the class of crown ratios. Lodgepole pine is also the only species to show a decrease in diameter growth rates, e.g. 75-95% crown ratio. This pattern can be explained as follows. Trees in the lowest crown ratio class are too suppressed to take full advantage of the newly created growing space while trees in the highest class already benefit from a well-developed crown and a competitive position in the stand overstory. Thus, the middle class has the most potential for response.



Table 3. Pre- and post-harvest individual tree diameter growth (inches per year) for the four major species in the sample. Values are referenced to the crown ratio as measured in 1984/5 for each tree. Values in brackets are standard deviations.

---

<b>Species</b>	<b>Crown Ratio</b>	<b>Pre-harvest</b>	<b>Post-harvest</b>	<b>N</b>
Douglas-fir	5-40	.05 (.03)	.08 (.05)	57
	45-70	.07 (.04)	.16 (.07)	238
	75-95	.15 (.08)	.21 (.06)	31
Western larch	5-40	.05 (.04)	.08 (.05)	27
	45-70	.08 (.05)	.15 (.06)	115
	75-95	.23 (.09)	.26 (.05)	31
Lodgepole pine	5-40	.07 (.04)	.10 (.05)	50
	45-70	.15 (.06)	.15 (.05)	72
	75-95	.33 (.08)	.28 (.07)	16
Ponderosa pine	5-40	.05 (.04)	.08 (.04)	40
	45-70	.07 (.03)	.14 (.06)	181
	75-95	.16 (.14)	.21 (.08)	16

Table 4. Pre- and post-harvest individual tree diameter growth (inches per year) for the four major species in the sample. Values are referenced to the relative diameter of the each tree. Values in brackets are standard deviations.

---

<b>Species</b>	<b>Relative Diameter</b>	<b>Pre-harvest</b>	<b>Post-harvest</b>	<b>N</b>
Douglas-fir	0.1-1.0	.06 (.05)	.14 (.08)	189
	1.1-2.0	.09 (.04)	.16 (.07)	128
	2.1+	.12 (.05)	.20 (.05)	9
Western larch	0.1-1.0	.09 (.08)	.15 (.08)	101
	1.1-2.0	.13 (.09)	.17 (.07)	70
Lodgepole pine	0.1-1.0	.14 (.10)	.14 (.08)	53
	1.1-2.0	.15 (.10)	.15 (.07)	83
	2.1+	.10 (.07)	.15 (.03)	2
Ponderosa pine	0.1-1.0	.06 (.06)	.12 (.07)	134
	1.1-2.0	.08 (.04)	.15 (.06)	102

---

Crown ratio is just one measure of a tree's ability to utilize growing space, the relative position of a single tree in the stand itself is also an indicator of response

potential. A tree's position in the hierarchy of stand structure will be illustrated by the concept of relative diameter (Table 4).

In this sample, the growth response for ponderosa pine and Douglas-fir is by and large identical regardless of the tree's relative diameter. Western larch of smaller relative diameters had more of a response than the larger sized trees.

Lodgepole pine, however, shows no response for any relative diameter, save the 2 trees with values greater than 2.1.

A tree's response to silvicultural practices is influenced by site factors as well. The concept of site index is useful as it is assumed to be an integrated measure of climate and other abiotic factors (Table 5).

Table 5. Pre- and post-harvest individual tree diameter growth (inches per year) for the four major species in the sample. Values are referenced to the site index on the plot where the tree occurs. Values in brackets are standard deviations. Site index (base-50) is from Milner (1993).

---

<b>Species</b>	<b>Site Index</b>	<b>Pre-harvest</b>	<b>Post-harvest</b>	<b>N</b>
Douglas-fir	30-50	.07 (.04)	.15 (.07)	79
	51-69	.07 (.05)	.14 (.07)	207
	70+	.08 (.05)	.18 (.10)	40
Western larch	51-69	.06 (.03)	.14 (.06)	88
	70+	.15 (.09)	.18 (.09)	85
Lodgepole pine	30-50	.05 (.01)	.07 (.02)	10
	51-69	.13 (.08)	.13 (.04)	67
	70+	.17 (.12)	.18 (.09)	61
Ponderosa pine	30-50	.06 (.03)	.10 (.05)	77
	51-69	.07 (.04)	.15 (.07)	143
	70+	.15 (.14)	.16 (.08)	17

---

Douglas-fir had approximately a twofold increase of post-harvest over pre-harvest diameter growth rates for all site indices. Ponderosa pine and western larch

register the greatest response in the mid-range of site index. Lodgepole pine shows negligible response at all levels of site index. With the exception of Douglas-fir, response is least at the high end of site index (70 and above).

A quantitative measure of harvest activity or cutting intensity is the amount of basal area removed at harvest (Table 6). Here, the growth response increases with cutting intensity. Lodgepole pine is the exception showing virtually no response at any level of cutting intensity.

In addition to harvest activity itself, the level of stocking immediately prior to harvest is of interest (Table 7). Western larch shows the greatest potential for

Table 6. Pre- and post-harvest individual tree diameter growth (inches per year) for the four major treatment types in the sample. Values are referenced to cutting intensity (the relative amount of basal area removed at harvest expressed as a percentage). Values in brackets are standard deviations.

---

<b>Species</b>	<b>Cutting Intensity</b>	<b>Pre-harvest</b>	<b>Post-harvest</b>	<b>N</b>
Douglas-fir	10-50%	.08 (.06)	.14 (.08)	116
	51-70%	.06 (.04)	.15 (.07)	159
	71+%	.09 (.05)	.19 (.08)	51
Western larch	10-50%	.12 (.10)	.16 (.09)	93
	51-70%	.08 (.04)	.15 (.05)	58
	71+%	.10 (.07)	.19 (.06)	22
Lodgepole pine	10-50%	.16 (.10)	.16 (.07)	99
	51-70%	.09 (.07)	.11 (.06)	36
	71+%	.09 (.02)	.09 (.05)	3
Ponderosa pine	10-50%	.07 (.07)	.12 (.07)	116
	51-70%	.07 (.04)	.14 (.07)	94
	71+%	.07 (.04)	.19 (.08)	27

---

release in the low range of stocking. Douglas-fir, as seen in other examples, and ponderosa pine both have a uniform response at all levels of initial stocking.

Lodgepole pine's response is negligible at all levels of stocking.

Table 7. Pre- and post-harvest individual tree diameter growth (inches per year) for the four major treatment types in the sample. Values are referenced to ranges of initial stocking (the absolute amount of cubic foot volume per acre immediately prior to entry). Values in brackets are standard deviations.

---

<b>Species</b>	<b>Initial Stocking</b>	<b>Pre-harvest</b>	<b>Post-harvest</b>	<b>N</b>
Douglas-fir	250-2000	.08 (.06)	.15 (.08)	162
	2001-3999	.06 (.04)	.15 (.08)	108
	4000-8000	.08 (.08)	.15 (.05)	56
Western larch	250-2000	.12 (.09)	.19 (.07)	112
	2001-3999	.08 (.05)	.10 (.05)	30
	4000-8000	.08 (.05)	.12 (.08)	31
Lodgepole pine	250-2000	.15 (.11)	.16 (.07)	102
	2001-3999	.11 (.07)	.11 (.06)	32
	4000-8000	.07 (.04)	.07 (.06)	4
Ponderosa pine	250-2000	.07 (.06)	.13 (.06)	126
	2001-3999	.07 (.04)	.15 (.07)	73
	4000-8000	.06 (.04)	.13 (.06)	38

---

## **Basal Area Increment**

Like diameter, BAI growth rates were calculated for pre- and post-harvest (Table 8).

Table 8. Net basal area increment (square feet per acre per year) for two intervals in time for all overstory treatment plots. Site index is base-50. Plot is forest management unit-location-plot. BAI was calculated by subtracting total plot basal area (per acre) at time zero from total basal area at time one. The difference was divided by the total number of years. Note that time since harvest is not the same for all plots. Site index is from Milner (1993).

---

<b>Plot</b>	<b>Pre-harvest</b>	<b>Post-harvest</b>	<b>Site Index</b>
7-1-1	1.0	1.9	61
7-2-1	1.3	1.8	58
7-3-1	0.9	2.7	68
21-4-1	1.1	3.0	57
23-1-1	1.4	2.1	49
24-1-1	0.7	2.2	51
28-1-1	1.5	1.7	58
28-3-1	0.5	1.2	60
28-4-1	0.7	1.4	42
29-1-1	0.5	2.2	53
31-1-1	1.0	2.2	56
31-2-1	1.3	1.6	61
33-1-1	0.7	2.2	58
38-1-1	0.9	1.7	50
45-2-1	1.0	1.7	38
53-1-1	2.9	4.2	96
53-3-1	0.9	5.4	79
53-3-2	0.8	4.9	74

---

In all cases basal area increment increased after harvest. For plots with higher site quality (all located near Libby, MT in FMU 53) the results were more pronounced than elsewhere.

### **Individual Tree Height Growth**

Examining heights is more problematic than examining at diameters. There are three main reasons for this. First, heights were subsampled so that approximately one-third of all trees have actual height measurements. Second, while it is straight-forward to reconstruct past diameters using increment core data, past height can not be read from an increment core. Lastly, height measurement is subject to a larger amount of error than diameter measurement.

Table 9. Post-harvest (1984/85 to 1996) mean height growth rates (feet per year) and standard deviations for the four most abundant species in the sample. Figures are referenced to 2-inch diameter classes and refer to the height sample trees only (see Data Primer in the Appendix).

---

<b>Species</b>	<b>Diameter Class</b>	<b>Post-harvest</b>	<b>N</b>
Douglas-fir	0-2.0"	1.30 (.30)	2
	2.0-4.0"	.88 (.50)	32
	4.0-6.0"	.80 (.46)	45
	6.0-8.0"	.71 (.48)	35
	8.0-10.0"	.79 (.43)	18
	10.0-12.0"	.69 (.39)	10
	12.0-14.0"	1.55 (.57)	3
	14.0-16.0"	.55 (.72)	3
Lodgepole Pine	0-2.0"	1.52 (.33)	4
	2.0-4.0"	.80 (.39)	10
	4.0-6.0"	.67 (.58)	20
	6.0-8.0"	.48 (.23)	10
	8.0-10.0"	.37 (.36)	8
	10.0-12.0"	.32 (.06)	2
Ponderosa Pine	0-2.0"	2.20 ( )	1
	2.0-4.0"	.52 (.54)	14
	4.0-6.0"	.68 (.44)	28
	6.0-8.0"	.70 (.62)	21
	8.0-10.0"	.76 (.26)	16
	10.0-12.0"	.44 (.89)	5
	14.0-16.0"	1.20 ( )	1

Western Larch	0-2.0"	1.30 (.42)	2
	2.0-4.0"	.94 (.67)	24
	4.0-6.0"	.93 (.37)	23
	6.0-8.0"	.55 (.62)	14
	8.0-10.0"	.82 (.36)	8
	10.0-12.0"	.15 (1.07)	4
	12.0-14.0"	.30 ( )	1

---

The values given cover a large range (Table 9). This range is the result, in many instances, of the small sample sizes and the range of site conditions in the sample itself. In some cases, the standard deviation is much larger than the mean. While large standard deviations (relative to the mean) can be expected for natural systems, in this sample they are in part caused by measurement errors. A large negative value for height growth would enlarge the range of values and therefore influence the standard deviation (western larch 10.0-12.0" DBH class for example).

Despite the problems associated with using the sub-sample height trees to get at height growth, this study does provide data suitable to compare pre- and post-harvest height growth. The off-plot height trees (Data Primer in Appendix) felled and analyzed (stem analysis) as part of this study will be used to compute height growth numbers. These trees have the advantage of virtually no measurement error. This advantage is somewhat counterbalanced by the trees not actually being located on the plot itself. Post-harvest height growth was always in excess of pre-harvest growth (Table 10). Douglas-fir showed a uniform response, in absolute terms, at all diameter classes whereas the other species'

response varied according to diameter. The largest absolute response was in the 8+" diameter class for all species.

Table 10. Pre- and post-harvest height growth (feet per year) for the off-plot height growth trees (see Data Primer in the Appendix). Values referenced to diameter class (a range of DBH's at harvest). Values in brackets are standard deviations.

Species	Diameter Class	Pre-harvest	Post-harvest	N
Douglas-fir	0-3.9"	.34 (.15)	.69 (.39)	18
	4.0-5.9"	.32 (.14)	.64 (.30)	16
	6.0-7.9"	.48 (.31)	.81 (.40)	26
	8.0+"	.55 (.40)	.93 (.61)	7
Western larch	0-3.9"	.51 (.36)	.79 (.71)	11
	4.0-5.9"	.41 (.67)	.96 (.97)	14
	6.0-7.9"	.56 (.28)	.90 (.54)	21
	8.0+"	.79 (.55)	1.28 (1.14)	3
Lodgepole pine	0-3.9"	.55 (.50)	1.08 (.75)	10
	4.0-5.9"	.64 (.32)	.91 (.60)	13
	6.0-7.9"	.72 (.40)	1.15 (.70)	6
	8.0+"	1.00 (.18)	1.49 (.45)	3
Ponderosa pine	0-3.9"	.49 (.26)	.81 (.36)	7
	4.0-5.9"	.43 (.25)	.79 (.44)	20
	6.0-7.9"	.81 (.48)	1.29 (.82)	13
	8.0+"	.59 (.46)	1.07 (.66)	11

Table 11. Pre- and post-harvest height growth (feet per year) for the off-plot height growth trees (see Data Primer in the Appendix). Values are referenced to crown ratio in 1984/5. Values in brackets are standard deviations.

Species	Crown Ratio	Pre-harvest	Post-harvest	N
Douglas-fir	5-40	.38 (.25)	.56 (.25)	28
	45-70	.40 (.30)	.79 (.43)	16
	75-95	.51 (.22)	1.25 (.27)	13
Western larch	5-40	.53 (.36)	.76 (.55)	31
	45-70	.35 (.52)	.86 (.43)	14
	75-95	1.02 (.56)	2.29 (1.45)	4
Lodgepole pine	5-40	.56 (.35)	.73 (.50)	16
	45-70	.73 (.34)	1.30 (.64)	12
	75-95	.88 (.70)	1.66 (.57)	4



Ponderosa pine	5-40	.50 (.40)	.81 (.59)	28
	45-70	.67 (.37)	1.12 (.58)	18
	75-95	.62 (.42)	1.36 (.71)	5

---

As with diameter growth, size is only one factor influencing height growth response. Crown ratio is perhaps more important as trees prioritize height growth over diameter growth (Oliver and Larson 1996) and that crown ratio is a measure of the tree's photosynthetic 'factory.' The pattern of response is characterized by successively larger growth increases, both relative and absolute, as crown ratio increases (Table 11).

When crown ratio is replaced with site index a different pattern of response emerges (Table 12). Douglas-fir exhibits, in absolute terms, a uniform response

Table 12. Pre- and post-harvest height growth (feet per year) for the off-plot height growth trees (see Data Primer in the Appendix). Values are referenced to site index (Milner 1993). Values in brackets are standard deviations.

---

<b>Species</b>	<b>Site Index</b>	<b>Pre-harvest</b>	<b>Post-harvest</b>	<b>N</b>
Douglas-fir	30-50	.40 (.20)	.69 (.35)	16
	51-69	.36 (.24)	.72 (.42)	43
	70+	.72 (.30)	1.04 (.31)	8
Western larch	51-69	.38 (.45)	.67 (.35)	23
	70+	.65 (.42)	1.13 (.91)	26
Lodgepole pine	30-50	.42 (.20)	.54 (.27)	11
	51-69	.76 (.46)	1.16 (.60)	15
	70+	.87 (.34)	1.76 (.52)	6
Ponderosa pine	30-50	.41 (.26)	.67 (.36)	16
	51-69	.63 (.43)	1.06 (.66)	31
	70+	.77 (.41)	1.64 (.48)	4

---

across all site indices. Western larch shows a twofold increase in post-harvest over pre-harvest height growth. Both lodgepole and ponderosa pine are characterized by increasing growth response as the level of site index goes up.

When post-harvest diameter growth of the same off-plot trees is used as a factor (Table 13), the following pattern emerges: as diameter growth response increases so too does height growth response. This is true regardless of species. Pre-harvest height growth also exhibits the same trend relative to post-harvest diameter growth.

Table 13. Pre- and post-harvest height growth (feet per year) for the off-plot height growth trees (see Data Primer in the Appendix). Values are referenced to the diameter growth (inches per year) of the same trees. Values in brackets are standard deviations.

---

<b>Species</b>	<b>Diameter Growth</b>	<b>Pre-harvest</b>	<b>Post-harvest</b>	<b>N</b>
Douglas-fir	.01-.10"	.32 (.19)	.48 (.23)	30
	.11-.15"	.46 (.27)	.79 (.33)	17
	.16+"	.52 (.30)	1.11 (.37)	20
Western larch	.01-.10"	.48 (.31)	.60 (.36)	25
	.11-.15"	.51 (.62)	1.08 (.66)	14
	.16+"	.65 (.50)	1.47 (1.14)	10
Lodgepole pine	.01-.10"	.42 (.53)	.64 (.52)	12
	.11-.15"	.76 (.56)	1.00 (.36)	8
	.16+"	.85 (.41)	1.52 (.54)	12
Ponderosa pine	.01-.10"	.42 (.27)	.67 (.37)	25
	.11-.15"	.58 (.40)	1.05 (.53)	14
	.16+"	.87 (.46)	1.55 (.71)	12

---

It is possible to compare the post-harvest growth of the off-plot height trees with that of the sub-sample height trees. In all instances, the post-harvest height growth of the off-plot trees is larger than that for the height sub-sample. There is

considerable overlap between the two distributions. The sub-sample trees' height growth covers a larger range and also shows more variability than the off-plot trees

### **Volume Growth**

Plot level volume growth increased in all but two stands as a result of harvest activity (Table 14).

Table 14. Pre- and post-harvest volume growth rates of residual stands (cubic feet per acre per year) for all plots with overwood removal treatment (see Appendix for other treatment types). Cutting intensity is the absolute amount of basal area removed at harvest while percent removal is the relative amount expressed as a percent. Note that time since harvest is not the same for all plots. Only plots that were remeasured in 1996 are shown.

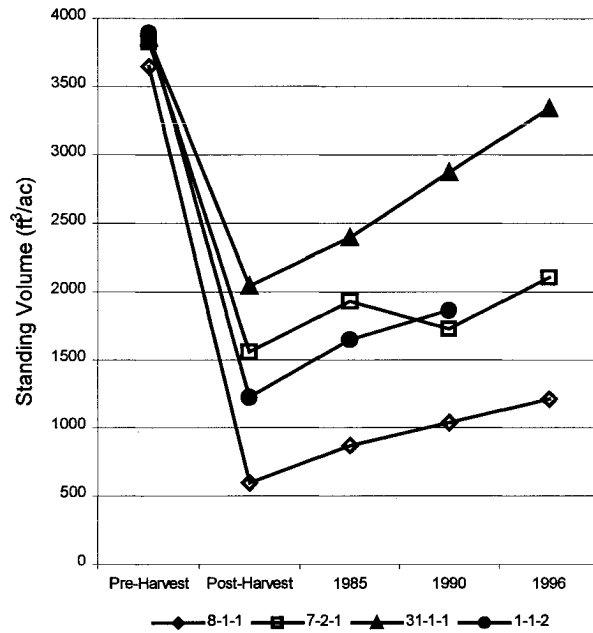
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<b>Plot</b>	<b>Post-harvest Volume Increment</b>	<b>Percent Removal</b>	<b>Cutting Intensity</b>
7-1-1	13	58	33
7-2-1	20	55	76
7-3-1	48	76	147
21-4-1	67	60	54
23-1-1	40	47	32
24-1-1	37	58	44
28-1-1	26	30	26
28-3-1	13	78	84
28-4-1	36	59	67
29-1-1	53	62	62
31-1-1	72	44	57
31-2-1	52	52	75
33-1-1	37	84	116
38-1-1	39	53	53
45-2-1	35	43	40
53-1-1	108	55	136
53-3-1	58	83	95
53-3-2	98	74	85

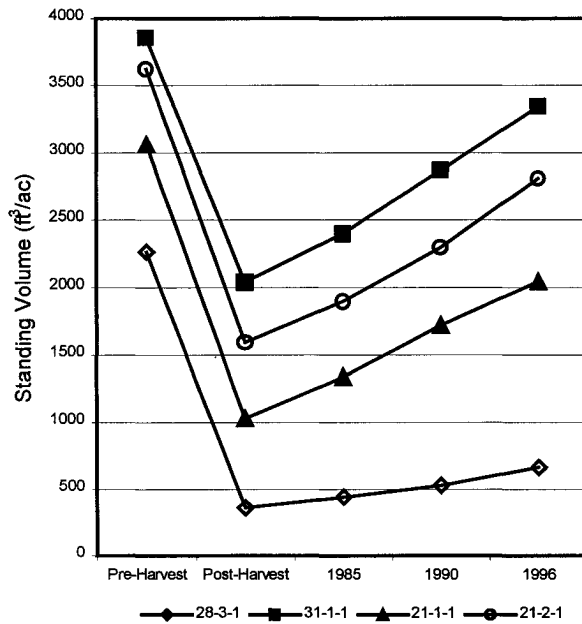
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Another way to look at changes in growth rates is to track the total standing volume through time. Figures 1 and 2 show four different stands and their volume trajectories through time. Initial stocking is held constant with cutting intensity

allowed to vary in Figure 1. In Figure 2, on the other hand, cutting intensity is constant with initial stocking varying. Note that in all cases, no stand achieves its pre-harvest level of standing volume.



**Figure 1.** Four different stands plotted through time. In this example, each stand has approximately the same initial stocking (cu. ft. per acre) but cutting intensity varies. Note that the time elapsed between pre-harvest and post-harvest is five years but that the time between post-harvest and 1985 varies by plot. The decrease in standing volume from pre- to post-harvest is the removal at harvest. For plot 1-1-2 no 1996 measurement was made.



**Figure 2.** Four different stands through time. In this example cutting intensity is the same but initial stocking varies. Time intervals are as in Figure 2 above. Note that in both examples pre-1985 volume has been reconstructed from increment core data.

Table 15. Standing volume for all plots (including those not measured in 1996) at five points in time: 5-years prior to harvest, at harvest and 1984/5, 1990 and 1996. Volume figures are cubic foot per acre. Name is FMU-location-plot number. Site index is from Milner (1993). Treatment is as follows: PT - precommercial thin, SE - shelterwood, CT - commercial thin, SE - selection cut, OR - overstory removal, NT - no treatment. An asterisk indicates no data.

Name	Standing Volume						Site Index	Treatment Type
	Harvest Removal	5-years before harvest	After harvest	1984/5	1990	1996		
1-1-1	4050	5966	2125	2735	3165	3872	53	SW
1-1-2	2799	3894	1223	1650	1863	*	63	OR
1-3-1	*	*	*	1929	2074	2208	34	NT
3-1-1	*	*	*	4498	4544	4750	62	NT
5-1-1	3394	4049	742	902	1060	*	54	SE
5-2-1	*	*	*	2824	3044	*	58	NT
7-1-1	1065	1476	510	654	884	1191	61	OR
7-2-1	2409	3828	1599	1931	1726	2104	58	OR
7-3-1	4434	5438	1108	1535	2068	2509	68	OR
8-1-1	3137	3646	592	867	1037	1209	69	SE
8-1-2	741	2480	1937	2648	3088	3498	79	SE
9-1-1	*	*	*	2122	2202	2339	43	NT
9-2-1	*	*	*	4189	4374	*	48	NT
20-1-1	2954	3191	261	408	453	*	47	OR
20-2-1	*	261	321	436	592	838	41	PT
21-1-1	2106	3057	1026	1337	1720	2042	63	SW
21-2-1	2127	3540	1592	1896	2294	2806	59	CT
21-3-1	967	1590	768	1168	1606	2161	52	SW
21-4-1	1191	1605	540	969	1410	1939	57	OR
21-5-1	*	255	318	445	666	968	55	PT
23-1-1	1144	1690	693	992	1249	1595	49	OR
24-1-1	1695	2251	617	817	1054	1425	51	OR
24-2-1	*	*	*	991	1056	1077	67	NT
28-1-1	718	1547	944	1112	1240	1498	58	OR
28-2-1	181	676	545	666	*	*	49	PT
28-3-1	1940	2263	361	442	527	661	60	OR
28-4-1	2331	3566	1340	1413	1655	1960	42	OR
28-5-1	537	888	397	537	735	981	51	PT
29-1-1	974	1555	635	839	1162	1600	53	OR
31-1-1	1961	3854	2040	2396	2870	3340	56	OR
31-2-1	2578	4124	1709	1936	2137	2482	61	OR
32-1-1	*	28	117	293	592	992	70	PT

33-1-1	5743	6068	416	760	1063	1273	58	OR
38-1-1	566	1236	743	981	1157	1572	50	OR
38-2-1	3217	5231	2149	2533	*	*	70	OR
44-1-1	*	*	*	1880	2167	2676	61	OR
45-1-1	90	196	183	455	630	851	52	PT
45-2-1	550	1455	1026	1061	1321	1591	38	OR
45-3-1	*	729	857	1977	2463	3079	60	PT
45-4-1	466	1730	1564	1972	2355	2847	70	PT
53-1-1	5246	7518	2661	3636	3947	5149	96	OR
53-2-1	352	932	781	994	1361	1506	77	PT
53-3-1	925	1113	287	904	1409	1934	79	OR
53-3-2	1681	2115	529	1204	1807	2694	74	OR
54-1-1	*	1842	2021	2665	*	*	70	PT

---

Volume trajectories for all stands (Table 15) show growth occurring for all stands; ingrowth and growth on stock is greater than mortality.

Mortality rates are also of interest (Table 16). The overall mortality rate, expressed as a percentage of standing volume lost during the period from harvest to 1996 for all species, was 0.41% per acre per year. Table 6 shows mortality percentages by species. The high value for Engelmann spruce was caused by the death of a 20" diameter tree whose total volume was larger than the remaining trees left in the sample. Wykoff et al (1982) state that mortality between 0.3 to 0.7% per acre per year are within the range of expectations for most management scenarios.

Table 16. Mortality percentages (% of standing volume lost to mortality per acre per year by species) for all commercial species in the sample. Data is based on 1985 to 1996 remeasurement data. No reconstructed data was used. Note the high value for Engelmann Spruce.

Species	Percent Mortality
Cedar	0.02
Douglas-fir	0.26
Engelmann Spruce	<b>5.19</b>
Grand Fir	0.30
Lodgepole Pine	1.19
Ponderosa Pine	0.28
Western Hemlock	0.56
Western Larch	0.47
Western White Pine	0.03

### ***Regeneration and Ingrowth Tallies***

Regeneration tallies are only available from 1985 onward. Absolute number of regeneration seedlings (from 6" to 4.5' in height), as well as ingrowth trees are given in Table 17:

Table 17. Regeneration (between 6" and 4.5' in height) stems per acre and ingrowth (new trees reaching breast height) at each measurement date. Only plots that were measured in 1996 are shown.

Plot	Regeneration (1984)	Regeneration (1990)	Regeneration (1996)	Ingrowth (1984-1990)	Ingrowth (1990-1996)
1-1-1	49	185	150	12	49
1-3-1	0	40	0	0	0
3-1-1	0	160	0	0	0
7-1-1	559	494	225	121	71
7-2-1	52	62	0	0	31
7-3-1	141	232	0	40	10
8-1-1	750	860	150	110	170
8-1-2	340	100	75	10	40
9-1-1	20	4920	75	0	0
20-2-1	20	1030	0	10	5
21-1-1	342	352	0	237	210
21-2-1	135	50	75	10	0
21-3-1	330	730	0	40	120
21-4-1	480	830	450	116	163
21-5-1	150	1050	75	90	90
23-1-1	150	215	0	10	30

24-1-1	90	130	0	10	25
24-2-1	80	120	75	40	20
28-1-1	315	425	150	30	85
28-3-1	795	2085	375	180	265
28-4-1	5	10	0	0	5
28-5-1	350	1885	225	0	45
29-1-1	10	200	0	10	0
31-1-1	120	630	150	40	130
31-2-1	110	1510	825	30	70
33-1-1	305	1790	300	175	200
38-1-1	1525	4935	675	520	575
44-1-1	1620	6080	750	20	60
45-1-1	220	285	150	30	15
45-2-1	25	200	75	0	0
45-3-1	230	2710	525	30	60
45-4-1	770	1845	225	55	60
53-1-1	1050	880	75	340	110
53-2-1	330	2890	600	60	135
53-3-1	1790	1000	150	390	250
53-3-2	870	1510	450	440	240

---

## ***Discussion***

In general, there is one single overriding trend found in the sample data. Individual tree post-harvest growth rates always exceeded pre-harvest growth rates. There were a few exceptions to this but these do not detract from the overall trend. The favorable response to harvest activity is independent of site index, harvest type, initial stocking, cutting intensity as well as crown ratio, size and species. Plot level measurements of growth also increased versus their pre-harvest rates. Two plots' volume increments actually decreased but these were the only exceptions. The increase in growth rates ranged from quintupling the pre-harvest growth rate to slight increase of 10%. The one anomaly to this is the diameter growth response of lodgepole pine on a individual tree basis. In this instance, pre- and post-harvest growth rates were in many cases identical with only the amount of variability changing.



The growth rates in this study are within the range of those found in literature. Table 18 offers a comparison of four different growth rates for stands after thinning in the western United States. The height growth rates in the sample data are generally in the lower range of the growth rates found in the forestry literature. Diameter growth rates are by and large identical. On the plot level, basal area increment is within the range of values found in published reports, albeit in the lower portion. Sample accretion, on the other hand, more exactly matches the accretion values in literature. However, both basal area increment and accretion as found in published analyses are based on more or less single species stands whereas most stands in the sample are mixed-conifer.

Table 18. Comparison of four growth rates from forestry literature and the sample. Values are ranges except for basal area averages from published reports. Accretion and basal area values are based on the entire sample and not species-specific. Basal area values from forestry literature and all values for individual tree growth rates are species-specific. Sample values always reference the post-harvest period.

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Species	Attribute	Literature	Sample	Source
Douglas-fir	Basal Area Increment (sq. ft. per acre per yr.)	~2.0	1.7 - 5.4	Hermann and Lavender 1990
	Diameter Growth (in. per year)	.2 - .3	.1 - .2	McDonald 1976
	Height Growth (ft. per year)	1.1 - 2.1	.6 - 1.3	Coble 1991a,b
	Accretion (cu. ft. per acre per yr.)	20 - 140	13 - 108	Hermann and Lavender 1990
Lodgepole pine	Basal Area Increment	~2.0	1.7 - 5.4	Lotan and Critchfield 1990
	Diameter Growth	.1 - .2	.1 - .3	Lotan and Critchfield 1990
	Height Growth	.2 - 1.7	.8 - 1.5	Schmidt and Seidel 1988
Ponderosa pine	Accretion	30 - 80	13 - 108	Edminster 1978
	Basal Area Increment	1.6 - 2.6	1.7 - 5.4	Boldt and Van Deusen 1974
	Diameter Growth	.1 - .2	.1 - .2	Boldt and Van Deusen 1974
	Height Growth	.6 - 1.2	.3 - 1.3	Barrett 1981
Western larch	Accretion	-3 - 72	13 - 108	Mowat 1961
	Basal Area Increment	~3.0	1.7 - 5.4	Cole and Schmidt 1986
	Diameter Growth	1 - .4	.1 - .3	Schmidt and Seidel 1988
	Height Growth	.8 - 1.5	.6 - 1.3	Schmidt and Seidel 1988
	Accretion	3 - 135	13 - 108	Seidel 1980

---

The overall volume mortality rate is also within the range of published mortality percentages for stands in the western U.S. Schmidt and Seidel (1988) report a range of percentage mortality of 0.1 to 0.6 for thinned western larch stands. In a spacing study Cochran and Barrett (1993) found mortality rates for ponderosa pine stands ranging from 0.4 to 7.5 (*sic*). As with larch, the higher figures are associated with narrower spacing and the lower figures with wider spacing. For a moderately stocked (less than 500 stems per acre) lodgepole pine stand with a base-100 site index of 75 ft. percent mortality ranged from 0.1 to 0.5 (adapted from Lotan and Critchfield 1990). These values rose to 1.0 and 4.5% respectively for a densely stocked (1880 stems/acre). In a thinning study of western larch stands where Douglas-fir was the second most abundant tree, the average mortality percent was 0.6 (Seidel 1980). Douglas-fir mortality generally ranged between 0.3 and 1.0% (adapted from Adams 1981) in the northern Rocky Mountains. Given that many residual stands generally consist of low vigor trees (Oliver and Larson 1996) the mortality figure from this sample may seem low. The higher mortality percentages in the forestry literature are invariably associated with dense stocking and/or overmature stands. These conditions do not exist in any of the stands used in this study. This explains why mortality on the sample plots was in the low end of the published mortality ranges.

## **Model Validation**

### ***Individual Tree Diameter Growth***

The model explained between 9 and 32% of the variation encountered in diameter growth over the 1984/85 to 1996 period. The effect of calibration was

marked. The amount of variation explained by the model increased for all species individually, except western larch, and overall (Table 19).

Table 19. Amount of variability explained by the FVS model for all species and the four major commercial species in the sample. Numbers are coefficients of determination from regressing actual on predicted values for diameter growth only. Note that western larch has both the highest values and is not positively influenced by calibration.

Species	With Calibration	Without Calibration	N
All Species	.23	.12	1879
Douglas-fir	.29	.13	703
Lodgepole pine	.20	.09	433
Ponderosa pine	.21	.11	344
Western larch	.30	.32	284

Also, patterns in residuals varied with calibration. For example, Douglas-fir tends to be uniformly underpredicted at all DBH's when projected with calibration (Figure 3). Without calibration (Figure 4) underprediction increased with increasing diameter. In both cases, a tendency to overpredict is absent.

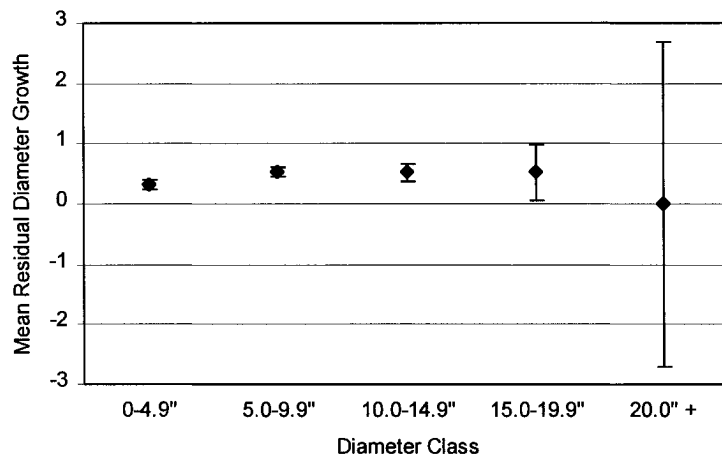
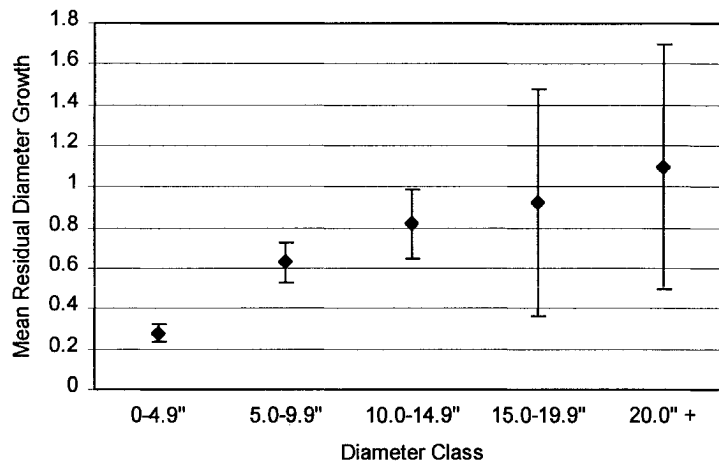


Figure 3. Mean residual diameter growth (in. per period) for *calibrated* model runs referenced to 5-inch diameter classes. Error bars show a 95% confidence interval. Only Douglas-fir is shown. N for each class is (from left to right) 377, 216, 89, 17 and three respectively. Note that the error bar of the largest diameter class overlaps the zero reference line.



**Figure 4.** Mean residual diameter growth (in. per period) for *uncalibrated* model runs referenced to 5-inch diameter classes. Error bars show a 95% confidence interval. Only Douglas-fir is shown. N for each class is (from left to right) 377, 216, 89, 17 and three respectively. In this figure, no error bar overlaps the zero reference line. Compare this with the preceding figure. Also, note how the mean error gets larger with tree size.

While its intuitive that larger trees have more variation associated with their respective prediction error than do their smaller counterparts, with diameter growth no such trend is present. The progressively larger error bars (Figure 4) are due to a decrease in sample size as diameter increases, not because of less variation. Larger prediction errors occur throughout the range of growth rates and initial conditions.

For all projections combined mean prediction errors range from -0.6 to 1.4 inches over the 10 year interval. Residual standard deviations changed only slightly due to calibration but in most cases the change is an improvement over uncalibrated model runs (Table 20). While precision remained largely unchanged, model bias was decreased as a result of calibration. Mean residuals are

Table 20. Summary of mean, median and standard deviation of diameter growth (residuals) prediction errors (in inches). Figures are for the four commercial species only and are referenced to five inch diameter classes.

Species	Diameter	Without Calibration			With Calibration			N
		Mean	Median	STD	Mean	Median	STD	
Douglas-fir	0-4.9"	0.3	0.2	0.8	0.3	0.2	0.8	377
	5.0-9.9"	0.6	0.5	0.8	0.5	0.5	0.7	216
	10.0-14.9"	1.0	0.9	0.9	0.5	0.4	0.7	89
	15.0"-19.9"	0.9	1.1	1.2	0.5	0.5	1.0	17
	20.0" and above	1.1	1.2	0.4	-0.1	0.4	1.5	3
Lodgepole pine	0-4.9"	-0.1	-0.1	0.7	-0.1	-0.2	0.6	247
	5.0-9.9"	0.4	0.3	0.7	0.1	0.1	0.7	137
	10.0-14.9"	0.7	0.7	0.6	0.02	0.1	0.7	49
Ponderosa pine	0-4.9"	-0.6	-0.4	0.8	-0.5	-0.3	0.7	100
	5.0-9.9"	0.1	0.1	0.7	0.4	0.4	0.6	160
	10.0-14.9"	0.6	0.5	0.7	0.4	0.3	0.7	64
	15.0" and above	1.0	1.1	0.6	0.2	0.2	0.7	19
Western larch	0-4.9"	0.3	0.1	0.8	0.3	0.2	0.8	87
	5.0-9.9"	0.5	0.5	0.7	0.2	0.2	0.7	161
	10.0-14.9"	0.7	0.6	0.8	0.4	0.2	1.0	30
	15.0" and above	1.4	1.4	0.8	0.2	0.0	0.8	6

consistently nearer 0 on calibrated projections, except for three exceptions where no change occurred (Douglas-fir, lodgepole pine and western larch in the 0-4.9" diameter class) and one occurrence of poorer performance (ponderosa pine in the 5.0-9.9" diameter class). Finally, note that the overall range of DBH prediction errors is generally smaller with calibration.

Accuracy, as reflected in the root mean square error, was largely unaffected by model calibration. Also, for individual tree diameter growth there was no single regression, either overall or on a species-specific basis, that was unbiased (Table 21).

Table 21. Coefficient of determination, parameter estimates and root mean square error for the regressions of observed on predicted individual tree diameter growth. Hypothesis tested are:  $b_0=0$ ,  $b_1=1$ . An \* indicates a significant result at  $\alpha=.05$ . There are no unbiased results ( $b_0=0$  and  $b_1=1$  at 95% confidence).

	With Calibration				Without Calibration			
	R <sup>2</sup>	b <sub>0</sub>	b <sub>1</sub>	RMSE	R <sup>2</sup>	b <sub>0</sub>	b <sub>1</sub>	RMSE
Douglas-fir	.29	0.7*	0.7*	0.7	.13	0.8*	0.6*	0.8
Western Larch	.30	0.6*	0.7*	0.7	.32	0.5*	1.0	0.7
Lodgepole pine	.20	0.5*	0.5*	0.6	.09	0.7*	0.4*	0.7
Ponderosa pine	.21	0.7*	0.5*	0.7	.11	0.8*	0.4*	0.7

Patterns to the residuals were more likely to be found on uncalibrated model runs, whereas projections with calibration had significantly fewer patterns (Table 22).

Table 22. Tabular summary of error patterns for the four major commercial species in the sample. Note that this only applies to diameter growth.

Species †	With Calibration	Without Calibration
Douglas-fir	Tendency to underpredict at all initial diameters, more so when DBH exceeds 16"	Increasing underprediction as DBH increases  Low vigor trees tend towards overprediction while high vigor trees tend towards underprediction
Lodgepole pine	General tendency to overpredict but order of magnitude is small  Low vigor trees tend towards overprediction while high vigor trees tend towards underprediction	Systematic underprediction of trees with initial DBH 10" and above  Trees of small DBH (2" and less) are overpredicted  Low vigor trees tend towards overprediction while high vigor trees tend towards underprediction
Ponderosa pine	Bias towards overprediction when DBH exceeds 4"  Low vigor trees tend towards overprediction while high vigor trees tend towards underprediction	Trees 12" DBH and larger biased towards underprediction  Smaller trees (5" and less) biased towards overprediction

		Low vigor trees tend towards overprediction while high vigor trees tend towards underprediction
Western Larch	Tendency to underpredict at all initial diameters of 10" or less	Systematic underprediction of trees with initial DBH 10" and above
	Systematic underprediction of trees with initial DBH 10" and above	Only slight bias towards underprediction under 10" DBH
		Low vigor trees tend towards overprediction while high vigor trees tend towards underprediction

### ***Individual Tree Height Growth***

Height growth was more poorly projected than diameter growth (Table 23). This is independent of species (except lodgepole pine) and calibration. There are three probable reasons for this. First, the error associated with measuring heights with a Relaskop is about three feet. Since height growth is the difference of two measured heights, a potential mis-measurement of up to six feet is possible. In the sample data the average height growth is about twelve feet for the 10 year interval. In the worst case scenario, then, one half of a tree's measured height growth could be attributable to measurement error. When such values are regressed on their predicted counterparts, the error part is unexplained. Second, studies have shown that height growth varies with vigor, shading and intertree interactions (Oliver and Larson 1996). These things are only approximately represented in the FVS height growth sub-model (Wykoff et al. 1982), namely through diameter growth, diameter, height and habitat type. Whether or not this representation is adequate or is biologically sound has yet to be determined. However, it is known that trees

Table 23. Amount of variability explained by the FVS model for all species and the four major commercial species in the sample. Numbers are coefficients of determination from regressing actual over predicted values for height growth only. Note that lodgepole pine has the much higher values than the other species.

Species	With Calibration	Without Calibration	N
All Species	.11	.06	538
Douglas-fir	.13	.06	220
Lodgepole pine	.41	.40	88
Ponderosa pine	.03	.05	120
Western larch	.20	.12	117

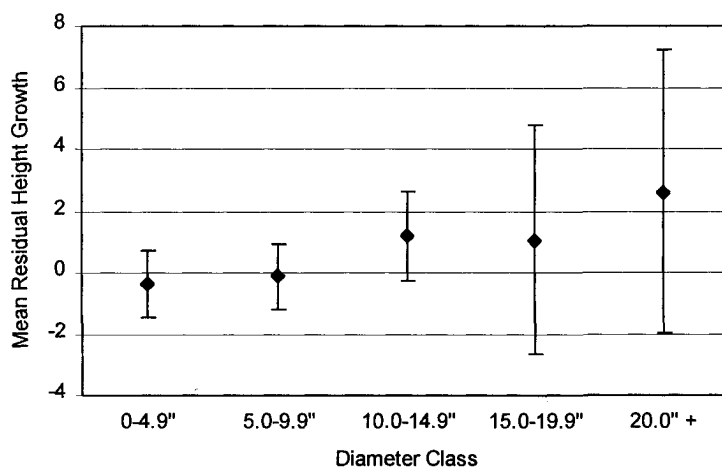
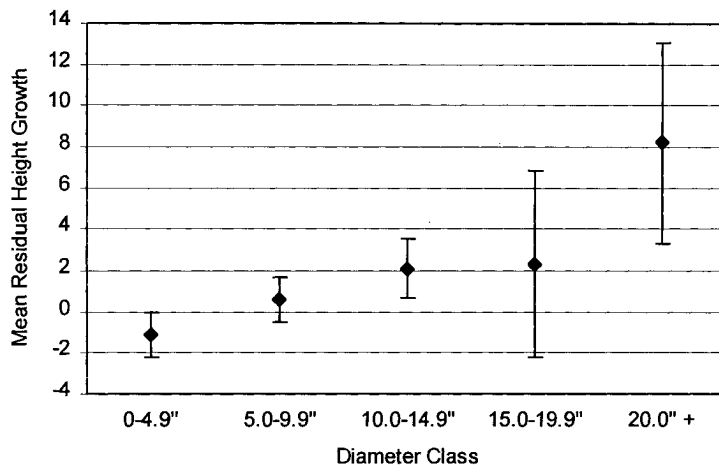


Figure 5. Mean residual height growth (ft. per period) for *calibrated* model runs referenced to 5-inch diameter classes. Error bars show a 95% confidence interval. Only Douglas-fir is shown. N for each class is (from left to right) 68, 85, 49, 15 and 4 respectively. Note that all error bars overlap the zero reference line. Also, note how the mean error gets larger with tree size.

prioritize height growth before diameter growth (Oliver and Larson 1996). Finally, the sample size for height growth is only 588, compared with the 1879 trees used for diameter growth. It is also possible that the height tree subsample scheme used (see Data Primer in the Appendix) has an inherent bias.





**Figure 6.** Mean residual height growth (ft. per period) for *uncalibrated* model runs referenced to 5-inch diameter classes. Error bars show a 95% confidence interval. Only Douglas-fir is shown. N for each class is (from left to right) 68, 85, 49, 15 and 4 respectively. Note that all error bars overlap the zero reference line. Also, note how the mean error gets larger with tree size.

Model performance was influenced by calibration. The amount of variation explained by the model increased except for ponderosa pine (Table 23). Residual patterns were influenced by calibration as well. For example, Douglas-fir underprediction starts at an initial DBH of 6" for calibrated projections (Figure 5). Without calibration the underprediction starts at 4" DBH (Figure 6). Douglas-fir is also representative of a general trend: precision decreases as tree size increases. This is in contrast to diameter growth where such a trend was absent.

As with diameter growth, calibration impacted both model bias and precision (Table 24). In most instances the calibrated model boasts mean residuals closer to zero and smaller standard deviations. Although the calibration done in this study involved diameter growth data, individual tree diameter growth is the principal variable in the height growth sub-model. Therefore, the effect of calibration is expected.

Table 24. Summary of mean, median and standard deviation of height growth prediction errors (in feet). Figures are for the four commercial species only and are referenced to five inch diameter classes.

Species	Diameter	Without Calibration			With Calibration			N
		Mean	Median	STD	Mean	Median	STD	
Douglas-fir	0-4.9"	-1.1	-0.7	4.4	-0.4	-0.6	4.5	68
	5.0-9.9"	0.6	0.7	4.8	-0.1	-0.4	4.9	85
	10.0-14.9"	2.1	1.6	5.1	1.2	1.9	5.1	49
	15.0"-19.9"	2.3	2.2	8.1	1.1	0.3	6.7	15
	20.0" and above	8.2	8.2	3.5	2.6	2.6	3.3	4
Lodgepole pine	0-4.9"	1.2	1.7	4.7	1.1	-0.1	5.0	23
	5.0-9.9"	1.7	1.9	3.8	0.8	0.8	3.2	44
	10.0-14.9"	1.6	2.0	3.7	0.2	0.0	4.1	19
Ponderosa pine	0-4.9"	-4.5	-4.3	5.0	-4.2	-5.1	4.8	32
	5.0-9.9"	-5.2	-4.8	6.4	-4.2	-3.7	6.5	50
	10.0-14.9"	-2.1	-2.9	5.0	-1.8	-2.0	5.0	30
	15.0" and above	0.5	2.6	6.6	-1.0	1.7	8.9	7
Western larch	0-4.9"	1.9	1.1	6.2	2.0	0.9	5.5	38
	5.0-9.9"	1.6	1.8	5.2	0.9	0.5	5.1	61
	10.0-14.9"	.03	0.6	5.5	-0.9	0.5	5.8	16

Of all the observed on predicted regressions done to evaluate the height growth sub-model only one was without statistical bias: lodgepole pine with calibration (Table 25). Model accuracy, as seen with diameter growth, was not greatly influenced by calibration. On the whole, error patterns were of similar magnitude

Table 25. Coefficient of determination, parameter estimates and root mean square error for the regressions of observed on predicted height growth. Hypothesis tested are:  $b_0=0$ ,  $b_1=1$ . An \* indicates a significant result at  $\alpha=.05$ . The only unbiased results ( $b_0=0$  and  $b_1=1$  at 95% confidence) are for lodgepole pine without calibration.

	With Calibration				Without Calibration			
	R <sup>2</sup>	b <sub>0</sub>	b <sub>1</sub>	RMSE	R <sup>2</sup>	b <sub>0</sub>	b <sub>1</sub>	RMSE
Douglas-fir	.13	3.8*	0.5*	4.6	.06	4.9*	0.4*	4.8
Western Larch	.20	3.0*	0.7*	5.3	.12	3.5*	0.7	5.5
Lodgepole pine	.41	0.2	1.1*	4.0	.40	0.7	1.1	4.0
Ponderosa pine	.03	4.2	0.2*	5.0	.05	3.6*	0.3*	4.9

as with diameter growth but not as influenced by calibration (Table 26). Also, as with diameter growth, the one trend found regardless of calibration was that low vigor trees tend towards overprediction while higher vigor trees tend toward underprediction.

Table 26. Tabular summary of error patterns for the four major commercial species in the sample. Note that this only applies to height growth.

<b>Species</b>	<b>With Calibration</b>	<b>Without Calibration</b>
Douglas-fir	Trees with initial height 75' and above tend to be underpredicted	Trees with initial height 80' and above tend to be underpredicted
	Trees with a starting DBH of 10" and above are biased towards underprediction	Trees with a starting DBH of 10" and above are biased towards underprediction
	Low vigor trees tend to be overpredicted while high vigor trees tend towards underprediction	Low vigor trees tend towards overprediction while high vigor trees tend to be underpredicted
Lodgepole pine	Low vigor trees tend towards overprediction while high vigor trees tend to be underpredicted	Trees with initial height of 70' and above were generally underpredicted
		Low vigor trees tend to be overpredicted while high vigor trees tend towards underprediction
Ponderosa pine	Systematic overprediction for all initial heights and diameters	Systematic overprediction for all initial heights and diameters
Western Larch	No bias	Low vigor trees tend to be overpredicted while high vigor trees tend to be underpredicted

## **Volume Growth**

The most striking thing about individual tree volume growth is how well it was predicted relative to diameter and height growth. The increase in amount of variation explained by the model (Table 27) is substantial.

Table 27. Amount of variability explained by the FVS model for all species and the four major commercial species in the sample. Numbers are coefficients of determination from regressing actual over predicted values for volume growth only.

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<b>Species</b>	<b>With Calibration</b>	<b>Without Calibration</b>	<b>N</b>
All Species	.64	.59	538
Douglas-fir	.65	.50	220
Lodgepole pine	.67	.70	88
Ponderosa pine	.66	.69	120
Western larch	.61	.51	117

---

There are two reasons for this significant improvement in model performance. The first reason for the increased predictive power of FVS is found in the way volume is generated. Volume is not observed or predicted but rather computed from other tree attributes that were either measured or projected. In order for FVS to be able to project a given tree, the user does not have to input height. Apart from the height subsample, which comprises roughly one-third of all trees tagged and sampled, the FVS model predicted a height using height-diameter relationships prior to projecting the stand. The height-diameter relationships used internally by FVS are statistical models. As such, they predict the average height. For example, a ten inch Douglas-fir will have one and only one possible height as

computed by FVS. This is true regardless of site quality, site utilization, crown class or stand structure. These attributes are exactly what causes variability in height growth, particularly in this sample of residual stands where management has, in many cases, consisted of 'take the best, leave the rest, (Milner, personal communication). Consequently, variability is masked (Hasenauer and Monserud 1996). Not only is this true of heights and height growth but also of volumes and volume growth. These equations rely solely on diameter and height. Variability is filtered out at two levels. The logical consequence is the appearance of higher coefficients of determination or a better model. This heuristic transformation of the data is the primary cause in the statistical, albeit spurious, improvement in model performance. The second reason for improved model performance is that many smaller trees are perfectly predicted by the FVS model. For example, assume that the magnitude of both predicted and actual height and diameter growth was such that no cubic foot volume, beyond the tenths place, was reported by the model. Since this analysis focuses on volume growth or the difference between time one and time two, both observed and predicted volume growth would be zero. Not that the tree has no volume. Rather, the model only reports volume to the nearest tenth of a cubic foot. Furthermore, trees with only a fraction of a cubic foot in volume could also be similarly predicted. In this case the prediction will not be perfect but the residuals involved will be relatively small compared to larger sized trees. These perfectly and near perfectly predicted trees serve to anchor the regression line which does have an effect on the coefficient of determination (Figure 7).

Calibration had a similar effect on volume growth prediction errors as seen with height growth (Table 28). Model bias and precision were, without exception, favorably impacted due to calibration.

Table 28. Summary of mean volume growth prediction errors (in cubic feet) and their standard deviations.

Species	With Calibration		Without Calibration		N
	Mean	STD	Mean	STD	
Douglas-fir	0.7	2.7	1.4	3.2	220
Lodgepole pine	-0.1	2.1	0.4	2.8	88
Ponderosa pine	0.4	2.8	0.5	2.9	120
Western larch	0.2	2.2	0.9	2.2	117

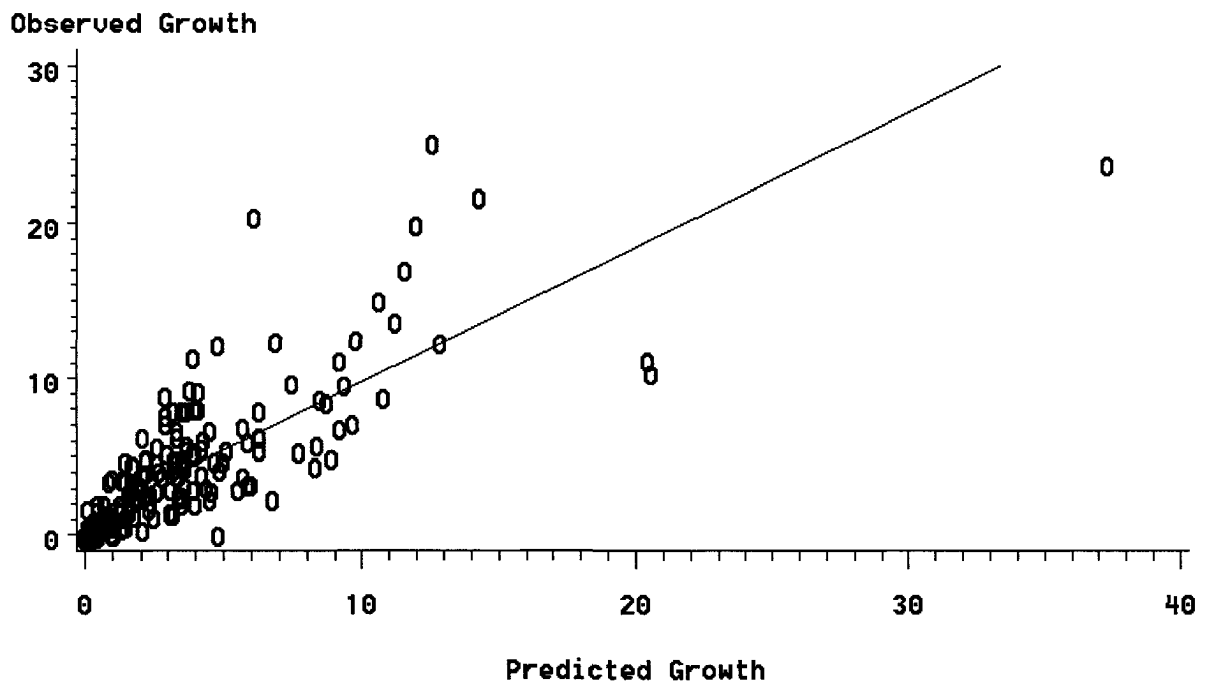


Figure 7. Observed over predicted individual tree volume growth. Only Douglas-fir from calibrated model runs is shown. This aspect of the model has bias (95% confidence interval of the intercept and slope estimates do not include zero and one respectively). Note the large blob of data in lower left corner. This acts to stabilize the regression.

Accuracy, in contrast to diameter and height growth, is influenced by calibration (Table 29). Model accuracy in predicting Douglas-fir volume growth rates is positively influenced by calibration whereas lodgepole pine shows a significant loss

in accuracy when calibrated. Patterns in the residuals, especially on calibrated model runs, are virtually nonexistent. Of the four major commercial species in the sample only ponderosa pine has any discernable patterns to its residuals on calibrated model runs (Tables 30).

Table 29. Coefficient of determination, parameter estimates and root mean square error for the regressions of observed on predicted individual tree volume. Hypothesis tested are:  $b_0=0$ ,  $b_1=1$ . An \* indicates a significant result at  $\alpha=.05$ . The only unbiased results ( $b_0=0$  and  $b_1=1$  at 95% confidence) are for western larch and ponderosa pine with calibration.

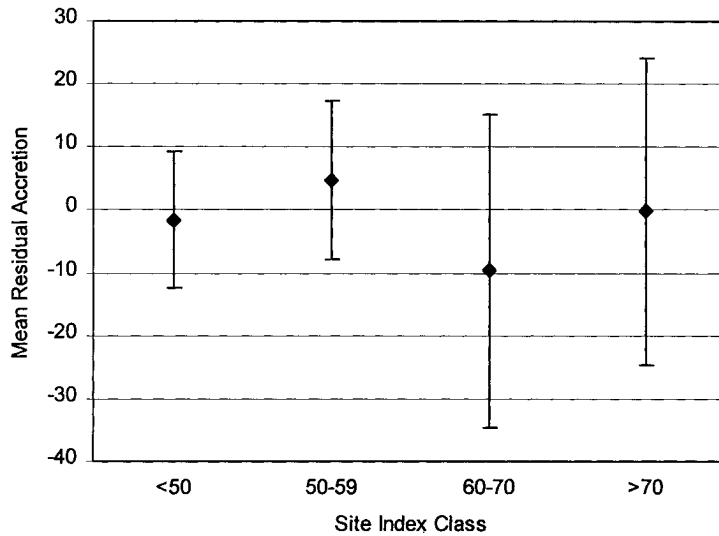
	With Calibration				Without Calibration			
	R <sup>2</sup>	b <sub>0</sub>	b <sub>1</sub>	RMSE	R <sup>2</sup>	b <sub>0</sub>	b <sub>1</sub>	RMSE
Douglas-fir	.65	1.1*	0.9*	2.6	.50	1.0*	1.2	3.1
Western Larch	.61	0.2*	0.7*	1.9	.51	0.4	1.2	2.2
Lodgepole pine	.67	0.9*	0.7*	1.8	.70	0.3	1.4*	1.7
Ponderosa pine	.66	0.4	0.1*	2.9	.69	0.1	1.1	2.8

Table 30. Tabular summary of error patterns for the four major commercial species in the sample. This only applies to volume growth.

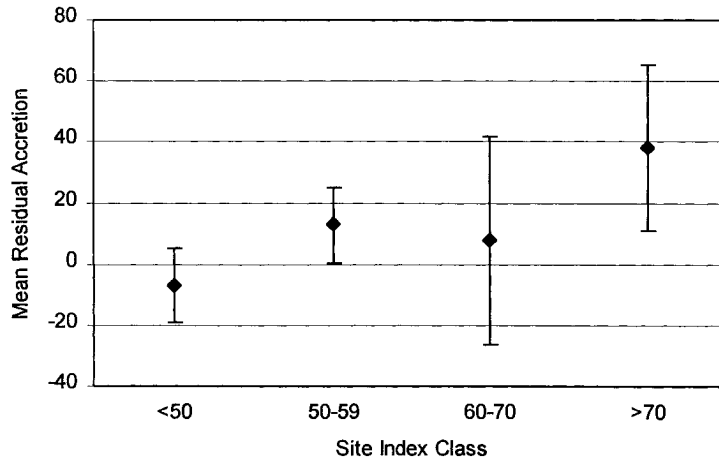
Species	With Calibration	Without Calibration
Douglas-fir	No bias	Trees with a starting DBH of 10" and above are systematically underpredicted
Lodgepole pine	No bias	Trees with starting volume in excess of 15 cubic foot were systematically underpredicted
Ponderosa pine	Trees with starting DBH of 12" and above tend towards underprediction  Trees where initial crown ratio exceeded 50% were generally underpredicted	Trees with starting DBH of 12" and above tend towards underprediction
Western Larch	No bias	Slight tendency for 8" and greater DBH trees to be underpredicted

## Accretion

As a plot level counterpart (an aggregate variable) to volume growth per tree, one would expect accretion to significantly outperform, i.e., be better predicted, individual tree volume growth. This is not the case with FVS. The model explained almost two-thirds of the variability in volume growth dynamics of



**Figure 8.** Mean residual annual accretion by site index class for *calibrated* runs only. N is (from left to right) 6, 13, 11 and 7 respectively. Error bars show 95% confidence interval. Note that all error bars cross the zero reference line.



**Figure 9.** Mean residual annual accretion by site index class for *uncalibrated* runs only. N is (from left to right) 6, 13, 11 and 7 respectively. Error bars show 95% confidence interval. Note that only the first and third site index classes' error bars include zero. Note also how the mean residual increases slightly with higher site qualities.



residual stands when calibrated ( $R^2=.65$ ,  $n=37$ ), slightly less than on the individual tree level. This was coupled with no trends to the prediction errors. Without calibration, the model explained only about one-third of the variability ( $R^2=.37$ ,  $n=37$ ). The decrease in predictive power, albeit slight when calibration is involved, relative to individual tree volume is puzzling. One possible explanation is that the loss of data points. While the individual tree analysis is based on close to 2000 trees, the plot level analysis of accretion has but 37 data points. The lower  $R^2$ -value could also be an artifact of the distribution.

For calibrated runs, mean residual accretion by classes of site index (Figure 8) is indicative of the overall lack of bias (Table 31). No specific trend is discernable and all mean residuals are not statistically different from 0 at  $\alpha=.05$ . For uncalibrated runs, patterns in the residuals were more pronounced (Figure 9 and see below). A general trend of larger prediction errors with increasing site index is present. However, residual analysis for accretion was somewhat frustrated by the lack of data points. The following patterns were apparent on uncalibrated projections:

- a) plots with a site index of 70 or greater tended to be underpredicted,
- b) for the range of aspects in the sample data (most plots within 30 degrees of North) no bias was present, data outside of this interval appeared biased towards overprediction,
- c) CCF, SDI and basal area had increasing prediction errors as their respective absolute values increased -the only instance of a fan-shaped scatter suggestive of non-constant variability.

Table 31. Coefficient of determination, parameter estimates and root mean square error for the regression of observed on predicted accretion. Hypothesis tested are:  $b_0=0$ ,  $b_1=1$ . An \* indicates a significant result at  $\alpha=.05$ . Mean is the mean residual.

---

	Without Calibration	With Calibration
$R^2$	.37	.65
$b_0$	8.4	6.2
$b_1$	1.1	0.9
RMSE	35.7	26.7
Mean	12.8	-1.6

---

Apart from bias, accuracy was also dependent upon calibration. The root mean square error (Table 31) decreased as a result of calibration.

### ***Discussion***

In general, the longer the prediction interval, the less accurate the prediction will be (Goodall 1972). Despite a relatively short projection period (ten years), residual stands were not as reliably predicted as with managed stands. Milner (1983), in his study of model performance in larch stands in western Montana, found that FVS explained a much larger amount of the variability encountered in both height and diameter growth (up to approximately 70%). Patterson and Stiff (1987) found that FVS was more suited to unmanaged stands where site index and stand age are difficult to determine. While the stands in this study may suffer from these same problems, FVS did not perform in a fashion suggestive of its use as a management tool.

Despite the general poor performance calibration did still have a discernable effect. Calibration positively influenced both model precision and bias in predicting

diameter growth, height growth and individual tree volume growth. The model's predictive power was also generally increased due to calibration. Accretion was, in all aspects of model behavior, favorably changed as a result of calibration. The dramatic increase on predictive power of the FVS model from diameter and height growth to volume growth and, to a lesser extent, accretion, was largely due to the heuristic transformation of the data. For individual tree volume to be upwards of five times better predicted, in terms of the model's predictive power, versus diameter or height growth was unexpected. Apart from the heuristic transformation and the stabilizing effect of the perfectly or near-perfectly predicted trees, one other point must be made. The actual individual trees volumes were computed via the same set of volume equations that FVS uses. In other words, the actual volume measurements were not observed but derived. This is in line with inventory practices and the nature of the study. An alternate procedure to measure volume directly is certainly technologically possible but invariably involves destroying the specimen or is prohibitory expensive. The heuristic transformation occurs on both sides of the equation and serves to inflate the model's ability to predict volume.

Bias was pervasive on all measures of individual tree growth for all species. Calibration did change the nature of bias but not its overall severity. The trend that trees of low vigor were overpredicted and those of higher vigor were underpredicted remained regardless of calibration. On the plot level, calibration completely eliminated bias for accretion.

Also of interest is how diameter growth for western larch was predicted relative to the other species. On uncalibrated runs, diameter growth for western larch was three times better than any other species in the sample and calibration had virtually no effect. A tentative explanation can be offered at this time. As larch is a shade intolerant tree, it can not be released as, for example, an overtopped Douglas-fir could. In other words, the growth dynamics of larch in residual stands are similar to those in unmanaged or even-aged stands. This is only feasible because western larch consistently outpaces its common associates in height growth (Schmidt and Shearer 1990) and must maintain itself in the overstory to be competitive. Another explanation applies to the lack of effect due to model calibration. It is possible that the trees encountered in this sample of residual stands could be similar to those used in model construction (from unmanaged or wild stands.). This is further supported because several but not all of the larch trees in this sample were older specimens of large size. These large specimens were probably unaffected by the release treatments. Their growth dynamics have not changed since they were never released. This could explain the negligible effect of calibration on model.

Another anomaly in this model study was the behavior of lodgepole pine. For height growth, this species was significantly better predicted than any other. Also, the effect of calibration was negligible. One hypothesis is the same as for western larch above. Namely the trees used in model development and those found in this sample are sufficiently similar to negate any benefits of calibration. However, as above, this implies that the growth dynamics of residual and normally

stocked stands for this species are also sufficiently similar. Since lodgepole pine is not shade intolerant like larch but can be released out of suppression, this explanation is likely false. Also, height growth is computed after diameter growth and has diameter growth as a variable in the equation. This implies that there should be a relationship between model precision in predicting diameter growth and height growth. With lodgepole pine this is not the case. Diameter growth was predicted significantly worse than height growth. (Note that for western larch this discrepancy is apparent but only slight.) Here, as above, this explanation is wanting. Height and diameter growth equations in FVS share terms but only a limited amount. The height growth equation makes no reference to site variables other than a habitat type dependent intercept term. The diameter growth function, on the other hand, incorporates measures of site utilization, site quality and topographical information. While a loose correlation between height growth and diameter growth may be intuitive, it is not borne out in this study or in the FVS equations. One must also take the different sample sizes into account (although the height subsample is supposed to be a representative sample of those trees whose diameter were measured). The reason for this anomaly is probably more fundamental than anything mentioned. Only 88 lodgepole pine trees had measured heights and given the number of trees used to calibrate the model (in excess of 10,000) it seems reasonable that the trees here are from a part of the height growth distribution where calibration would not have a great impact and where, by chance, they are predicted better than their counterparts.

## Summary and Conclusion

Individual tree height and diameter growth, as well as the plot level basal area increment and volume growth, responded favorably to harvest. This was true regardless of site potential, stocking, cutting intensity, tree vigor, size and species. The exception is lodgepole pine diameter growth which, in many cases, showed no response whatsoever. The magnitude of the response for the three other species varied considerably, ranging from at 10 percent increase to a quintupling of the pre-harvest growth rate. Given the range of initial conditions and site characteristics, the variation in response is expected. Despite the range of diameter and height growth rates found in this sample, there is overlap between them and the published growth rates reviewed here.

While the variability, range of growth values and relationships between growth rates and explanatory variables in this data set may be indicative of residual stands within western Montana, caution must be exercised. The size of the data set, the sources of variation ignored during plot establishment, the reliance on increment core data to reconstruct pre-harvest and at-harvest conditions and the relatively small interval of actual remeasurement data versus a full rotation should serve to temper any generalizations based on this summarization of growth rates in residual stands.

The FVS model did not perform well on these residual stands. Both height and diameter growth were predicted with little precision and much bias. The predictive power of FVS concerning diameter and height growth rates is slight for all species. In contrast to this, both individual tree volume growth and plot level

accretion were significantly better predicted by the FVS model. This was primarily due to the volume calculation itself which serves to mask variability and the aggregation of an individual tree level variable to a plot level variable. respectively. Bias, in the form of patterns to the prediction errors, also proved to be a significant problem in updating individual tree dimensions of residual trees. While looking for patterns in scatters of residuals over some initial condition is a somewhat subjective exercise (Ek and Monserud 1979), virtually all regressions of observed on predicted values were statistically biased (intercept not equal to zero and slope of prediction line not equal to one at 95% confidence). In the end the user of the model must judge whether the weaknesses shown here disqualify the model from use as a tool or not. Finally, it is recommended that the FVS model be used with calibration whenever possible. This had a positive effect on model performance.

## **Appendix**

### ***Data Primer***

In 1984 the following attributes were measured or observed for each tree that had reached breast height on each plot: diameter at breast height (DBH) with a D-tape to the nearest tenth of an inch, radial increment on all trees with a 1984 DBH of at least three inches (at least back until five years prior to harvest) with an increment borer to the nearest 50<sup>th</sup> of an inch, height and height to base of live crown (sub-sample trees only) using a Relaskop to the nearest whole foot, age (read of an increment core for height trees only), bark thickness using a gauge, crown ratio (ocular estimate of a balanced crown), crown class (dominant to overtopped based on available sunlight) species, damage and status codes (both ocular). The damage and status codes were supplementary notes on the measured trees. Things such as beetle infestations, sweeps, broken tops, ingrowth, new tree etc. were noted. See Champion plot procedures guide for more details (Permanent Plot Procedures, 1984). Each tree so measured was tagged and its azimuth and distance from plot center was noted. At the plot level, the following measurements or observations were made: Site index (based on increment cores from randomly located trees of each major species on or near the plot), slope, aspect, elevation (from USGS maps), timber type (CIC internal records), soil type (USGS data), topographical code (ocular, gives relief of stand, 1= top of ridge, 2= mid-portion of ridge etc.; see Permanent Plot Procedures (1984) for more details), parent material and geomorphic type from USGS data, declination, month/day/and year of harvest



(from CIC records) and measurement, type of harvest (CIC records) township, range, section (CIC records) and plot size.

The regeneration tally and cover survey was done in the following manner. First, the plot was divided into four quadrants (all plots are square or rectangular).

Second, the center of each quadrant was then located. At this point a 1/300<sup>th</sup> acre plot centered at quadrant center was laid out. Cover within this sub-plot was an ocular estimate in percent based on lifeform (grass, forb shrub) and height class (1, 2 and 2+ foot) and finally overall. (Note that in 1984 and 1990 dominant individual species not lifeform). Regeneration tallies were done in the same manner. After the 1/300<sup>th</sup> acre sub-plot had been located the absolute number of each species regeneration trees was counted (greater than 6" , less than 4.5').

(Note that in 1984 and 1990 the entire quadrant was surveyed, not just the sub-plot). In 1984, the first measurement, two other measurement suites were made.

First, stumps were tallied by diameter class and species. Diameter at stump height was measured on all stumps 4" or greater. A sub-sample of the trees 4.5' and larger had also been measured for diameter at stump height. This was done in order to make diameter at stump height-DBH equations so that the stand could be reconstructed. (Note that all tree measurements took place after harvest activity).

The second set of measurements made in 1984 only was off-plot height growth.

Here trees near the plot and with the same growing conditions were felled and sectioned so that their exact height trajectories could be mapped out. Trees were chosen based on thirds of the on-plot diameter distribution by major species.

Within each third two trees were felled. One corresponding to poor vigor and the other corresponding to a high vigor tree.

In addition to the above one final set of measurements was done at each plot.

After the plot had been divided into quadrants, regeneration trees (greater than 6' but less than 4.5' in height) were selected. Selection was done, for each species present, as follows: First, the best tree was subjectively selected (best meaning that tree which appeared to have the best potential for survival and growth).

Second, the first tree within each quadrant (first being the first tree encountered when , starting with an initial bearing of due north, rotating clockwise from quadrant center). Measurements on these trees were the same as for those 4.5' in height and greater save the following differences: Height was to the nearest tenth of a foot. Past height growth was measured back five years by counting whorls.

Diameter was not measured. (Note that if the first tree was the best tree then an alternate was selected by picking the first tree going counterclockwise.)

As indicated above, some tree attributes were sub-sampled. Height, age and bark thickness were all sub-sampled with the following procedure. At any given plot the diameter distribution was divided into four groups. The groups are 0-2.9", 3-6.9", 7-9.9" and 10" (DBH) and above. Within each class, each species was to be subsampled thrice (providing there were enough trees). This was usually done by dividing the number of trees into thirds.

Data collection was not the same for each measurement period. Some changes have been mentioned in the previous section. However, there are certain attributes that were measured only once, in 1984. These include: All plot level

variables (with the date of measurement being updated). Off-plot height growth trees were only felled and sectioned in 1984. Stump tallies were also only done in 1984. Bark thickness, age, radial growth and height growth information for on-plot trees was done only in 1984.

Finally, there are some observations that were made or changed on a need basis. For example, in 1984 each plot was located (site map, bearing and distance from marked tree) and flagged. For some plots the flagging and the point of departure tree had to be renewed. Also, in the initial measurement, each plot corner and center was poled and reference trees for plot center were located. Here, again, this procedure was redone as needed. Some trees grew into the 4.5' height class between measurement periods. These trees were added to the list of tagged trees and were measured as detailed above. Finally, some trees died and had to be replaced if they were measured regeneration trees or, if they were height subsample trees, an alternate had to be found and measured.

## Tables

**Table 32.** Summary of plot characteristics. Name is FMU-location-plot number. Year is treatment year. Elevation is in feet and slope and aspect are in degrees. Site index is base-50. Plots whose names are preceded by an asterisk were not remeasured in 1996 and were discarded from most analyses. Note that no treatment plots were assigned an arbitrary treatment date of ten years prior to plot establishment. This served as a benchmark for increment core data.

Name	District	Year	Elevation	Aspect	Slope	Mean Age	Site Index	Treatment Type
1-1-1	Lincoln	1977	4800	250	11	77	53	Shelterwood
*1-1-2	Lincoln	1974	4800	30	13	82	63	Overstory Removal
1-3-1	Lincoln	1974	6000	320	24	79	34	No Treatment
3-1-1	Lincoln	1974	5000	10	15	80	62	No Treatment
*5-1-1	Lincoln	1974	4400	240	10	73	54	Selection
*5-2-1	Lincoln	1974	4400	100	18	60	58	No Treatment
7-1-1	Potomac	1976	4100	260	32	28	61	Overstory Removal
7-2-1	Potomac	1972	4200	70	7	86	58	Overstory Removal
7-3-1	Potomac	1972	4300	330	8	86	68	Overstory Removal
8-1-1	Potomac	1972	4300	270	3	56	69	Selection
8-1-2	Potomac	1972	4200	300	1	77	79	Selection
9-1-1	Potomac	1974	3900	70	15	68	43	No Treatment
9-2-1	Potomac	1974	4200	270	10	76	48	No Treatment
*20-1-1	Hellgate	1964	5000	320	14	92	47	Overstory Removal
20-2-1	Hellgate	1979	4800	300	30	53	41	Precommercial Thin
21-1-1	Hellgate	1977	4000	110	16	74	63	Shelterwood
21-2-1	Hellgate	1977	3800	90	25	65	59	Commercial Thin
21-3-1	Hellgate	1974	4000	0	12	55	52	Shelterwood
21-4-1	Hellgate	1974	3800	50	15	40	57	Overstory Removal
21-5-1	Hellgate	1978	5000	340	25	74	55	Precommercial Thin
23-1-1	Frenchtown	1972	3800	90	26	51	49	Overstory Removal
24-1-1	Frenchtown	1976	4500	220	34	54	51	Overstory Removal
24-2-1	Frenchtown	1974	4400	290	6	59	67	No Treatment
28-1-1	Frenchtown	1973	3500	0	0	73	58	Overstory Removal
*28-2-1	Frenchtown	1974	3200	0	0	60	49	Precommercial Thin
28-3-1	Frenchtown	1974	5500	240	23	69	60	Overstory Removal
28-4-1	Frenchtown	1977	4800	140	31	111	42	Overstory Removal
28-5-1	Frenchtown	1977	4400	0	31	57	51	Precommercial Thin
29-1-1	Frenchtown	1976	3400	150	7	68	53	Overstory Removal
31-1-1	Pleasant Valley	1976	3800	0	2	79	56	Overstory Removal
31-2-1	Pleasant Valley	1977	3900	200	7	59	61	Overstory Removal
32-1-1	Pleasant Valley	1979	3700	250	8	12	70	Precommercial Thin
33-1-1	Pleasant Valley	1973	3700	200	8	49	58	Overstory Removal
38-1-1	Pleasant Valley	1974	3400	0	1	85	50	Overstory Removal
*38-2-1	Pleasant Valley	1977	4600	2	19	85	70	Overstory Removal
44-1-1	Thompson River	1977	3800	20	7	74	61	Overstory Removal
45-1-1	Thompson River	1969	3900	320	28	30	52	Precommercial Thin
45-2-1	Thompson River	1978	3600	10	12	55	38	Overstory Removal
45-3-1	Thompson River	1968	3400	220	6	48	60	Precommercial Thin

45-4-1	Thompson River	1977	3900	10	11	42	70	Precommercial Thin
53-1-1	Kootenai	1975	2300	0	1	70	96	Overstory Removal
53-2-1	Kootenai	1978	2500	340	6	36	77	Precommercial Thin
53-3-1	Kootenai	1973	2600	200	1	45	79	Overstory Removal
53-3-2	Kootenai	1973	2600	0	0	46	74	Overstory Removal
*54-1-1	Kootenai	1974	2600	25	4	69	70	Precommercial Thin

**Table 33.** Basal area increment (sq. ft. per acre per yr.) and volume increment (cu. ft. per acre per year) for pre- and post-harvest time periods. Site index is base-50 (Milner 1993). Cutting intensity is the absolute amount of basal area removed at harvest while percent removal is the relative amount expressed as a percent. Note that time since harvest is not the same for all plots. Treatment types are as follows: PT - precommercial thin, SW - shelterwood, CT - commercial thin, SE - selection cut. Only plots that were remeasured in 1996 are shown. An \* indicates missing data.

Plot	Pre-Harvest BAI	Post-Harvest BAI	Pre-Harvest Volume Increment	Post-Harvest Volume Increment	Percent Removal	Cutting Intensity	Treatment Type	Site Index
1-1-1	1.2	2.7	41	100	60	118	SW	53
8-1-1	2.0	3.1	17	23	58	88	SE	69
8-1-2	2.2	3.2	40	64	28	46	SE	79
20-2-1	0.5	1.7	10	36	*	*	PT	41
21-1-1	0.4	1.9	15	51	73	86	SW	63
21-2-1	1.2	2.7	27	66	56	75	CT	59
21-3-1	1.1	2.8	26	67	61	59	SW	52
21-5-1	0.7	2.0	12	32	*	*	PT	55
28-5-1	0.5	1.8	9	34	67	50	PT	51
32-1-1	1.7	3.7	19	48	*	*	PT	70
45-1-1	1.7	2.3	15	25	37	13	PT	52
45-3-1	1.1	2.9	26	84	*	*	PT	60
45-4-1	1.9	2.5	59	76	29	26	PT	70
53-2-1	2.3	3.5	40	55	26	17	PT	77

### **Model Description**

All facets of projected tree development are dependent on diameter growth. Species-specific diameter growth is (for tree with DBH>2.9") predicted from initial DBH, crown ratio as well as measures of site quality (slope, aspect, elevation, location, habitat type) and utilization (crown competition factor and basal area of larger trees). For DBH>10" height increment is predicted from initial DBH, diameter increment, height and habitat type. For trees less than 3" DBH, height increment is predicted from initial height, crown competition factor, basal area of larger trees and site quality. Trees within this range (3<DBH<10") are grown using a weighted combination of the above. Mortality predictions are species-dependent and based on DBH, relative diameter, diameter growth, basal area and habitat type. An approach to normality and a maximum stand basal area sub-models are also part of the mortality component in FVS. Optional calibration procedures use diameter growth data from the actual stand to adjust the coefficients in the diameter growth model. Note that in order to project a tree, FVS needs only species and DBH. For more information see Wykoff et al. (1982).

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