University of British Columbia

FORESTRY

FRST 498 – Forest Sciences Graduating Thesis

Accounting for Stand Variability in LMS:
A case study on San Juan Island

Sarah Braun

April 2009

Primary Advisor: **Dr. Bruce Larson**
Secondary Advisor: **Dr. Valerie Lemay**

Abstract

Forest growth models are important tools used to support management decisions and to answer research questions. They can estimate future forest conditions under different scenarios, and therefore help predict outcomes of management practices and test hypotheses at both a stand and a landscape level. This study compared three different methods of inputting data from San Juan Island National Historical Park into a forest growth model (the Forest Vegetation Simulator) using the Landscape Management System (LMS). These methods were: (M1) the 'plot-by-plot' method, in which each plot per stand were input into the model as independent stands and the outcomes at the time of projection were averaged together; (M2) the 'summed-plot' method, in which all the plots per stand were input into the model as a single large plot; and (M3) the 'representative-plot' method, in which a single plot was selected based on a lowest squared Euclidean distance to represent the entire stand in the model. Five variables were considered in the analysis of the different model outputs at three projections: 20, 40, and 60 years into the future. The five variables that were considered were total stand volume, and volume by species; total basal area (BA), and BA by species; and total mean DBH. The results of this study showed that if the stands had been stratified appropriately prior to sampling, and if there was little spatial variation between plots within a stand, then the results from M1 were statistically the same as M2 and as M3. Differences between M1 and M2 were only observed with regards to total DBH, for one highly variable stand. Differences between M1 and M3 were observed in the outputs of BA by species, and volume by species. The only stand which resulted in no differences between the outputs of M1 and M3 was very uniform in density, species composition and structure. If LMS were adapted to more easily incorporate the inclusion of multiple plots per stand, field sampling would consistently be more efficient.

Key Terms: Forest Modeling; Stand Dynamics; FVS – Forest Vegetation Simulator; San Juan Island National Historical Park; Stand stratification; Forest Management

Table of Contents

Index of Figures

Index of Tables

Acknowledgements

This study was part of a larger project titled: *Modelling Future Forest Conditions: a planning tool for Park managers and scientists,* which was funded by the Cooperative Ecosystem Study Unit through the U.S. National Park Service. My participation in this project was funded, in part, by an undergraduate student research award (USRA) presented by the Natural Sciences and Engineering Research Council of Canada (NSERC).

I would like to thank my supervisor Bruce Larson for the many opportunities he has offered me throughout my degree, and for his encouragement of me while working on this project. Thanks also to my secondary advisor Valerie Lemay for willingly aiding me with my thesis on a short notice.

I am grateful to Mariano Amoroso for his hours spent in the field, and for all of his time spend helping me with my analysis and report. I am also appreciative of Chris Davis at the San Juan National Park office for his enthusiasm for and support of our field work.

I am especially grateful to my fiancé Jesse Wildeman for his help in the field, and for his constant love, and encouragement. I would like to also express my thanks to my parents for supporting me throughout my degree.

1.0 Introduction

Many of the tree species native to the forests of the Pacific Northwest, such as Douglas fir (*Pseudotsuga menziesii*), have long life spans. It can take decades for these trees to reach diameters that are of merchantable quality or for the forest stand structure to reach a level of complexity that is of value for particular wildlife species. The full implications of decisions made by the forest managers of today will likely not be known in the span of their careers, or even during their lifetimes. Therefore, testing and assessing the long-term implications of management decisions in these forests is challenging. Forest growth models are an important tool used to support management decisions and answer research questions. They can produce predictions of future forest conditions under different scenarios, and therefore help predict outcomes of management practices and test hypotheses at both a stand and a landscape level. They can have a variety of applications, ranging from the critical analysis of silviculture treatments (Stage, 2002) to the evaluation of goods and services, such as wildlife habitat (Imaki, 2007).

Essentially a forest growth model is composed of a set of assumptions about how trees grow, based on a wide range of variables (Andreassen and Tomter, 2002; Crookston and Dixon, 2005). There are many different forest growth models developed for various regions and forest types. These models aim to accurately describe forest stand dynamics, growth, and yield, based on knowledge tree growth patterns of various species regionally, and based on an understanding of how trees competitively interact in their natural environments. However, they are all inherently limited in their ability to predict forest growth.

Natural forest ecosystems are dynamic systems and are known to contain variability (Oliver and Larson, 1996). A forest may vary throughout with regards to species composition, stand density, soil productivity, moisture regime, and topographical features. Though forests can be stratified into stand components to minimize this variability when sampling, some natural variation within stands still remains (Moeur and Stage, 1995). When modeling, not all of this variability can be captured. There are often field limitations regarding the amount and nature of the data that can be collected. Even if such limitations did not exist, there would still be a limited number of variables that could be entered into most models in order to direct growth predictions. Furthermore, even if all variables could be included, growth models are based on generalizations about how trees grow. Most early forest growth and yield models were developed for even-aged, single-species conifer stands, in a limited number of regions (Crookston and Dixon, 2005). Growth models have since been developed to project mixed species stands. However, these still have limitations, as the descriptive relationships between species used to guide tree or stand growth have restricted applicability (Porte and Bartelink, 2002). It is important that these limitations be recognized when using forest growth models for decision making. Moreover, it is equally important that managers and researchers alike make every effort to best inform the models so as to most accurately project the forest of interest according to their needs.

This study compared three different methods of inputting data into a forest growth model using the Landscape Management System (LMS). LMS is, in essence, a framework that coordinates many separate programs, such as forest growth models and visualization tools, as a way of making growth estimates and producing output in visual, graphical, and tabular forms (McCarter et al., 1998). It was developed as a cooperative between the University of Washington College of Forest Resources, and the Yale School of Forestry and Environmental Studies. The growth model used by LMS in this study was the Pacific Northwest variant of the Forest Vegetation Simulator (FVS_{PN}) (Edminster et al., 1991). FVS is an individual-tree model and is widely used across the United States (Crookston and Dixon, 2005). According to the latest tutorial update, only one plot can be entered into LMS for a given stand (Rural Technology Initiative & Landscape Management Project, 2005). As a result, data is generally entered into the program in one of two ways. Often all the data from multiple plots in a stand are entered together into the program as though they were all one large 'summed' plot (Turnblom et al., 2002). In other cases, a single plot that has as many possible attributes similar to the mean value for each attribute is selected to represent the entire stand (Ceder, 2002). In both cases the information is expanded over the entire stand, based on an expansion factor, and grown through time.

There are thought to be flaws in both these methods. When growing one summed plot, the variability between plots is thought to be lost. Stand density is an influential factor in the competition, and thus the growth of trees in a plot. In this method, it is spread out across the entire stand. When selecting a single most 'representative plot', it is thought that variation is lost because there is less information being entered into the model to inform it about the stand.

This project was designed to test an alternative way of running the model, which was expected to better account for stand variability. In this method, each plot in a stand was entered into the model as if it were its own stand, as in the 'representative plot' method described above. After projection, these plots were averaged together to get an estimate for the entire stand. This method represents many plots in one stand, while maintaining the differences in stand dynamics within those plots. It was therefore predicted that the output from the model using this third method would be significantly different than either of the other two methods. This was tested for 16 stands in the San Juan National Park forests, projected in the model to 2028, 2048 and 2068.

My null hypothesis was that running LMS on a plot-by-plot basis would not be significantly different than running LMS on a 'representative-plot', or a 'summed-plot' basis.

2.0 Methods

This study was part of a larger research project in the San Juan National Historical Park, and was a collaborative effort between the University of British Columbia and U.S. National Park Service. The larger project was designed to look at how modeling future forest conditions could be used to develop effective monitoring systems in parks. A subset of the field data collected for the larger project was used for this study. The sampling design and study site for this study were therefore selected based on the larger project.

2.1 Study Area

2.1a San Juan Island

San Juan Island is located in the Juan de Fuca Strait between the northern coast of Washington State, U.S. and the southern tip of Vancouver Island, Canada. It is part of a group of islands known as the 'San Juan Islands' which lie south of the Canadian 'Gulf Islands'. These islands experience dry weather conditions when compared with the surrounding regions, due to the rain shadow created by the Olympic Mountains and Vancouver Island to the West. The mean annual precipitation ranges from 508 mm at the southern end of the island to 737 mm at the northern end (National Park Service, 2009). This is less than a quarter of the amount of precipitation that falls in the surrounding regions, such as the west coast of Vancouver Island and in the Olympic Mountains. About 70 percent of the annual precipitation in the San Juan Islands falls between October and April (National Park Service, 2009). The mean annual temperature is 9.5 °C, ranging from 3.3 to 15.5 °C average temperatures in the months of January and July respectively (Western Regional Climate Center, 2007).

The resulting dry island ecosystems are typically characterized by open Douglas fir forests, with a prominent Pacific madrone (*Arbutus menziesii*) component, in addition to open Garry oak (*Quercus garryana*) woodlands. The forests of San Juan Island are also composed of a variety of other coastal species, including grand fir (*Abies grandis*), red cedar (*Thuja plicata*), western hemlock (*Tsuga heterophylla*), lodgepole pine (*Pinus contorta*), and red alder (*Alnus rubra*). More detailed descriptions of these ecosystems can be found in Franklin and Dyrness (1988), and in Meidinger and Pojar (1991).

The development of the current forest ecosystems on San Juan Island have been influenced by natural and anthropogenic disturbances (Hetsch, 2005). Logging practices have altered these forests beginning with the first European settlers in the mid 1800's, through to the mid 1960's. There is also a long-standing fire history on the island. In the past, low intensity fires were set by local native communities to maintain the open woodlands (Agee, 1984). Both past and present wind disturbance have influenced, and currently impact, the structure and development of the San Juan Island forests.

2.1b Study site descriptions

As previously mentioned, the study sites for this project were located within the National Historical Park on the island. The park is split into two parts known as 'British Camp' (BC) and 'American Camp' (AC), as illustrated in Figure 1. Both parts of the park consist of forests which vary with respect to species composition, soil type, age class, stand structure and disturbance history. These forests were stratified based on their stand characteristics.

Stratification was completed in a two step process. First, prior to going to the field, high-definition photos were used in combination with soil maps of the park to stratify the study area into broad stands. Second, in the field, extensive ground-based verification of the drafted stand

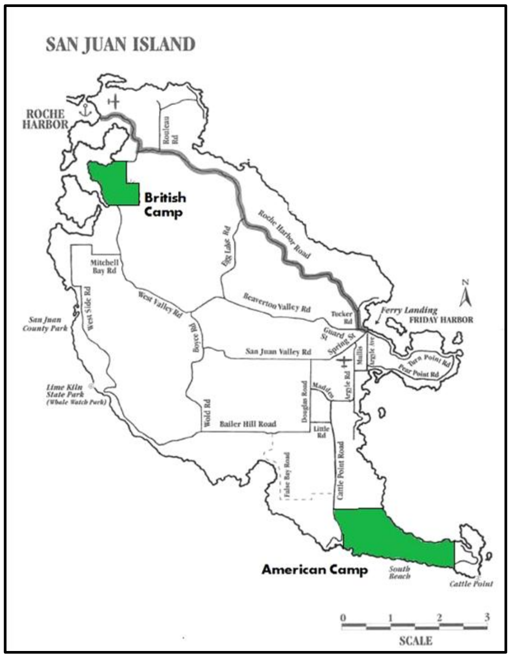

Figure 2: San Juan Island with the National Park Illustrated in Green. British Camp is at the northwestern end of the island and American Camp is at the southern end.

delineations was done. This involved walking transects of the whole park, recording stand characteristics systematically every 100 meters. As a result, the stand boundaries were redrawn. The stratification process was done to reduce the number of plots needed to accurately depict the forest types, and to help account for variability. This made sampling more efficient and effective. Some stands were grouped together because of similar characteristics such as dominant species composition, age and structure, and were later analyzed as stand-types; this further reduced sampling.

In total, for the larger research project, the forests across both areas were stratified into 41 stand-types. For this study, 9 of the stands in AC, and 7 of the stands in BC were selected for analysis (Figures 2 and 3). These stands were selected based on specific criteria: a minimum age of 50 years; dominant coniferous stand component (≥60%); a minimum of 5 plots measured in the stand; more than 50% of the plots were forested. The corresponding stand descriptions are outlined in Tables 1 and 2. The species codes listed in these tables correspond to those used by LMS, and are included in Appendix 1.

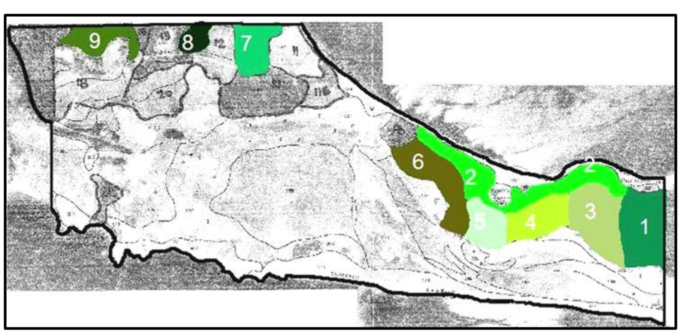

Figure 1: American Camp stand delineations. Coloured stands represent those selected for this study (9). Different colours correspond to different stands as indicated by the stand numbers

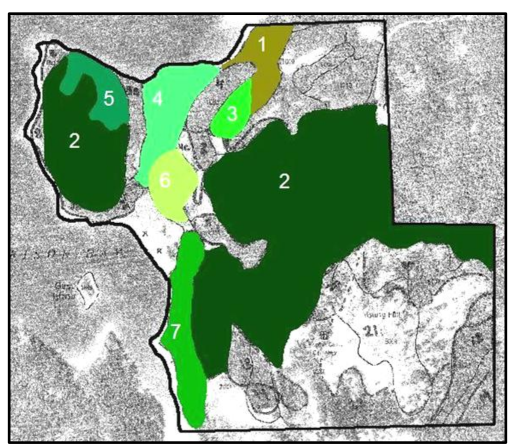

Figure 3:English Camp stand delineations. Coloured stands represent those selected for this study (7). Different colours correspond to different stands as indicated by the stand numbers.

Table 1: Descriptions of the selected stands in American Camp (species in parenthesis indicate minor components)

Stand #	Summary of Tree species	Basic description	[1]Stand Age
1	WH, RC, GF (RA, PY, DF)	This stand is a relatively even mix of WH, RC and GF. The stand composition varies along the slope.	162
2	DF, GF, WH, DM, RC (PY)	This stand follows the coastline. There is a high GF component in parts (especially regenerating in the understory), while WH is relatively more dominant in other areas. The understory is mostly open and there are areas with steep slopes. It is highly variable.	151
3	RC, WH, DF (GF, RA)	This Stand is primarily dominated by RC, especially at the top of the hill where the canopy is completely closed (very dense pure RC with zero understory).	154
4	WH, DF (GF, DM, RC)	This stand is dominated by mature WH, with some DF and minor components of GF, and RC.	75
5	WH, RC, RA (DF, GF, DM)	This stand has a higher deciduous component relative to the rest of the hillside, including RA and Douglas maple.	77
6	DF (GF, RC, WH)	This stand is very uniform. It consists of pure, even-age mature DF with little to no understory.	112
7	DF	This stand an open stand of mature DF.	81
8	DF, RA	This stand is mixed open RA and DF.	88
9	DF, LP	This stand is mature DF and LP with little to no understory.	90

Table 2: Descriptions of the selected stands in British Camp (species in parenthesis indicate minor components)

Stand #	Summary of Tree species	Basic description	[1]Stand age
1	DF (RC, AM, GF, BM)	This stand is primarily mature DF. There is a RC component in the lower strata. Compared with stand-2 there is a higher component of BM and RC, and less AM.	102
2	DF, AM,	This stand is even aged, and is dominated by mature DF with AM. There is some RC in the lower strata in places. Some veteran DF fire survivors.	95
3	DF (GF, RC, AM)	This stand is primarily dominated by DF. Relatively uniform.	103
4	DF (GF, RA, LP, J, AM)	This stand is similar to stand-3 but is more variable.	110
5	DF (GF, RC, OT)	This stand is similar to stand-2 but more GF.	95
6	DF, GF	This stand is similar to stand-2 but with more old veterans. There was an AM component which didn't fall into any of the sample areas.	90
7	DF, GF, RC (BM, AM, PY)	This stand primarily consisted of mature DF and GF. It has steep slope with changing aspects. The understory was fairly open (no dense shrub cover).	134

[1] Stand Age to be defined on page 8.

2.2 Data Collection

The number of plots for each stand was determined based on stand size and variability of vegetation within the stand. Plots ranged from 5 to 20 per stand, but was generally in the range of 6 to 9. Plots had a fixed radius of 8 meters, and were systematically sampled. A 32-m sampling grid was used to avoid sampling overlap. Plots were first identified on a map, and then found in the field.

At each plot the following information for each tree was recorded: species, diameter at breast height (DBH), strata (A-emergent, B-main dominant canopy, C-mid strata, D-lower strata), and crown class (D-dominant, C-co-dominant, I-intermediate, S-suppressed). All trees that were at least 1.3-m (breast height) tall were measured. Tree cores were taken for 1 to 5 trees in the plot, using increment borers. Generally 1 to 3 of these were cored to determine the 'site index' of the plot. Dominant, healthy Douglas firs were selected, where available. To determine the lower age-class limit, 1 to 2 small or suppressed trees were also cored. Finally, one healthy individual of a prominent species in the stand was selected and cored, to get an estimate of the ages of the various species. The heights of the site index trees were measured using a Forest Pro laser (Laser Technology Inc., 2009). These data were input into the growth model.

2.3 Stand Modeling

All of the above information was entered in MS Excel and later imported into LMS. The age of stand-replacement was determined based on tree age data, and was used as an estimate of the total stand age. Stand-replacement refers to the onset of regeneration establishment following a major disturbance. Within a stand, minor differences in age between plots were ignored, because tree ages do not actually influence how the model predicts trees growth (Dixon, 2007). The site index (SI) of each plot was calculated in TIPSY v.4.1 (BC Ministry of Forests and Range, 2007), using the ages and heights of the dominant Douglas firs where available. For plots where there was no SI data, the average stand SI was used in stands with little variation between plots. In stands with more variation between plots, the SI from the most similar plot (with regards to species composition, stand density, slope and aspect) was used. Due to the location of the study area, the Pacific Northwest variant was used for the growth model, to most accurately grow the stands.

Using LMS as a framework, FVS was run in three different ways, as introduced above. In all three cases the stands were projected 20, 40, and 60 years into the future. The 'plot-by-plot' method was the first way the model was run (M1). For this method, each plot per stand was entered into LMS as though it were a complete stand. Variation between plots with regards to site conditions such as slope and SI, and variation in stand conditions such as density and species composition were therefore retained. Once the plots had been projected to ages 20, 40 and 60, all of the plots in each stand were averaged together, to obtain entire stand estimates.

The 'summed-plot' method was the second way the model was run (M2), where the sum of all the plots in each stand were entered and projected. With this method all of the plots were listed together as one large plot. An average SI, slope, and aspect were selected to represent the entire stand. A single output was obtained for the entire stand at the projected ages.

The 'representative-plot' method was the final way the model was run (M3), and was done on only four stands. In this method, a representative plot from each of the stands was selected and then projected in the model. These representative plots were chosen by calculating squared Euclidian distances, using measures of stems per hectare, mean DBH, and volume per hectare, for all the plots in the stand and selecting the plot which was most representative of the mean (lowest squared Euclidian distance). To best represent both parts of the park, 2 stands from each of AC and BC were chosen. These stands were all considered to be representative of the typical forest types found throughout the park. One relatively homogeneous stand, and one more variable stand was selected from each camp. This was done to test if the results would differ for variable versus non-variable stands. Variability was determined based on personal observation in the field regarding homogeneity in the data collected from plot to plot with respect to dominant species composition and stand density. The resulting stands used for this analysis were AC-4, AC-6, BC-2 and BC-7, where stands AC-7, and BC-2 were considered more uniform, and AC-4, and BC-7 were more variable. M3 was then carried out on these stands.

The outputs from these three modeling methods were then compared using statistical analysis. In some cases, stands were also visualized in LMS using SVS (McGaugney, 1997), a stand visualization tool, to aid in identifying the key differences between various plots and stands.

2.4 Calculations and Statistical Analysis

M1 was compared with both M2 and M3. Five variables were considered in the analysis of the different model outputs at the three different projected ages. The five variables that were considered were total stand volume, and volume by species; total basal area (BA), and BA by species; and total mean DBH. Each of these variables was considered for three different projected years: 2028, 2048, and 2068. For each of these variables a single value was retrieved from the outputs of M2 and M3. The individual outputs from each plot per stand in M1 were averaged, to obtain a mean value with a standard deviation for each variable per stand. T-tests were used to determine if the mean outputs from running the model on a plot-by-plot basis (M1) were statistically different than the individual outputs from running the sum of all the plots (M2), and the representative plots (M3). All statistical tests were done using SAS9.1 (SAS Institute

Inc., 2005). M2 and M3 were not compared directly using statistics as the values obtained from the output of these methods were not means with standard deviations.

3.0 Results

3.1 M1 versus M2

For the three ages considered in this study, the number of years the stand was projected into the future did not influence whether or not the two methods differed. This is shown in Figure 4, which shows the differences between M1 and M2 for the 2028, 2048, and 2068 projections, using DF-volume in AC stand-1 as an example.

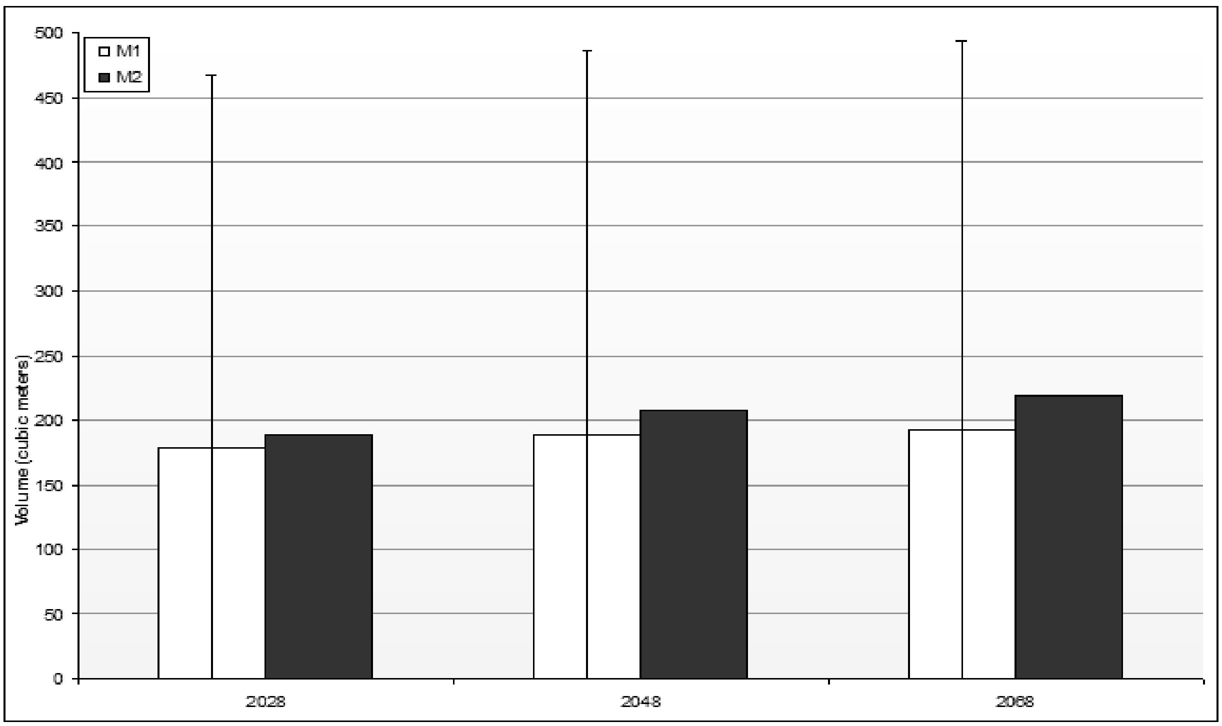

Figure 4: Total DF volume (m^3) projected to 2028, 2048, and 2068 from M1 (white)(Error bars indicate a 95% CI) and M2 (grey). Values from American Camp stand-1

When comparing M1 and M2, there were no significant differences regarding BA or volume of the total stands, or by species (α=0.05). Using AC stand-1 in 2068 as an example, Figure 5 illustrates that the total-volume and volume-by-species from M2 were very similar to the volume means from M1. The overlap of the large 95% confidence intervals around the means from M1, with the values from M2 illustrate the lack of significance. There were no obvious trends in the differences between M1 and M2 for BA or volume. Volume values were not consistently higher for either M1 or M2. The values for BA were extremely similar between the two methods (p-values were primarily in the range of 0.8-0.99).

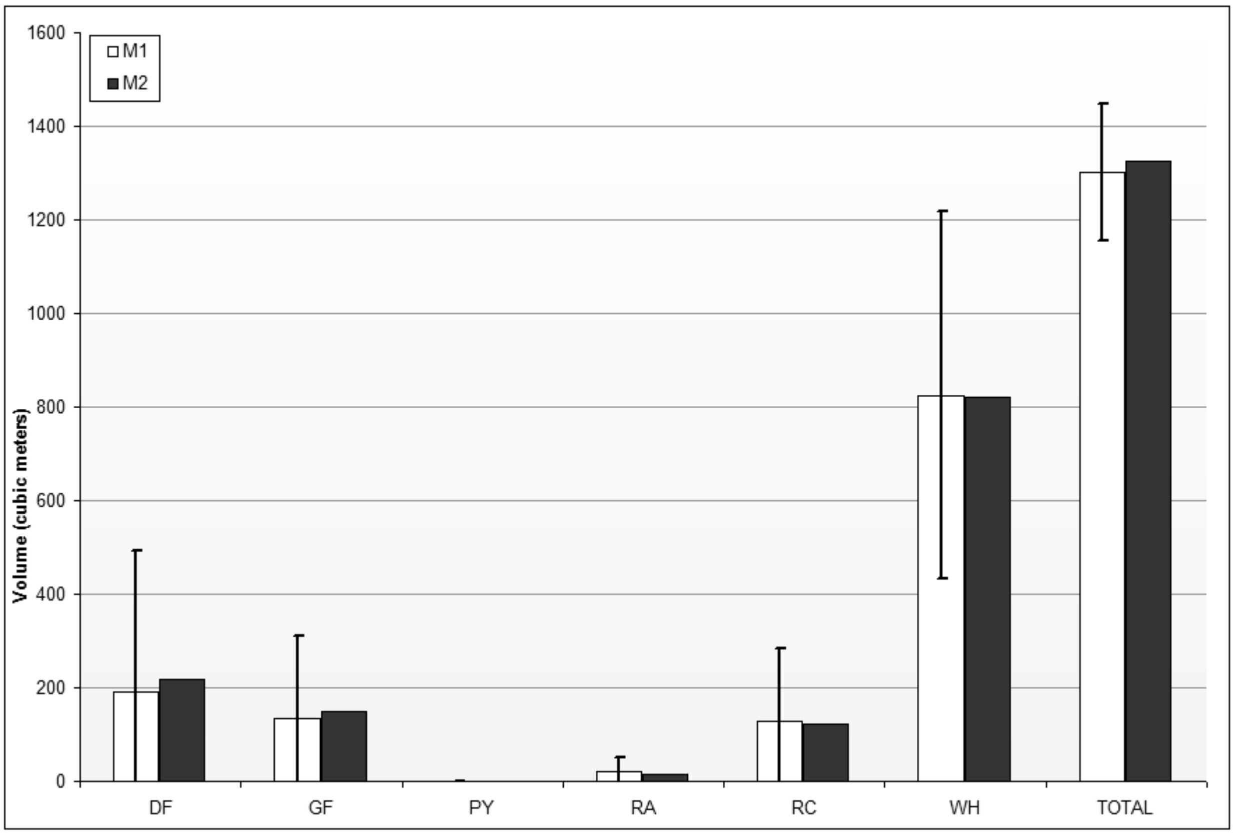

Figure 5: Values for total volume and volume by species (m^3) in 2068 from M1 (white) (error bars indicate 95% CI) and from M2 (grey). Values from American Camp stand 1.

Out of the 16 stands, 15 showed no significant differences in total-DBH between M1 and M2. Regardless of statistical significance, however, when graphed, the differences in total-DBH output from the two methods followed a trend. Figure 6 illustrates the trend in the differences in total DBH between M2 and M1 for the 9 stands in American Camp. In every case (all 16 stands) the total DBH was higher from M2 than from M1. There was a significant difference (α=0.05) in

AC stand-2 (p=0.04), between the mean total DBH value from M1 and the total DBH value from M2. This is shown in Figure 6 by the distinct lack of overlap between the 95% CI of M1 and the value from M2.

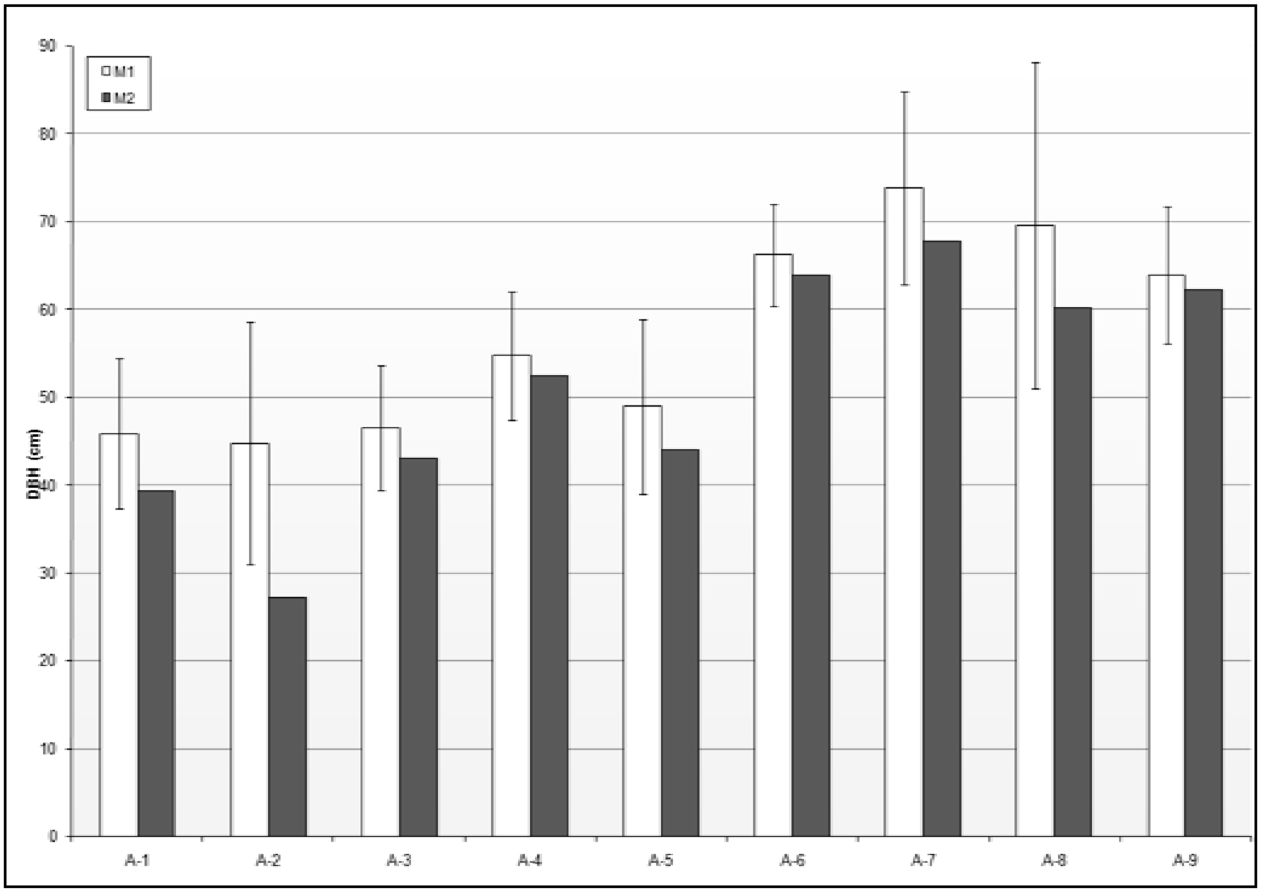

Figure 6: Mean values for total-DBH (cm) for all the stands in American Camp in 2068 from M1 (error bars indicate 95% CI) and from M2.

To better understand the isolated case in which there was a significant difference for total DBH between M1 and M2, it was visualized in LMS through SVS. Figure 7 shows a stand visualization of AC stand-2 in 2028, as output from M2, where all the plots were summed together. In all cases, the diameter and species distribution graphs were included with the visualizations to provide a more complete picture of the stand.

AC stand-2 was very diverse with regard to the stand structure and species composition. Figure 8 shows the individual stand visualizations from each of the plots in AC stand-2. There were some plots with large components of natural GF regeneration in the understory, while others had very little, or no regeneration. For example, plot 3 was primarily composed of grand fir regeneration, while plot 5 had no grand fir, or regeneration of any kind. There were also differences in species composition between plots, which are illustrated by the species distribution graphs in Figure 8. Douglas fir was the major overstory stand component in all of the plots, but the other species were not consistently present. Though it is not illustrated in the visualizations in Figure 8, this stand was also one of the most variable with regards to slope, because it followed the coastline. In this stand the slope ranged from 1 to 37 degrees. As a result, the average slope used for the 'summed plot' in M2 was taken from a wide range of values. The stand results from M2 as illustrated in Figure 7 illustrate how all the species and diameter distributions were combined into one. Even though Douglas fir was the dominant species in the overstory in this stand, the depiction of the total stand in Figure 7 shows that diameter distribution was skewed by the large grand fir understory component present in some of the plots.

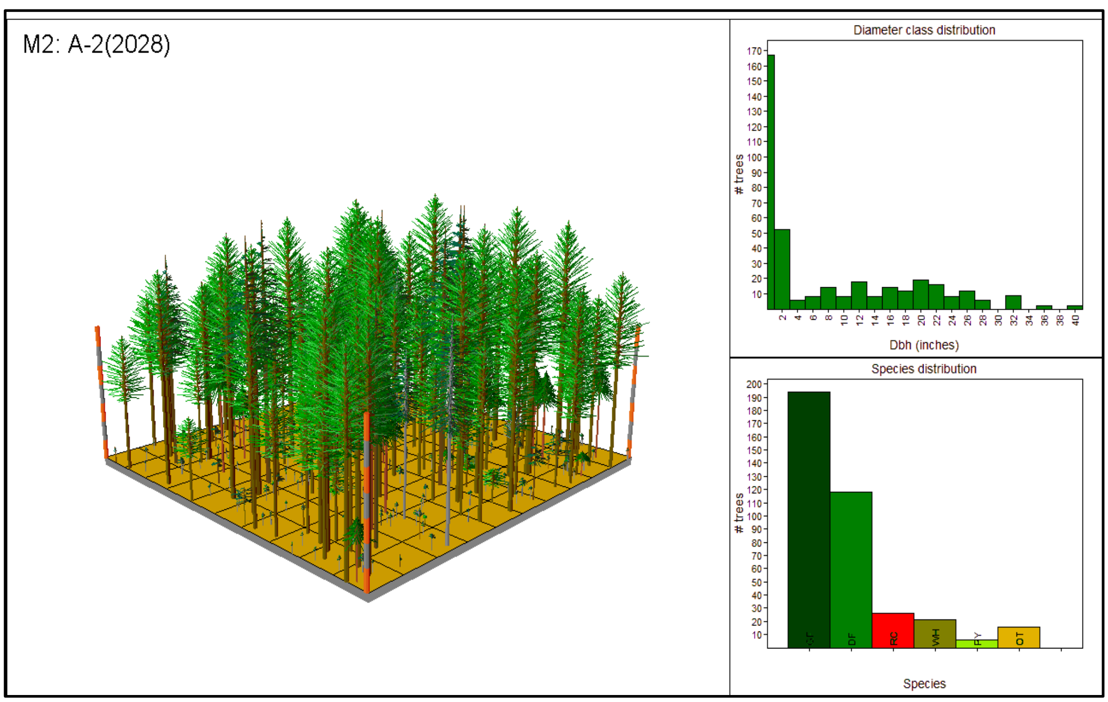

Figure 7: Visualization of American Camp stand-2 in 2028 as depicted by the output in M2. Diameter and species distribution graphs are included on the right. Graphs and visualizations were output in LMS through SVS.

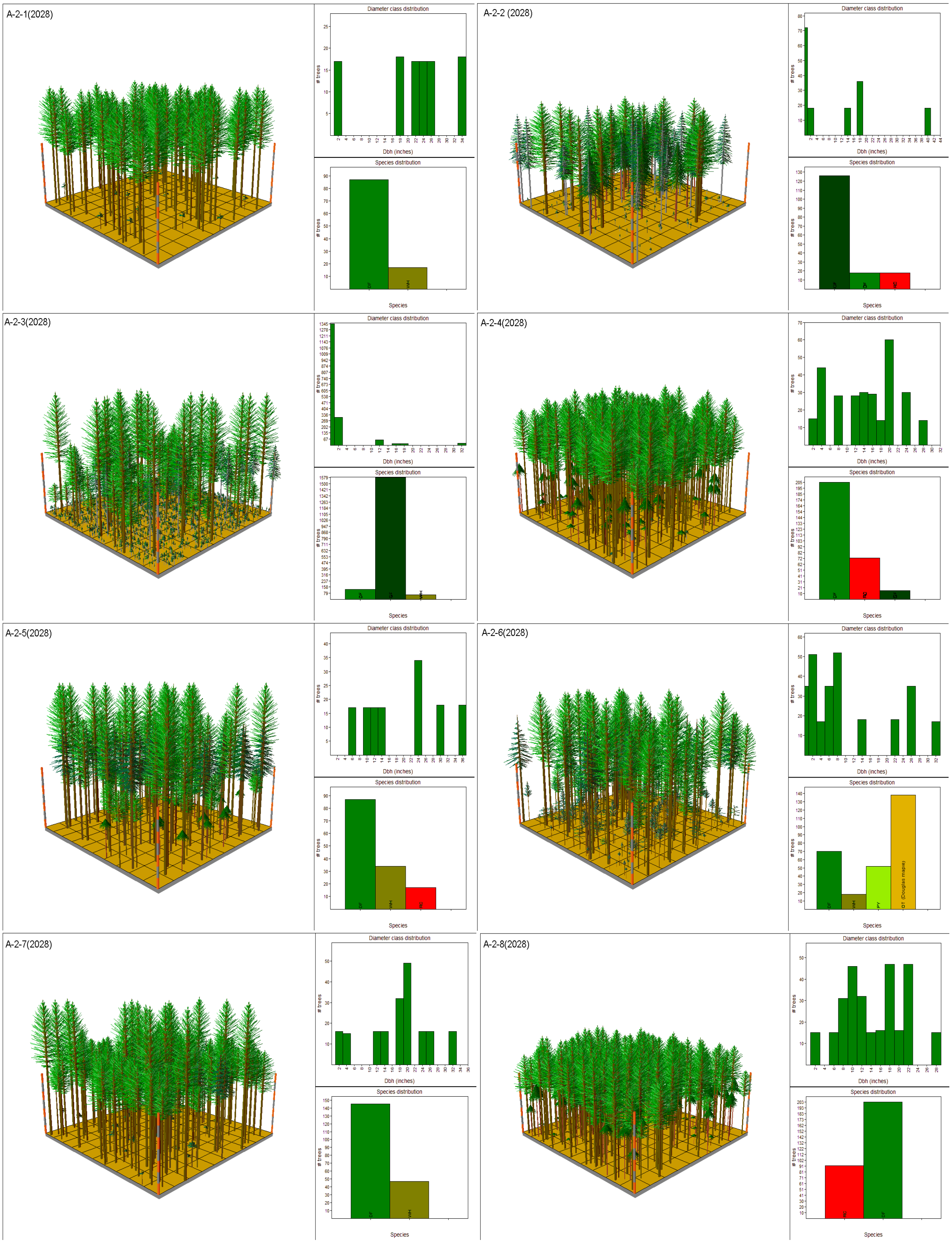

Figure 8: Visualizations of the plots in American Camp stand-2 in 2028. Diameter and species distribution graphs are included on the right. Graphs and visualizations were output in LMS through SVS.

3.2 M1 versus M3

When comparing M1 and M3, there were no significant differences in total DBH, total BA or total volume. However, when doing comparisons of BA and volume with regards to species, some significant differences were observed. These differences are summarized in Table 3. Three quarters of the stands showed at least some significant differences in volume by species in 2028, and 2068 when comparing M1 and M3. Similar results were found for BA, though only 2 of the 4 stands showed a significant difference between M1 and M3 in 2028, while 3 were different in 2068.

Table 3: Percentage of stands (out of 4) that showed significant differences (α=0.05) when comparing M1 and M3.

		2028	2068
DBH	Total	0	0
BA	By Species	**50**	**75**
	Total	0	0
Volume	By Species	**75**	**75**
	Total	0	0

The representative plot did not always have all the species that were in the stand, and there were therefore zero values for a number of species in M3. When comparing M1 and M3 in those cases, the differences were expected to be significant. However, the significant differences by species between these methods were always in cases where the species in question was present in the representative plot (Tables 4 and 5). In the cases where a species was not present in the representative plot, the mean value of BA or volume from M1 always had a 95% confidence interval which incorporated zero. For the results that were significant, no distinct trends were observed. In most cases, if a species had significantly different BA values between M1 and M3, then it usually also had significantly different volume values between the two methods (Tables 4 and 5). There were two cases where a difference in BA between M1 and M3 that was not significant in 2028, became significant when projected further to 2068. This was the case for WH in AC stand-4, and for GF in BC stand-2. The only stand which showed no significant differences between these two methods was stand AC-6, which was one of the most uniform stands sampled, and was the most uniform stand considered in this subset analysis.

Table 4: Summary of the results for differences in BA by species between M1 and M3 in 2028 and 2068. * indicate significance (α=0.05)

BA	AC -4				AC-6				BC-2				BC-7			
Species	Present or not in Rep. plot	% of plots the species occurred in	Statistical significance		Present or not in Rep. plot	% of plots the species occurred in	Statistical significance		Present or not in Rep. plot	% of plots the species occurred in	Statistical significance		Present or not in Rep. plot	% of plots the species occurred in	Statistical significance	
			2028	2068			2028	2068			2028	2068			2028	2068
BM	N/A				N/A				N	10			Y	43		
DF	N	43			Y	100			Y	95			Y	100		
GF	N	43			Y	14			Y	40		*	Y	86		
OT	N	43			N/A				N/A				N/A			
PY	N/A				N/A				N	5			N/A			
RA	N/A				N/A				N	5			N/A			
RC	Y	86	*	*	N	14			N	15			N	71		
WH	Y	100		*	N	14			N/A				N/A			
WA	N/A				N/A				Y	15			Y	29	*	*

Table 5: Summary of the results for differences in volume by species between M1 and M3 in 2028 and 2068. * indicate significance (α=0.05)

Vol	AC -4				AC-6				BC-2				BC-7			
Species	Present or not in Rep. plot	% of plots the species occurs in	Statistical significance		Present or not in Rep. plot	% of plots the species occurs in	Statistical significance		Present or not in Rep. plot	% of plots the species occurs in	Statistical significance		Present or not in Rep. plot	% of plots the species occurs in	Statistical significance	
			2028	2068			2028	2068			2028	2068			2028	2068
BM	N/A				N/A				N	10			Y	43		
DF	N	43			Y	100			Y	95			Y	100		
GF	N	43			Y	14			Y	40	*	*	Y	86		
OT	N	43			N/A				N/A				N/A			
PY	N/A				N/A				N	5			N/A			
RA	N/A				N/A				N	5			N/A			
RC	Y	86	*	*	N	14			N	15			N	71		
WH	Y	100			N	14			N/A				N/A			
WA	N/A				N/A				Y	15			Y	29	*	*

4.0 Discussion

The results of this study were not as expected. Both M2 and M3 were found to produce outputs that were statistically the same as M1 for total DBH, BA and volume, with the exception of the total DBH values for stand AC-2 when comparing M1 and M2. It was originally predicted that M1 would differ from both M2 and M3 because M1 included all the inventory, unlike in M3, and the variability in stand structure and density between plots was retained, unlike in M2. There were some statistical differences in BA and volume by species when comparing M1 and M3. In general, the number of years the stand had been projected in time did not affect significance as originally expected. An understanding of how FVS uses the inventory to project the stands is necessary for interpreting the above results.

4.1 FVS – How the growth model projects tree growth

4.1a Differences between M1 and M2

The same individual tree inventory was entered into the model for both M1 and M2. However, the stand data used in M1 differed from that used in M2 in ways that were expected to influence the growth of the trees included in the inventory. First of all, in M1 different slopes and aspects were included for each plot per stand, while in M2 an average slope and aspect were selected. Slope and aspect influence tree growth in FVS as a circular effect (Crookston and Dixon, 2005). In FVS, optimal site characteristics vary by species but are generally characterized by south-facing moderate slopes (Crookston and Dixon, 2005). In some of the stands these characteristics ranged widely from plot to plot. For example, in EC stand-2 the slope varied from 1 to 33 degrees, and in AC stand-1 there were plots with southern aspects, and others with northern aspects.

Second of all, site indexes differed between plots per stand in M1, while an average site index was selected for M2. SI is a factor influencing height growth of large trees in FVS (Dixon, 2007). The differences in SI between plots were generally minimal, but were expected to result in some differences in the output.

The third difference in the inventory between M1 and M2 was that stand density varied between plots within stands in M1, while M2 had an 'average' stand density. For example, in stand-5 in British Camp, the number of live trees per plot ranged from 2 to 41. In M2 these plots were combined and projected forward together, and the distinction between the plot densities was lost. The differences in DBH, BA, and volume were not, however, significant between M1 and M2 for this example. This was surprising, because stand density influences growth in the model by reducing height growth as density increases (Crookston and Dixon, 2005). This is done indirectly for large trees as density reduces the diameter increment, which in turn influences height (Crookston and Dixon, 2005).

Stand density is particularly influential on the growth of small trees in FVS (Crookston and Dixon, 2005). Stand AC-2 was the only stand considered in this study that had a large regeneration component. It was also the only stand where there were significant differences in diameter between M1 and M2. Increasing density directly decreases the height increment curve for small trees based on the crown competition factor (CCF) (Crookston and Dixon, 2005). The CCF is related to the available growing space of a tree compared with that of an open grown individual (Krajicek et al., 1961). The rate of reduction in the height curve related to density varies based on the shade tolerance of the species in question (Dixon, 2007). When an individual plot is considered, such as plot-3 in AC stand-2, which had 98 trees, most of which were small grand firs in the understory, it would be expected that the competition would be higher than in a less dense plot such as plot-1 where only 6 live trees were measured. When combined, as in M2, there would be the same total number of trees as when grown separately, but the 98 small trees from plot-3 would be spread out over a larger area, and the competition factor would be expected to decline for those small trees. This factor alone would be expected to cause the trees in the dense plots to grow more slowly in M1 than M2, and those in the open plots to grow more quickly in M1 than M2.

Mortality, as it relates to density, may have been a factor that influenced the differences between the mean diameter outputs from M1 and M2. The PN variant of FVS uses the Prognosis-type mortality model for all species (Forest Vegetation Simulator Staff, 2008). In this mortality model, the predicted mortality rates for small trees are high when there are a relatively large number of them in a stand (Dixon, 2007). It is possible that relatively high densities of small diameter trees in certain plots would result in higher mortality rates of those trees when grown via M1 rather than M2. This would better emulate what would happen in the natural environment. If this were true, and more small trees die due to density when grown via M1 compared with M2, then it may have contributed to the lower diameter distribution in M2. If more small diameter trees survive in M2, then there would be more small individuals contributing to the total mean diameter than in M1. If this were the case, then the differences would be expected to increase with the length of projection.

The differences between M1 and M2 did not noticeably increase between the 20, 40 and 60 year projections in this study. The lack of difference in level of significance between the projected ages was unexpected. It is possible, however, that the length of projection would have had more of an influence on significant differences between M1 and M2 if a longer projection length had been used.

Overall, the main trend that was observed when comparing M1 and M2 was that the outputs for the mean total DBH from M1 were always higher than the values of total DBH from M2. This is primarily because FVS determines the growth rate of trees based on their position in the canopy (Crookston and Dixon, 2005). The trees are ranked based on their height, and the dominant trees in the inventory are grown at faster rates than the other trees. A tree that is ranked as the tallest in its plot, may not be ranked as high in the overall stand. In M1 every plot has a dominant tree, however in M2 not all of those same trees would be considered dominant. There are therefore, more trees in M1 which would be attributed a faster growth rate than in M2. As a result, the mean diameter can only decrease as the inventory from the plots are clumped together. M1 better emulates the natural environment, because in reality trees are only competing with others in their vicinity (e.g. within their plots) and not with all of the trees in the stand.

The lack of differences between M1 and M2 in the outputs of BA or volume is assumed to be due, in part, to the nature of these variables. With diameter, the largest difference between M1 and M2 were observed when one or more plots had a large number of small diameter trees, which skewed the overall stand diameter distribution. A large number of small diameter trees have a large effect on the average diameter. However, a large number of small trees have a relatively small influence on the overall BA or volume. Therefore, when comparing M1 and M2, although there were changes in average diameter over time, there were little to no differences in BA or volume.

Despite the one example of total DBH in AC stand-2, overall the differences between the data input in M1 and M2 did not have a significant influence on the outputs from the growth model. The FVS guide book states that using ‘average values’ for stand variables increases the probability that the model projections would be inaccurate (Dixon, 2007). The stand stratification process was a critical step, because it reduced the variation between plots in a single stand, and thus the average values used for stand variables in M2 did not have to be that different from any one particular plot. Stage and Wykoff (1998) suggested a model adaptation to account for special variability within stands, rather than just increasing the number of sample plots per stand, or only focusing on uniform stands, as these methods are subject to sampling error. In 2005, it was noted in an FVS review that work was being done to apply this method (Crookston and Dixon, 2005).

4.1b Differences between M1 and M3

Stand stratification was found to be critically important when using M3 as well. If the stand had not been classified according to a set of uniform characteristics, no single plot could represent the stand well. AC stand-6 was the most uniform of the stands considered in the comparison of M1 and M3. Consequently, it was also the only stand in which no statistical differences were observed for any of the variables considered. Overall, there were more differences observed between M1 and M3 than between M1 and M2. In particular, differences in BA and volume by species were observed when comparing M1 and M3. This would have important implications for managing a stand with specific objectives for a particular species. If, however, the overall stand volume was the primary management concern, the differences observed might be less relevant.

In this study the representative plot was selected based on a minimum squared Euclidean distance for total DBH, total BA and total volume, which were the same variables that were being compared in the outputs of M1 and M3. The resulting representative plot did not always contain all the species present in the stand. Although differences in BA and volume by species between M1 and M3 were not statistically significant due to large 95% confidence intervals, there would be management implications of modeling a plot which misrepresents the true species composition of the stand in question. Users of LMS are known to select a representative plot for model simulations (Rural Technology Initiative and Landscape Management Project, 2005; B. Larson *personal comm.*, 2009). However, it is difficult to find a detailed description in the literature of how these plots are generally selected. It would be recommended that plots be selected based on a wide range of factors including species composition. As described above, stand-variables also influence how trees are grown in FVS, therefore variability in stand characteristics between plots should also be minimized through stand stratification.

There was no apparent influence of the length of projection on signficance when comparing M1 and M2 for the ages considered in this study. However, there were some differences in significance between the projections to 2028 and 2068 when comparing BA by species in M1 and M3. It would be expected that these differences would increase with the length of projection. The influence of time would likely affect the differences between M1 and M3 for species which were not present in the representative plot in particular. In M1 these trees would continue to grow, and their volume or BA in the stand would increase, while in M2 their volume or BA would remain zero.

4.2 The practicality of the different methods (M1 vs. M2 and M3)

The results of this study have important implications with regards to the practical differences in running the model with M1 versus M2 or M3. Using M1 was the most time consuming because the outputs from each stand needed to be exported to MS Excel and averaged together. However, the results showed that very accurate stratification is less necessary with this method than when using M2 or M3. The results from M2 and M3 differed the most from M1 when stratification had been done poorly, or when stands had a lot of internal variability.

Accurate stratification was a time consuming process. Marzluff et al. (2002) based their stand stratification solely on aerial photographs. However, we found that the initial stand delineations, which had been drawn based on the high definition photos, required a lot of refinement in the field. According to our field experience, doing stratification without extensive ground-truthing would likely not reduce within stand variability enough to obtain the same results from M2 or M3 as with M1. In other words, there is a trade-off between either spending more time in the field (M2 or M3) or spending more time running the model (M1). In general spending time in the field is more costly than time in the lab, and therefore M1 may be more desirable.

5.0 Conclusions and Management Implications

There are different methods of inputting data into LMS. Some differences and trends in the results were observed when running the model in the three methods considered in this study. In general, however, if the stands had been stratified appropriately prior to sampling, and if there was little spatial variation between plots within a stand, then the results from M1 were statistically the same as M2 and M3. In those cases, I was not able to reject the null hypothesis that these methods would be the same. In cases where the plots within a stand were highly variable with regards to species and diameter distributions, such as AC stand-2, the null hypothesis was rejected for total DBH when comparing M1 and M2. In cases such as this, or where stratification had been done poorly, it would be recommended that M1 be used. The differences between M1 and M3 were all related to species specific cases. Depending on the management objectives for which the model is being used, M3 could be sufficient, if total volume was, for example, the primary concern. The only stand which resulted in no differences between the outputs of M1 and M3 was highly uniform regarding species composition, structure, and stand characteristics such as slope, aspect and density. Using M3 would only be recommended in cases where the stand being modeled is homogeneous as described above.

Currently M1 is time consuming in the lab, though it captures more of the variability of natural stand growth, and therefore requires less accurate stand stratification than M2 or M3. If LMS were adapted to more easily incorporate the inclusion of multiple plots per stand, field sampling would consistently be more efficient.

6.0 Literature Cited

Agee, J. (1984). *Historical Landscapes of San Juan Island National Historic Park.* Seattle: University of Washington.

Andreassen, K., & Tomter, S. M. (2002). Basal area growth models for individual trees of Norway spruce, Scots pine, birch and other broadleaves in Norway. *Forest Ecology and Management* , 180:11-24.

BC Ministry of Forests and Range. (2007). *TIPSY. 4.1* . Victoria, BC: Province of British Columbia.

Ceder, K. (2002). *Satsop Forest Management Plan Initial Management Alternatives.* Seattle, WA: College of Forest Resources, University of Washington.

Crookston, N. L., & Dixon, G. E. (2005). The forest vegetation simulator: A review of its structure, content, and applications. *Computers and Electronics in Agriculture* , 49:60-80.

Dixon, G. E. (2007). *Essential FVS: A User's Guide to the Forest Vegetation Simulator.* Fort Collins, CO: Forest Service: Forest Management service center.

Edminster, B., Mowrer, H. T., Mathasen, T. M., Schuler, W. K., & Hawsworth, F. G. (1991). *GENGYM: A variable density stand table projection system calibrated for mixed conifer and ponderosa pine stands in the Soutwest.* USDA Forest Service Research Paper.

Forest Vegetation Simulator Staff. (2008). *Pacific Northwest Coast (PN) Variant Overview.* Fort Collins, CO: United States Forest Service: Forest Management Service center.

Franklin, J. F., & Dyrness, C. T. (1988). *Natural vegetation of Oregon and Washington* . Corvallis: Oregon State University Press.

Hetsch, S. (2005). *Reconstruction of stand development - a case study on San Juan Island, Washington, USA.* Vancouver: Undergraduate Thesis to the University of British Columbia.

Imaki, H. (2007). Optimizing timber harvest revenue with wildlife constraints for old-forest species using a spatially explicit habitat model and open source GIS. *A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science.* University of Washington, Seattle.

Krajicek, J. E., Brinkman, K. A., & Ginrgrich, S. F. (1961). Crown competition - A measure of density. *Forest Science* , 7: 35-42.

Larson, B. (2009, March 18). Personal communication.

Laser Technology Inc. (2009). *Tree Height Measurements*. Retrieved March 15, 2009, from Laser Technology Inc.: http://www.lasertech.com/Tree-Height-Measurement.aspx

Marzluff, J. M., Millspaugh, J. J., Ceder, K. R., Oliver, C. D., Withey, J., McCarter, J. B., et al. (2002). Modeling changes in wildlife habitat and timber revenues in response to forest management. *Forest Sciences* , 48:191-202.

McCarter, J., Wilson, J., Baker, P., Moffett, J., & Oliver, C. (1998). Landscape management through integration of existing tools and emerging technologies. *Journal of Forestry* , 96:17-23.

McGaugney, R. J. (1997). Visualizing forest stand dynamics using the stand visualization system. *Proc. Am. Soc. Photogram. Rem. Sens.* , 4:248-257.

Meidinger, D. V., & Pojar, J. (1991). *Ecosystems of British Columbia.* Research Branch: Special report series.

Moeur, M., & Stage, A. R. (1995). Most Similar Neighbor: An Improved SamplingIn ference Procedure for Natural Resource Planning. *Forest Science* , 41:337-359.

National Park Service. (2009). *San Juan Island National Historical Park*. Retrieved March 3, 2009, from npg.gov: http://www.nps.gov/sajh/naturescience/weather.htm

Oliver, C. D., & Larson, B. C. (1996). *Forest stand dynamics: updated edition.* New York: John Wiley and Sons.

Porte, A., & Bartelink, H. (2002). Modelling mixed forest growth: a review of models for forest management. *Ecological modeling* , 150:141-188.

Rural Technology Initiative & Landscape Management Project. (2005, April 3). *Creating a New Portfolio with LMS 2.0.* Retrieved 11 28, 2008, from Landscape Managment System - Tutorials: http://lms.cfr.washington.edu/download/14-NewPortfolio.pdf

SAS Institute Inc. (2005). *SAS® 9.1.3 Language Reference: Concepts, Third Edition.* Cary, NC: SAS Institute Inc.

Stage, A. R. (2002). Using FVS and Its Fire and Fuels Extension in the Context of Uncertain Climate. *USDA Forest Service Proceedings* , 104-107.

Stage, A. R., & Wykoff, W. R. (1998). Adapting Distance-Independent Forest Growth Models to Represent Spacial Variability: Effects of sampling design on model coefficients. *Forest Science* , 44:224-238.

Turnblom, E. C., Amoroso, M. M., Ceder, K. W., Lippke, B. R., Mason, C. L., & McCarter, J. B. (2002). *Estimation of Sequestered Carbon in King County Forests.* Seattle, WA: College of Forest Resources, University of Washington.

Western Regional Climate Center. (2007). *Western U.S. Climate Summaries*. Retrieved March 3, 2009, from Historical Climate information: http://www.wrcc.dri.edu/NEWWEB.html

7.0 Appendix

Appendix 1: Species codes from the Pacific Northwest variant of FVS (FVS_{PN})

Code	Species Name	Code	Species Name
SF	Pacific silver fir	BM	Bigleaf maple
WF	White fir	RA	Red alder
GF	Grand fir	WA	White alder/pacific madrone
AF	Subalpine fir	PB	Western paper birch
RF	California red fir	GC	Giant chinkapin/tanoak
SS	Sitka spruce	AS	Quaking aspen
NF	Noble fir	CW	Black cottonwood
YC	Yellow-cedar/ Western larch	WO	OR white oak/ CA black oak
IC	Incense-cedar	J	Juniper
ES	Engelmann spruce	LL	Subalpine larch
LP	Lodgepole pine	WB	Whitebark pine
JP	Jeffrey pine	KP	Knobcone pine
SP	Sugar pine	PY	Pacific yew
WP	Western white pine	DG	Pacific dogwood
PP	Ponderosa pine	HT	Hawthorn
DF	Douglas-fir	CH	Bitter cherry
RW	Coast redwood	WI	Willow
RC	Western redcedar	---	
WH	Western hemlock	OT	Other species
MH	Mountain hemlock		