UNIVERSITY OF ALBERTA

THE USE OF GROWTH MODELS IN FOREST INVENTORY

BY

MIKE BOKALO

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Abstract

In recent years considerable attention has been placed on the development of growth simulation models in an attempt to provide forest managers with a useful tool to assist in the decision making process and more recently, as a means for adjusting inventories to reflect changes in condition.

The focus of this thesis is to address three questions: 1) How well do selected growth models perform?; 2) Can growth model data be incorporated into the traditional theory of Sampling with Partial Replacement (Ware and Cunia, 1962), and if so, do they improve the precision of growth and volume estimates?; and 3) What are the implications of answers to the first two questions on inventory update in the Alberta Forest Service?

Three growth models, the Alberta Forest Service/Dempster procedure, the Mixedwood Growth Model and the Stand Projection System were evaluated by comparing growth model predictions of gross volume/ha, basal area/ha, density/ha, average diameter and average height to actual remeasured permanent sample plot data. Performance was evaluated for five species groups, spruce, pine, aspen, mixed deciduous and mixed coniferous using paired t-tests and by determining which model predictions were within 10 percent of the actual values. Results indicated that growth models can provide unbiased estimates of growth for projections up to 15 years. It was also determined that no one model was capable of successfully projecting all species accurately. All models performed reasonably well for the coniferous species but poorly in the deciduous species types.

The original theory of Sampling with Partial Replacement was modified to incorporate growth model projections of the unmatched plot data on the initial occasion. The Modified Sampling with Partial Replacement theory was evaluated against other growth and current volume estimation procedures using an illustrative example. If the

necessary assumptions are met the new theory improves the precision of volume and growth estimates over the original SPR design.

The Alberta Forest Service must obtain estimates of current volume for annual allowable cut calculations. One source of this information is the Phase 3 inventory, however it is up to 23 years out of date. Four alternatives to obtain estimates of current volume and a methodology to update the Alberta Phase 3 inventory are presented and discussed.

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Chapter 1

Introduction

To successfully manage the Alberta forest resource, it is essential that forest managers have an accurate estimate of the current growing stock. Unfortunately, an accurate estimate of growing stock is not easily attainable considering Alberta's forest resource spans over 311,564 square kilometers (AFS Map Cover Type Specifications, 1985). The difficulties in managing the resource are also complicated because the forest is dynamic. Changes occur due to first, growth, fire and disease and second, through harvesting, oil or gas exploration and land clearing. Although most changes occurring in the forest are easily monitored, the past and future changes occurring due to growth are difficult to evaluate and predict. In recent years considerable attention has been placed on the development of growth simulation models in an attempt to provide forest managers with a useful tool to assist in the decision making process and more recently, as a means for adjusting inventories to reflect changes in condition.

Although numerous forest growth models are available, their operational use has been limited mainly due to the high cost of computer resources. Today, the availability of powerful inexpensive desktop computers has made the use of growth models in forest management decision-making possible. Three growth models are of particular interest in Alberta. In 1983, W.R. Dempster developed for the Alberta Forest Service (AFS) empirical yield tables using a whole stand modelling approach referred to as the AFS/Dempster (DMP) procedure. Morton and Titus (1984), and Huang (1992), developed the Mixedwood Growth Model (MGM). In 1988 the Stand Projection System (SPS) (Arney, 1985) was calibrated for Alberta tree species (Lakusta, 1993).

The focus of this thesis is to address three questions: 1) How well do selected growth models perform?; 2) Can growth models be incorporated into the traditional theory of Sampling with Partial Replacement (Ware and Cunia, 1962), and if so, do they improve the precision of growth and volume estimates?; and 3) What are the implications of answers to the first two questions on inventory update in the Alberta Forest Service?

In the second chapter, three growth models are evaluated to determine if they can provide unbiased estimates of forest growth. In the third chapter, an extension to Sampling with Partial Replacement is presented that incorporates growth model projections. The fourth chapter presents four alternate methods to obtain estimates of current volume and suggests an approach to updating the Alberta Phase 3 inventory. General conclusions and recommendations for additional research are presented in the final chapter.

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Chapter 2

Evaluation of Growth Models

2.1 Introduction

As the pressure increases to utilize more of the forest resource, the impact of poor management decisions today jeopardizes the sustainability of the future forest resource. To make sound forest management decisions it is necessary to know what is the current status of the forest resource. Because forest inventories spanning large areas can take years to complete, information regarding the current status of the forest as a whole, is rarely known. The projection of past inventory data to the present provides a means to estimate the current status of the forest resource from which management decisions can be based. To evaluate the possible implications of different management strategies, it is necessary to project the forest into the future to provide some insight into the possible outcomes. In recent years, the development of forest growth simulation models has become a useful tool in projecting forest data.

This study evaluated how well three growth models predict actual growth of stands in Alberta by comparing predicted and actual changes in stand volume, basal area, density, diameter and height. Comparisons were made for five broad classes of stands by species composition. The performance was evaluated using the paired t-test and also by determining which model predictions of the forest characteristics were within ±10 percent of the actual characteristics. The growth models selected for the study are; the Mixedwood Growth Model (MGM), Morton and Titus (1984) and Huang (1992), the Stand Projection System (SPS), Arney (1985), and the AFS/Dempster procedure (DMP), Dempster (1983). Three different types of models are represented; MGM is an individual tree, distance-independent growth model; SPS is described by Arney (1985) as an individual tree, distance-independent growth model; and DMP a whole stand model. The models were selected first, because the data available from the remeasured plots was sufficient to drive the models and second, because the models were calibrated for Alberta tree species.

2.2 Methods

Alberta Forest Service (AFS) permanent sample plots (PSP) were chosen for the evaluation because they contained actual measured plot data on two or more occasions. Using the AFS PSP Index Catalogue (AFS, 1992), all PSP that were not appropriate for projection were identified and deleted. Permanent sample plots established after April 1981 were deleted because they had a different plot configuration than those established prior to April 1981. PSP established prior to April 1981 are referred to as PSP groups; a group consists of four separate plots with a buffer boundary surrounding the entire group. A complete description of the PSP plot design is available in the AFS publication, Permanent Sample Plots: Field Procedures Manual (AFS, 1990). PSP groups where all four plots were damaged between the first and second occasion were also deleted. PSP groups with buffer damage were not considered damaged.

The acceptable PSP groups were stratified into five species categories, white spruce (SW), pine (PL), aspen/poplar (AW), mixed deciduous (DEC) and mixed coniferous (CON). PSP's identified in the pure species categories, SW, PL and AW contained a total basal area of greater than 80% of the primary species. The two mixedwood types contained a total basal area of greater than 51% for all of the coniferous or deciduous species.

Twenty PSP groups per species category were randomly selected; ten with a re-measurement interval of between five and nine years and ten with an interval of between ten and 14 years. From each PSP group, one plot was randomly selected from plots numbered two, three, or four. The first plot in each group was excluded from the selection process to avoid trees previously used in development of growth models. To keep the number of trees manageable, a sample of 50 trees, having a minimum diameter at breast height of 9.1 cm were randomly selected[1]. Trees with less than a 9.1 cm diameter at breast height were considered saplings or regeneration and were ignored. For converting estimates to per hectare values, an expansion factor was computed based on the original PSP size in hectares and the total number of trees found in the PSP. The same trees were used for both the initial and final measurement.

Five stand characteristics of interest, total gross volume/ha (m^3), total basal area/ha (cm^2), density (trees/ha), quadratic mean diameter (cm) and average height (m) were calculated for each plot on both occasions. Because the majority of individual tree heights were not measured, the unknown heights were estimated using the height diameter functions developed by Huang, (1992). Total tree volumes were estimated using Schumacher's volume function presented in the AFS publication, Alberta Phase 3 Forest Inventory: Single Tree Volume Tables: Method of Formulation (AFS, 1985) with coefficients by volume sampling region as presented in the AFS publications, Alberta Forest Inventory: Single Tree Volume Tables: Volume Sampling Regions 1 through 11 (AFS, 1985).

The Stand Projection System (SPS) projection of the PSP's was made using version 2.3a of SPS, calibrated for Alberta tree species (Cieszewski and Bella, 1990). Because plot data alone did not provide the minimum input data for SPS, it was necessary to perform some pre-projection calculations to obtain estimates of total stand age, stand site index and individual tree heights. Site index for each plot, reference age 50, was calculated using the formulae presented in the AFS publication, Phase 3 Forest Inventory: Yield Tables for Unmanaged Stands (AFS, 1985). The site index was calculated on the plot establishment date using all four PSP plots to maximize the number of trees with height and age measurements. It was assumed that the site index is stable over time.

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[1]Based on a preliminary study that compared actual plot characteristics with estimates based on subsamples, it was determined that a subsample of 50 trees contain negligible bias when predicting plot characteristics.

Optional tree variables, breast height age, live crown percent and taper were not known and therefore ignored during analysis. The clumpiness parameter, representing the average portion of the area stocked, was changed from the default of 0.9 to 1.0 because it was assumed that PSP were fully stocked.

The Mixedwood Growth Model (MGM) normally does not require any pre projection calculations as it accepts the raw AFS PSP data as an input format. However, because the study used a subsample of trees from a PSP, a tree factor was added to the input file. Additionally, the site productivity index (Huang and Titus, 1993) used by MGM is an optional input parameter however, because values from a larger sample were used to calculate site index for SPS and DMP, the site productivity index values for MGM were calculated and included in the input file.

Dempster's whole stand approach (DMP), unlike MGM and SPS was not available as a computer program but only as a descriptive procedure which included a list of equations and coefficients for different species categories. The complete procedure including formulas and coefficients is presented in the AFS report, Alberta Phase 3 Forest Inventory: Yield Tables for Unmanaged Stands (AFS, 1985). The input required to drive the model was the average breast height age and the site index reference age 50. The site index, reference age 50 was calculated using the dominant and codominant trees from the four PSP plots and converted into the AFS rating system of good, medium and fair based on the standards outlined in the AFS publication, Alberta Phase 3 Forest Inventory, Yield Tables for Unmanaged Stands (AFS, 1985). To carry out the projections the DMP procedure was written as a SAS (SAS Institute Inc., 1988) program.

The deviations between the actual and the predicted characteristics for each model were plotted against the actual characteristic to obtain a visual presentation of the performance. A paired t-test was also conducted using a .05 level of significance to determine if there was a significant difference between the average of predicted and actual values. Because statistically significant differences may or may not be important when using model predictions, additional comparisons with a limit of ±10 percent of the actual mean were also made.

Although the t-test is essentially a univariate statistical technique, its usage here has some elements of multivariate techniques since statistics are computed for three growth models, five species groups, and five stand characteristics. Inferences about how models perform are made mainly on the collective t-statistic results. Strictly speaking this leads to a large Type I error rate on an experiment-wise basis than is expected on a comparison-wise basis (Moffitt and Boardman 1977, Morrison, 1976. pp. 134). For this study, no attempt was made to adjust for this increased error rate since the sample sizes are reasonably large and model performance is expected to be highly variable. Adjusting for the collective inferences would reduce the sensitivity of the comparisons unnecessarily.

2.3 Results

2.3.1 Paired t-test

Summaries of overall performance are presented in Tables 2-1 and 2-2a. Out of the 25 possible species group and stand characteristic combinations, 12 predicted characteristics for both DMP and MGM were not significantly different from the actual characteristics, while only 10 predictions for SPS were not significantly different from the actual. In examining the results, several trends are evident. Height predictions for all models are significantly different from the actual heights for all species groups and growth models (Table 2-2b). As expected, the whole-stand model (DMP) performed well in predicting stand volume and basal area with nine out of ten predictions not significantly different from the actual, compared to MGM with five out of ten and SPS with three out of ten predictions significantly different from the actual (Table 2-2b). The strength of the individual tree models, MGM and SPS, was evident in predicting stand density and quadratic mean diameter with seven out of 10 predictions not significantly different from the actual, compared to DMP with three out of 10 predictions not significantly different. The evaluation of predictions by species group showed that the models had different strengths (Table 2-2c). For the coniferous species groups, MGM was superior with four out of the five predictions not significantly different from the actual for the SW and CON groups and three out of five for the PL group. SPS predictions were not significantly different from the actual, three out of five times for the PL and CON groups and two out of five for the SW group. DMP predictions were not significantly different from the actual four out of five for the CON group and two out of five times for the SW and PL groups.

Table 2-1: Differences between actual and predicted mean stand values by species and model. Shaded areas indicate no significant difference between the actual and the mean predicted values based on a paired t-test (alpha .05).

Species	Growth Model	Volume (m^3/ha)	Basal Area (m^2/ha)	Density (stems/ha)	Quadratic Mean Diameter (cm)	Height (m)
AW	DMP	2.0621842	1.2160368	-238.0526	5.156163	-6.0183526
CO	DMP	-5.2315333	2.5938278	64.5	-0.284622	-10.0810111
DE	DMP	-14.8691562	-2.1818313	-192.875	2.977206	-3.9138063
PL	DMP	9.8674	1.769425	-247.8	1.682235	-5.08786
SW	DMP	-21.84693	-1.89464	268.25	-3.32619	-9.940855
AW	MGM	55.1941263	6.3946574	85.47753	1.236484	-0.3970211
CO	MGM	-0.379025	0.457975	25.85385	0.003505	-0.603965
DE	MGM	31.867025	3.659495	83.4546	0.35378	-0.27843
PL	MGM	-17.92627	-0.51802	3.0348	-0.10894	-0.891925
SW	MGM	-17.85435	-1.21501	20.06215	-0.117205	-0.59478
AW	SPS	-52.6782368	-5.0296368	-72.52632	-0.592311	-3.4726316
CO	SPS	25.1871333	-1.8193722	-26.33333	-0.110378	-4.26
DE	SPS	-25.9252706	-5.5741294	-64.35294	-0.579394	-3.6547059
PL	SPS	8.92678	-1.74915	-70.95	0.07162	-4.055
SW	SPS	18.80025	-6.373065	-82.75	-0.442705	-6.0405

For the deciduous species groups, no model performed well. MGM predictions were not significantly different from the actual, one out of five and zero out of five for AW and the DEC species groups respectively. The weakness of SPS was also in the deciduous groups with one out of five predictions not significantly different for both the AW and DEC species groups. DMP predictions were not significantly different from the actual two out of five for both the AW and the DEC species groups.

Table 2-2: Summary of model performance based on the t-test results; (a) overall summary, (b) summary by model and forest characteristic, (c) summary by model and species.

(a)

Model	Total
DMP	12/25
MGM	12/25
SPS	10/25

(b)

Model	Volume	Basal Area	Density	QMD	Height
DMP	4/5	5/5	2/5	1/5	0/5
MGM	2/5	3/5	3/5	4/5	0/5
SPS	2/5	1/5	2/5	5/5	0/5

(c)

Model	AW	CON	DEC	PL	SW
DMP	2/5	4/5	2/5	2/5	2/5
MGM	0/5	4/5	1/5	3/5	4/5
SPS	1/5	3/5	1/5	3/5	2/5

2.3.2 The 10 percent test

Predictions that are within ±10 percent of the mean of actual values are shaded in Table 2-3 and summarized in Table 2-4a. Out of a possible 25 species group and stand characteristic combinations, MGM predicted within ±10 percent of the actual 20 times, while for SPS 15 were within ±10 percent and for DMP, 13 were within ±10 percent of the actual (Table 2-4a).

For all groups MGM predictions of quadratic mean diameter and height were within ±10 percent of the actual, four out of five for volume and three out of five for both basal area and density (Table 2-4b). SPS predicted within ±10 percent of the actual five out of five for quadratic mean diameter, four out of five for both volume and density, two out of five for basal area and zero out five for height (Table 2-4b). For all species groups DMP performed well by predicting volume and basal area within ±10 percent of the actual values. However, only three out of a possible 15 predictions were within ±10 percent of the actual for density, quadratic mean diameter and height (Table 2-4b).

The trends by species groups show that for coniferous species, MGM is superior by predicting all stand characteristics within ±10 percent of the actual, for the CON, SW and PL groups (Table 2-4c). SPS predicted within ±10 percent of the actual, four out of five times for the CON and PL groups and three out of five for the SW group (Table 2-4c). DMP predicted within ±10 percent of the actual, four out of five for the CON group, three out of five for the PL group and two out of five for the SW group (Table 2-4c).

Table 2-3: Percent differences between actual and predicted mean stand values by species and model. Shaded areas indicate predictions within 10 percent of actual value.

Species	Growth Model	Volume	Basal Area	Density	Quadratic Mean Diameter	Height
AW	DMP	0.696422	3.653281	-37.35855	18.83816	-29.54594
CO	DMP	-1.60315	6.684214	6.089502	-1.209333	-57.17938
DE	DMP	-4.501174	-6.149716	-27.11203	11.12846	-19.05224
PL	DMP	3.55036	4.840995	-14.69533	9.678241	-32.94179
SW	DMP	-6.420842	-4.904971	25.73635	-13.93326	-50.82367
AW	MGM	18.63966	19.21116	13.41433	4.517523	-1.949098
CO	MGM	-0.116148	1.180187	2.440885	0.014892	-3.425683
DE	MGM	9.646751	10.31466	11.73104	1.322389	-1.355385
PL	MGM	-6.449997	-1.417258	0.179973	-0.626754	-5.774846
SW	MGM	-5.247417	-3.145499	1.924796	-0.490967	-3.040875
AW	SPS	-17.79002	-15.1103	-11.38185	-2.16402	-17.04821
CO	SPS	7.718342	-4.688466	-2.486153	-0.468985	-24.16267
DE	SPS	-7.848069	-15.71126	-9.045957	-2.165709	-17.79095
PL	SPS	3.211918	-4.785525	-4.207561	0.412044	-26.25445
SW	SPS	5.525418	-16.49902	-7.939173	-1.854472	-30.88269

For the deciduous groups, no model was able to predict within ±10 percent of the actual for all five characteristics. MGM characteristic predictions were within ±10 percent of the actual, three out of five and two out of five for the DEC and the AW groups respectively. The weakness of SPS was also evident in the deciduous groups with three out of five characteristic predictions within ±10 percent of the actual for the DEC group and one out of five for the AW group. DMP predictions were within ±10 percent of the actual for two out of five characteristics for both the AW and the DEC groups.

Table 2-4: Summary of model performance based on predictions within ±10 percent of actual; (a) overall summary, (b) summary by model and forest characteristic, (c) summary by model and species.

(a)

Model	
DMP	13/25
MGM	20/25
SPS	15/25

(b)

Model	Volume	Basal Area	Density	QMD	Height
DMP	5/5	5/5	1/5	2/5	0/5
MGM	4/5	3/5	3/5	5/5	5/5
SPS	4/5	2/5	4/5	5/5	0/5

(c)

Model	AW	CO	DE	PL	SW
DMP	2/5	4/5	2/5	3/5	2/5
MGM	2/5	5/5	3/5	5/5	5/5
SPS	1/5	4/5	3/5	4/5	3/5

2.4 Discussion

The results show that under the current evaluation criteria, no one model can accurately predict all five forest characteristics for all species groups. MGM is clearly superior in predicting the coniferous types, SW, PL and CON with a total of 15 out of 15 predictions not significantly different from the actual using the results of the 10 percent test. With respect to the AW and the DEC groups, no one model was able to predict well across the entire range of forest characteristics. DMP was superior in predicting volume and basal area while MGM was superior in predicting quadratic mean diameter and height.

SPS possessed the potential to do well with the coniferous types however its poor performance in predicting height constrained its success.

Although it is beyond the scope of this paper to solve internal problems within each model, it is possible to make some general comments regarding problem areas.

DMP's inability to adequately predict density, quadratic mean diameter and height are primarily due to the fact that the model was originally constructed to predict stand level characteristics such a volume/ha and basal area/ha. By briefly summarizing the steps involved in projecting a plot using the DMP procedure, the inherent problems are revealed. The procedure begins by using height, site index and breast height age to obtain DMP's estimate of volume/ha on the initial occasion. By dividing the actual volume/ha on the initial occasion by the DMP estimate of volume/ha on the initial occasion, an adjustment ratio between actual and predicted is obtained. The projection length is then added to the initial age and a DMP second occasion estimate of volume is obtained. This second occasion volume is adjusted by the ratio calculated on the initial occasion to obtain the final predicted volume for DMP. The basal area is automatically adjusted because it is a function of volume. However, in the DMP procedure volume is a function of height, not height a function of volume, therefore the new adjusted volume is not related to the original height. Since no mechanism is provided to obtain an adjusted height, both the quadratic mean diameter and density are also not related to the volume because they too are a function of height.

MGM's main difficulty was with predictions for deciduous species. From Table 2-3 it is evident that in the AW and DEC species groups the heights and diameters are within 5% of the actual values. The basal area, density and volume on the other hand, are over predicted by greater than 10% suggesting that an overestimate in density is the probable cause for the high volumes and basal areas. From the AW and DEC density graphs in Appendix 1 it is clear that as density increases the deviation from the actual increases suggesting that mortality decreases in severity as density increases. This trend is contrary to the theoretical expectation.

With SPS there are several areas of concern. The poor performance in predicting height is most likely due to a poorly calibrated height function. Volume and basal area predictions are not consistent with theoretical expectations. Because volume and basal area are highly correlated it is expected that if volume is over estimated the basal area should also be. However, in Table 2-3 under the SW group the volume is overestimated by 5% and the basal area underestimated by 16%. This condition also exists in the CON species group where the volume is overestimated by 4% and the basal area is underestimated by 7%. The other two models do not show this conflicting trend.

Other important factors in deciding which model to use, such as data input requirements and ease of use, are not reflected in the quantitative results. The DMP model required the most effort to obtain the projection results. The DMP procedure was taken from a publication and converted into a executable computer program which required extensive programming time and error checking. Furthermore, problems arose from the fact that DMP is a stand model which required stand information that was not directly available from a PSP such as average stand breast height age, average height and site index. To obtain the site index code a separate subroutine was written to obtain this value which then was converted into the three classes, good, medium and fair. With respect to tree height, only a few tree heights on each PSP were actually measured therefore a height diameter function was required to obtain individual tree heights. Those were then averaged to obtain average stand height. The need for an average breast height age created the greatest problem because PSP age measurements were only taken on the plot establishment date. If the date of the projection was anything other than the PSP establishment date, it was necessary to return to the original establishment record and adjust the age accordingly to represent the age at the time of projection.

SPS came as an executable program requiring the input data to be formatted in the standard SPS input format. In our case, we were using a subsample of a PSP therefore the selected raw data was already stored as a SAS (SAS Institute Inc., 1988) dataset requiring little effort to make the alteration. Under other circumstances, the conversion of the raw PSP data to the SPS input format would be an additional step. The input data requirements for SPS were also not entirely met by the raw PSP data. SPS was not able to calculate the heights from the individual tree diameters therefore the tree heights were calculated separately and appended to each record. A site index value for each plot was also required and was calculated separately and appended to the header record. As in the case of DMP, SPS also required an average stand age, if the initial date was other than the PSP establishment date, it was necessary to return to the original establishment record and adjust the age accordingly to represent the age at the time of projection.

MGM also came as an executable program and required the least amount of effort to project the data. Under normal circumstances MGM is capable of directly reading an AFS PSP and projecting future stand growth from the raw PSP data. Information such as heights and site index are calculated internally if not available. The input format used was the original PSP format with the addition of the site productivity index value that was a necessary calculation for SPS and DMP. This ensured that no model was given an unfair advantage. From the implementation perspective MGM required the least amount of time and effort to complete the projection.

2.5 Conclusions

Results clearly show that none of the three models is superior for all species groups and forest characteristics. Based on the ±10 percent evaluation criteria, MGM performed the best for the coniferous species groups SW, PL and CON having a success rate of 100%. For the deciduous species groups no model was able to predict all five stand characteristics within ±10 percent. For all species, DMP predicted average stand volume and basal area within ±10 percent of the actual values.

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Chapter 3

Modified Sampling With Partial Replacement

3.1 Introduction

In 1962, Ware and Cunia published a paper presenting the theory of sampling with partial replacement (SPR). The basic aim of the theory was to provide estimators for current stand volume and growth which improved the precision of the estimates by taking advantage of the correlation between repeated measurements. These estimators were based on the theory of weighted means (Brownlee, 1974) and provided a basis for combining unmatched temporary sample plot (TSP) data from two occasions with remeasured permanent sample plot (PSP) data. The improvement in precision came first, from a direct increase in sample size and second, from applying the correlation coefficient from the matched PSP's to the unmatched TSP's on both occasions.

Since the original paper, several extensions of the original theory have appeared in the literature. In 1965, Cunia extended the theory of SPR to use multiple regression estimates. This extension showed that using multiple linear regression to estimate the second occasion parameter was better and more efficient than the simple linear estimates used in the original SPR theory. In 1969, Cunia and Chevrou extended the theory of SPR to accept measurements on three or more occasions from the same forest population. In 1974, Newton, Cunia and Bickford developed multivariate estimators for sampling with partial replacement. This theory allowed for the simultaneous estimation in the change of many forest characteristics over time. The procedure was considered more efficient because it takes advantage of the inherent correlation that exists between different forest characteristics. A thorough literature review of the SPR theory was presented by Huang (1988). This chapter extends the SPR theory in a new direction by incorporating growth projections for the temporary plots. It is assumed that the growth simulation model provides unbiased future volumes subject to error so that the initial and projected values are not perfectly correlated. Application of this approach is presented using simulated plot data.

3.2 The modified SPR model

Notation for the development of estimators of current value, growth, and variances follows that of Ware and Cunia (1962). The naming conventions to derive the modified SPR estimators are presented in Table 3-1. The sample volumes from the first occasion are algebraically represented by the letter X. The sample volumes from the second occasion are represented algebraically by the letter Y. Unmatched temporary sample plot volumes from the initial occasion are represented by X_u. New TSP's on the second occasion are represented by Y_n. Remeasured (matched) PSP data are algebraically represented on the first occasion by an X_m and Y_m on the second occasion.

The new source of data for the modified SPR procedure is a prediction from a growth model and is represented algebraically by symbol Z_u. The input data for the growth model is the same TSP data X_u representing the unmatched data on the initial occasion. Since the TSP data is assumed to be a random sample from the population and the growth model is assumed to provide unbiased projections, it is also assumed that the model predictions are random, unbiased estimates of the population stand volume on the second occasion. It is also assumed that the growth model used to make the predictions is an individual tree growth model composed of relationships derived from independent data.

Table 3-1: The sample data sources for the Modified SPR sampling design

Initial Occasion		Second Occasion	
unmatched TSP's	$X_{u1}, X_{u2}, ..., X_{ui}, ..., X_{uu}$	matched Model	$Z_{u1}, Z_{u2}, ..., Z_{uk}, ..., Z_{uu}$
matched PSP's	$X_{m1}, X_{m2}, ..., X_{mi}, ..., X_{mm}$	matched PSP's	$Y_{m1}, Y_{m2}, ..., Y_{mj}, ..., Y_{mm}$
		unmatched TSP's	$Y_{n1}, Y_{n2}, ..., Y_{nh}, ..., Y_{nn}$

3.2.1 Current Volume Estimator

The formulation of the modified SPR volume and growth estimators are based on sample means obtained from each of the five data sources (Table 3-1). The modified SPR minimum-variance mean current volume estimator ($\bar{y}$) is derived following the same procedure presented by Ware and Cunia (1962). The estimate of current volume ($\bar{y}$) is:

$$(3.1) \qquad \bar{y} = a(\bar{X}_m) + b(\bar{X}_u) + c(\bar{Y}_m) + d(\bar{Y}_n) + e(\bar{Z}_u)$$

where a, b, c, d and e are constants.

Because the data are obtained by random sampling, the following assumptions about expected values of sample means make the volume estimator unbiased.

$$E(\bar{X}_m) = E(\bar{X}_u) = \mu_1, \quad E(\bar{Y}_m) = E(\bar{Y}_n) = E(\bar{Z}_u) = \mu_2$$

where:

μ_1 = the true population volume estimate on the initial occasion.

μ_2 = the true population volume estimate on the second occasion.

The assumption $E(\bar{Z}_u) = \mu_2$ requires that the model predictions are unbiased estimates of the true population. This assumption is acceptable based on the results in presented in Chapter 2 indicating that growth models can provide unbiased estimates of the population mean for reasonably short projections. For $\bar{y}$ to be an unbiased estimate of the true population volume at μ_2, two restrictions are imposed: $(a + b) = 0$ and $(c + d + e) = 1$. Then the following simplifications are made:

$b = -a,$

$e = (1 - c - d)$

Now, the general volume equation (3.1) be rewritten as:

$$(3.2)\quad \bar{y} = a\bar{X}_m - a\bar{X}_u + c\,\bar{Y}_m + d\,\bar{Y}_n + (1-c-d)\bar{Z}_u$$

The variance $\sigma^2_{\bar{y}}$ of the estimate $\bar{y}$ is:

$$(3.3)\quad \sigma^2_{\bar{y}} = a^2\sigma^2_{\bar{X}_m} + a^2\sigma^2_{\bar{X}_u} + c^2\sigma^2_{\bar{Y}_m} + d^2\sigma^2_{\bar{Y}_n} + (1-c-d)^2\sigma^2_{\bar{Z}_u} - 2a(1-c-d)\rho_2\sigma_{\bar{X}_u}\sigma_{\bar{Z}_u} + 2ac\rho_1\sigma_{\bar{X}_m}\sigma_{\bar{Y}_m}$$

where:

ρ_1 = true population correlation coefficient between X_m and Y_m

ρ_2 = true population correlation coefficient between X_u and Z_u

Given the following assumptions,

$$\sigma^2_{X_m} = \sigma^2_{X_u} = \sigma^2_X$$

$$\sigma^2_{Y_m} = \sigma^2_{Y_n} = \sigma^2_Y$$

$$\sigma^2_{Z_u} = \sigma^2_Z$$

the equation is further simplified:

$$(3.4)\quad \sigma^2_{\bar{y}} = a^2\sigma^2_X\left(\frac{1}{m} + \frac{1}{u}\right) + c^2\frac{\sigma^2_Y}{m} + d^2\frac{\sigma^2_Y}{n} + (1-c-d)^2\frac{\sigma^2_Z}{u} - 2a(1-c-d)\rho_2\frac{\sigma_X\sigma_Z}{u} + 2ac\rho_1\frac{\sigma_X\sigma_Y}{m}$$

To solve for the constants a, c, d that minimize $\sigma^2_{\bar{y}}$, partial derivatives of equation (3.4) were taken with respect to a, c and d. These equations were set to zero and solved as a system of equations. The derived formulae for a, c, and d are as follows:

$$a = \frac{1}{AD - BC}(D\beta_2 - Bk_2)/u$$

$$c = \frac{1}{AD - BC}(Ak_2 - C\beta_2)/u$$

$$d = \frac{n\beta_1 a}{k_1 m} + \frac{nc}{m}$$

where:

$$A = \frac{1}{m} + \frac{1}{u} + \frac{n\beta_1\beta_2}{k_1 um}$$

$$B = \frac{\beta_2}{u} + \frac{\beta_1}{m} + \frac{\beta_2 n}{mu}$$

$$C = \frac{\beta_2}{u} + (\frac{k_1}{n} + \frac{k_2}{u})\frac{n\beta_1}{k_1 m}$$

$$D = \frac{k_2}{u} + \frac{n}{m}(\frac{k_1}{n} + \frac{k_2}{u})$$

$$k_1 = \frac{\sigma_y^2}{\sigma_x^2}$$

$$k_2 = \frac{\sigma_Z^2}{\sigma_X^2}$$

$$\beta_1 = \rho_1\left(\frac{\sigma_Y}{\sigma_X}\right)$$

$$\beta_2 = \rho_2\left(\frac{\sigma_Z}{\sigma_X}\right)$$

$$\rho_1 = \frac{\text{cov}(X_m, Y_m)}{\sigma_X \sigma_Y}$$

$$\rho_2 = \frac{\text{cov}(X_u, Z_u)}{\sigma_{X_u} \sigma_Z}$$

3.2.2 Growth Estimator

The formulation of the Modified SPR growth (g) estimator obtains the minimum variance estimator of the population growth. Growth is the change in volume between the first and second occasion. The following is an overview of the procedures followed in deriving the growth estimators.

The formulation of the modified SPR estimation begins with the development of the general growth equation using the five sample means.

$$(3.5) \quad g = A\overline{Y}_m + B\overline{X}_m + C\overline{Y}_n + D\overline{X}_u + E\overline{Z}_u$$

where: A, B, C, D, E are constants.

Because the sample data is obtained by random sampling, the following assumptions make the growth estimator unbiased.

$$E(\overline{X}_u) = E(\overline{X}_m) = \mu_1, \qquad E(\overline{Y}_m) = E(\overline{Y}_n) = E(\overline{Z}_u) = \mu_2$$

The assumption $E(\overline{Z}_u) = \mu_2$ requires that the model predictions are assumed to be unbiased estimates of the true population. For g to be an unbiased estimator of the true population growth ($E(g) = (\mu_2 - \mu_1)$), two restrictions are imposed: $A + C + E = 1$ and $B + D = -1$. Then, the following simplifications are made:

$$E = (1 - A - C)$$
$$D = -(B + 1)$$

The general equation (3.5) can be now rewritten as:

$$(3.6) \quad g = A\overline{Y}_m + C\overline{Y}_n + (1 - A - C)\,\overline{Z}_u + B\overline{X}_m - (B+1)\overline{X}_u$$

The resulting variance σ_g^2 of the estimator g is

$$(3.7) \quad \sigma_g^2 = A^2\sigma^2_{\overline{Y}_m} + C^2\sigma^2_{\overline{Y}_n} + (1-A-C)^2\sigma^2_{\overline{Z}_u} + B^2\sigma^2_{\overline{X}_m} + (B+1)^2\sigma^2_{\overline{X}_u} + 2AB\rho_1\sigma_{\overline{X}_m}\sigma_{\overline{Y}_m} - 2(B+1)(1-A-C)\rho_2\sigma_{\overline{X}_u}\sigma_{\overline{Z}_u}$$

Given the following assumptions,

$$\sigma^2_{X_m} = \sigma^2_{X_u} = \sigma^2_X$$

$$\sigma^2_{Y_m} = \sigma^2_{Y_n} = \sigma^2_Y$$

$$\sigma^2_{Z_u} = \sigma^2_Z$$

the general equation can be further simplified;

$$(3.8) \quad \sigma_g^2 = A^2\frac{\sigma_Y^2}{m} + C^2\frac{\sigma_Y^2}{n} + (1-A-C)^2\frac{\sigma_Z^2}{u} + B^2\frac{\sigma_X^2}{m} + (B+1)^2\frac{\sigma_X^2}{u} + 2AB\rho_1\frac{\sigma_X\sigma_Y}{m} - 2(B+1)(1-A-C)\rho_2\frac{\sigma_X\sigma_Z}{u}$$

To solve for the constants *A, B, C,* partial derivatives of equation (3.8) were taken with respect to A, B, and C. These equations were then set to zero, to minimize σ_g^2 and were solved using systems of equations. The derived formulae for the constants A,B and C are as follows:

$$A = \frac{1}{QT - RS}(T(k_2 - \beta_2) - R(\beta_2 - 1))/u$$

$$B = \frac{1}{QT - RS}(Q(\beta_2 - 1) - S(k_2 - \beta_2))/u$$

$$C = \frac{An}{m} + \frac{B\beta_1 n}{mk_1}$$

where:

$$Q = \frac{k_2}{u} + \frac{n}{m}\left(\frac{k_1}{n} + \frac{k_2}{u}\right)$$

$$R = \frac{\beta_2}{u} + \frac{\beta_1 n}{mk_1}\left(\frac{k_1}{n} + \frac{k_2}{u}\right)$$

$$S = \frac{\beta_1}{m} + \frac{\beta_2}{u} + \frac{\beta_2 n}{mu}$$

$$T = \frac{1}{m} + \frac{1}{u} + \frac{\beta_1 \beta_2 n}{mk_1 u}$$

$$k_1 = \frac{\sigma_Y^2}{\sigma_X^2}$$

$$k_2 = \frac{\sigma_Z^2}{\sigma_X^2}$$

$$\beta_1 = \rho_1 \frac{\sigma_Y}{\sigma_X}$$

$$\beta_2 = \rho_2 \frac{\sigma_Y}{\sigma_Z}$$

$$\rho_1 = \frac{\text{cov}(X_m, Y_m)}{\sigma_X \sigma_Y}$$

$$\rho_2 = \frac{\text{cov}(X_u, Z_u)}{\sigma_{X_u} \sigma_Z}$$

3.3 An Illustrative Example

In this section an application of the modified SPR theory is presented using simulated plot data. Additional estimates using traditional approaches are also included for comparison. The designs selected for the comparison along with description of the data sources they utilize is presented in Table 3-2.

Table 3-2: List of sampling designs and required data sources to estimate volume and growth.

Volume Estimation Sampling Designs	Data Sources						Growth Estimation Sampling Designs	Data Sources					
	X_u	X_m	Y_m	Y_n	Z_u	Total		X_u	X_m	Y_m	Y_n	Z_u	Total
TSP's	-	-	-	16	-	16	-	-	-	-	-	-	-
PSP's	-	-	8	-	-	8	-	-	-	-	-	-	-
TSP's & PSP's	-	-	8	16	-	24	PSP's	-	8	8	-	-	16
Original SPR	15	8	8	16	-	47	Original SPR	15	8	8	16	-	47
Modified SPR	15	8	8	16	15	62	Modified SPR	15	8	8	16	15	62

A complete listing of the data and summary statistics used in the illustration are presented in Table 3-3. The unmatched plot data consisted of 15 TSP's representing the initial occasion (X_u) and 16 TSP's for the second occasion (Y_n). The matched plots were represented by eight PSP's on both occasions (X_m and Y_m). The matched growth model data (Z_u) consisted of 15 plots obtained by projecting the unmatched TSP on the initial occasion (X_u) to the second occasion. Each of the TSP's and PSP's used in the illustration were simulated to represent the likely relationships that would exist under normal conditions.

Estimates of current volume and growth with their associated variances for each of the five sampling designs were calculated and are presented in the results section.

Table 3-3: Data and associated summary statistics used in illustration.

TSP Time 1 (X_u)		PSP Time 1 (X_m)		PSP Time 2 (Y_m)		Model Time 2 (Z_u)		TSP Time 2 (Y_n)	
plot number	volume (m^3)	plot number	volume (m^3)	plot number	volume (m^3)	plot number	volume (m^3)	plot number	volume (m^3)
1	228.33	1	213.00	1	219.00	1	234.06	1	235.85
2	172.32	2	278.40	2	281.00	2	177.59	2	326.57
3	322.79	3	286.70	3	290.60	3	328.90	3	183.65
4	248.97	4	266.00	4	270.00	4	254.68	4	240.45
5	294.52	5	230.00	5	240.00	5	300.42	5	304.92
6	195.02	6	225.89	6	234.00	6	200.60	6	268.73
7	282.92	7	276.00	7	277.00	7	288.72	7	246.14
8	242.88	8	290.00	8	298.00	8	248.37	8	210.66
9	308.79					9	314.87	9	231.68
10	244.20					10	249.73	10	297.44
11	262.82					11	268.64	11	242.24
12	252.47					12	258.11	12	309.44
13	227.72					13	233.32	13	224.84
14	195.90					14	201.48	14	291.31
15	245.19					15	250.79	15	206.72
								16	254.54
$\bar{X}_u$	248.32	$\bar{X}_m$	258.25	$\bar{Y}_m$	263.70	$\bar{Z}_u$	254.02	$\bar{Y}_n$	254.70
$^{s}X_u$	1786.34	$^{s}X_m$	927.34	$^{s}Y_m$	836.83	$^{s}Z_u$	1802.82	$^{s}Y_n$	1703.13
$^{s}\bar{X}_u$	119.08	$^{s}\bar{X}_m$	115.92	$^{s}\bar{Y}_m$	104.60	$^{s}\bar{Z}_u$	120.19	$^{s}\bar{Y}_n$	106.44
				$cov(X_m Y_m)$	877.30	$cov(X_u Z_u)$	1673.91		
				r	0.99	r	0.93		

3.4 Current Volume

The current mean volume estimates and their variances for the five estimation procedures are presented in Table 3-4. Comparing the different variances it is clear that the modified SPR sampling theory is superior having the lowest variance (5.64). The three more traditional methods, TSP's alone, PSP's alone and a combination of TSP's and PSP's performed significantly poorer with variances of 1703.14, 836.83 and 1384.22 respectively. The original SPR model performed considerable better than the traditional methods with a variance of 51.9, but not as well as the Modified SPR model.

Precision differs between the different sampling designs because of the variation in the different sample data sets and the correlation of the matched PSP data. The traditional methods (TSP's and PSP's) utilize only samples taken from the second occasion, therefore the number of samples is relatively small compared to the SPR procedures.

Table 3-4: Comparison of current mean volume estimates and their variances for different sampling designs.

Sampling Design	Volume Estimate (m^3/ha)	Variance of the Estimate
Only TSP's	254.69	1703.14
PSP's	263.70	836.83
TSP's & PSP's	257.70	1384.22
Original SPR	256.73	51.90
Modified SPR	256.71	5.64

Furthermore, these samples are independent and therefore no covariance term exists to reduce the variance. The original SPR has a larger sample size because data is incorporated from both occasions. In addition, the matched PSP data is dependent and correlated. Algebraically, the improvement appears when two times the covariance is subtracted from the variance. The modified SPR increases the sample size even further by adding more samples (due to growth projections of the TSP) on the second occasion. Also, the TSP projected by a growth model allow an additional reduction in the variance.

3.3.2 Growth

The growth estimates and their variances are presented in Table 3-5. As expected, the traditional PSP procedure is most precise with a variance of 9.57. The next most precise method is modified SPR followed by the original SPR with variances of 12.68 and 77.98 respectively.

The precision of the PSP design is due to the strong correlation between matched plots and is consistent with theoretical expectations. The growth estimate based only on

PSP data appears to underestimate the actual population growth when compared to the estimates of 5.86 and 5.80 m^3/ha with the SPR designs. The larger growth estimate obtained with the SPR schemes is attributable to the larger sample of data but the precision is not as great because of increased variation and independence among the two data sets.

Table 3-5: Comparison of growth estimates and their variances for different sampling designs.

Estimation Procedure	Growth Estimate (m^3/ha)	Variance of the Estimate
PSP's	5.40	9.57
Original SPR	5.86	77.98
Modified SPR	5.80	12.68

3.4 Discussion

3.4.1 Numerical Results

If all assumptions are met, the results of the practical example clearly show that the modified SPR sampling theory improves the precision of volume estimates over any other procedure described. The modified SPR growth estimates had a smaller variance than the original SPR but not smaller than the traditional remeasurement of PSP's. Small variance indicates a higher level of precision. Variation in the sample means is expected since some sample sizes are small. If the underlying assumptions are met, all approaches are theoretically accurate estimates of the population mean.

If assumptions are not met estimates may be biased. For example, PSP's may not be random samples of the population if they are placed in fully stocked stands. Estimates of volume in this instance may be much higher than the population value. Growth on the other hand may not be optimum because of the increased competition due to the higher density of trees. From an applied perspective, if non-random PSP's alone are used to estimate growth, the precision may be high (9.57), but bias may be present. The modified SPR model increases the accuracy because it incorporates the non-random PSP data, random TSP data from 2 occasions and growth model data, thus increasing the sample size and decreasing the overall effect of the bias introduced by the PSP data set.

3.4.2 Variance of Growth Model Estimates

Because most empirical growth models are deterministic in nature, if two different TSP's having exactly the same stand characteristics are projected to the second occasion, they will have the same second occasion stand characteristics. The result is a perfect correlation between current a projected characteristics and this provides no new information about the population on the second occasion. The impact of a zero variance in the context of the modified SPR theory, is no improvement in the precision of the estimate over the original SPR model. It is however possible to minimize the likelihood of a zero variance with careful selection of the type of model. For example, if the growth model selected is a stand model, projections are based on average stand characteristics such as average stand age, average stand height and site index. The likelihood of two stands having these same stand dynamics is high. On the other hand, if the growth model uses individual tree characteristics such as height, age and diameter to make the projection, the chances of obtaining two TSP's with exactly the same characteristics is highly unlikely. To minimize the likelihood of a zero variance, it is recommended that individual tree models be used for the projections.

3.4.3 Correlation Coefficients

The formulas for the population correlation coefficients in the modified SPR model are:

$$\rho_1 = \frac{\operatorname{cov}(X,Y)}{\sigma_X \sigma_Y}, \qquad \rho_2 = \frac{\operatorname{cov}(X,Z)}{\sigma_X \cdot \sigma_Z}$$

where: σ_X = population standard deviation for the volume on the initial occasion (X)

σ_Y = population standard deviation for the volume on the second occasion (Y)

σ_Z = population standard deviation for the projected volume on the second occasion (Z)

Because the population standard deviations are unknown, it is necessary to estimate them from the sample data. Theoretically, there are several acceptable methods to make these estimates. In the original publication, Ware and Cunia used a weighted average of the unmatched and matched data. This method is appealing because the sample size used to obtain the estimate of standard deviation is larger. However, because the covariance terms in the numerator are from only the matched data, using a combined estimate of the standard deviations could result in a correlation coefficient outside the permissible (-1 to 1) range . Scott 1984, suggests that this situation is a result of not meeting the assumption that the true population variances and covariance's are known. Cunia and Chevrou, 1969, suggested that only the matched data be used to make the estimates. Scott (1984) acknowledges that using only the matched data solves these inconsistencies but adds that the information from the unmatched data is lost. In 1981, Titus proposed using the matched data to obtain the covariance term and the combination of the unmatched and matched to estimate the population standard deviations. In Scott's paper, new volume and growth estimators are derived. These estimators are weighted to reflect the variances, eliminating the correlation coefficient inconsistencies. Further studies to better understand the complex correlation coefficient issue should be pursued.

3.5 Conclusions

The modified SPR sampling design further improves the estimates of volume and growth by taking advantage of predictions from a growth model. The estimators for volume and growth and their variances are mathematically very complicated with the internal interactions not being quite as intuitive as in the original SPR design. Further study into the calculation ؛ the correlation coefficients is necessary to resolve the question of which method is most appropriate.

From the applied perspective, if the original design is already being used, the application of the modified design does not require any changes with exception of using the new estimators and obtaining a suitable growth model. The decision to change from traditional designs to the modified SPR design is more appealing than the original design because of the significantly greater gains at no extra expense.

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Chapter 4

Inventory Update

4.1 Introduction

The last census inventory of the public forested lands of Alberta was completed in 1984. This map inventory, called Phase 3, was interpreted from aerial photographs over a 14 year period with the goal of producing planning and forest cover type maps. These maps were to be used for operational planning, monitoring industrial development, determining harvest levels and planning forest protection. The maps depicted the spatial arrangement of forest stands, lakes, roads, survey lines and rivers as well as describing each forest stand by its species composition, height, crown density, site quality, commercialism and origin date. The map information was stored in the Alberta Forest Service Inventory Storage and Maintenance System (AFORISM), a computer database created to provide a means of summarizing and reporting the information collected. A maintenance program was also carried out on the Phase 3 maps and AFORISM to account for changes caused by fire, harvesting and development.[2]

In 1996 the Alberta Forest Service (AFS) is required by a legislative mandate to provide a new annual allowable cut (AAC) calculation for forested public lands of Alberta. To obtain this estimate, the current volume of these forested areas must be known and projections of growth will be required. Although the most complete source of census information available to estimate volume is the Phase 3 inventory data, the information does not reflect current forest conditions. One alternative to overcome this obstacle is to apply an update procedure to the original Phase 3 inventory data to obtain estimates of current volume.

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[2]This program also provided for correction of gross errors made during the interpretation process. This program is referred to as an "update" in the Alberta Forest Service and should not be confused with the different use of the term in this chapter.

This Chapter begins by presenting four alternative procedures for estimating growth and current volume. The remainder of the Chapter presents and discusses an approach to update the Alberta Phase 3 inventory to obtain estimates of current volume.

4.2 Alternate Approaches to Estimating Current Volume

The goal is to obtain for a population, an accurate, precise estimate of the current (second occasion) volume, based on an old outdated (initial occasion) description of the population. The population can be a stand (a group of trees), a group of similar stands, or an entire forest. Four alternate update procedures to estimate current volume are presented in Table 4-1.

The first method involves obtaining an independent sample of the current population to estimate volume (Table 4-1a). Because in a census inventory the total area of the population is known, a ratio estimation procedure can be used. This methodology uses the ratio between the total area of the population and the total area sampled to determine the precision of the estimate. A complete description of the ratio estimation procedure and the required formulae are presented in "Sampling Techniques" by Cochran (1977).

The second method uses a growth model to project a sample of temporary sample plots (TSP) from the population on the initial occasion (X_u) to the second occasion (Table 4-1b). The updated TSP's (Z_u) obtained from the growth projection, provide the necessary information to obtain an estimate of current volume. In Chapter 2, three computer growth models were evaluated. The results indicate that computer growth models can successfully make unbiased estimates of current volume by predicting stand growth from initial occasion plot data.

The third methodology presented is based on the theory of Sampling with Partial Replacement (SPR) developed by Ware and Cunia, 1962 (Table 4-1c). The methodology assumes that TSP's (X_u and Y_n) and permanent sample plots (PSP) (X_m and Y_m), for the population on both occasions are available. Estimates of current volume and growth along with their variances are obtained using the formulae presented in the original publication.

The final methodology is based on the theory of Modified Sampling with Partial Replacement presented in Chapter 3 (Table 4-1d). This theory, an extension of the original SPR theory by Ware and Cunia, incorporates an additional source of data obtained by projecting the TSP's (X_u) from the initial occasion to the second occasion (Z_u) using a growth model. Formulae to obtain estimates of current volume and growth, along with their variances are presented in Chapter 3.

Table 4-1: Four alternate methods of updating census inventories including the type and timing of the required data sources. Data sources in the same row are correlated.

a) Independent Sample		b) Growth Model		c) Original SPR		d) Modified SPR	
Initial Occasion	Second Occasion	Initial Occasion	Second Occasion	Initial Occasion	Second Occasion	Initial Occasion	Second Occasion
		TSP (X_u)	Model (Z_u)	TSP (X_u)		TSP (X_u)	Model (Z_u)
				PSP (X_m)	PSP (Y_m)	PSP (X_m)	PSP (Y_m)
	TSP (Y_n)				TSP (Y_n)		TSP (Y_n)

4.3 Alberta Phase 3 Inventory Update Methodology

This section presents one promising method of updating the Phase 3 inventory to obtain an estimate of current volume. The update methodology is broken down into 3 components. The first component presents one method for aggregating stands to obtain a manageable number of subpopulations. The second component describes one method of partitioning the Phase 3 inventory into regions with common inventory collection dates. The final component discusses the advantages and disadvantages of using the different estimation procedures presented in section 4.2. The section will conclude by summarizing the steps involved in updating the Phase 3 inventory.

4.3.1 Stand Aggregation

The Phase 3 inventory uses a classification scheme that allows each stand to be represented according to tree species (3 species codes), stand density (4 classes), stand height (6 classes) and site (3 classes). This description of the stand is referred to as the Phase 3 forest cover type. In the ideal situation, each stand is updated independently in an attempt to maintain the uniqueness of the forest. Although the AFS has an abundance of TSP, PSP, large scale photography (LSP) and felled tree data, sufficient data to update individual stands is generally not available. Instead, it is necessary to aggregate stands until sufficient data are available too successfully carry out the update procedure. An additional consideration is the total number of subpopulations that can be feasibly updated given the current resources available to the AFS.

The first level of aggregation assumes that stands with the same Phase 3 forest cover type have similar dynamics and therefore can be grouped to represent one population, regardless of their location. Because the total number of possible unique forest cover types under the Phase 3 classification scheme is extremely large, it is necessary to aggregate further similar forest cover types. The Phase 3 inventory classification scheme normally allows for a list of up to three tree species, presented in order of decreasing stand content, to describe the stand composition. Species with greater than 20 percent of the total composition are presented using normal notation, species with between 11 and 20 percent total content are bracketed and species with less than 10 percent are ignored. To further aggregate the forest cover types, only two species with greater than 20 percent content of the total composition are considered. All other species including bracketed species are ignored.

From the Permanent Sample Plots: Field Procedures Manual (AFS, 1990), the AFS recognizes 16 tree species, white spruce (*Picea gluaca* (Moench) Voss) (Sw), black spruce (*Picea mariana* (Mill.) B.S.P.) (Sb), englemann spruce (*Picea englemanii* Parry)

(Se), lodgepole pine (*Pinus contorta* var. *latifolia* Engelm.) (Pl), jack pine (*Pinus banksiana* Lamb.) (Pj), limber pine (*Pinus flexilis* James) (Pf), whitebark pine (*Pinus albicaulis* Engelm.) (Pw), balsam fir (*Abies balsamifera* L.) (Fb), alpine fir (*Abies lasiocarpa* (Hook.) Nutt.)(Fa), Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) (Fd), tamarack (*Larix laricina* (Du Roi) K. Koch) (Lt), alpine larch (*Larix lyallii* Parl.) (La), western larch (*Larix occidentalis* Nutt.) (Lw), trembling aspen (*Populus tremuloides* Michx.) (Aw), balsam poplar (*Populus balsamifera* L.) (Pb), and white birch (*Betula papyrifera* March.) (Bw). Because some of the species are either limited in distribution or have very similar growth patterns with other species, it is possible to aggregate the 16 species into four species groups (Table 4-2).

Table 4-2: Aggregation of Alberta tree species into four species groups.

Species Groups	Species
Sw	Sw, Se,Fb, Fd,Fa,Lw
Sb	Sb, Lt,La
Pl	Pl, Pj,Pf,Pw
Aw	Aw, Pb, Bw

Assuming that only two species are considered for the update process, combined with the aggregation of all the species into four species groups, the number and type of species combinations is reduced to 16 (Table 4-3).

Table 4-3: Permutations using four species groups, grouping by two with replacement.

	Sw	Sb	Pl	Aw
Sw	Sw	SwSb	SwPl	SwAw
Sb	SbSw	Sb	SbPl	SbAw
Pl	PlSw	PlSb	Pl	PlAw
Aw	AwSw	AwSb	AwPl	Aw

The 16 groups are reduced further to 13 by grouping into four stand types, pure, coniferous, mixed coniferous and mixed deciduous (Table 4-4). Pure stands are defined as having only one of the four species groups, Sw, Pl, Sb or Aw describing the stand composition. The coniferous stand types contained two of the three possible coniferous species groups resulting in three possible species combinations, SwPl, SwSb, PlSb, assuming the order of the species was interchangeable. The mixed deciduous stand type contained Aw as the first species and one of the three coniferous species as the second species resulting in three unique species combinations, AwSw, AwSb and AwPl. The mixed coniferous stand type contained one of the three coniferous species as the first species and Aw as the second resulting in another three unique species combinations, SwAw, SbAw, PlAw.

Table 4-4: Summary of the forest cover types grouped by the four stand type categories.

Pure	Coniferous	Mixed Deciduous	Mixed Coniferous
Sw	*SwPl	AwSw	SwAw
Sb	*SwSb	AwSb	SbAw
Pl	*PlSb	AwPl	PlAw
Aw	-	-	-

*indicates order of species is assumed interchangeable

For each of the 13 species group combinations presented in Table 4-4, it is necessary to add the six height classes (Table 4-5) and the four density classes (Table 4-6) to encompass all the possible species, height and density combinations.

Table 4-5: Definition of Phase 3 inventory height classes

Height Class	Average Height of Dominants and Codominants
1	0.0 - 6.0 m
2	6.1 - 12.0 m
3	12.1 - 18.0 m
4	18.1 - 24.0 m
5	24.1 - 30.0 m
6	30.1 m +

Table 4-6: Definition of Phase 3 inventory crown density classes.

Density Class	Crown Density
A	6-30%
B	31-50%
C	51-70%
D	71-100%

Figure 4-1 illustrates the matrix of forest cover types created by combining the different species, heights, and densities for the pure stand type. Because 96 possible forest cover type combinations for the pure stand type are still too many, the forest cover types are grouped into four height groups and two density groups. The result is eight groupings of forest cover types per species group (Figure 4-1). The aggregation results for the coniferous, the mixed deciduous and the mixed coniferous stand types are presented in Figures 4-2, 4-3 and 4-4 respectively.

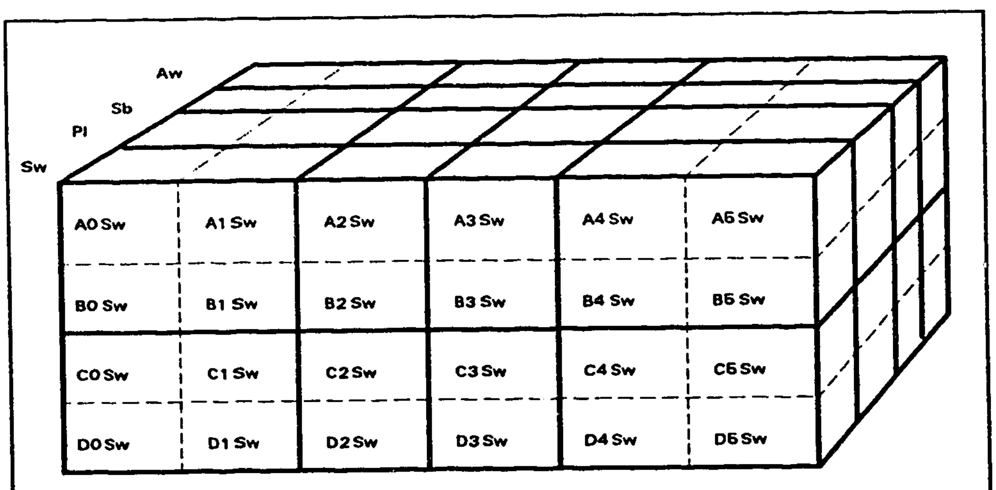


Figure 4-1: All possible combinations of species groups, height and density for the pure stand type. Solid lines indicate boundaries used for grouping.

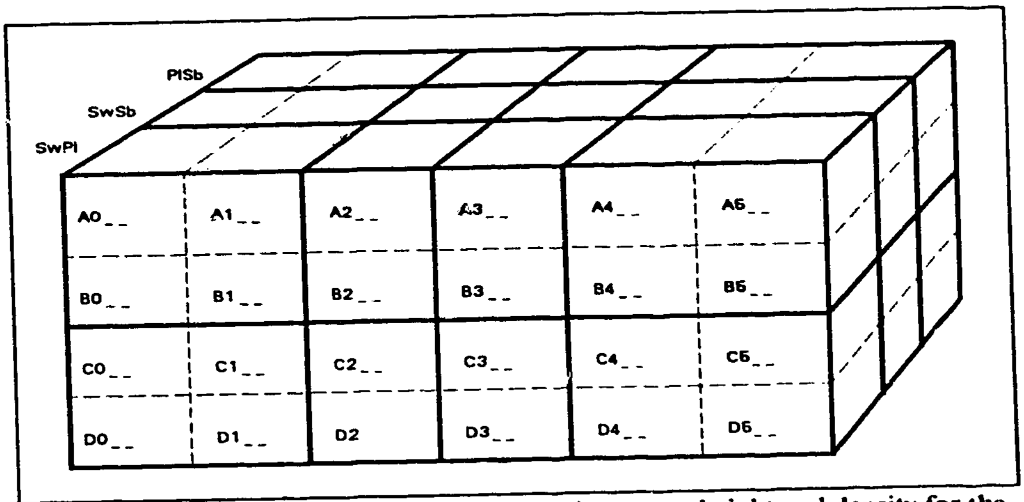


Figure 4-2: All possible combinations of species group, height and density for the coniferous stand type assuming species order is interchangeable. Solid lines indicate boundaries used for grouping.

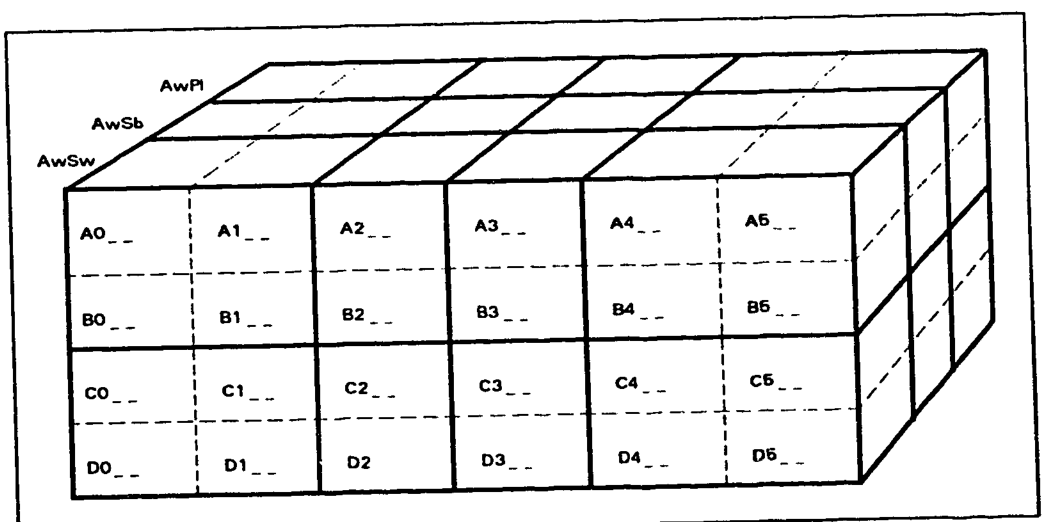


Figure 4-3: All possible combinations of species group, height and density for the mixed deciduous stand type. Solid lines indicate boundaries used for grouping.

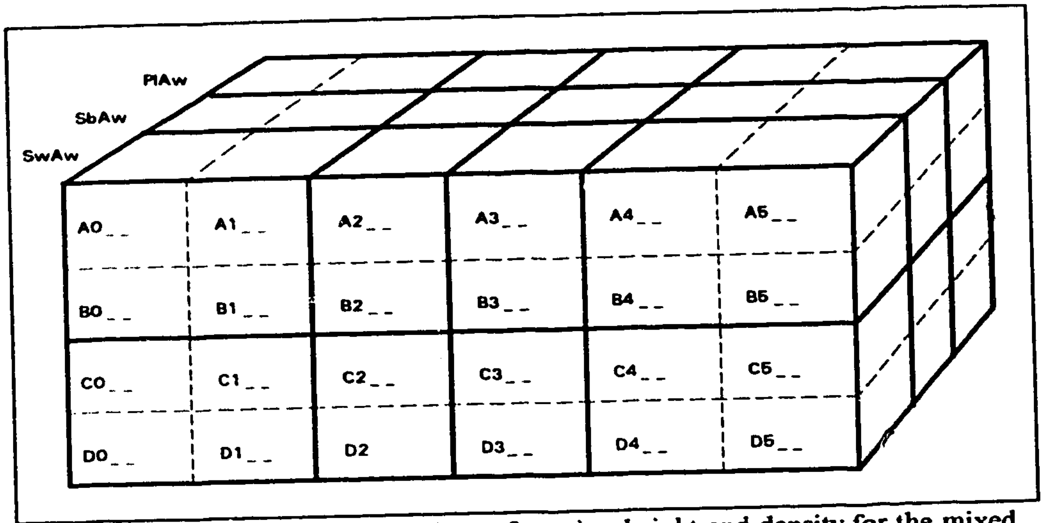


Figure 4-4: All possible combinations of species, height and density for the mixed coniferous stand type. Solid lines indicate boundaries used for grouping.

To incorporate three Phase 3 site quality categories (good, medium and fair), each of the four stand types are tripled to represent all the forest cover type and site quality combinations. Under this aggregation methodology, a maximum of 312 (13 species groups by 4 height classes by 2 density classes by 3 site index classes) unique populations are represented. Table 4-7 presents the number of populations by stand type.

Table 4-7:Number of forest cover type groups by stand type.

Stand Type	Total Number of Forest Cover Groups
Pure	96
Coniferous	72
Mixed Deciduous	72
Mixed Coniferous	72
Total	312

4.3.2 Partitioning the Phase 3 Inventory

Because the Phase 3 inventory was completed over 14 years, the grouping of stand types must consider different interpretation dates to maintain similar growth projection lengths. This requires partitioning the Phase 3 inventory into units with similar data collection dates. The following four conditions, presented in order of importance reflect the goals of the partitioning process.

1) compatibility with the projection method
2) compatibility with the existing AFS growth and yield boundaries (VSR's)
3) compatibility with the Phase 3 inventory administrative boundaries
4) compatibility with the new Alberta Vegetation Inventory (AVI)

The following discussion describes the methodology used to obtain the partitioning presented in Table 4-8. The first condition is the requirement that the stratification be compatible with the projection method. This condition highlights the necessity that any population being updated must have a common collection date. Because the Phase 3 inventory is interpreted from aerial photographs, the photography date is considered the collection date. In most cases the photo coverage coincides with the AFS Forest Management Units (FMU). By using the FMU as the smallest unit in the partitioning, the requirement for common collection dates and therefore common projection lengths are met. In the cases where several FMU's have the same photography date, it is possible to group to minimize the number of update populations. Additional subjective grouping of FMU's with similar photography dates is also done, under the assumption that the change in volume in ±3 years is not significant enough to warrant special delineation.

The second condition addresses the differences in the growth and yield characteristics over the Phase 3 inventory. The AFS during the time of the Phase 3 inventory, conducted numerous growth and yield studies that identified differences in forest growth rates over the province. To address these differences, the AFS created nine Volume Sampling Regions (VSR). Because the majority of growth and yield information that currently exists for Alberta is based on the VSR, further partitioning of the land base by VSR is considered essential (Table 4-8).

Table 4-8: One alternate method of partitioning the Phase 3 inventory in preparation for updating to account for the accrual of growth..

Forest	Photo Date	FMU	Group	VSR
Athabasca	1950	13	1	8
	1972	5,7	2	8
	1976	2	3	8
	1977	1,6,8		8
	1978	3,4,11		8
	1982	10,12	4	8
	1982	9	5	9
Bow Crow	1972	C5	1	11
		B6		11,1
		B7		11
		B8		11,1
	1988	C4	2	1
Edson	1972	1,2	1	4
	1972	11	2	5
	1974	4	3	5
	1975	6,7A,8,10		5
	1978	5	4	5
	1980	1N,3,9,H1		5
	1982	7N		5
Footner	1949	19,20	1	10
	1950	10		10
	1976	1,2,8,9	2	6,10
	1978	4,5,6,7	3	10
	1979	12,13,14,15, 16,17,18		10
	1981	11		6,10
	1983	3	4	7
Grande Prairie	1975	7	1	5
	1979	1,2,8,9,10,11	2	6
	1981	5		6
	1981	3,4	3	5
	1982	6		5
Lac La Biche	1978	1,2,3,4,5,6,8	1	8
	1990	9	2	8
Peace River	1970	6	1	6
	1976	5,10	2	6
	1977	3		6
	1978	1,2,4,11		6
	1979	7,9	3	6
	1981	8		6
Rocky	1974	3,6,8,9	1	3
	1973	4	2	2
	1975	1,2,5,7		2
Slave Lake	1971	5,8	1	7
	1973	6	2	4
	1974	2		4
	1977	1	3	4
	1977	7	4	8
	1977	9	5	7
	1978	4,10,11,15		7
	1979	3		7
	1980	12		7
	1983	13	6	7
	1984	14		7
White Court	1970	2	1	4
	1975	10	2	4
	1976	1		4
	1977	5,6,8		4
	1978	3,4,9,11		4

Fortunately the boundaries for the FMU's coincide with the VSR boundaries therefore no further grouping was necessary with the exception of the Bow Crow forest. In this area, two VSR's divide the FMU's therefore further partitioning to into smaller units is necessary.

The third condition addressed the issue of maintaining compatibility with the AFS administrative boundaries. Alberta is subdivided into 11 administrative regions called "Forests". Fortunately the FMU is a subunit of the "Forest" therefore no further partitioning was necessary.

The final condition addressed the issue of maintaining compatibility with the new Alberta Vegetation Inventory (AVI). Because the AVI was initiated in 1991, the estimates of volume have not changed significantly therefore it is recommended that any estimates of volume available from AVI should be used in place of the Phase 3 volumes. An additional AVI compatibility issue deals with the new "Ecoregion" forest classification scheme that identifies nine new ecoregions to replace the traditional VSR's. These ecoregions are based on grouping areas of similar vegetation and climate. Although it may be desired that current volume estimates appear by Ecoregion, it is necessary to use the VSR classification scheme until the estimates of volume are obtained. If necessary, adjustments to represent the volumes by Ecoregion can be made.

4.3.3 Selecting the Update Procedure

Because the goal of the update process is to obtain reasonable estimates of current volume, some variation in the appropriate update procedure may be necessary for each population. Although the main factor controlling the selection of an update procedure is the availability of plot data, it is also necessary to evaluate the costs and benefits of selecting one method over another. The following section discusses the application of the available update procedures on the Phase 3 inventory.

There are several situations where the use of an independent sample is appropriate. One likely scenario is where insufficient plot data is available to obtain an estimate of current volume. Although there are few areas in Phase 3 with no plot data, a lack of confidence in the plot collection procedures may make the existing data suspect and warrant either new plots or additional plots to validate estimates. Another scenario is to provide additional current (second occasion) plots for one of the other update procedure that requires second occasion plots. This may be appropriate in highly commercial areas, where precise estimates are highly desirable, but insufficient current (second occasion) plot data is available to use more precise update procedures such as MSPR. The drawbacks are the high costs and the time factor involved in sampling.

The growth projection procedure is the simplest of the available update procedures in that it requires only TSP's on the initial occasion and an unbiased growth model to obtain estimates of current volume. One important aspect of this method is that it parallels the current AFS methodology of using TSP's to obtain estimates of volume. The most appealing aspect of this method is that the TSP's representing the initial occasion can come from any plot data collected after the inventory collection date as long as the original Phase 3 forest cover type is used in selecting the TSP's for the given population. For example, if a TSP was placed into the population five years after the original Phase 3 collection date, it represents the forest cover type plus five years of growth. When the TSP is projected using the growth model, the projection length is shortened by five years to account for this growth. One negative aspect of this procedure is that the accuracy of the estimate is solely dependent on the number of TSP's available for the particular population and how well the growth model projects the TSP's. This is a concern in situations where only a few TSP's are available and the projection lengths are long.

The benefit of using SPR is improved precision for estimates of growth and current volume. The negative aspects revolve around the requirement that the plot data must be available for the population on both occasions. Under normal circumstances, the likelihood of having a sufficient number of TSP's representing the initial occasion is good however having a sufficient number TSP's representing the second occasion is highly unlikely. One solution is to adjust, through a growth projection, some of the more recent TSP's forward in time to ensure that both occasions are sufficiently represented. Similar adjustments may be required for the PSP data. Another possibility is to carry out an independent sample of the current population to provide the necessary TSP's on the second occasion. An intensive PSP remeasurement program addresses the lack of second occasion PSP data.

The benefits of using the MSPR update procedure is even further improvements in the precision of growth and current volume estimates. Although the MSPR theory has the same negative aspects as SPR, the further improvements over SPR, are obtained at no significant increase in cost or effort if an unbiased growth model is available. It is recommended that in instances where the SPR theory is to be used, the MSPR theory be considered as a replacement.

4.3.4 Summary of the Phase 3 Update Methodology

In Figure 4-5 the main steps involved in updating the Phase 3 inventory are presented. The first step requires partitioning the inventory to units with common collection dates to ensure that the projection lengths are the same or similar. The second step involves aggregating the forest cover types within each partition into groups that will be identified as unique updatable populations. The third step involves summarizing the type and quantity of plot data available for the each of the populations identified. The fourth step involves selecting the appropriate volume estimation procedure for each population. If insufficient data are available to meet the desired level of precision, it may be necessary to continue aggregation of forest cover types until sufficient data is available. Once the update procedure for each population is determined, the appropriate update procedure is applied to each population.

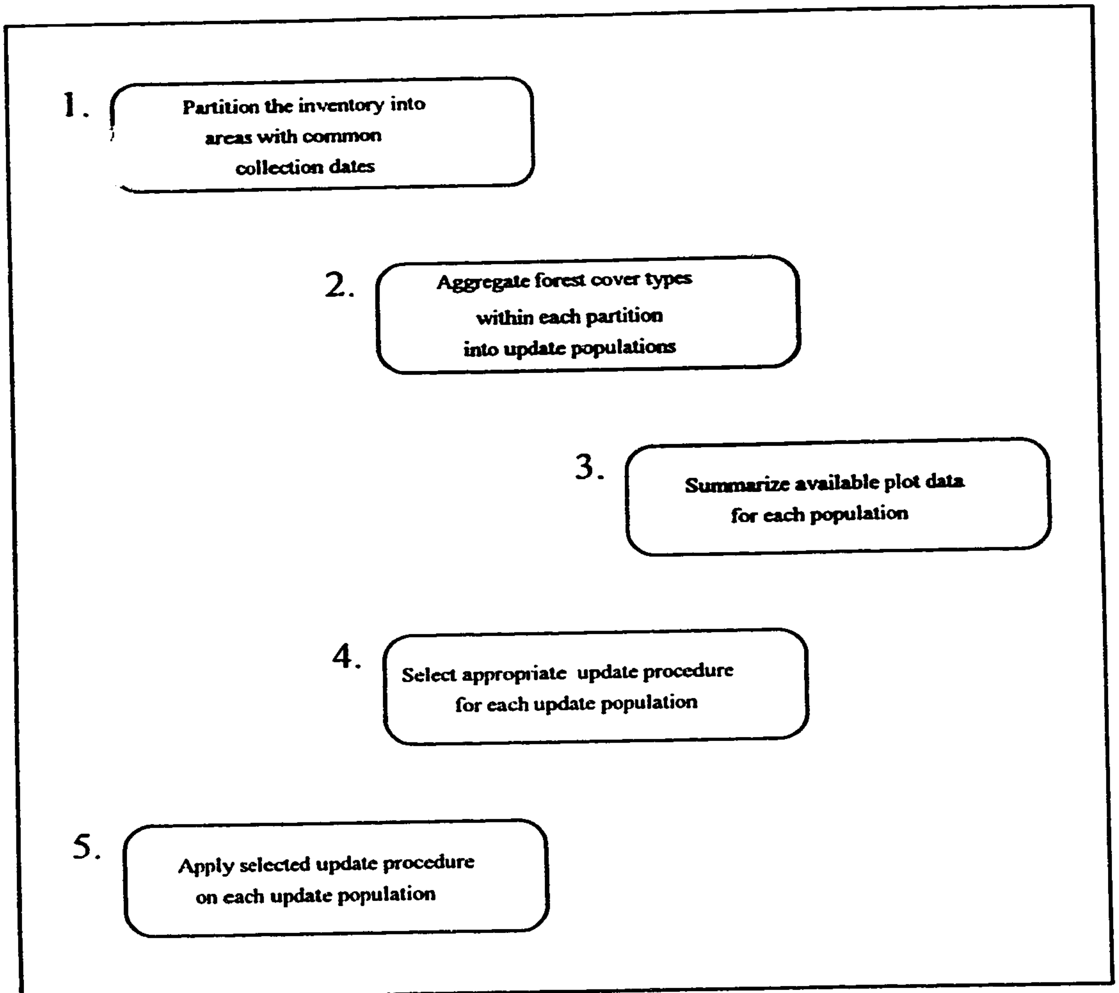


Figure 4-5: Flow chart representing the steps involved in updating the Phase 3 inventory.

4.5 Conclusions

Update of the Phase 3 inventory is a difficult task that requires a skillful integration of diverse data, reasonable assumptions, and probably a few compromises. The four projection methods presented are all viable alternatives in projecting the Phase 3 inventory. The selection of one method over another must take into consideration the desired accuracy and precision of the estimates, the simplicity of the projection method and the data requirements. From the updating of Phase 3 perspective, it is possible to use combinations of all four methods. Some areas of Alberta are highly commercial and the effort in obtaining the "best" estimates of volume are desirable. In wetlands of little value for wood production, the simplest method may be sufficient to validate that little growth is occurring. The methods of partitioning the inventory and aggregating the Phase 3 forest cover types were suggested based on the information currently available. Although they are mandatory component of the overall update process, it is expected that the stratification and the aggregation will change as problems and difficulties arise through implementation of the update procedure.

4.6 References

AFS, 1990. Permanent Sample Plots: Field Procedures Manual. Alberta Forest Service, Edmonton, Alberta. FMOPC 83-03.

Cochran W.G., 1977. Sampling Techniques. Ed. 3. John Wiley & Sons Inc., New York.

Ware, K.D. and T. Cunia. 1962. Continuous Forest Inventory with Partial Replacement of Samples. Forest Science Monograph 3.

Chapter 5

General Discussions and Conclusions

Forest growth models have the potential to provide valuable information on the past and future forest growth and can play an important role in forest inventory. In chapter 2 it was shown that growth models used in Alberta can provide unbiased estimates of projected volume. It was also determined that no single model, was capable of successfully projecting all species accurately. All models performed reasonably well for the coniferous species but poorly for the deciduous species types. In chapter 3 the modified SPR sampling design was developed. The theory improved the precision of volume and growth estimates over the SPR design by incorporating growth model projections. Chapter 4 identified four alternatives for estimating of growth and current volume: 1) conduct an independent sample; 2) use a growth model to project old TSP's to the present and use them to estimate current volume; 3) use the original SPR sampling design; and 4) use the Modified SPR design. An inventory update methodology consisting of three components is suggested for the Alberta Forest Service Phase 3 inventory. First, the inventory area is partitioned into regional units having the same data collection date to ensure a common projection length. Second, the individual stands are aggregated to minimize the number of populations being updated and to ensure sufficient data is available to drive the update procedures. The final component is the selection of the volume estimation procedure. Because each of the estimation procedures has strengths and weaknesses, it is recommended that the selection of the most appropriate procedure for estimating growth and current volume be made on a population by population basis taking into consideration the costs and the benefits.

By answering the questions set out in chapter 1, this study has not only brought new insights and new opportunities for the use of growth models but has also identified some areas of concern and new questions that need to be addressed. For example, the results in chapter 2 showed that the growth models failed to successfully predict deciduous species growth. Although this outcome is not surprising considering the lack of deciduous growth and yield data, before growth models can become an accepted management tool, improved predictions for deciduous types are critical.

Although the illustrative example of MSPR in chapter 3 clearly shows improved estimates of current volume and growth, a better understanding of the behavior of MSPR under more applied conditions is essential. The method for estimating the correlation coefficients must be resolved. Further research is required to determine the optimum proportion of TSP's, PSP's and growth model data. Further studies to understand the sensitivity of the estimators when all the assumptions are not fully met is also necessary.

In chapter 4 the inventory update issue is discussed and a methodology to update the Phase 3 inventory presented. The methodology assumes that unbiased growth models are available. To date the performance of the models has been evaluated on fully stocked mature, natural stands. Stands regenerated after harvest may not have the same species composition or growth characteristics as natural stands. Will growth relationships in regenerated stands be the same as in natural stands?

Both temporary and permanent plots are assumed to be random samples from the populations. However, since many traditional inventories carried out by the Alberta Forest Service were not random samples, but were instead selective samples of areas of interest, it is uncertain to what extent it is appropriate to use this data. A more careful rationalization of plot data collection and retention is needed to provide a clear basis for inventory analysis and estimation of growth and current volume.

The most difficult data to obtain for the SPR and MSPR designs are the second occasion unmatched temporary sample plot data. Theoretically, it is possible to develop another sampling design similar to SPR by eliminating the second occasion unmatched TSP's and replacing them with growth model data projected from the first occasion TSP's (Table 5-1). This type of design would take advantage of the correlation of the PSP data while integrating better with available temporary plot data. Development of estimators for this design are possible following the approach used in this study.

Table 5-1: The sample data sources for the theoretical model SPR sampling design

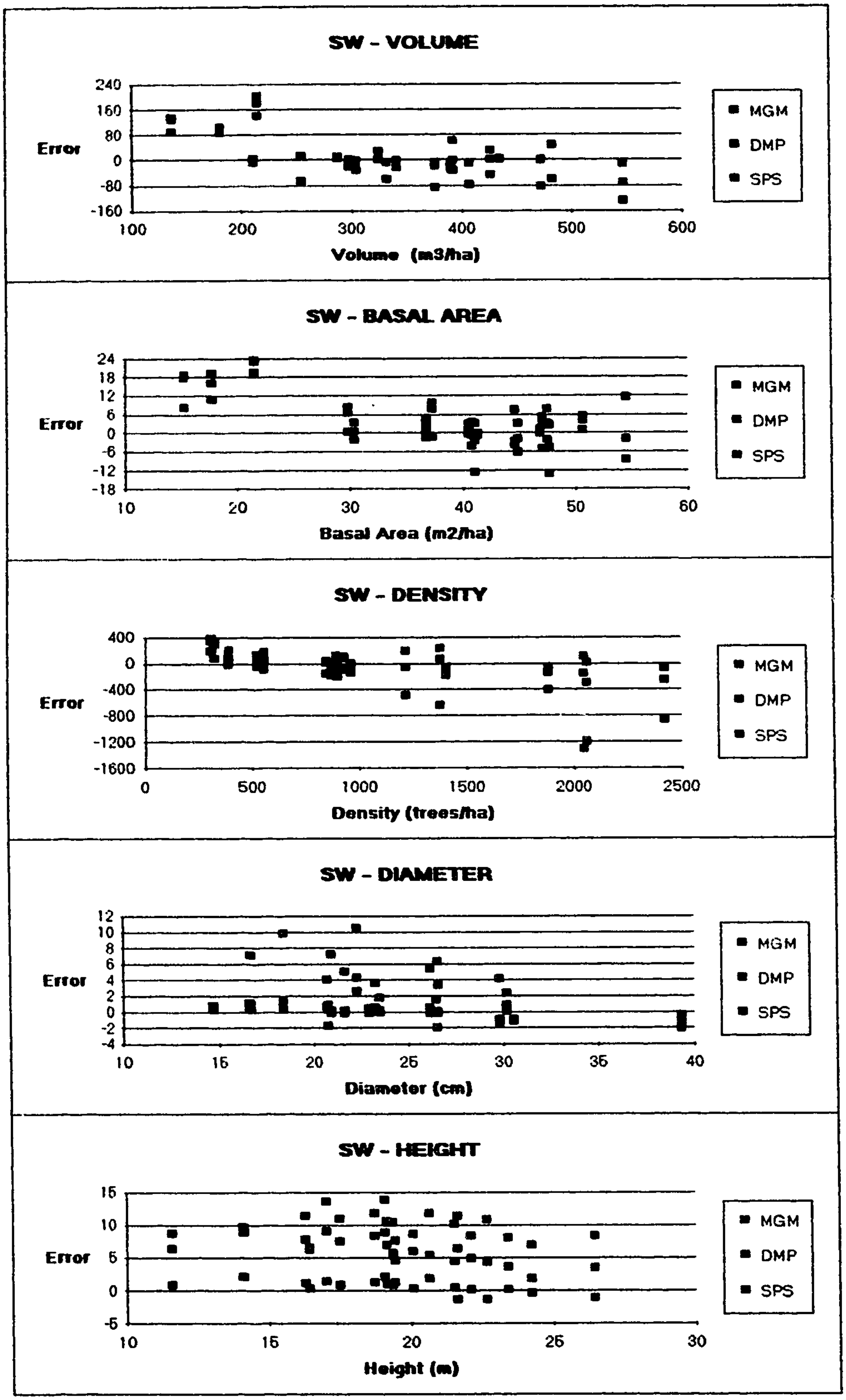
Initial Occasion	Second Occasion
unmatched TSP's $X_{u1}, X_{u2} \ldots, X_{ui} \ldots, X_{uu}$	matched Model $Z_{u1}, Z_{u2} \ldots, Z_{uk} \ldots, Z_{uu}$
matched PSP's $X_{m1}, X_{m2} \ldots, X_{mi} \ldots, X_{mm}$	matched PSP's $Y_{m1}, Y_{m2} \ldots, Y_{mj} \ldots, Y_{mm}$

This study has clearly demonstrated that the application of forest growth modelling has the potential to have a major impact in the management of our forest resources. The possibility of projecting past data to the present gives forest managers the opportunity to manage the forest resource based on current conditions. The ability to project the current forest into the future allows forest managers evaluate different management strategies based on expected outcomes. This study not only encourages the use of growth models but opens new avenues for the development of growth models and inventory designs.

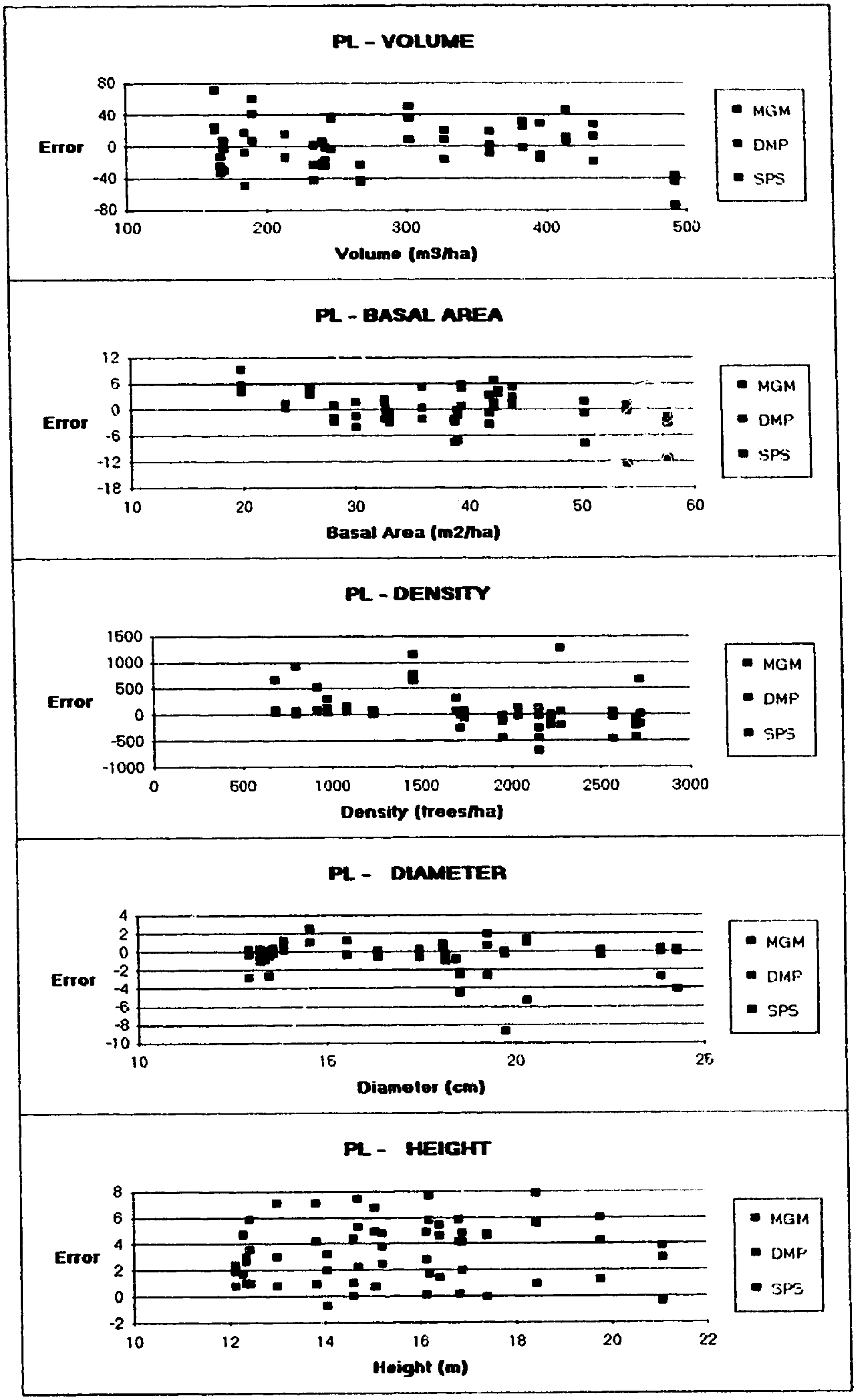
Appendices

Appendix 1.

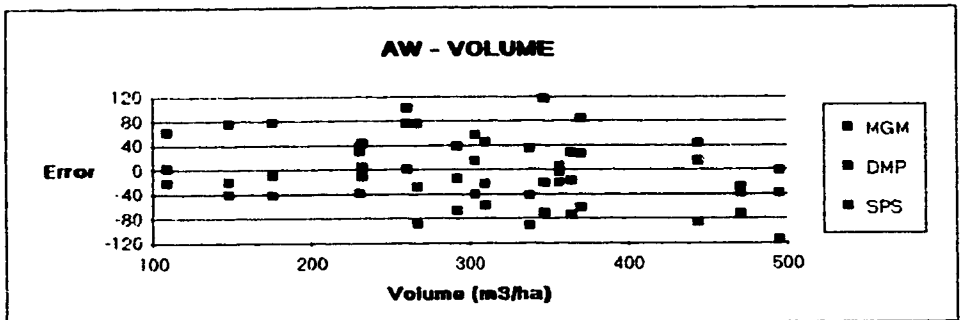
Plots presenting the deviations between the actual and the predicted volume/ha, basal area/ha, density/ha, average height and average quadratic mean diameter for each model..

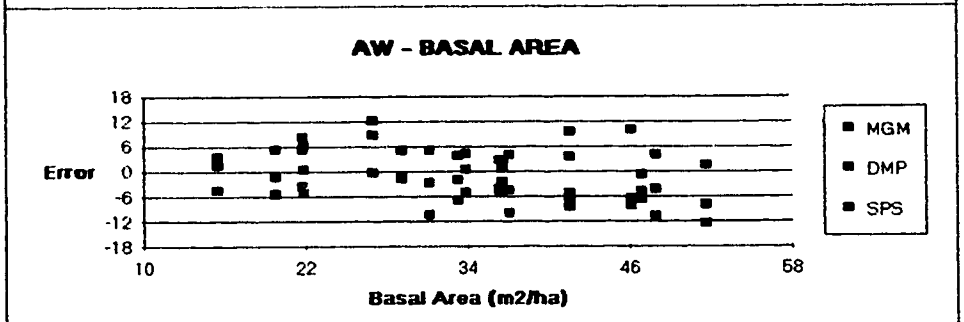


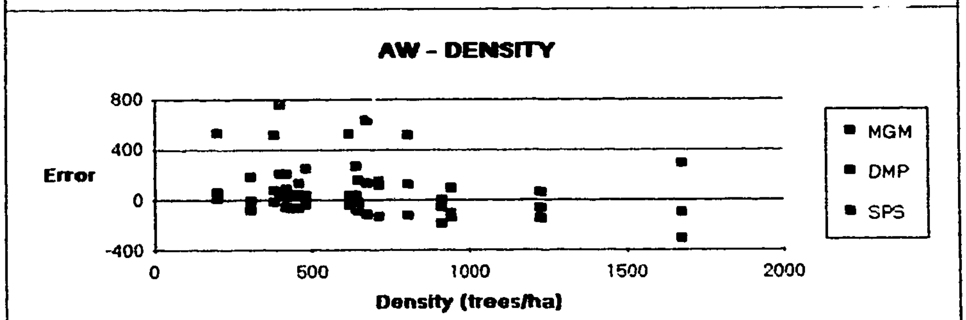
SW - VOLUME
Error
240
160
80
0
-80
-160
100
200
300
400
500
600
Volume (m3/ha)
MGM
DMP
SPS
SW - BASAL AREA
Error
24
18
12
6
0
-6
-12
-18
10
20
30
40
50
60
Basal Area (m2/ha)
MGM
DMP
SPS
SW - DENSITY
Error
400
0
-400
-800
-1200
-1600
0
500
1000
1500
2000
2500
Density (trees/ha)
MGM
DMP
SPS
SW - DIAMETER
Error
12
10
8
6
4
2
0
-2
-4
10
15
20
25
30
35
40
Diameter (cm)
MGM
DMP
SPS
SW - HEIGHT
Error
15
10
5
0
-5
10
15
20
25
30
Height (m)
MGM
DMP
SPS

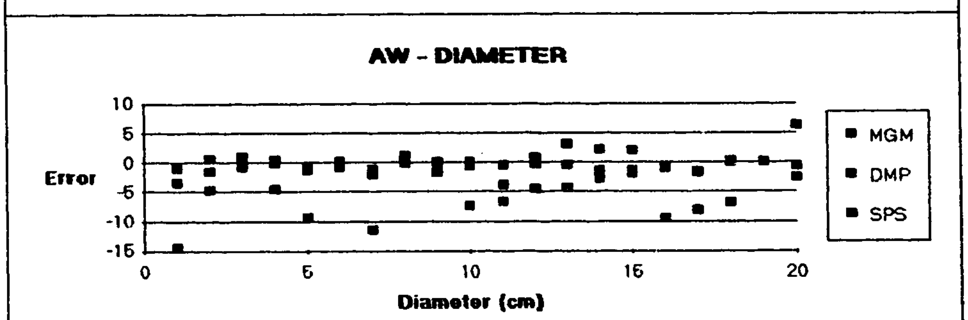


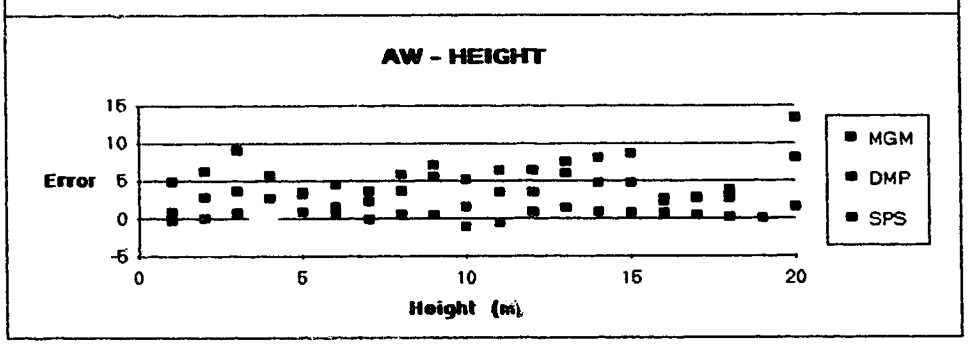
PL - VOLUME
Error
80
40
0
-40
-80
100
200
300
400
500
Volume (m3/ha)
MGM
DMP
SPS
PL - BASAL AREA
Error
12
6
0
-6
-12
-18
10
20
30
40
50
60
Basal Area (m2/ha)
MGM
DMP
SPS
PL - DENSITY
Error
1500
1000
500
0
-500
-1000
0
500
1000
1500
2000
2500
3000
Density (trees/ha)
MGM
DMP
SPS
PL - DIAMETER
Error
4
2
0
-2
-4
-6
-8
-10
10
15
20
25
Diameter (cm)
MGM
DMP
SPS
PL - HEIGHT
Error
8
6
4
2
0
-2
10
12
14
16
18
20
22
Height (m)
MGM
DMP
SPS

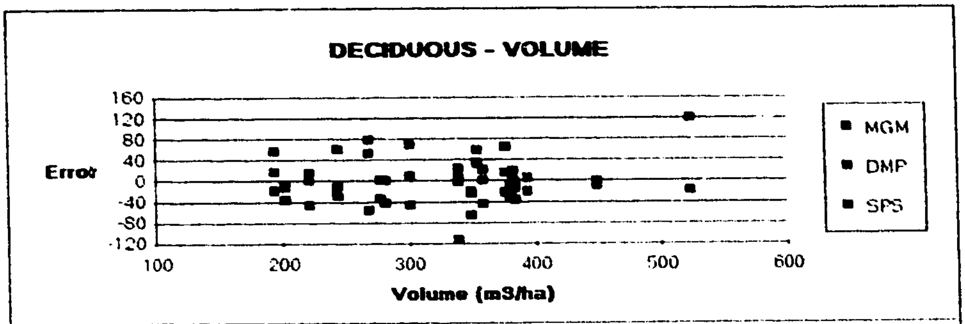

AW - VOLUME
Error
120
80
40
0
-40
-80
-120
100
200
300
400
500
Volume (m3/ha)
MGM
DMP
SPS

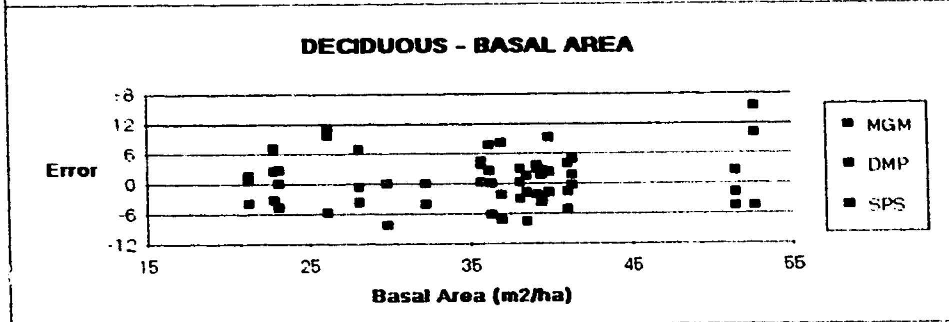

AW - BASAL AREA
Error
18
12
6
0
-6
-12
-18
10
22
34
46
58
Basal Area (m2/ha)
MGM
DMP
SPS

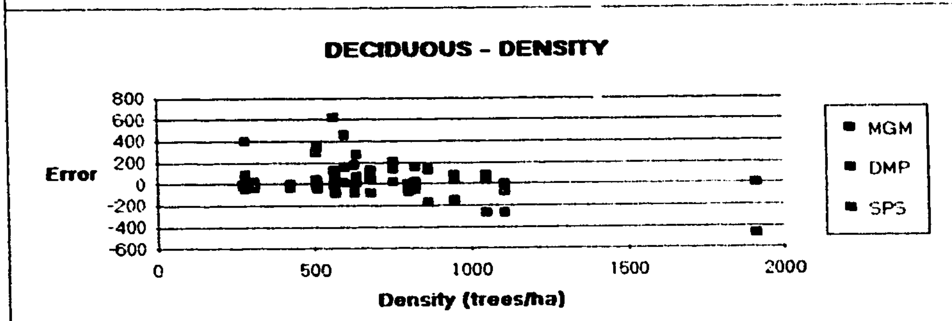

AW - DENSITY
Error
800
400
0
-400
0
500
1000
1500
2000
Density (trees/ha)
MGM
DMP
SPS

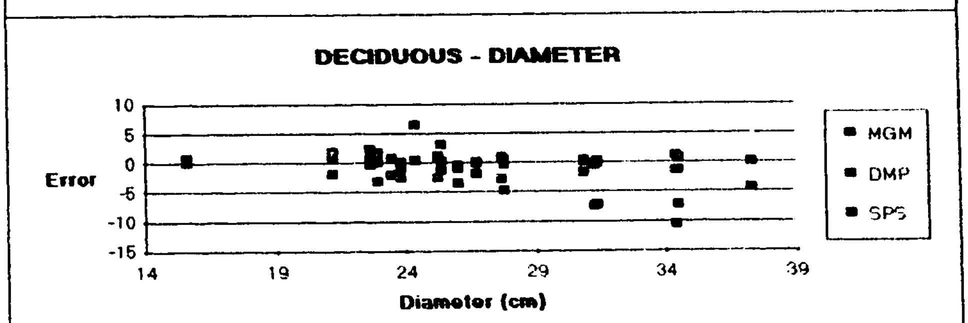

AW - DIAMETER
Error
10
5
0
-5
-10
-15
0
5
10
15
20
Diameter (cm)
MGM
DMP
SPS

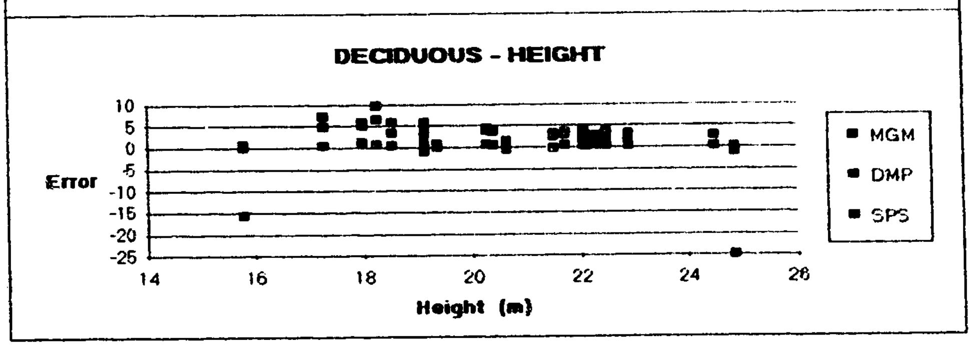

AW - HEIGHT
Error
15
10
5
0
-5
0
5
10
15
20
Height (m)
MGM
DMP
SPS

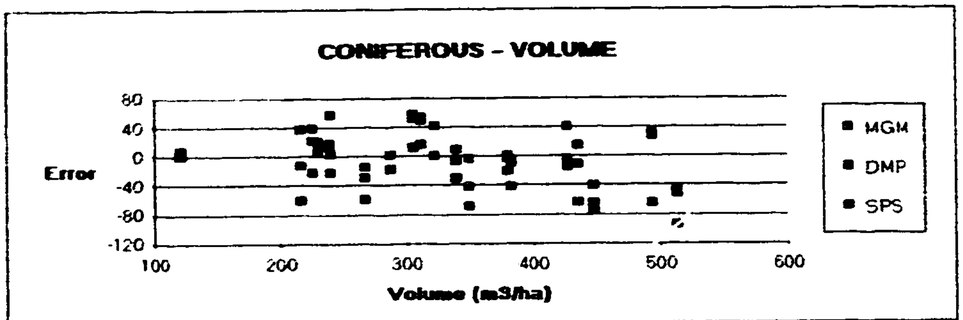

DECIDUOUS - VOLUME
Error
Volume (m3/ha)
MGM
DMP
SPS

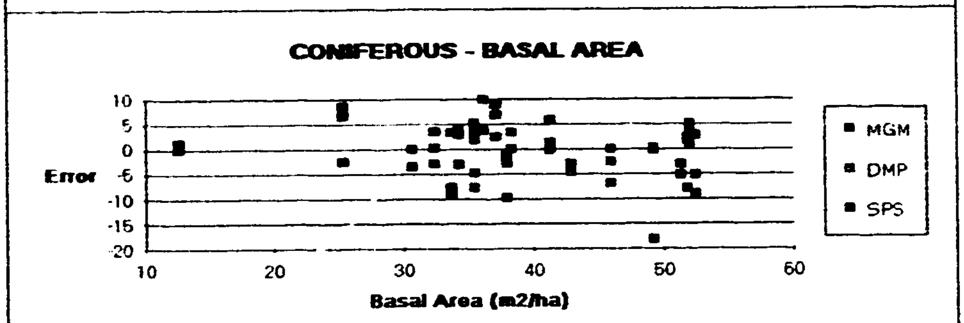

DECIDUOUS - BASAL AREA
Error
Basal Area (m2/ha)
MGM
DMP
SPS

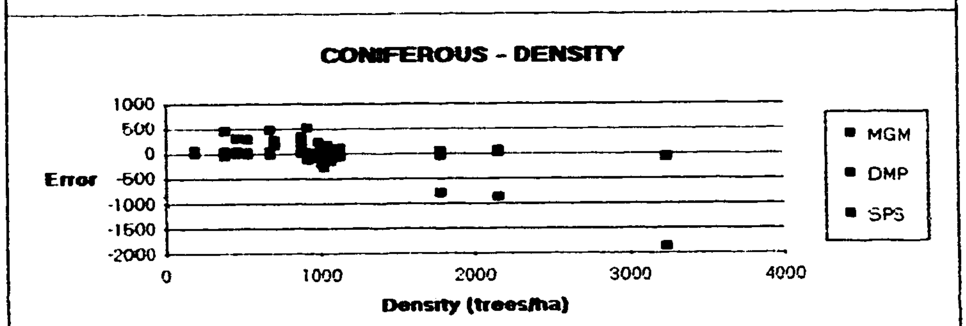

DECIDUOUS - DENSITY
Error
Density (trees/ha)
MGM
DMP
SPS

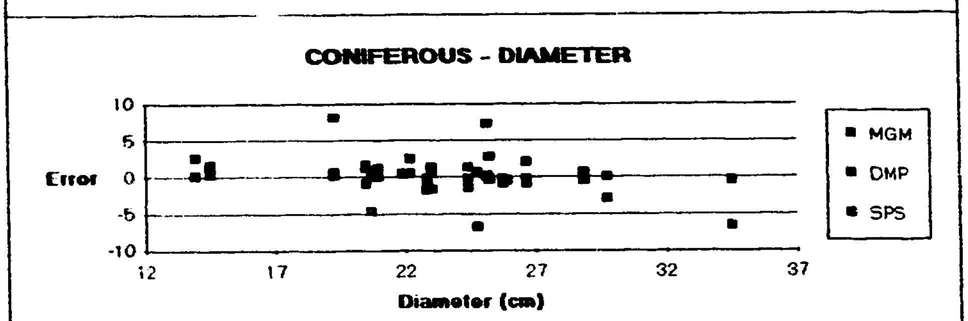

DECIDUOUS - DIAMETER
Error
Diameter (cm)
MGM
DMP
SPS

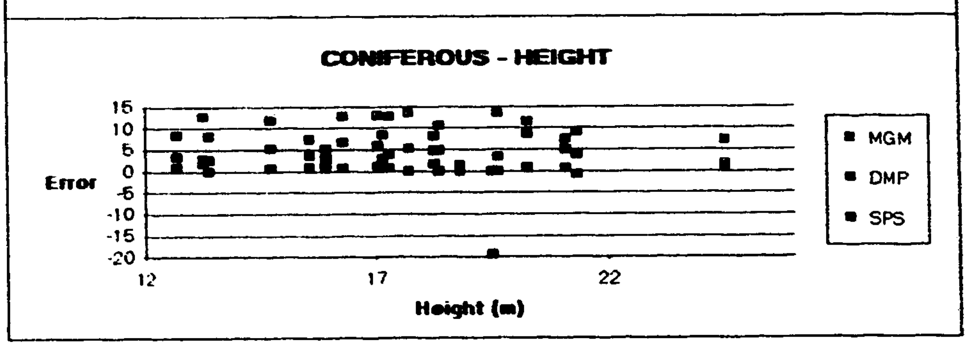

DECIDUOUS - HEIGHT
Error
Height (m)
MGM
DMP
SPS


CONIFEROUS - VOLUME
Error
80
40
0
-40
-80
-120
100
200
300
400
500
600
Volume (m3/ha)
MGM
DMP
SPS


CONIFEROUS - BASAL AREA
Error
10
5
0
-5
-10
-15
-20
10
20
30
40
50
60
Basal Area (m2/ha)
MGM
DMP
SPS


CONIFEROUS - DENSITY
Error
1000
500
0
-500
-1000
-1500
-2000
0
1000
2000
3000
4000
Density (trees/ha)
MGM
DMP
SPS


CONIFEROUS - DIAMETER
Error
10
5
0
-5
-10
12
17
22
27
32
37
Diameter (cm)
MGM
DMP
SPS


CONIFEROUS - HEIGHT
Error
15
10
5
0
-5
-10
-15
-20
12
17
22
Height (m)
MGM
DMP
SPS