EXAMINATION OF CROPTYPING IN FOREST ESTATE MODELLING

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ABSTRACT

Alternative strategies for aggregating stands into croptypes were evaluated. Strategies tested included traditional grid methods, clustering methods, and a variable resolution approach. A benchmark stand-level model was developed within the FOLPI forest estate modelling system for a 231 stand estate. Croptyping strategies were evaluated for their ability to match the results from this stand-level model. Comparisons were made in terms of the variation within croptypes, objective function value, forecast cash flows and woodflow volumes, stands specified for harvest over the short term, and problem size. The best croptyping strategy was the variable resolution approach in which the unique identity of the 41 stands within 6 years of harvesting was preserved while the 190 younger stands were aggregated into croptypes. This hierarchical approach represents a compromise between the need for short-term detail and the desirability of modelling long-term consequences within the same model.

Keywords: croptype; forest estate modelling; FOLPI.

INTRODUCTION

An underlying concept of New Zealand forest estate modelling is that of the croptype, which was adopted to link stands and forests. A croptype is the aggregation of forest stands which may differ in age and time of harvest but are regarded as uniform with respect to silviculture, yield production, and the associated streams of inputs and outputs. For forest planning purposes stands are aggregated into croptypes, each involving a table of areas by age class for stands with a common yield table. The concept has facilitated forest planning in New Zealand and is flexible enough to accommodate a range of situations. For example, at one extreme each stand might be a unique croptype whereas at the other end all stands might be assigned to the same croptype.

Aggregation of stands is generally done on the basis of species, silvicultural treatment, site productivity, and logging characteristics (e.g., terrain). For long-term planning a forest estate will generally be aggregated into 20 to 60 different croptypes, with the number of stands aggregated into each croptype depending on the estate being modelled.

Aggregation of stands into croptypes causes loss of detail as, rather than being able to model management activity by individual stand, the management unit becomes the age class of a croptype. The assumption that all stands in a croptype have a common yield table causes additional loss of detail. The variation in total merchantable volume at age 30 for 37 stands aggregated into one croptype is illustrated in Fig. 1. After croptyping all stands are assumed to have a volume at age 30 of 430 m^3/ha.

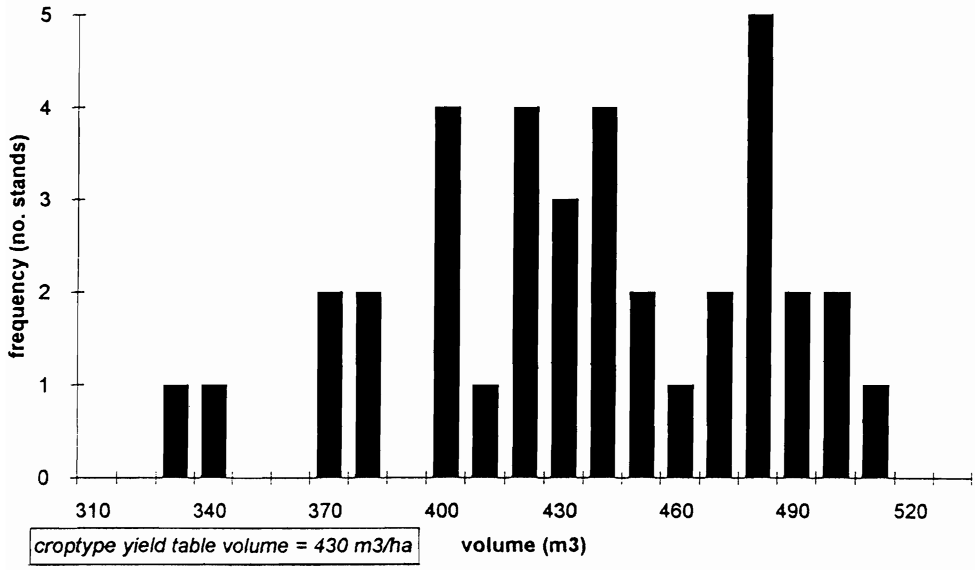

FIG. 1–Distribution of the actual age 30 total realisable volumes of stand yield tables for stands aggregated within a croptype.

On the other hand, use of croptypes reduces the planning problem to a tractable size and enhances comprehension of both the problem and the results. Model aggregation results in smaller models which are quicker to build and solve. Because they are more responsive they can more readily be used to explore the "what-ifs" and hence can facilitate the development of a strategic overview.

Consequently, the development of a model often involves a compromise between the level of detail required and the desired tractability (including "turn-around" time and available computer memory considerations). Computer software and hardware developments have been such that the "appropriate" level of aggregation has moved towards less aggregation. It is now possible to model at least small forests at the stand level.

As well as the trade-offs between level of detail and model tractability, the purpose of forest estate modelling has to be considered in determining the appropriate level of aggregation. For example, the FOLPI (Forest Oriented Linear Programming Interpreter) (Garcia 1984) forest estate modelling system has been used for yield regulation, management strategy evaluation, investment analysis, and forest valuation (*see* Manley *et al.* 1991; Manley & Threadgill 1991). The focus of forest estate modelling has been on long-term strategic and tactical planning over 60 to 90 years. However, over recent years there has been an increasing use of FOLPI for short-term planning such as the scheduling of stands for harvest (Manley 1994). Whereas aggregations of stands for long-term planning is generally acceptable, it is less so for short-term planning. Hence, the appropriate level of aggregation depends on the planning purpose and the time span being considered.

A number of different approaches to croptyping have been used in New Zealand. The most common approach has been a "grid" method whereby croptypes are defined in terms of a range for each classification factor (e.g., site index 25–28 m, pruned height from 4 to 8 m, thinned to 200–400 stems/ha, slope less than 15°). Another approach has been to allocate a particular age class to a unique croptype. This has generally been a surrogate for the grid method in the sense that the stands in the age class have similar characteristics. An alternative approach used by one company has been the use of cluster analysis in which stands are allocated to croptypes on the basis of similarity of yield.

In the study reported here the effects of different croptyping strategies on the outcome of a FOLPI estate-planning exercise were examined.

METHOD

The study consisted of two parts. In Part 1, seven different strategies for croptyping were selected and the effects of each on the results of a single FOLPI estate-modelling exercise were compared. The data sets used were from a single forest and differed only in croptype definition. A standard FOLPI problem was run for this forest for all croptyping strategies, varying only in the data files used. In Part 2, the effect of a sequential reduction of the number of croptypes within one croptyping strategy was examined.

Definition of a Forest Estate

The forest chosen for the exercise comprised a large number of individual stands for which records and inventory data were available. These records were supplied by a forest-owning company. A total of 231 *Pinus radiata* D.Don stands with a net stocked area greater than 10 ha were selected. Of these, 14 were stands more than 22 years old for which MARVL (Deadman & Goulding 1979) pre-harvest inventory data records were available.

Constructing Yield Tables for the Forest Model

Stand records provided stand data: the stand name, year of establishment, net stocked area, stockings per hectare, the forest-owning company croptype based on terrain and silvicultural treatment (or management intention), site index, dates of inventory measurement and estimates of basal area, site index, and current stocking. Pruning and thinning measurement records gave data on all pruning and thinning operations including average heights of pruning lifts, number of stems pruned, residual stockings, and ages at each operation. The STANDPAK (Whiteside 1990) stand prediction model was used to construct a unique yield table by log grades using these records for each individual stand. For very young stands (prior to, or with silvicultural operations incomplete) silvicultural operations and measurements were randomly allocated based on the records of older stands of the same silvicultural intention. For stands which had a MARVL assessment this information was grown forward in GROMARVL annually for 10 years, outputting log product volumes for each year.

FOLPI Modelling

The yield tables generated by STANDPAK and MARVL were converted to a FOLPI data file format giving area by age class and realisable volumes for total volume, pruned log, export A grade, export K grade, S1, L1, S2, and Pulp grade volumes, and clearfell revenue realisable at each potential clearfelling age.

A base model for comparing various croptyping strategies was constructed at the stand level of detail as a FOLPI problem. Each stand was represented by a unique croptype and a standard set of modelling assumptions and criteria was derived that could be applied to all subsequent models based on croptyping methods. The base problem was constrained to reflect a real and general management problem. Realistic minimum and maximum clearfell ages were set and non-declining yield constraints were set for total, pruned, and unpruned export grade volumes. Similarly, a standard procedure for modelling the replanting of stands after harvest was selected. The prodedure was based on replanting areas to croptypes composed of the youngest stands which indicated the most likely future silvicultural intention. This resulted in 176 replanting croptypes from 231 initial stands in the stand model.

Part 1: Croptyping Strategies

In each strategy, the 231 stands of the model forest were grouped differently and a yield table was created to represent all stands in that group. A new data file for each croptyping strategy was generated for FOLPI problems.

Strategy 1—stand-based model

In the base model, against which all croptyping models were compared, each individual stand was treated as a unique croptype.

Strategy 2—averaged starting point yield tables

The stand data obtained from the company owning the forest included an assignment of stands to one of the 14 company croptypes the basis for which is illustrated in Fig. 2. This

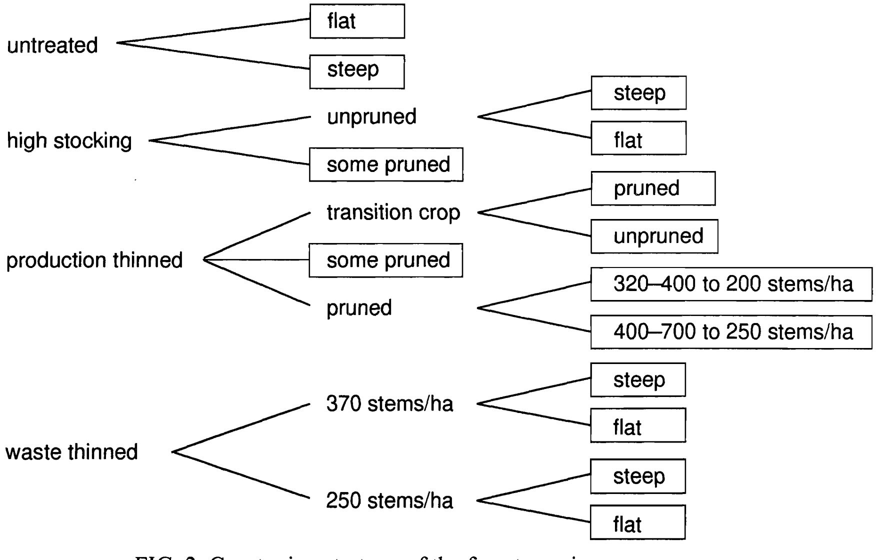

FIG. 2–Croptyping strategy of the forest-owning company.

method of aggregating stands was retained for our croptyping. Various stand statistics, based on silviculture (such as the average residual stems per hectare after thinning and the average age at which thinning occurred) were compiled and averaged within each croptype. These average statistics were then used to provide starting points and describe treatments in order to create new yield tables in STANDPAK for each of the 14 croptypes.

Strategy 3—averaged yield tables

Again, the 14 company croptypes were used to aggregate stands. Yield tables were this time created by averaging the individual stand yield tables (generated for the stand model) for each croptype using the "AVGYLD" utility in FOLPI which simply produces an area-weighted yield table for a specified set of stands.

Strategy 4—stand factor croptypes

This strategy attempted to aggregate stands that were the most similar in terms of individual yield table volumes, stand and site factors, and management history, and it resulted in a new set of 21 croptypes. Average yield tables were generated by the AVGYLD utility using the individual stand yield tables for each stand in a croptype (Fig. 3).

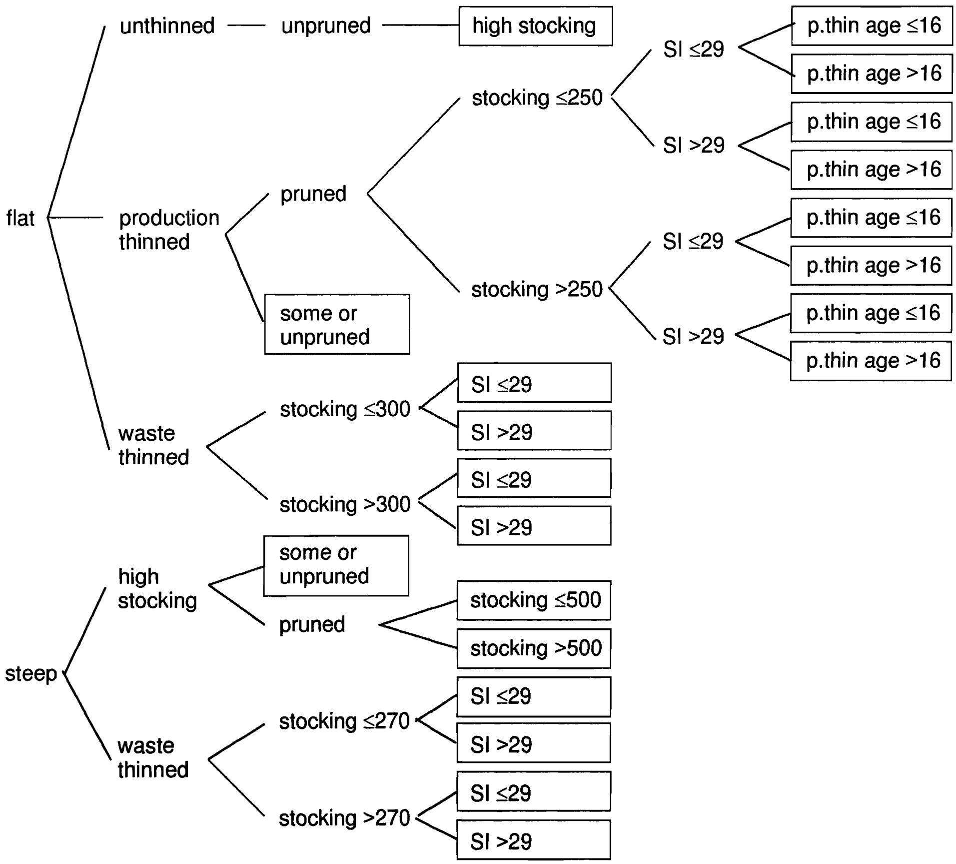

FIG. 3–Aggregation decisions for creating 21 croptypes in Strategy 4. Boxes represent the final feature defining croptypes.

Aggregation decisions related to:
- whether the site was steep or flat
- production thinning or waste thinning
- final stocking
- pruning
- site index

Strategy 5—variable resolution

A single data set was created that combined two croptyping strategies. All stands at age 23 and older were treated individually as unique croptypes. There were 41 such stands and they represented the only ones that could be harvested within the 6-year short-term because of the specified minimum clearfell age of 28 years. The stands younger than 23 years were re-aggregated by AVGYLD into the croptypes used in Strategy 4 (based on stand factors). The combined strategy data set was run as a single FOLPI model. After harvest of the oldest stands, the area was replanted into the aggregated croptype into which the stand would have been replanted into in Strategy 4, according to the basic replanting strategy.

Strategy 6 and Strategy 7—cluster analysis on yields

Cluster analysis using SAS (*see* SAS Institute Inc. 1989) was used to group stands based on the likeness of log grade volumes at age 30. The CLUSTER procedure finds hierarchical clusters of the observations in an input data set. It was used here to group stands based on volume to give (arbitrarily) approximately 20 clusters for separate croptypes which allowed reasonable comparisons to be made with other croptyping methods.

Under the cluster method, stands were replanted into those croptypes which had large proportions of young stands (ages 0 to 5) reflecting the likely future plans for management.

Strategy 6—centroid cluster: The centroid cluster method was used for Strategy 6. In this method, the distance between two clusters is defined as the (squared) Euclidean distance between their means. It is robust to outliers and tends to produce clusters that have few observations (SAS Institute Inc. 1989).

In this strategy clustering resulted in one particularly large cluster containing most of the younger stands and the older stands of the same company croptype designation. A number of small clusters containing one, two, or three stands were formed which tended to contain the older stands where management and silviculture did not reflect that of the general forest. New yield tables were generated by AVGYLD from the yield tables of the component stands in each clustered croptype.

Strategy 7—Ward's cluster: The Ward's minimum-variance method defines the distance between two clusters as the ANOVA sums of squares between the two clusters. The Ward's method is strongly biased towards combining clusters with a small number of observations (SAS Institute Inc. 1989).

The Ward's method produced a number of small clusters of two to seven observations (containing the older stands generally) and four moderately large clusters. New yield tables were generated by AVGYLD.

Part 2: Loss of Detail Due to the Number of Croptypes

A series of FOLPI problems were formulated based on Strategy 4, where croptypes were successively combined, reducing the number of croptypes each time. Strategy 4 was selected because it achieved relatively low variances for volumes within croptypes and was a simpler model in which to re-aggregate croptypes than the cluster models (which actually set out to minimise variance within croptypes).

Numbers of croptypes were reduced by sequentially combining the most similar stands in terms of management history, site index, and total realisable volumes (at age 30). Croptypes that were least different were combined first. New yield tables were generated for new croptypes by AVGYLD. A sequence of six models was formed with 21, 17, 11, 6, and 2 croptypes and one single-forest croptype.

ANALYSIS

For each model, reports specified the optimal annual harvest volumes by total and log product volumes, the resultant clearfelling revenue, and the objective function value (net present value) over the 70-year planning period. They also provided the harvest plan (areas cut each year by croptype and age-class) for 70 years. Summaries for each model were compared to the stand model with comparisons being in absolute terms. There was also no replication for each croptyping strategy (each strategy related to the one forest) and therefore statistical tests of probability (i.e., that one strategy was likely to be better than another) were not valid. Analysis showed the extent of change from the most detailed model—the stand model—because of croptyping.

There were five types of comparisons under which croptyping models were evaluated in relation to the stand model.

(1) Variation within croptypes

The variation within multiple-stand croptypes for each strategy was analysed. This involved examining the total volume at age 30 from each individual stand's unique yield table. Using a method of analysis of variance in the statistical software package SAS, the residual standard deviation (or root mean square error, RMSE) of individual stand volumes and croptype volumes was calculated for each strategy. The stand volumes were also weighted by net stocked area to obtain a weighted RMSE for each strategy. Low values of residual standard deviation imply low variation in stand volumes within croptypes.

Standard deviation for the stand model was zero as each croptype contained a single stand and hence there could be no "within-croptype" stand variation.

(2) Objective function values

The objective function for these models was to maximise present net worth. The objective function of each strategy model was compared to the stand model value and the differences for each croptyping model were expressed as a percentage of the stand strategy model value.

(3) Annual and periodically summed residuals

Residuals were calculated for each strategy. A "residual" was defined as the absolute difference between FOLPI summary values for croptyping models and the stand model for each year. Residual values were calculated for total volume, pruned volume, unpruned combined export grade volumes, and clearfell revenues. Residuals were expressed as an average percentage of the stand model values for the short term (years 1 to 5), mid term (years 6 to 30), long term (years 31 to 60), and the first 60 years combined. Years 61 to 70 were ignored.

(4) Stands specified for harvest

The percentage of stands specified for harvest over the short term (first 5 years) for each strategy which matched the stand model harvests was calculated. Strategy 5 allowed direct comparisons of stands because stand detail for harvestable stands was maintained for this period. For all other strategies, comparisons relied on age-class detail as the stand detail was lost in the process of croptyping. Comparisons were made between the stands cut in the stand model and the equivalent croptype age-class of the aggregate model.

(5) Problem size

Problem size was compared in terms of constraints and variables, matrix building and solution times for FOLPI for each model.

RESULTS

Part 1: Croptyping Strategies

Variation within croptypes

For croptype yield tables, measures of variance showed how closely individual stand volumes for stands within a croptype were grouped around the mean volume, and hence the extent of detail lost due to croptyping. The company croptypes used in Strategies 2 and 3 were the most variable in terms of individual stand volumes within croptypes (Table 1). Strategy 4 had less variation than Strategies 2 and 3 as shown by its lower RMSE. It was differentiated by the stand factors and this split some of the most variable croptypes of Strategies 2 and 3. However, the RMSE was still high relative to the other stratgies. Strategy 6 (centroid cluster on volumes) produced 10 croptypes for which there was only one stand, whereas Strategy 7 did not contain any single-stand clusters. This feature gave Strategy 6 some aggregated croptypes that contained large numbers of stands and hence greater variability, even with the most variable stands treated as individual croptypes, than Strategy 7. Strategy 7 (Ward's clusters) produced croptypes which minimised the differences between stand volumes, and consequently a low RMSE. Overall Strategy 7 performed best of all because its biggest croptypes had low variance for stand volumes. Strategy 5 (the variable resolution model) had a similar RMSE to Strategy 7. Stands constituting the most variable croptypes of Strategies 2 to 4 were the older stands and were treated as individual croptypes in Strategy 5; hence there was less variability in stand volumes in the resultant aggregated croptypes.

The numbers of croptypes and replanting croptypes for each strategy, the residual standard deviation (or RMSE) between stand volumes within croptypes for each strategy, and the same statistic but with stand volumes weighted by their net stocked area (NSA) are given in Table 1.

TABLE 1–Numbers of croptypes and replanting croptypes and measures of variance for croptypes formed for each strategy.

Strategy	Number of croptypes	Number of replanting croptypes	Residual standard deviation (RMSE)	Weighted residual standard deviation by NSA*
Stand model	231	176	0	0
Strategies 2 & 3	14	5	74.3	461
Strategy 4	21	12	60.5	359
Strategy 5	61	12	45.0	297
Strategy 6	22	3	53.0	356
Strategy 7	20	4	44.6	238

* NSA = net stocked area

Objective function values

The objective function values for the seven strategies are given in Table 2. This is the discounted sum of net revenues (i.e., present net worth) resulting over the 70-year planning term. There was little deviation for all models and the deviations were only small percentages of the stand model value. Strategy 2 was furthest from the stand model. Strategy 7 was also relatively divergent as was Strategy 3, although the range of differences for each of these was only 0.6% to 1.9% of the stand model. Strategy 4 was closest to the stand model, followed by Strategy 5.

TABLE 2–FOLPI objective function values (maximum present net worth) and percentage difference from base case value for croptyping strategies

Strategy	Objective function value (million $)	Difference from stand model (%)
Stand model	145.9	–
Strategy 2	148.6	1.9
Strategy 3	146.8	0.6
Strategy 4	146.0	0.1
Strategy 5	146.1	0.1
Strategy 6	145.5	0.3
Strategy 7	147.4	1.0

Annual and periodically summed residuals

The residuals of the difference between stand model values and each strategy (expressed in absolute values) for total realisable volume, pruned volume, unpruned export-grade log volumes, and clearfell revenues over the 60 years are shown graphically in Fig. 4 to 7. The lower the graph values, the closer the values of a model to the stand model. On average over both the short and the long term, the differences from the stand model were least for Strategy 5 followed by Strategy 6.

An indication of the relative size of the residuals is given in Fig. 8 and 9. Here the actual volumes and clearfell revenues for the stand model and for Strategy 7 are plotted, illustrating the magnitude of the differences.

The quantified residuals are given in Table 3. The absolute differences annually between harvests and clearfell revenues of each model and the stand benchmark values have been

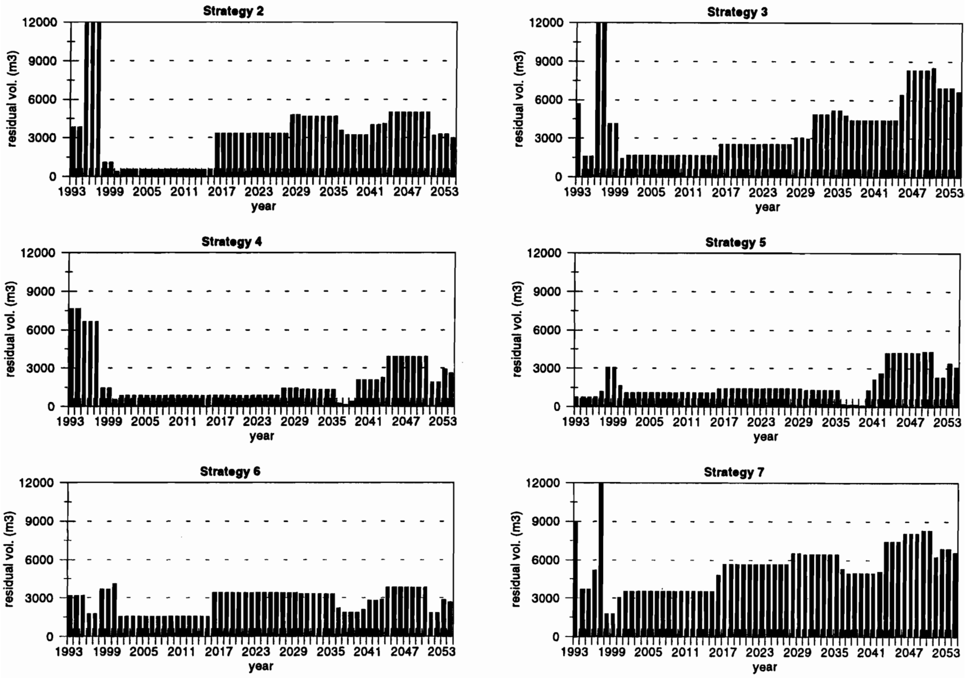

FIG. 4–Absolute residuals from stand model total volume for Strategies 2 to 7 (truncated for presentational clarity).

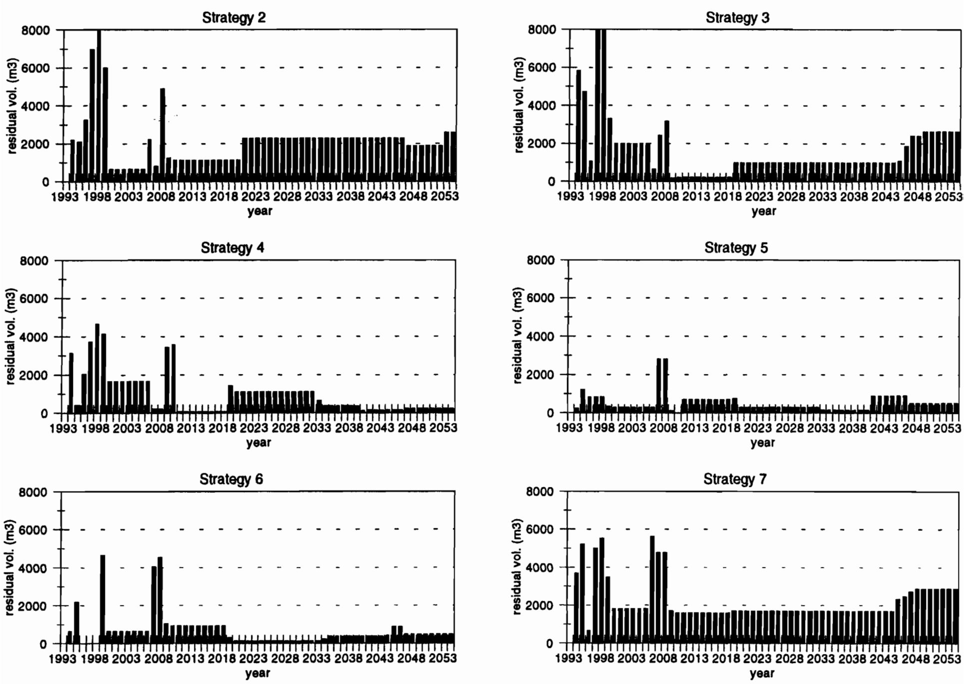

FIG. 5–Absolute residuals from stand model pruned volume for Strategies 2 to 7 (truncated for presentational clarity).

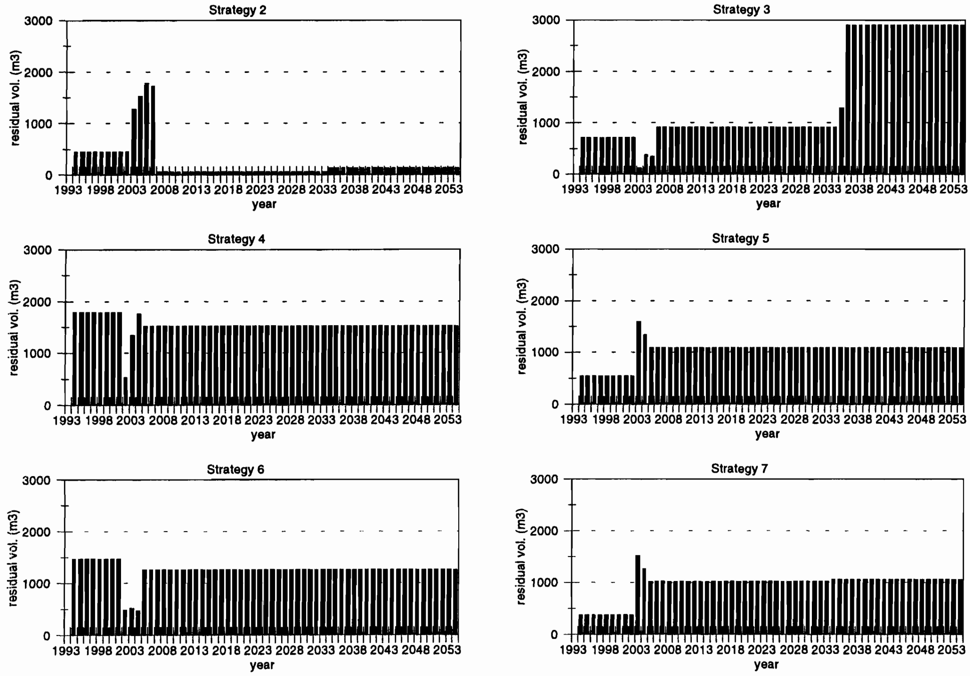

FIG. 6–Absolute residuals from stand model unpruned export grade volume for Strategies 2 to 7 (truncated for presentational clarity).

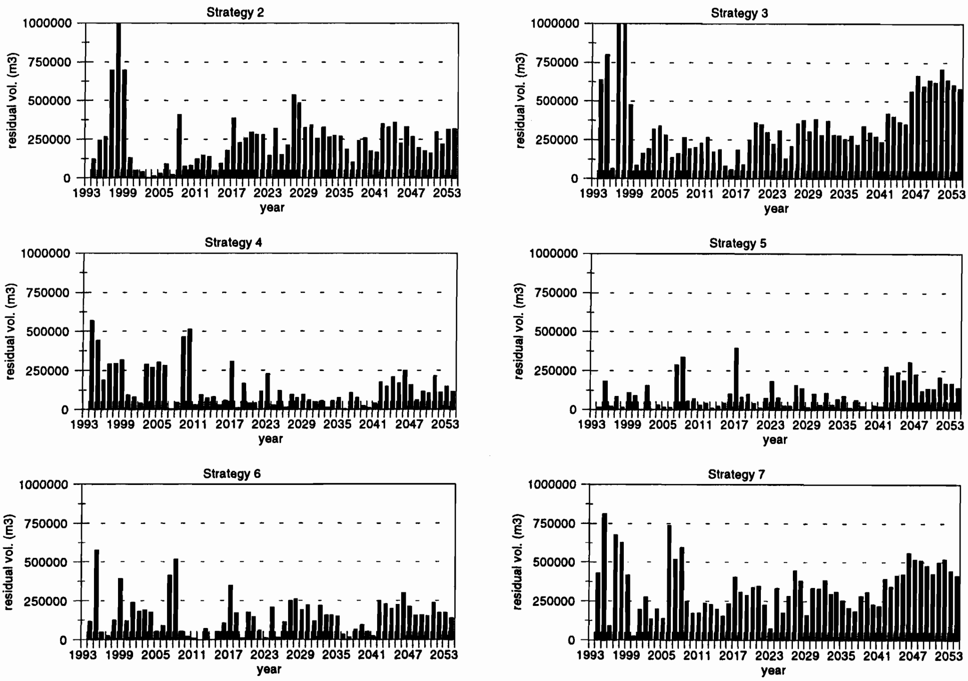

FIG. 7–Absolute residuals from stand model clearfell revenue values for Strategies 2 to 7 (truncated for presentational clarity).

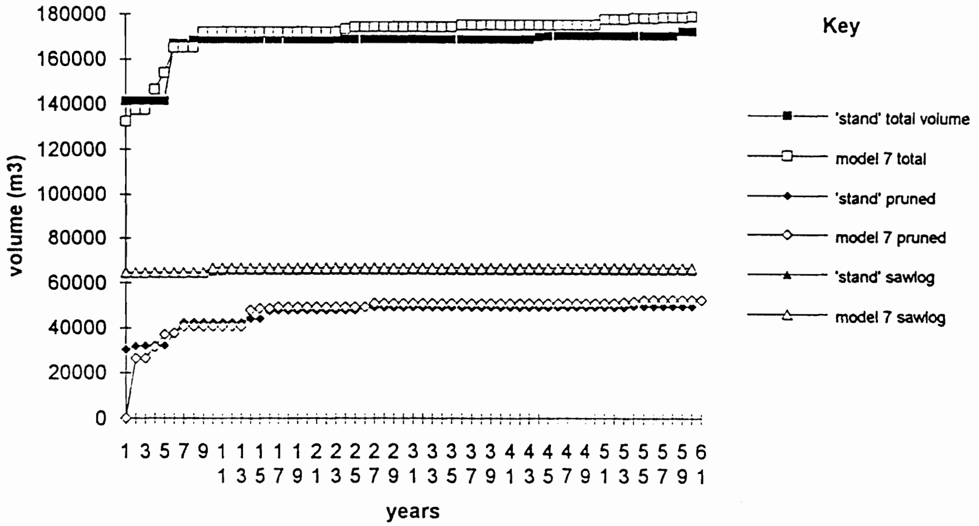

FIG. 8—Difference between total and log product volume forecasts for the stand model and an example model—Strategy 7.

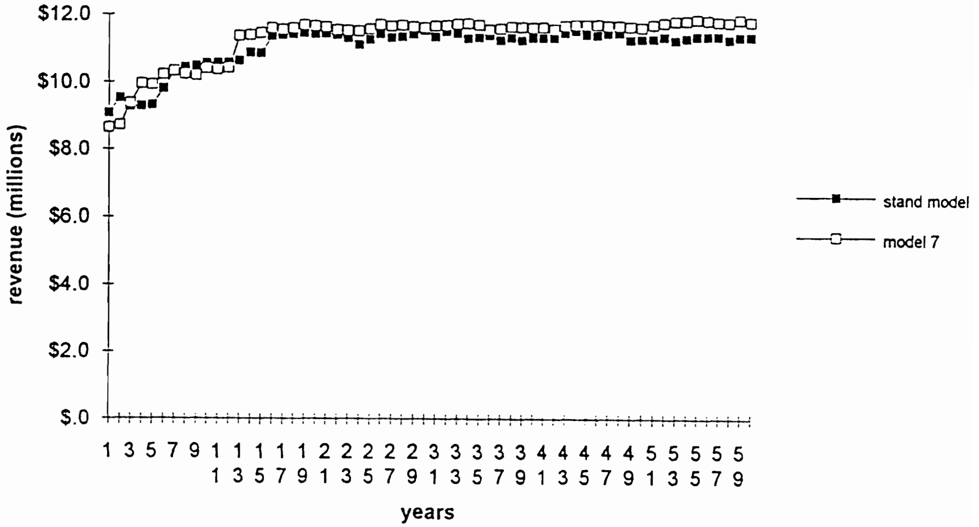

FIG. 9—Difference between clearfell revenue forecasts for the stand model and an example model—Strategy 7.

expressed as a percentage of the stand model value. Figures have been averaged for the short term (initial 5 years), the mid term (years 6 to 30), and the long term (years 31 to 60). Finally, an overall figure for the period (years 1 to 60) has been calculated.

The variable resolution Strategy 5 was the most consistently similar to the stand model. In particular, Strategy 5 tracked total volume and pruned volume closely over all periods and over the short term. Strategy 6 (centroid cluster) performed relatively steadily over-all, particularly in the short term. Strategy 4 deviated only slightly from the stand model in all

TABLE 3–Percentage difference between croptype models and stand level model over the short term, mid term, and long term by total volume, log product volumes, and clearfell revenue.

	Strategy 2	Strategy 3	Strategy 4	Strategy 5	Strategy 6	Strategy 7
Short-term difference between croptype and stand model (%)						
Total volume	7.9	6.4	5.0	0.6	1.8	4.8
Pruned	16.0	17.9	8.8	2.5	1.8	12.7
Unpr. export	0.7	1.1	2.8	0.8	2.6	0.6
Clearfell rev.	5.3	7.7	3.9	0.7	1.9	5.7
Mid-term difference between croptype and stand model (%)						
Total volume	0.8	1.3	0.5	0.8	1.4	2.3
Pruned	3.4	2.6	2.7	1.4	2.6	4.8
Unpr. export	0.6	1.2	2.3	1.6	1.8	1.4
Clearfell rev.	1.5	2.0	1.5	0.8	1.3	2.5
Long-term difference between croptype and stand model (%)						
Total volume	2.4	3.0	1.2	1.3	1.8	3.8
Pruned	4.5	5.8	3.0	1.0	0.9	4.2
Unpr. export	0.2	3.3	2.3	1.7	1.9	1.6
Clearfell rev.	5.3	7.7	3.9	0.7	1.9	5.7
Over-all difference between croptype and stand model (%)						
Total volume	2.2	2.5	1.2	1.0	1.6	3.3
Pruned	5.0	4.0	2.3	1.2	1.6	5.1
Unpr. export	0.4	2.3	2.4	1.6	1.9	1.4
Clearfell rev.	2.3	3.2	1.3	0.9	1.4	3.1

comparisons except in the unpruned export grade volumes and over the short term. Strategy 4 residuals tended to decrease over time. Strategies 2 and 3 had the highest and most inconsistent residuals, particularly in the long term.

Stands specified for harvest

For each model, the match between the croptypes specified for harvest and the stands specified for harvest in the stand model over the first 5 years is shown in Table 4. Strategy 5 cuts 90% of the stand area harvested in the stand model in the first year, and within the first 5 years has cut 99% of the area harvested in the stand model in years 1 to 5. Because Strategy 5 has stand level detail for the first 5 years, its comparisons are the most accurate. The two cluster models—particularly Strategy 6—were also good estimators by the fourth and fifth years, as was Strategy 3.

Problem size

The problem size, and the matrix generation and solution times for each model are given in Table 5. The combined matrix generation and solution time for the stand model was 285 minutes compared to the combined times of 5 minutes for the most highly aggregated models. The more detailed the model, the greater the problem size and run times. Increasing problem size not only had an impact on solution times but was limited by the extended memory capacity of the computer. Problems were solved on a 486, 50-Megahertz personal computer.

TABLE 4—Comparison of stands (croptype age classes) cut in aggregate models with stands cut in the stand model.

	Percentage of area in stands specified for harvest in stand level model which are harvested over:				
	1 year	2 years	3 years	4 years	5 years
Strategy 2	57	50	62	58	77
Strategy 3	41	67	70	80	94
Strategy 4	69	64	68	73	79
Strategy 5	90	94	94	98	99
Strategy 6	63	78	85	91	93
Strategy 7	62	68	70	80	94

TABLE 5—Effects of stand level modelling *v.* aggregated models on computer resources. Times are for a 50 MHz 486 PC using the LP package C-Whiz*

	Constraints	Variables	Matrix generation time (min)	Solve time (min)
Base	13 805	34 633	125	160
Strategy 2	1 056	3 674	2	3
Strategy 3	1 053	3 674	2	3
Strategy 4	2 111	8 138	4	10
Strategy 5	2 497	9 086	14	32
Strategy 6	945	2 499	3.7	3
Strategy 7	1 248	3 756	3.5	6

* Ketron Management Science, 1700 North Moore Street, Suite 1710, Arlington, Virginia 22209, USA.

Part 2: Loss of Detail Due to the Number of Croptypes

Objective function values

The increasing difference from the stand model objective function ($145.9 million) with increasing level of aggregation is shown inTable 6.

Annual and periodically summed residuals

The residuals over the whole period for total, pruned, and unpruned export-grade volumes and clearfell revenue are shown graphically in Fig. 10 to 13. With each successive aggregation there was a trend of increasing deviation from the stand model. Overall, there was only a small difference between examples with 17 and 21 croptypes.

TABLE 6—Objective function values for models varying in the number of croptypes describing the forest.

Number of croptypes	Objective function value (million $)	Difference from base (%)
21 (base model)	146.0	0.08
17	146.0	0.10
11	146.4	0.40
6	146.2	0.20
2	144.1	1.20
1	142.0	2.70

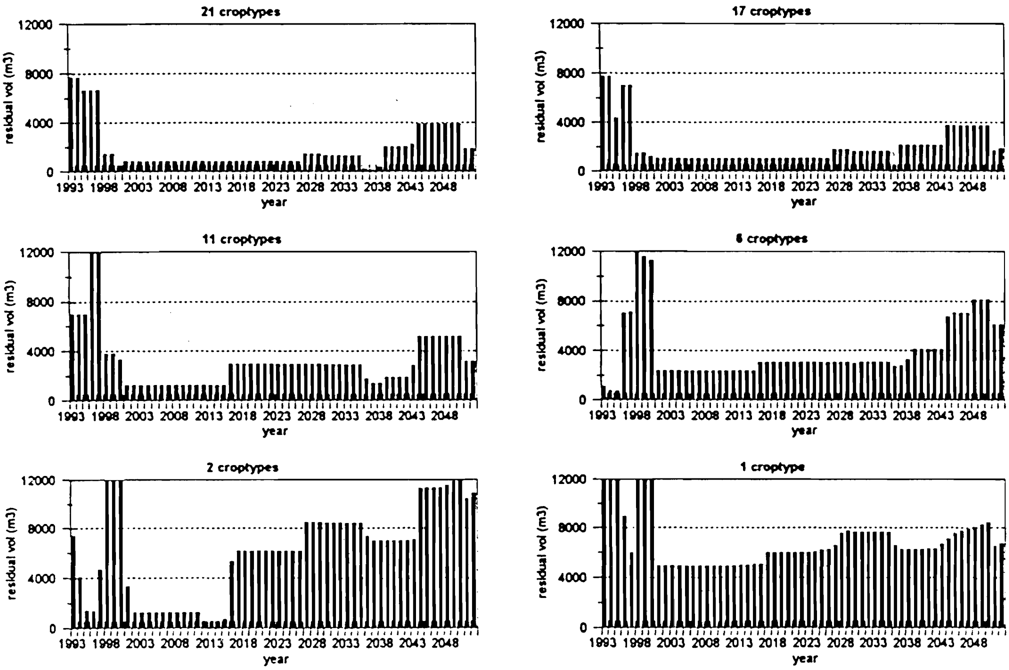

FIG. 10–Absolute residuals from stand model total volume for the series of reducing numbers of croptypes (truncated for presentational clarity).

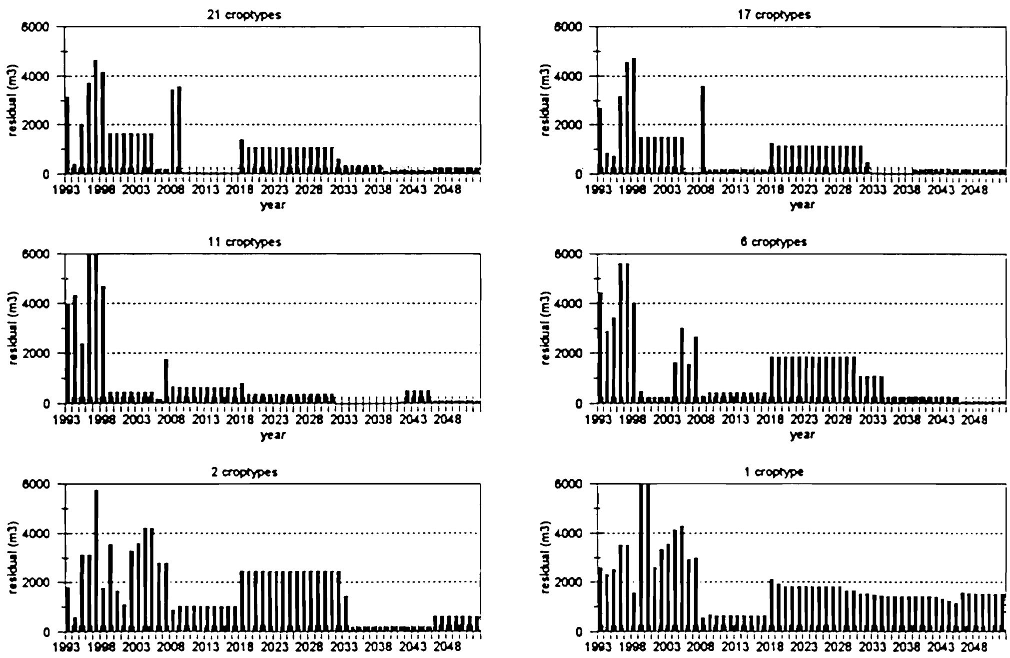

FIG. 11–Absolute residuals from stand model pruned volume for the series of reducing numbers of croptypes (truncated for presentational clarity).

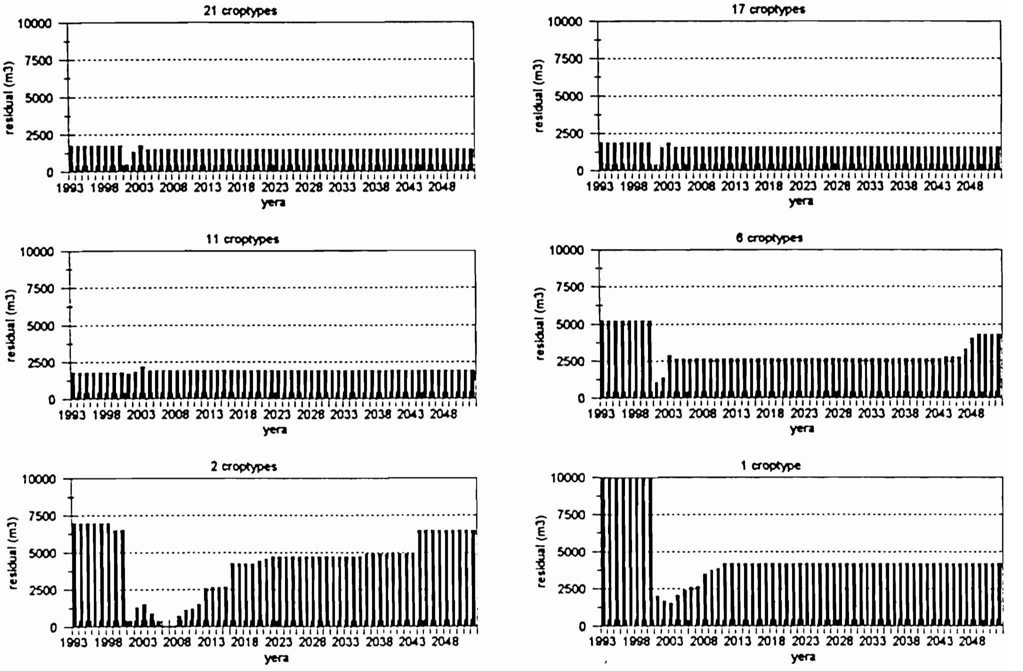

FIG. 12–Absolute residuals from stand model unpruned export grade volume for the series of reducing numbers of croptypes (truncated for presentational clarity).

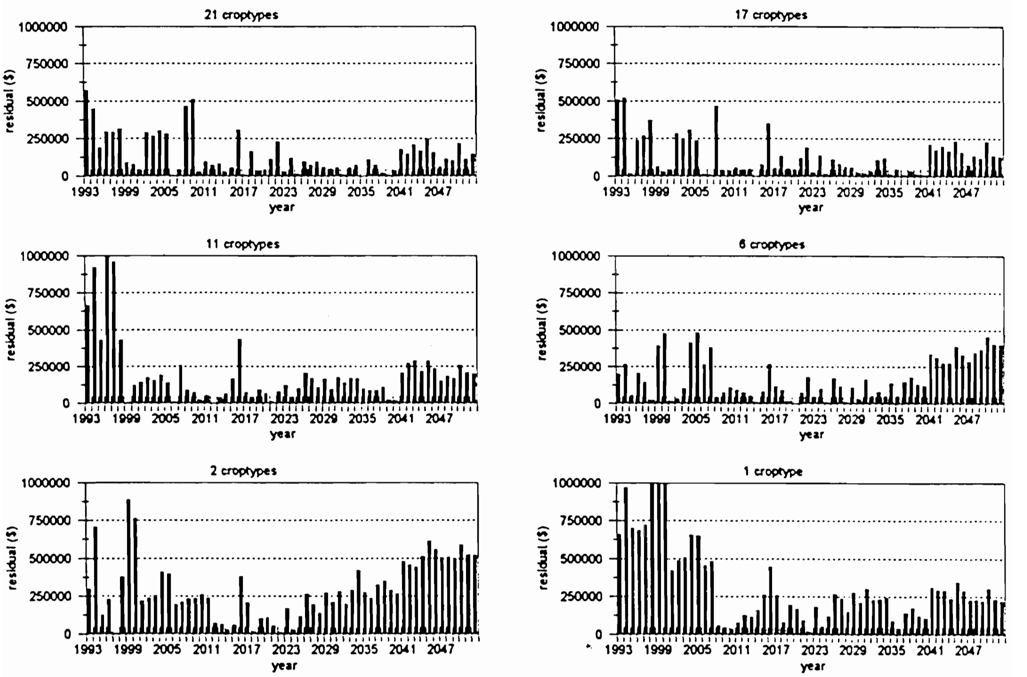

FIG. 13–Absolute residuals from stand model clearfell revenue for the series of reducing numbers of croptypes (truncated for presentational clarity).

The residuals are again quantified in Table 7 which shows percentage differences between annual harvests and clearfell revenues for the stand benchmark and each model.

TABLE 7–Percentage difference between croptype and stand model for the series reducing numbers of croptypes over the short term and the long term by total volume, log product volumes, and clearfell revenue.

	Number of croptypes					
	21	17	11	6	2	1
Short-term difference between croptype and stand model (%)						
Total volume	5.0	4.8	8.1	2.4	2.7	8.8
Pruned	8.8	7.6	19.0	13.9	9.0	9.1
Unpr. export	2.8	2.9	2.8	8.1	10.9	19.2
Clearfell rev.	3.9	3.3	8.7	1.9	2.9	8.0
Mid-term difference between croptype and stand model (%)						
Total volume	0.5	0.7	1.2	2.3	2.6	4.9
Pruned	2.7	2.4	1.7	2.5	4.6	5.0
Unpr. export	2.3	2.5	2.9	4.4	4.3	6.9
Clearfell rev.	1.5	1.2	1.1	1.4	2.2	4.0
Long-term difference between croptype and stand model (%)						
Total volume	1.2	1.3	1.9	2.8	5.2	4.2
Pruned	1.0	0.9	0.4	1.5	2.2	3.1
Unpr. export	2.3	2.5	2.9	4.6	8.2	6.4
Clearfell rev.	0.8	0.9	1.4	1.8	3.2	1.9
Over-all difference between croptype and stand model (%)						
Total volume	1.2	1.3	2.1	2.5	3.9	4.9
Pruned	2.3	2.1	2.5	2.9	3.7	4.4
Unpr. export	2.4	2.5	2.9	4.8	6.8	7.7
Clearfell rev.	1.3	1.2	1.9	1.6	2.7	3.2

DISCUSSION

Questions about what is the best strategy for croptyping and whether the stand detail model is optimal must be considered in line with management objectives. The greater the level of detail, the greater the problem complexity and consequent limitations to iterative and explorative modelling, and the greater the costs in database preparation and computer time.

In this exercise, a stand-based forest (as opposed to one based on croptype descriptions) was modelled over a long-term planning period. The model gives detail for harvest planning and yield regulation relevant to management units for forest operations. The stand-based model is the most efficient of all the strategies evaluated here in that it utilises all existing stand information for the forest at stand level, instead of averaging the detail in croptyping. However, models with less detail can be more useful for forest managers, particularly in the long term.

The croptyping exercise showed that the forest was relatively robust in many senses. The objective function values for present net worth of the forest over the long term for the various croptyping strategies were very similar. The process of modelling the same forest every time by LP optimisation meant that similar objective function values were achieved, as the same forest database was used each time and all models had the same FOLPI constraints. Even where the entire forest was aggregated into one croptype, the objective function value was still comparable. Although a manager would be interested in the difference of $4 million relative to the total of $146 million, it must be remembered that the stand-based model is itself only a representation of true stand values.

The examination of harvest plans, yield realisations, and net revenues through time showed distinctive responses due to croptyping method. Stand level detail is important to managers in the short term for decision making, as the units relevant to management decisions in this time frame are stands. Over the longer term, stand detail is less useful. Annual harvest specifications for each croptyping strategy compared with the stand model harvest specifications indicated the loss of detail due to croptyping. The company croptype-based models (Strategies 2 and 3) sacrificed most detail in croptyping, as shown by the residual standard deviations of stand volumes within croptypes, and were least similar to the stand model. Strategy 4 demonstrated how stand level information can be better utilised for croptyping. Although this strategy did not closely follow the short-term optimal harvest strategy for individual stands, it deviated to a smaller extent than Strategies 2 and 3 over the whole planning period.

Strategy 5—with stand level detail for at least the first 5 years—was very similar to the stand model in the short term. It almost completely matched the specified harvests of the base model, stand by stand. Being based on the same aggregated croptypes as Strategy 4, it continued to closely mimic the stand model throughout the long-term planning period. Strategy 5 allowed short-term flexibility in the selection of stands for harvest while providing a long-term broader planning overview in a single model.

Strategy 6 was good in the short term but less so over the longer term, reflecting the effect of the number of single-stand croptypes in the model. A high proportion of stands specified by the stand model for harvest in the first 5 years were correspondingly cut. The fact that the centroid cluster has been an effective croptyping method is probably due to the nature of the forest in that the older, near harvestable stands tended to be more variable in terms of volume and were picked up as outliers by the centroid cluster method. This possibly created a chance situation leading to a good performance for this forest database. Ward's method for cluster analysis used in Strategy 7 was not as effective because the reduction of variation between clusters makes it sensitive to outliers, and so stands that were treated as single-stand clusters in the centroid method tended to be clustered with other stands under Ward's, leading to an increased loss of detail compared with Strategy 6. Therefore, while the Strategy 7 croptypes had low variance with stand volumes, there was less short-term stand detail as there were fewer single-stand croptypes. It was still relatively accurate over the short term but was increasingly different from the stand model through the long term.

The number of croptypes had a significant effect on the extent of deviation of the croptyping strategy from the stand model. The results clearly showed that a decreasing number of croptypes increased the deviation from the stand model as the detail of the forest was successively aggregated. However, with more croptypes the difference between models with similar numbers of croptypes decreased. For example, the difference between 21 and 17 croptypes was less than that between two and one croptypes.

Decisions relating to the choice or determination of the best model cannot be made in isolation from the "costs" involved with that method. It has been shown that the bigger and more complex the model, the more it costs in terms of the time it takes to solve in FOLPI. When there are a number of planning options for a forest to be modelled, problems that take a couple of hours—or even only 45 minutes—to build and solve are an impediment to the planning process. The decision as to the optimal strategy and, hence, the size of FOLPI problems involves considering how much detail is worth in terms of solution time, and a rational assessment of exactly what level of detail is required for planning purposes. Additionally, other practicalities need to be considered. Building the forest database for this sequence of models was the most time-consuming factor in the process. Compiling individual yield tables for the whole forest based on inventory and measured data, and compiling data files of the forest information took 10 weeks. Deriving the FOLPI problems, exploring constraint options for these problems, and running them took less than 4 weeks. Correspondingly, combined generation and solution times varied from nearly 5 hours for the stand model, to 45 minutes for the variable resolution model, and less than 5 minutes for the smallest models. However, it should be recognised that much of the work required in setting up a database can be automated, in which case it may take less time to produce detailed stand-based yield tables than aggregated yield tables if the aggregation process requires subjective decision-making by the planner—for example, where aggregation is based on yield tables rather than starting points (for deriving yield tables).

Strategy 5—the composite, hierarchical, or variable resolution model—most satisfactorily balanced the trade-offs involved in compromising a degree of detail and problem-solving practicalities and costs (financial and time-wise). This model reduced the FOLPI computing time to one-sixth that of the stand model while the corresponding inaccuracies relative to the stand model were minimal, particularly over the short and mid term, and lower than for all other strategies. Strategy 4 compromised short-term detail but solved faster and provided good modelling for planning and management interests in the long term. Strategy 6 provided good short-term detail but, as discussed above, this may have been coincidental and should be tested further on more forest databases with differing age class distributions. Strategy 7 may prove to be more effective in a forest less affected by "outlier" stand yield tables.

CONCLUSIONS

Stand-based modelling is feasible for small forests over the long term. However, the usefulness of long-term detail may be offset by its cost both in database building and in solution times.

Short-term stand detail enables decisions to be made at the stand level rather than at croptype level. Strategy 5 offered the most favourable croptyping approach where losses of detail were insignificant; short-term plans were specified by stand, and longer-term aggregation enhanced comprehension of the planning problem and reduced the size of the FOLPI problem, thus shortening solution times.

The centroid method of cluster analysis was a successful strategy attempt for this forest database but it was not as effective as the variable resolution approach. In this exercise clustering tended towards sacrificing long-term detail because of high levels of aggregation in the croptypes comprising the younger stands and hence the replanting croptypes.

Strategy 4 illustrated the potential for enhancing croptyping and hence improving the value of estate modelling by making aggregation decisions based on key stand and site factors.

The number of croptypes generated in a croptyping strategy influences optimal solutions for specified harvests, yields, and revenues. With low numbers of croptypes, the deviations from the stand model (and from other strategies with more croptypes) increases. As the number of croptypes is increased, the model is better able to represent the stand model. The number of croptypes can have considerable impact on the losses of detail in harvest and planning specifications by FOLPI. Likewise, the number of croptypes should reflect the needs of management and the appropriate levels of trade-offs to meet these needs as too many croptypes may not enhance the returns to the management process but will affect preparation, solution times, and planner comprehension.

The variable resolution model with short-term stand detail and long-term aggregated croptypes is a good model for the forest database that has been used here. However, it is not safe to draw definite conclusions about croptyping strategies from this study which covered only one forest. The forest age class distribution and yield variability will influence the effectiveness of different methods. It is recommended that these croptyping strategies be evaluated on a range of forest estates. With at least two more forests, statistical tests of probability could be applied to validate the performance of croptyping strategies.

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