Yield Control

R.B Tennent

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Course Outline

Yield Control

Course Design Objective

The objective of this course is to introduce the participants to the topic of yield control. The participants will be given the theory behind yield control, and will have the importance of yield planning explained. The following sub topics will be presented

- Objectives
- Needs
- Yield prediction systems
- Tree volume functions
- Growth models

The participants will be taught methods of yield control which can be applied with the use of low level computer hardware and software, and will be introduced to more advanced methods which required specialised software.

At the end of the course the participants will be expected to understand the principles of yield control, and to be able to prepare yield control plans.

The participants will be given a number of exercises that will enable them to develop the skills required in yield control planning.

Dr R.B. Tennent will present the course. The structure of the presentation will be formal lecture sessions, followed by group discussion of the material presented. The participants will be presented with opportunities to carry out exercises, followed by a group discussion of the exercises.

Reading List

The following list of general references may be of value to the participants.

Bitterlich, W. 1984: The Relascope Idea. Commonwealth Agricultural Bureaux

Cochran, W.G. 1977: Sampling Techniques. John Wiley & Sons

Cochran, W.G, Cox, G.M. 1957: Experimental Designs. John Wiley & Sons

Draper, N.R., Smith, H. 1966: Applied Regression Analysis. John Wiley & Sons.

Freese, F. 1962: Elementary Forest Sampling. USDA Forest Service Agricultural Handbook 232

Freese, F. 1967: Elementary Statistical Methods for Foresters. USDA Forest Service Agricultural Handbook 317

Hogg, R.T, Craig, A.T. 1970: Introduction to Mathematical Statistics. Macmillan Publishing

Raj, D. 1968: Sampling Theory. McGraw-Hill

Spurr, S.H. 1952: Forest Inventory. Ronald Press.

Upton, J.G., Fingleton, B. 1985: Spatial Data Analysis by Example. John Wiley & Sons

Yield Control

Introduction

Before a forest manager can begin to manage his forests, he must know how much forest he has, what amounts of forest products his forest contains, and how fast his forest produces these products.

The first stage is inventory. After a well designed inventory has been conducted, the manager should know the answers to all the questions given above.

The next stage is to assess the rate at which the forest changes over time, if the forest manager does not harvest the forest.

The final stage is to examine the effects of management on the forest, combining the inventory information with the yield information.

Objectives

To predict allowable cut

The objective of a yield control system is to predict how much timber or other forest products can be removed at any particular time, without running out of wood in the future, and without building up too much surplus wood.

The key element is understanding what yield can be achieved from a forest. This is achieved through yield tables and growth models.

Given an understanding of the yield available form a forest, and the structure and area of forest types, the effects of various cutting strategies can be simulated, either manually or by computer.

Needs

Inventory information

Yield calculations are based in inventory data, both current and past. Current inventory data is used to prepare forest types, and to evaluate the current conditions.

Past inventory data is used to prepare yield predictions. One of the best sources of data for preparing yield calculations is remeasured sample plots.

Such plots should be large, of about 1 hectare in size. Trees should be numbered if possible, and recorded in diameter classes by species if individual numbering is not possible.

For the preparation of the most accurate yield predictions, the position of each tree should be recorded. This can be challenging, but if done, more accuracy growth models can be developed

Growth models

Growth models are of three main types, stand models, diameter distribution models, and individual tree models.

Stand Models

Stand models are the simplest to prepare. Inventory data is used to prepare averages over time, and these averages are used for prediction purposes.

Diameter distribution models

Diameter distribution models predict the change in status of a diameter distribution over time. They are suitable for tropical rainforest, although they require a considerable amount of data.

Individual tree models

Individual tree models predict the growth of individual trees in a forest. The growth of each tree is predicted after assessing the effect of surrounding trees.

Individual tree models have considerable potential for tropical rainforest growth prediction, although they require a high degree of expertise to prepare, as well as demanding specialised inventory data.

Yield prediction systems

Total approach

A Yield Control system takes data from an inventory, and uses a yield prediction system to predict the status of a forest at some point in the future, after a series of management operations.

Each element in the yield control system must be suitable for the required purpose. The inventory must have collected the appropriate data to a suitable level of accuracy. The yield prediction system must be capable of predicting future yield to a satisfactory level of accuracy. The management simulator must be logically constructed.

Tree volume equations

Tree volumes are needed for yield prediction, as most inventories concentrate on measuring diameter and a sample of heights.

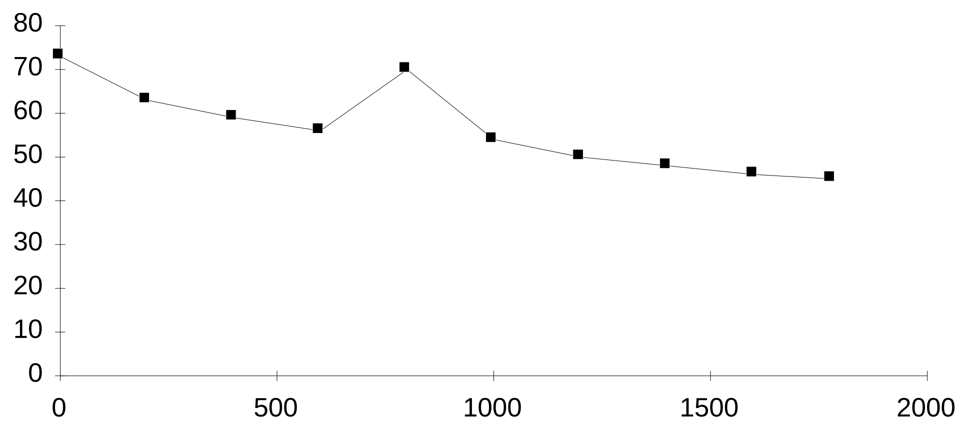
Tropical rainforest species typically have a flared buttress, a bole, and then a crown break. The stem may be hollow, or have cankers and other defects on it. Tree volume equations are prepared for normal well formed trees, and an assessment is made of the amount of timber recovered, to allow for the defects mentioned above.

Tree volume functions are prepared as follows.

1. A sample of trees is measured, either by climbing, felling, or relaskope.
2. On each tree the diameter above buttress is measured, along with the height of the measurement above stump, and the height to the top of the bole.
3. Further measurements are taken along the stem, recording the diameter and the height of the measurement point., and the bark thickness on at least a sample of trees
4. Other information is recorded, such as the species and location of the tree.

After the data has been collected, it is next punched into computer form, and cleaned. The cleaning is best done by graphing each tree, and inspecting the graphs for punching errors.

Diameter on length



The next step is to calculate the volume of the tree, either over or under bark. This is done by adding up the volume of the segments. Each segment is assumed to be a conic segment. The volumes are usually calculated by using one of the following formulae.

- Smalian's Formula

$$v = \pi \frac{d_t^2 + d_b^2}{8} l$$

- Huber's Formula

$$v = \pi \frac{d_m^2}{4} l$$

- Newton's Formula

$$v = \pi \frac{d_b^2 + 4d_m^2 + d_t^2}{24} l$$

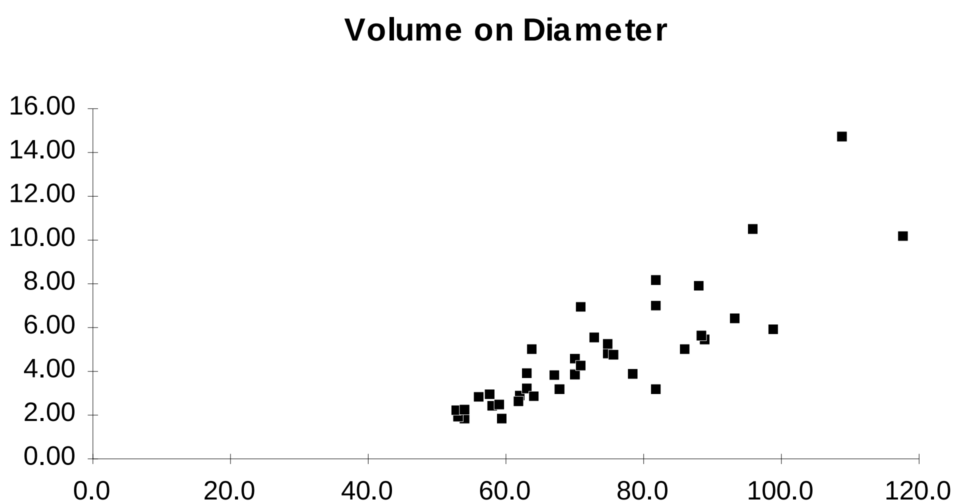
where d_b = diameter at bottom of segment

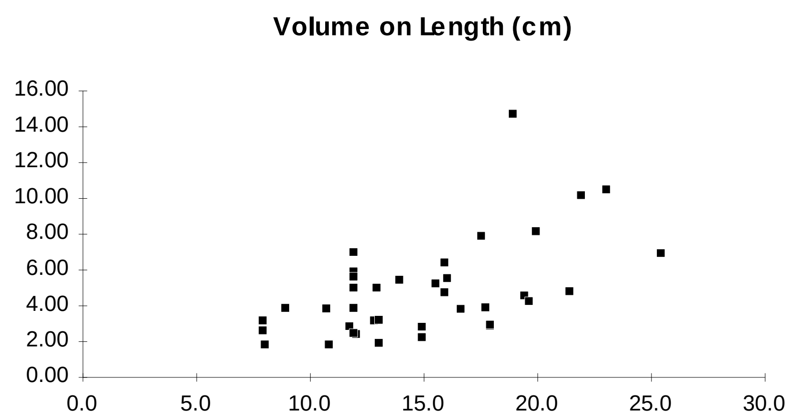
d_m = diameter at middle of segment

d_t = diameter at top of segment

Newton's formula is more accurate, but the inaccuracies of Smalian's formula can be reduced by decreasing the distance between measurement points at the base of the tree, where measurement intervals of about 1.5m are required. Above the 3m height, 3 m lengths can be used.

The volumes can now be plotted on diameter and length, to inspect the data for bad data points.





Graphing the data points will show any suspect points, which can be eliminated from the data set.

The data may need to be weighted, to remove bias.

The clean data set is next used to calculate a set of function coefficients.

There are many functions that can be fitted to the data. The following are often used.

$$v = b_0 + b_1 d + b_2 d^2$$

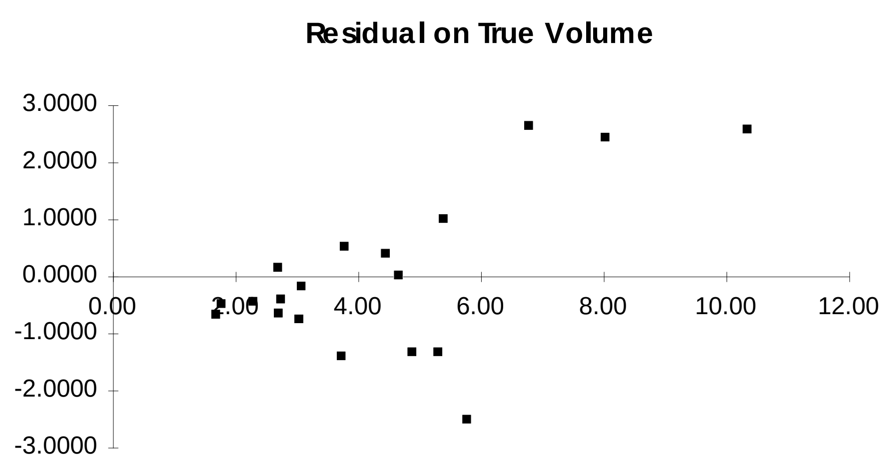
$$v / d^2 = b_0 + b_1 l$$

$$\ln(v) = b_0 + b_1 \ln(d)$$

$$\ln(v) = b_0 + b_1 \ln(l) + b_2 \ln(d)$$

Further functions can be found in published volume tables.

The functions selected should be fitted with a statistical package. The residuals, the difference between the volume of the tree and the predicted volume, should be plotted on the predicted volume, to test for bias.



The graph of residuals should be inspected. If the pattern is not even, the data will either need to be cleaned further, or a new equation selected, and the function coefficients re-estimated.

After the volume function has been prepared, the function can be used in a growth model, or to produce a volume table.

Growth models

Growth models require a set of data derived from inventory plots or long term measurement series from sample plots

The principle behind a growth model is that past growth can be used to predict future growth. The assumption is that the future growth of forest under investigation will be similar to forest that has been measured in the past.

If the two forest types are markedly different, the assumption will be incorrect, and the growth model will be unlikely to provide accurate assumptions.

Simple Growth Model

The simplest form of growth model for tropical rain forest is to assume that recruitment balances mortality in a steady state climax forest. After making this assumption, inventory data is inspected to determine the commercial harvest volume that can be obtained from a climax forest and an estimate is made of how long the forest will take to recover.

Given these assumptions, a per annum growth figure can be calculated. For example, if a volume of 50 cubic metres can be taken, and the forest is assumed to require 50 years between harvests, the growth model estimate is 1 cubic metre per annum.

Matrix Growth Models

One form of growth model that has been used extensively is the matrix growth model. A matrix model is a form of diameter distribution model.

The data required for a matrix model are diameter distributions measured at intervals over time. Matrix models can be constructed from a range of data.

Like all growth models, matrix models have limitations. The limitations are based on the principle that past growth is used to predict future growth.

The form of the matrix model is as follows.

$$\mathbf{n}_{\mathbf{t+1}} = Q \bullet n_t$$

where n is a vector containing the diameter distribution at time t.

The matrix model predicts the future diameter distribution from the current diameter distribution, multiplied by the transition probability matrix Q

As an example we will build a matrix model which predicts the change in a diameter distribution over a five year period.

From an inventory we calculate the following diameter distribution, where we have 10 cm diameter classes.

Diameter	10	20	30	40	50	60	60+
Frequency	130	90	60	40	20	15	10

We use past inventory plots to calculate that non-suppressed trees grow at approximately 1 cm in diameter each year. This means that in one five year period we can expect trees to grow 5 cm.

However, our long term plots also show that small trees are likely to be suppressed, and large trees are not likely to be suppressed. We find out from the inventory that the following proportions of trees are likely to be suppressed during a five year period.

Diameter	10	20	30	40	50	60	60+
Suppressed	.5	.4	.3	.2	.1	0	0

We also find out that small trees are more likely to die, and that the large trees to die ultimately. From the records we work out the following mortality rates over a five year period.

Diameter	10	20	30	40	50	60	60+
Mortality	.25	.20	.15	.10	.05	.01	.04

We now know that a 10 centimetre tree has a 50% chance or being suppressed, and a 25% chance of dying. We also know that the remaining trees are growing at an average rate of 5 cm every five years, which means that on average half of them will grow out of our 10 cm class every five years.

This means that the out of the trees in our 10 cm class, 12.5% will grow into the 20 cm class, and 25% will die, leaving 62.5% still in the 10 cm class.

Similar calculations show that in the 20 cm class 20% will grow into the 30 cm class, and 20% will die, leaving 60% still in the 20 cm class.

This means that at the start of the next period, the 20 cm class will consist of 60% of the trees currently in the 20 cm class, plus 12.5% of the trees currently in the 10 cm class.

We can calculate the following transition probability matrix, which shows the proportions of trees left in each class, and the proportion which grow into the next class.

.625						
.125	.6					
	.2	.575				
		.275	.55			
			.35	.525		
				.425	.495	
					.495	.96

This table is the basis of our matrix model. However the model has no provision for ingrowth. We have not allowed for small trees growing into the 10 cm class.

Ingrowth is one of the biggest limits of Matrix models. Ingrowth is difficult to estimate, as the structure of the forest has a considerable effect. The shape of the diameter distribution affects the amount of ingrowth. A forest with many large trees will have little ingrowth, due to shade suppression. A forest with many little trees will have little ingrowth due to competition.

Ingrowth is added to the model through the addition of a vector to the row of the Q matrix. This vector will vary with the structure of the forest. A number of different vectors may be needed for different forest structures.

The following vector will be used for example.

.1	.05	.02	.0	.0	-.1	-.2

The negative elements indicate that large trees suppress ingrowth, while the positive elements indicate that where there are some small trees, there is likely to be more ingrowth.

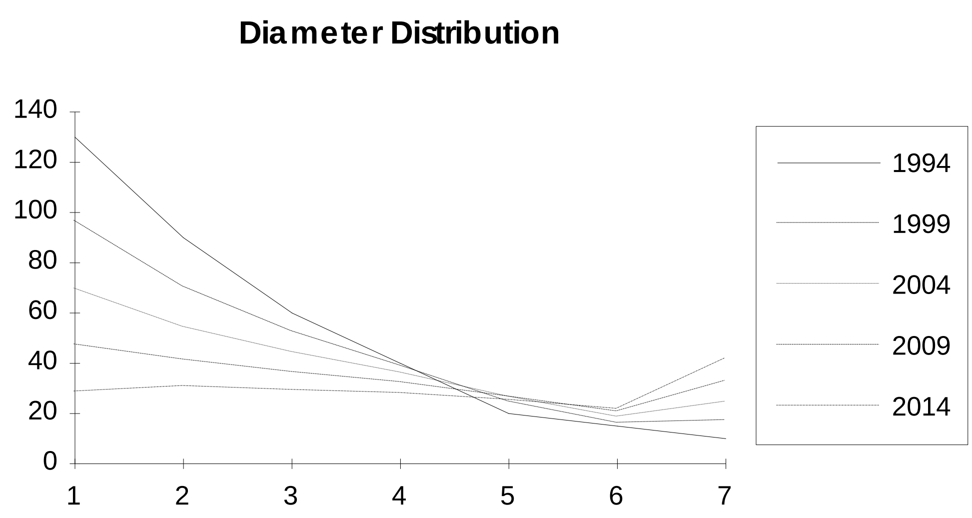
The final form of our transition probability matrix is as follows.

.725	.05	.02	.0	.0	-.1	-.2
.125	.6					
	.2	.575				
		.275	.55			
			.35	.525		
				.425	.495	
					.495	.96

This produces the following predicted diameter distributions over time.

Period	10	20	30	40	50	60	60+
1994	130	90	60	40	20	15	10
1999	96	70	53	39	25	16	17
2004	69	54	44	36	26	18	24
2009	47	41	36	32	26	21	33
2014	28	31	29	28	25	22	42

The following graph shows the distribution over time.



A matrix model is conceptually powerful, and can be prepared with the aid of a computer spreadsheet. The model can be used to prepare predictions over time, and if prepared in a spreadsheet form, the results can be subjected to sensitivity analysis with ease.

Disturbance

Catastrophic change renders most models inaccurate. Minor change can often be assumed to not invalidate the model. The table below shows what predictions the model would make if all stems above 30 cm were removed, along with 20 % of remaining stems.

Period	10	20	30	40	50	60	60+
1994	104	72	48	0	0	0	0
1999	80	56	42	13	0	0	0
2004	62	44	35	19	5	0	0
2009	48	34	29	20	9	2	0
2014	37	26	24	19	12	5	1

Major change

Matrix models depend on a relationship between past growth and future growth. The model demonstrated above would be unlikely to give representative answers if the diameter distribution was subjected to massive change, as in a cyclone, for example.

Catastrophic change would result in all the coefficients being subject to change. In the above example, the 50% suppression figure would be likely to change markedly. The mortality figures would change, and the growth rate may change.

Extremely severe logging damage would constitute major change, and invalidate the matrix model. Matrix models can give satisfactory predictions for logging which is carefully controlled, does not remove a major amount of the forest, and does not damage surrounding trees.

Species mix

The matrix model shown above has combined all species into the one diameter class. This was for simplicity. The matrix model can be generalised, to allow for additional species. This is more complex.

Combining all species into one diameter frequency implies that any harvest removes species in the same proportion. If a harvest removes all of one species, and leaves another species entirely, subsequent growth may produce a different forest type from the original. This would invalidate any future growth predictions.

Sustained Yield Calculation

The most basic form of yield control is to calculate and apply a sustained non-declining yield.

The procedure is as follows.

- Inventory the forest to assess the merchantable volume of each forest type to be managed.
- Determine the area suitable for sustained management purposes. This should exclude any ecologically significant areas, any environmentally unstable areas, and any areas with social constraints.
- Calculate a cutting cycle, the period between harvesting the same area of forest. Note that the cutting cycle should be estimated conservatively, with allowance for risks such as typhoon and fire.
- The estimate of sustained yield is the total volume divided by the cutting cycle.

This is a rudimentary method, which is suitable for global planning at a national or regional level. The calculations must be done conservatively, as the method does not allow for any uneven distribution of forest by type. The figures calculated are of considerable use, and should be calculated if only to check any other figures which may be derived.

Yield Control Systems

Total approach

A Yield Control system takes data from an inventory, and uses a yield prediction system to predict the status of a forest at some point in the future, after a series of management operations.

Each element in the yield control system must be suitable for the required purpose. The inventory must have collected the appropriate data to a suitable level of accuracy. The yield prediction system must be capable of predicting future yield to a satisfactory level of accuracy. The management simulator must be logically constructed.

Yield control systems use combinations of similar forest term forest types. An inventory should produce results based on forest types. These forest types for the basis of the yield control system.

Preparation of inventory tables

The first step in using a yield control system is to prepare summary tables showing the area of each forest type that the forest manager has to manage.

This is done by using the inventory data to work out how many different forest types the manager has. The inventory results should already be in forest types, which may or may not be suitable for yield control. Inventory forest types can be combined if desired.

The area of forest in each forest type is calculated. Note that any time elements should be reflected within forest type, and not as a forest type.

Example of forest type table

Forest Type	**Type Code**	**Area**
Mixed Dipterocarp	MDIP	1200
Hardwoods	HARD	500
Degraded Forest	DEGF	2500
Logged Forest	LOGD	500

Yield Tables

A yield table should be prepared for each forest type.

Yield tables can be prepared from inventory data or growth models.

To prepare a yield table from inventory data, the inventory data for each forest type is averaged, providing an indication of the average yield for different forest conditions.

If a growth model is used, the growth model should be run to produce the predicted growth for each forest type.

The yield tables should show the yields from the current time period onwards.

In the example given below, the mixed Dipterocarp forest is growing slowly, the hardwood forest is not growing, the degraded forest has a low volume, and grows slowly, and the logged forest has no initial volume, but grows rapidly.

Example of Yield tables

Period	MDIP	HARD	DEGF	LOGD
5	45	60	20	0
10	50	60	22	5
15	55	60	24	10
20	60	60	26	16
25	60	60	30	22
30	60	60	34	28
35	60	60	38	34
40	60	60	42	40
45	60	60	44	48

Preparing a yield control plan

The forest manager can now begin to prepare his yield control plan.

This can be done either by hand or with specialist computer programs. The principles are the same. The manager must allocate timber from his forest to fill demand without overcutting the forest.

The manager must carry out a series of calculations. For each yield period he must allocate the cut from a certain area of forest to a certain wood use. The area cut must then be reassigned to a new forest type, such as replanted, or logged. The areas available are updated for the next period.

Example of yield scheduling

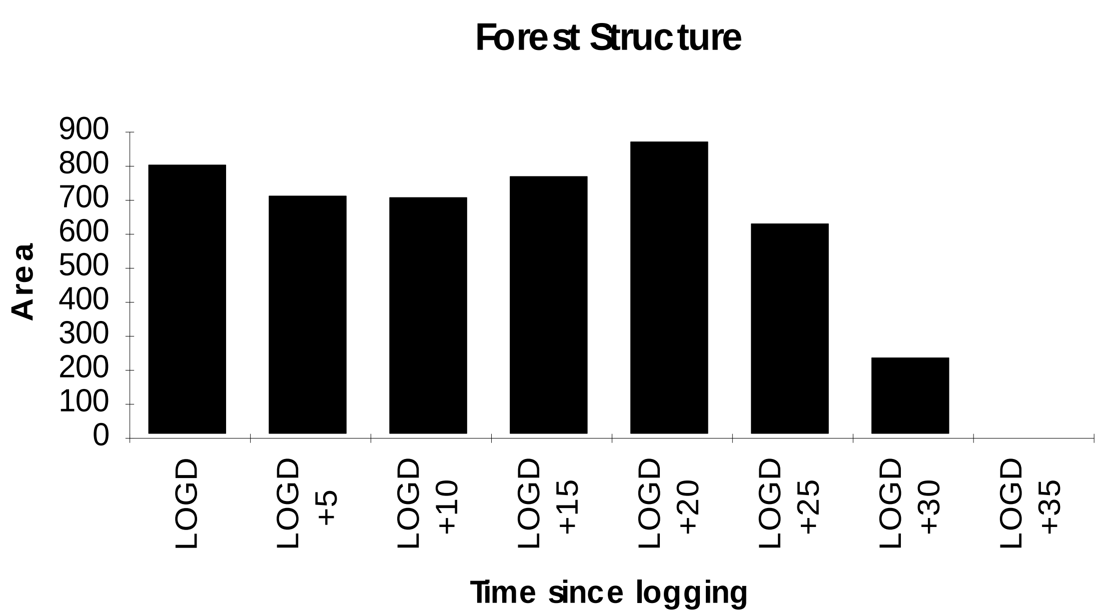
For the data given above, the manager decides to manage the 4700 hectare forest on a 40 year cutting cycle. He calculates that he can achieve a volume of 44 cubic metres. He plans to cut a volume of approximately 26,000 cubic metres over a period of five years. On average, he expects to log about 115 hectares per year, or about 590 hectares over a five year period.

The manager decides to cut the forest type HARD first, followed by MDIP, and DEGF. Each period the forest that was cut the following period is added into the class LOGD, which is classified by time since planting. After he has logged the entire forest, he will begin logging the previously logged forest in the LOGD class.

The manager plans to remove the following volume, from the classes shown over the next few five year periods.

Period	Volume	MDIP	HARD	DEGF	LOGD	Area
1995	26040		434			434
2000	26010	441	66			507
2005	26015	473				473
2010	26000	286		340		626
2015	26010			867		867
2020	26010			528	237	765
2025	26014				703	703
2030	26022				708	708
2035	26026				799	799

The logged over forest will have the following structure at the end of the period.



The forest manager should simulate the cutting of his forest over a long enough period to check whether he can meet projected demand. For this example we have simulated 9 periods. It would be more desirable to simulate for at least two cutting cycles.

From the information above, the manager can see that after three periods he will have to increase his area cut to meet his target of 5200 cubic metres per year.

Other constraints may enter. The manager may be required to start with a lower cut, and increase to a final target. To test a range of options can involve a considerable amount of calculating.

There are a variety of computer models that can do the bulk of the work. These include deterministic models, where the manager makes the decisions, and optimising models, where the manager imposes a set of constraints, and the computer provides a series of solutions.

Such models are available from universities and research institutes in Australia and New Zealand.

Exercises

1. What information would be needed to prepare a diameter distribution growth model? Where could this information be obtained?
2. How can a volume function be tested for bias? What data is needed, and what procedure should be followed?
3. An area of forest was harvested in 1952, producing 43 cubic metres of timber, and leaving a residual standing volume of 10 cubic metres. The forest was left untouched until 1993, when a further harvest produced 40 cubic metres of timber, and a residual standing volume of 11 cubic metres. What is the best estimate of the annual productive capacity of the forest?
4. Given the following diameter frequency distribution, what would be the predicted distribution in five years, using the five year period transition probability matrix shown below?

Diameter	10	20	30	40	50	50+
Frequency	100	90	60	40	20	0

Transition Probability Matrix

.5	.1				-.1
.2	.5				
	.1	.5			
		.1	.6		
			.2	.7	
				.2	.9

5. In the example of yield scheduling given in the notes, the manager decides that he is overcutting his forest. He decides to reduce his annual cut to 4800 cubic metres. He also decides to cut a minimum of 100 hectares of forest each year, by cutting a mixture of MDIP and HARD from the start, instead of cutting all the HARD followed by the MDIP, as in the example. How many hectares of MDIP should be cut during the first year, and how many hectares of HARD?