

# Simple diameter class and cohort modelling methods for practical forest management

Denis Alder<sup>1</sup>

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## Summary

Two simple growth models are compared. MYRLIN is a diameter class projection model, whilst GEMFORM is a cohort model. Both can be downloaded from the Internet as open source software; they are Visual Basic modules embedded in Microsoft Excel workbooks. Both employ a simple basic model, with diameter increment and mortality rate constant over size class and stand density for a species group. Recruitment is assumed to replace losses (mortality or harvesting). The models differ somewhat in their forest management interface. MYRLIN simulates a whole forest, dividing a number of strata into equal area coupes. GEMFORM is a stand model, but can optimise harvest intensity on each stand to maximize AAC over multiple felling cycles, and project several strata simultaneously. GEMFORM has better forest inventory analysis features, and is designed to incorporate stem quality and merchantability scores.

The method of diameter class projection is compared with that of cohort projection. In a diameter class model, inventory data is summarised into classes, and assumptions are required to relate diameter increment to transition frequencies. Cohort models can work directly from a tree list, or may summarise data into 1-cm cohorts. Cohorts can be tagged with characteristics such as form and decay defect, as in GEMFORM.

Both methods are used to make a projection of a 26 years old PSP from Guyana. It was found that the chi-squared probability that actual and projected final diameter distributions were the same was 15% with the diameter class projection, and 76% with the cohort method. The lower accuracy of the diameter class method is attributed to the information loss when data is summarised, and the extra assumptions required. The example also shows how cohort models can be very simple.

The issue of whether simple models without density dependence or other interactions can be useful is examined by describing a testing method based on analysis of residuals from a model. A stand parameter such as basal area increment can be compared on actual and projected PSPs. The  $R^2$  between these is the Coefficient of Determination of the model. The residual ratios (observed over predicted basal area increments) can be regressed with a stand density index to derive a multiplier; this can be used to provide a more complex, density sensitive model. It was found from GEMFORM, using Guyana PSP data with 16 species groups, that 80% of variation was explained by the basic model, and 86% by the model including stand density.

However, both MYRLIN and GEMFORM are designed for processing partial and incomplete inventory data. In these cases, addition of a stand density factor would limit the models utility. It is concluded that the models are useful for first-order management planning applications, such as calculating future yields and Annual Allowable Cut, but not for comparisons among treatments or other more sensitive issues.

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<sup>1</sup> Consultant in Forest Biometrics. 9 Stansfield Close, Oxford, UK. Email: denis@bio-met.co.uk

## Introduction

### Proposition

In many situations where moist tropical forest is being managed, the growth and yield information available is very limited, or perhaps even non-existent; inventories of baseline data are also often partial and incomplete. This paper considers the types of simple models that can usefully be applied in such situations, to assist in planning sustainable yield. It especially contrasts the classical diameter class projection method with the cohort modelling approach. The latter is often thought to be more elaborate, and perhaps requiring a basis of richer growth data than classical stand projection. However, it is shown here that it can also be seen as being as simple and practical as diameter class projection, and perhaps intrinsically more accurate.

### Literature Review

There are now a large number of examples of forest growth models that have been applied to forest management in moist tropical forest managed under natural regeneration (MTF). The archetypal ones are those of Kofod and Korsgaard (Kofod, 1982; Korsgaard, 1982, 1991), and Vanclay (1989). Both of these models had well-defined precedents in temperate and sub-tropical forestry from simpler forest types. This literature has been extensively reviewed by many authors. Vanclay (1994) is thorough and extensive with respect to literature prior to that date. Vanclay (1995) is a more condensed and accessible review.

Korsgaard's (*op. cit.*) approach, developed for forest management in Malaysia, was based on a computerisation of the classical method of stand projection. This has been used in some form in tropical forest management since the time of Brandis in Burma in 1856 (Brasnett, 1953). We will refer to this as the *diameter class modelling* method.

Vanclay's (1989) method, by contrast, employed the idea of *cohort modelling* for his work on the management of the North Queensland rainforests. This has its roots in an Australian tradition extending back to the work of Gibson *et al.* (1969) and Opie (1970) on models of Radiata Pine and Eucalyptus forests, respectively.

There are other approaches to modelling mixed natural forests, notably the North American tradition of so-called gap models (*eg.* Shugart *et al.*, 1977, Urban *et al.*, 1991); the family of models based on spatial analysis of competition among individual trees (*eg.* Young & Muetzfeldt, 1993, Gourlet-Fleury & Houllier, 2000); and the process-based stand models of Appanah *et al.* (1991) which have been developed in Malaysia. However, these latter methods require fairly extensive growth data for calibration, and are not suitable for basic or introductory forest management. They are not discussed further in this paper.

A separate tradition is that of *matrix modelling*. This derived from plant and animal demographic models, with the first introduction into forest management by Usher (1966). The topic is reviewed by Vanclay (1994) and Alder (1995). There are a number of examples of matrix models in tropical forestry (*eg.* Mengin-Lecreulx, 1990; Zagt, 1997; Eba'a Atyi, 2000). However, we may note that the majority of matrix models of forest growth, whatever their aetiology, are essentially formalised mathematical presentations of diameter class projection.

## A basic diameter class model: MYRLIN

### Description

As an example of the simulation technique used in a diameter class projection model, we may consider the MYRLIN model (Alder *et al.*, 2002). This model and its documentation can be downloaded as open source software from <http://www.bio-met.co.uk/myrlyn>. It is a *Microsoft Excel* application comprising three modules, incorporating both worksheet layouts and programs in Visual Basic that are run as macros. The website includes complete documentation.

In this system, species data from an inventory is summarised by species groups into diameter classes. The model is flexible as to the diameter limits employed, but is likely to work best with 10-cm classes. The model also works on a flexible time step, which can typically be from 1-5 years.

Growth, in terms of diameter increment, is assumed to be constant across all size classes, as is mortality, but may be different for each species group. Simulation proceeds by calculating the trees lost from each class by mortality over a time period. After this, the moving trees are calculated, using the simple assumption of uniform growth rates and distribution of trees within a size class. In this case, in a class of width  $w$  cm, and increment of  $i$  cm/year, the proportion moving to the next class over  $t$  years will be  $t.i/w$ .

The model deals with recruitment by allowing the user to define a recruitment factor  $f$ . If the total number of trees lost by mortality or harvesting is say  $L$ , then recruitment into the lowest class is  $f.L$ . If  $f$  is 1, then population will remain constant.

Harvesting is carried out by removing trees from the upper diameter classes. The model allows a percentage of trees above a minimum size class to be harvested. Each species group may have its own minimum size and felling percentage. The size limit must however equate to a diameter class boundary, otherwise only trees in the next classes above are considered for felling.

Felling damage is applied in each class as a loss factor, or induced mortality, that is proportional to the intensity of the harvest. If the volume harvested is  $V_h$ , and the volume before harvest is  $V_o$ , then the proportion killed are calculated as  $k.V_h/V_o$ .  $k$  is a parameter supplied by the user: a value around 1 would be fairly typical (eg.. Tang, 1976).

### Management context

The MYRLIN growth modelling engine is applied to multiple stands as a simple concession management tool. The entire forest area can be split into a number of blocks, each with their own stand table and area. The model applies simple area control to these blocks. If the user specifies a rotation of  $T$  years, with a  $t$  year time step, then the forest is split into  $T/t$  coupes. If total forest area is  $A$  ha, then the area cut in each period will be  $A.t/T$  ha. The model takes the blocks (which may be one or more) in the sequence supplied by the user and subdivides them or pools them (depending on their relative size) to create coupes consisting either of a partial block, or a combination of whole blocks and a partial block, to achieve the regulated area in the period.

The growth model is applied to each block independently. The outputs from MYRLIN show the harvests by period in aggregate, and listed for each block. They are designed to provide the basis for a simple management plan.

This management context for the model is not part of the diameter class projection process. The same type of simple growth model can be applied to single stands, or alternatively in much more complex ways, as for example in the IwoPlan harvest scheduling model (Alder, 2001).

## Model behaviour

A simple diameter class projection model has some inherent behaviour that is a direct mathematical consequence of its structure. These properties include:

- ❑ Equilibrium exponential distribution: The model will tend to produce a stable diameter distribution with a form close to the exponential distribution.
- ❑ Equilibrium volume or basal area: The total volume or basal will tend to a stable limit with a single species.
- ❑ Ecological succession driven by mortality rate: With several species, if recruitment is proportional to stock at the last cycle, species with higher mortality will die out. This may lead to the appearance of a non-equilibrium volume in the multi-species case.

## A simple cohort model: GEMFORM

### General description of cohort modelling method

GEMFORM is another model that can be downloaded and used freely from the Internet (<http://www.bio-met.co.uk/gemform>). Like GEMFORM, it is written as an Excel application, although it is structured slightly differently, as an Excel Add-In with the various macros executed from its own toolbar. The website gives documentation, although this is more limited than that for MYRLIN.

There are basically two routes to building a cohort model. The first constructs data into small diameter classes (typically 1 cm) by summarisation. In a conventional diameter class model, this summary would be arranged in the computer as a species x size class array. In a cohort model, it is rather structured as a list, with each list element being a data structure at least the following items:

SPP	<i>Species code</i>
DIAM	<i>Cohort diameter</i>
NKM	<i>Numbers of trees per unit area</i>

This structure might often have additionally, entries for quality class and crown position depending on the design of the model. When data is compiled to a cohort list by summarisation, the cohort diameters are taken as the mid-point of whatever classes are used. Empty classes are not included in the list.

The second route to constructing a cohort model starts with individual trees from a sample plot or stock survey as a list. A list as above is constructed, but each individual tree will have an entry. The cohort diameter will then be the same as the tree diameter. The number of trees per unit area will be the same for all trees from the same type of sample unit.

The method of simulating growth in a cohort model is different to that in a diameter class model. Table 1 summarises the differences.

**Table 1: Growth simulation in diameter class and cohort models**

<b>Growth process</b>	<b>Diameter class model</b>	<b>Cohort model</b>
Increment	<i>Numbers in classes adjusted, usually based on the assumption that outgrowth will be given by <math>t.i/w</math>, where <math>t</math> is time interval, <math>i</math> is class increment, and <math>w</math> is class width.</i>	<i>Increment for the cohort is added directly to the cohort diameter.</i>
Mortality	<i>Numbers in the class are reduced by the annual mortality rate compounded over the time step.</i>	<i>Cohort numbers are reduced by the annual mortality rate compounded over the time step.</i>
Recruitment	<i>Numbers are added to the first class based on a function to calculate recruitment by species.</i>	<i>New cohorts are added to the list to simulate recruitment. Initial cohort diameters, numbers, and species may all be determined by functions.</i>

There are a number of other devices that can be employed in a cohort model for greater elaboration. Some of these are described in Vanclay's (1989) paper on the North Queensland model and related publications (eg.. Vanclay, 1991, 1992). The present author has employed other techniques in his own more complex models (eg.. Alder, 1995, 1997, 1998a). In particular, cohorts can be split to represent changes in a property such as defect or crown status for a proportion of trees, based on some function of tree and stand properties. Cohorts which become empty as the stocking parameter falls to negligible levels may be removed from the list.

### **The design of GEMFORM**

Like MYRLIN, GEMFORM is designed for situations where only rudimentary or assumed growth data is available. It is assumed that each species or species group has a mean diameter increment, and mortality rates for sound, healthy trees or damaged/decayed ones. Data is compiled initially from inventory plots into cohorts which are characterised by the variables shown in Table 2. Because of the way the model works, it is not necessary to retain species identity internally: Only the essentials are retained, which are the applicable growth model serial number, and whether or not it is a timber species. Tree diameter is retained as a 1-cm class value for the cohort, with numbers per km<sup>2</sup> of all applicable cohort members being summed. Cohorts are also differentiated by form defect and damage or decay status. Form defect affects utilisation in harvesting, whilst decay or damage result in differential mortality rates being applied.

Increment and mortality do not involve any elements of competition, and are essentially linear functions. GEMFORM produces outputs for each felling cycle, and because intermediate values are not displayed, it therefore makes growth and mortality projections across the whole felling cycle in a single step. If a cohort has an initial diameter of  $D$  cm, and increment if  $i$  cm yr<sup>-1</sup> and the felling cycle is  $t$  years, then diameter at the next felling cycle,  $D_t$ , will be :

$$D_t = D + i.t \qquad \qquad \qquad \{eq.1\}$$

**Table 2 : Data structure for GEMFORM cohorts**

Symbolic name	Variable type	Description
MODEL	Integer	<i>The growth model serial number applicable to this species</i>
TIMSPP	Logical	<i>TRUE if the species is a timber species, FALSE otherwise.</i>
DIAM	Real	<i>The cohort diameter. Tree data is initially compiled into 1-cm cohorts.</i>
DEFECT	Logical	<i>TRUE if the tree has form defect sufficient to prevent its use, FALSE otherwise.</i>
DECAY	Logical	<i>TRUE if the tree has significant indications of decay or damage, FALSE otherwise.</i>
NKM	Real	<i>The number of trees per km<sup>2</sup> in the cohort.</i>

Similarly for mortality, calculations are made over the whole cycle in a single step. If  $N_o$  is the number of trees in a cohort at the start of a cycle (after harvesting), and  $m$  is the annual mortality rate, the numbers at the next cycle (after  $t$  years) will be:

$$N_t = N_o.(1-m)^t \quad \text{\{eq.2\}}$$

Recruitment is a little more complex, as it is continuous during the cycle. It is simulated in the model by a sub-process within an annual loop. The total number of recruits to be generated is calculated so as to exactly balance losses from mortality in each cohort. This is a simple assumption that will result in the long run in a stable population and maintains the same proportions of species, defect and form classes.

Recruits are added in principle as annual cohorts between each felling cycle. The size of the recruit cohort established in year  $t-k$  at the next felling will be given by equation {1} as:

$$D_r = D_b + i.(t-k) \quad \text{\{eq.3\}}$$

where  $D_b$  is the base diameter for recruitment, specified as a parameter to the model. This should be the smallest measured diameter in the inventory data.  $D_r$  is the diameter of the cohort at the next felling cycle, and  $k$  is the number of years prior to the next cycle in which the recruit cohort is established. The numbers of the cohort will be given from equation {2} as:

$$N_r = (N_m/t).(1-m)^{t-k} \quad \text{\{eq.4\}}$$

where  $N_m$  is the total mortality in the 'parent' cohort, and  $N_r$  is the number of recruits surviving to the next felling cycle.

This picture is complicated slightly by the need to avoid dealing too much with cohorts with stockings that are small fractions of 1 per km<sup>2</sup>. Such cohorts can create problems in the model as they can grow to very large sizes (and hence volumes) whilst being invisible on outputs showing N/km<sup>2</sup> rounded to the nearest integer. To avoid this the model treats as empty any cohort with less than 0.1 tree/km<sup>2</sup>. This logic would result in many recruits being eliminated at the outset. Accordingly, if the number of annual recruits calculated,  $N_m/t$  is less than 1 per km<sup>2</sup>, then the recruits are established periodically, at evenly spaced intervals of years, within the felling cycle, rather than annually. The interval is calculated to ensure that each recruit cohort has a stocking of at least 1 (or if  $N_m$  is less than 1).

### **Harvesting and yield regulation**

Harvesting in GEMFORM is controlled by a minimum felling diameter, and additionally by one of three possible regulatory parameters. These are:

- ❑ Percentage of trees above the minimum felling diameter that may be felled.
- ❑ Number of trees per ha above the minimum felling diameter that may be felled.
- ❑ Annual allowable cut (AAC), or maximum volume in  $\text{m}^3\text{ha}^{-1}\text{yr}^{-1}$  that may be felled.

The two former methods correspond to conservation rules that the author has found in use in various localities.

In the simulation, felling is carried out by reducing tree numbers in cohorts that are eligible for harvest as: (1) above the diameter limit, (2) of commercial species, (3) of acceptable form and (4) not decayed, until the requisite constraint is met. This is done in practice as a percentage of each cohort that may be felled. The other two types of constraint (N/ha or AAC) are converted to this basis by a preview of the total possible number of harvestable trees.

In addition, GEMFORM has an optimising mode, in which it searches for the maximum sustainable AAC over a specified number of cycles. This is done by using a first estimate based on felling of all available trees, and then alternatively halving and doubling the difference to the next estimate. The simulation re-runs itself automatically until it finds the largest value that can be sustained over the indicated number of cycles.

### **Management context**

GEMFORM does not operate as a direct planning tool for a complete felling series as MYRLIN does. However, cohort lists are compiled and model runs presented for each statistical stratum specified in the inventory, or for a selected subset of them. Its normal use would therefore be to determine the sustainable AAC for each stratum. This information could then be used externally to calculate appropriate coupe sizes and felling series.

## **Comparative testing of the models**

### **Features in MERLYN and GEMFORM**

MERLYN and GEMFORM share a common approach based on a very simple growth model. They differ in that one uses the diameter class projection paradigm, whilst the other is a cohort-based model. They also differ in a number of features with regard to their application for forest management planning. Table 2 clarifies these similarities and differences.

This table purely compares the modelling features of the two systems. Both also provide stand table and inventory calculation facilities, but these are not of direct interest to this paper. It should be noted however that GEMFORM is able to provide inventory analysis from a variety of data formats, whereas MYRLIN only produces basic stand tables from a standardised data layout. MYRLIN however also includes a tool to assist in estimating growth rates where direct data on a species is unavailable.

**Table 2 : Comparison of features in MYRLIN and GEMFORM**

<b>Feature</b>	<b>MYRLIN</b>	<b>GEMFORM</b>
Diameter increment and mortality	<i>Growth assumed constant across size classes, differing only by species. No competition/stand density effect. No effect due to defect. A table of increment and mortality rates for each species group is supplied.</i>	<i>The same, except that mortality rates can be differentiated for sound and damaged/decayed trees.</i>
Recruitment.	<i>Total recruitment in a time step equals total losses. Recruits are partitioned among species according to their frequencies after the losses have occurred. Harvesting losses are replaced by recruits in the following period. Recruitment added to first size class.</i>	<i>Total recruitment equals total losses, based on frequencies by species and also form and decay classes.</i>
Time step	<i>Variable, with best results from 1-5 years. Outputs report one line per period, so 5 years step has 1/5th detail of 1 year step.</i>	<i>Corresponds to felling cycle, can be very long. Typically may be 20-40 years. Recruitment done on 1-year step within felling cycle.</i>
Diameter classes	<i>Can be variable. Model does not allow growth across more than one class per time step. Last class includes all trees above a size limit, making volume calculation uncertain if too low. Growth model assumes trees uniformly distributed within class.</i>	<i>No diameter classes, as cohort model. No inaccuracies about volumes of large trees, or assumptions required for distribution of trees within classes.</i>
Harvesting	<i>Trees above diameter limit removed to a percentage limit. Diameter limit must correspond to class boundary. Diameter limit can differ between species</i>	<i>Trees removed above diameter limit, may be any value. Further controlled by either % of stand, maximum N/ha or AAC.</i>
Stem quality	<i>Stem quality is not modelled in MYRLIN. All trees above a size limit are treated as potentially commercial.</i>	<i>The model discriminates form defect and defect due to decay and/or damage. Both affect merchantability. The latter also affects survival.</i>
Forest management	<i>Operates as concession planning tool using area control. Total forest area subdivided into blocks or strata, allocated to coupes of equal area. Each coupe modelled separately. Outputs show total forest yields.</i>	<i>Shows separate projection for each block. Has optimising mode for each block that will maximize sustainable AAC.</i>

### **Comparisons with long-term PSP measurements**

To test growth models properly requires long-term PSP measurements. Such data is not very common, implying that there is considerable uncertainty about the accuracy of different kinds of models.

In this paper, the diameter class and cohort methods are compared and tested using data for one species from a single plot. This was a plot established in central Guyana in 1964, and re-measured several times up to 1975. Selected sample trees, rather than a fixed plot area, were measured over an indefinite perimeter. In 2000, the plot was cleaned and the trees that could be identified re-measured. For the initial work, only a single species was selected for re-measurement, Greenheart (*Chlorocardium rodiei*).

A total of 62 trees were located in 2000 from the initial data sets 98 measured in 1964. It was reasonably certain that the missing trees had died: some of the deaths were recorded on the intermediate measurement sheets. Average increment was 0.186 cm yr<sup>-1</sup> over the period 1964-2000 for the surviving trees; annual mortality rate was estimated at 1.26% per annum. There was almost no correlation of increment with either tree size or crown position (R<sup>2</sup> was 0.059 and 0.058 respectively, with 62 sample trees), based on average growth over the period for each tree.

To compare the diameter class and cohort methods precisely and transparently for this simple case, a spreadsheet was set up directly to use each type of modelling method to project growth. For the diameter class model, the 1964 data were grouped into 10-cm classes, and projected in 5-year steps, using the fixed increment and mortality rates noted above to calculate diameter class

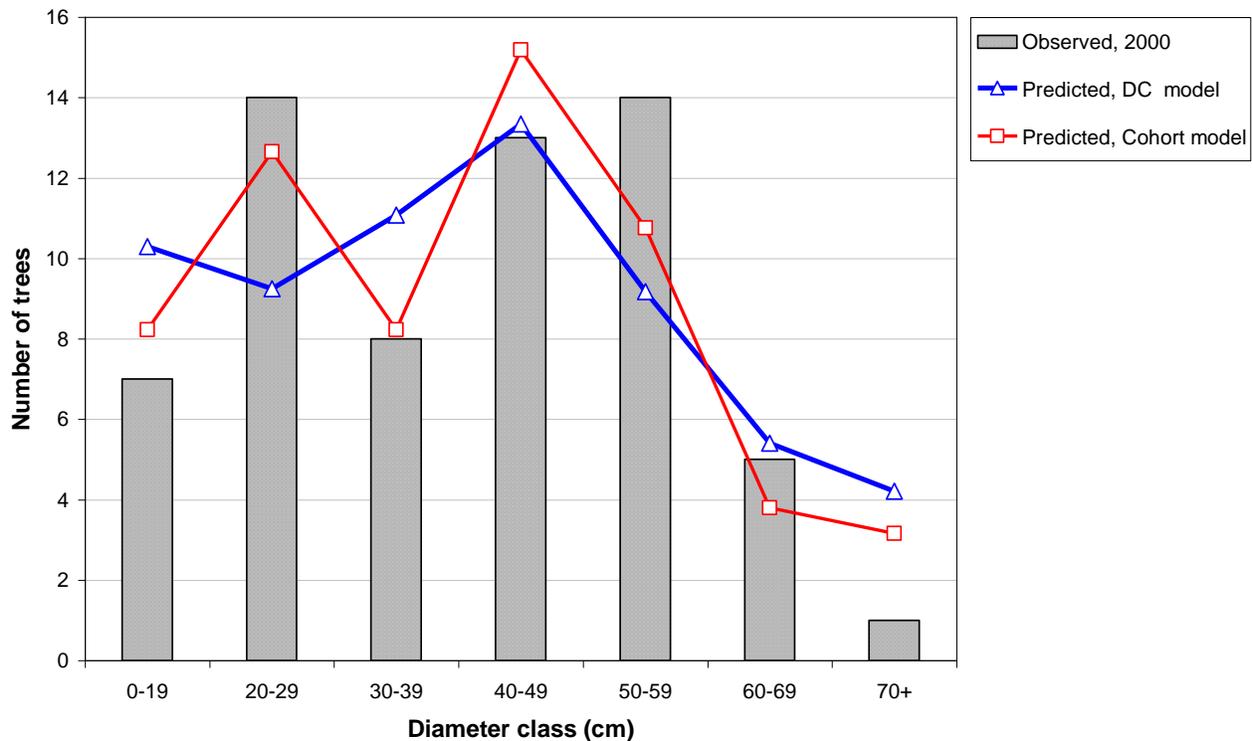
transitions at each time step. No recruitment was simulated, as the plot data also does not provide this information.

For the cohort model, the original tree list was used. Each tree was treated as a cohort with a density of 1 per unit area (bearing in mind that actual plot area is unknown). Total increment over the 36 year period of 6.70 cm was added to all cohorts ( trees) to give an estimated year 2000 diameter. The numbers per unit area were reduced by the 36-year survival function from 100% to 63.3%. This list provided the cohort model estimate of the new stand. Figure 1 shows the actual year 2000 distribution as bars, and estimated distributions from the diameter class and cohort models as lines.

The  $\chi^2$  (chi-squared) statistic was used to quantify the similarity of the predicted and actual distributions. For the diameter class model, there was 15.3% probability that the observed data were from the same distribution as the model predictions. For the cohort model, there was a 74.6% probability that they were the same. A null model was constructed for comparison, comparing the 1964 and 2000 distributions directly. These had a less than  $10^{-6}$  probability of being the same. Table 3 shows the full data for the 1964 and 2000 distributions and the projections by both methods, together with the  $\chi^2$  values and probabilities. The classes are grouped to avoid a zero frequency in any of the predicted values, which makes  $\chi^2$  impossible to calculate.

**Figure 1 : Diameter distribution of natural Greenheart stand after 36 years, with projected values by diameter class and cohort modelling methods.**

*Data from Guyana Essequibo –SP 7-64, courtesy Guayana Forestry Commission.*



**Table 3 : Observed and projected data for the Essequibo Greenheart PSP**

Projected diameter classes	Numbers of trees on plot							Total			
	0-19	20-29	30-39	40-49	50-59	60-69	70+ cm		$\Sigma$	df	$P(\chi^2)$
<i>Observed, 1964</i>	28	12	21	23	6	6	2	98			
<i>Observed, 2000</i>	7	14	8	13	14	5	1	62			
<i>Predicted, DC model</i>	10	9	11	13	9	5	4	63			
<i>Predicted, Cohort model</i>	8	13	8	15	11	4	3	62			
<b>Chi-squared calculation</b>											
<i>(f-F)2/F, DC model</i>	1.06	2.45	0.86	0.01	2.54	0.03	2.45	9.38	6	15.3%	
<i>(f-F)2/F, Cohort model</i>	0.18	0.14	0.01	0.31	0.98	0.38	1.48	3.49	6	74.6%	
<i>(f-F)2/F, Null model</i>	15.75	0.33	8.05	4.35	10.67	0.17	0.50	39.81	6	0.0%	

### Extending and validating simple models

Both MYRLIN and GEMFORM can be regarded as minimalist designs in terms of current forest modelling technology. There is no effect of stand density. There is no variation in either increment or mortality with tree size or other factors. Can such models truly be useful in predicting stand growth?

The author has come to this approach through the development of more complex models, notably CAFOGROM versions 1 and 2 (Alder, 1995; Alder & Silva, 2000), and SIRENA (Alder, 1997). He has found that if long-run PSP measurements (15 years or more) are available, then it is possible to genuinely discern second order processes such as competition and changes in speciation; but with short-run plot data, including assumed relationships simply seems to accentuate bias without improving performance. This process of testing and evaluation whilst adding complexity to the model was described with regard to the PINFORM model (Alder, 1998a, 1998b).

This process was followed when developing the original GEMFORM cohort model for Guyana (Alder, 2000), and is explained here in a little more detail. Given a set of PSPs, an initial version of a simple model, which we may call  $M_0$ , is set up to project growth on each plot, applying whatever treatments were actually applied on the plot, and starting with the plot initial stock. A descriptive variable that encapsulates model performance over the period of the plot is calculated from the model output. In this case, plot basal area increment,  $\Delta G$ , was used.

A graph is then made of the expected values of  $\Delta G_0$  from  $M_0$  and plotted against the observed values, as shown in Figure 2. The  $R^2$  of this regression is the *Coefficient of Determination* of the model itself with respect to this particular output variable. If the model  $M_0$  were a simple linear regression with  $\Delta G$  as the dependent variable, its  $R^2$  would be the same as the  $R^2$  of a graph of observed on predicted values from the regression.

Conventional residual analysis plots observed minus predicted values against either the predicted value, or an independent variable (see *eg.* Draper & Smith, 1966, Ch. 3). These types of plots are useful in examining the quality of a regression. However, the plot of observed on predicted value seems to the author more useful when dealing with complex models, as they give an  $R^2$  value for the model. Bias is indicated by the deviation from the 1:1 line (*ie.* observed =

predicted). If the regression line of observed and predicted has coefficients whose confidence limits encompass 0 for the intercept, and 1 for the slope, the model can be said to be unbiased.

Figure 2 : Regression of observed and predicted basal areas of Guyana PSPs using the GEMFORM model.

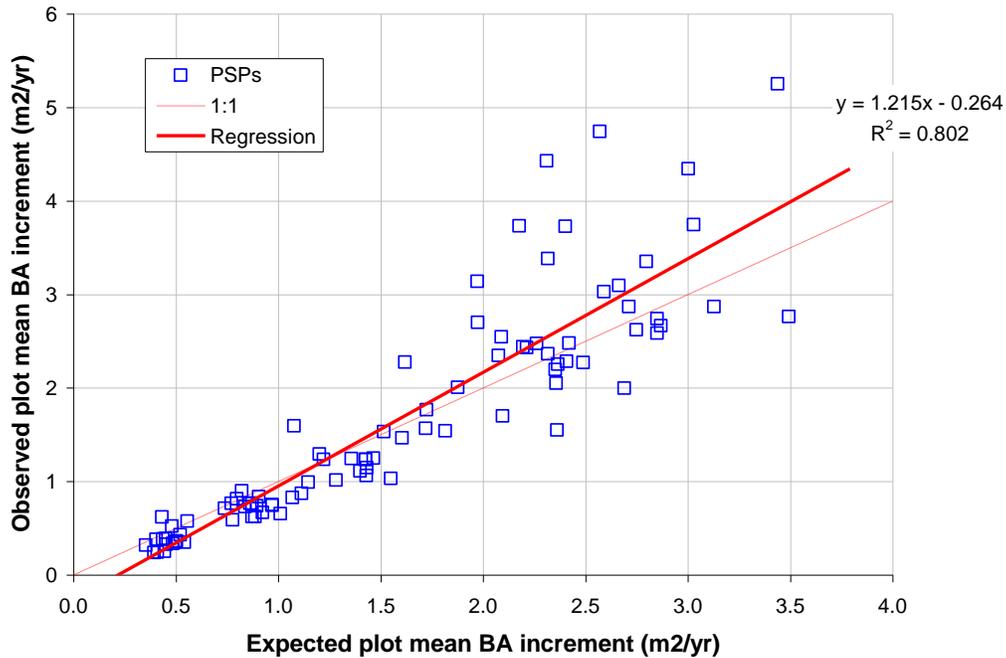


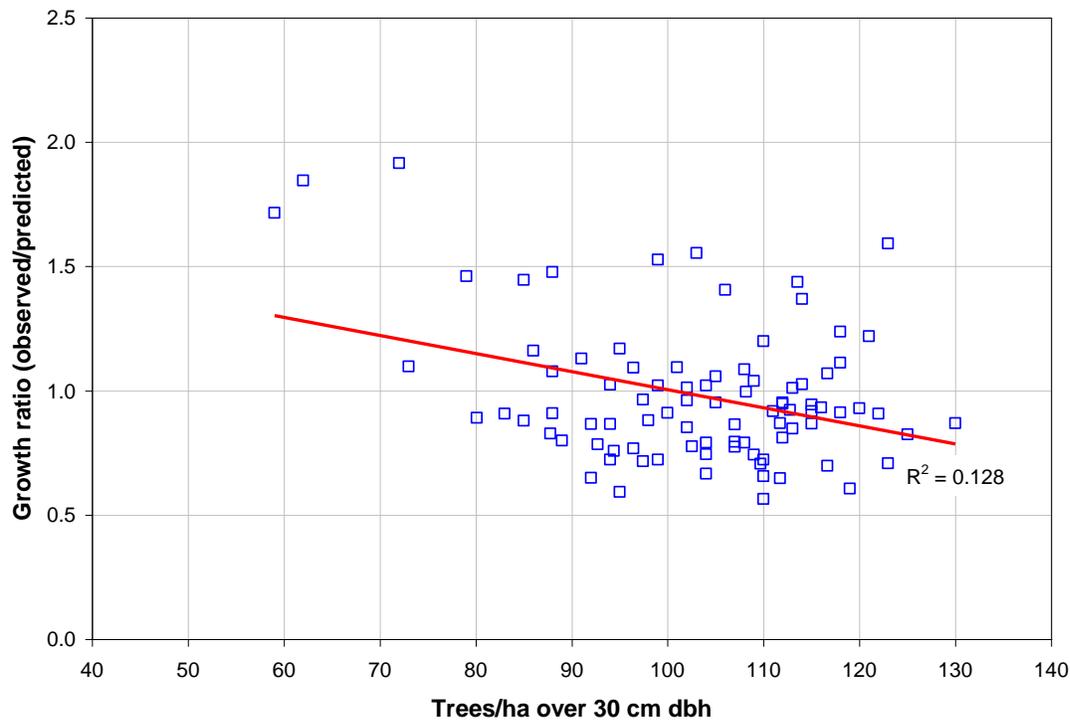
Figure 2 above shows that the basic GEMFORM model in Guyana, as reported in Alder (2000) accounted for 80.2% of the variation in plot basal area increment on the various PSPs. This basic model grouped species into 16 groups, and used a simple average increment and mortality rate for each group.

The ratio of the observed over predicted values (here  $\Delta G/\Delta G_o$ ) can be plotted against factors external to the model  $M_o$  to discern further relationships that can improve the model. This can also be done with the conventional residual,  $(\Delta G - \Delta G_o)$ , but as will be seen, leads less directly to a method of upgrading the model.

Figure 3 shows a plot of  $\Delta G/\Delta G_o$  against the most practical competition index available for inventory data sets in Guyana. This was the total count per ha of trees over 30 cm dbh. A significant regression exists, with  $R^2$  of 12.8%, indicating a mean decline in basal growth rate with increasing stand density by a factor of some 30-40% over the range of observed values (from 60 to 130 trees/ha over 30 cm dbh).

This can be used to develop a corrector factor for the basic  $M_o$  model. If the regression is:

$$\Delta G/\Delta G_o = \alpha + \beta.N_{30}$$



**Figure 3 : Regression of residual ratio on a stand density index for the GEMFORM data**  
*(residual ratio is the observed/predicted estimates for each PSP using the basic model)*

Then a new model  $M_1$  can be devised such that:

$$M_1 \equiv M_0.(\alpha + \beta.N_{30})$$

This is shown as an equivalence relation, rather than a mathematical equation, as  $M_0$ ,  $M_1$  are complex objects (*ie.* computer programs). In  $M_1$ , the variable  $N_{30}$  will be computed internally. Figure 4 shows the performance of  $M_1$ . With the stand density effect, the overall model *Coefficient of Determination* rises from 80.2% to 86.5%.

This process can be continued to develop further generations of the model. In the PINFORM study for the Papua New Guinea ITTO plots (Alder, 1998b), both stand density and site effects were incorporated in this way. The method allows the incremental improvement in the model due to added complexity to be observed, and also provides a check on bias at each stage.

## Conclusions

This paper has presented two very simple forest growth models: MYRLIN and GEMFORM. Both are available on the Internet as open source software. They are written in Visual Basic, embedded within Microsoft Excel workbooks (MYRLIN) or as an Excel Add-In (GEMFORM).

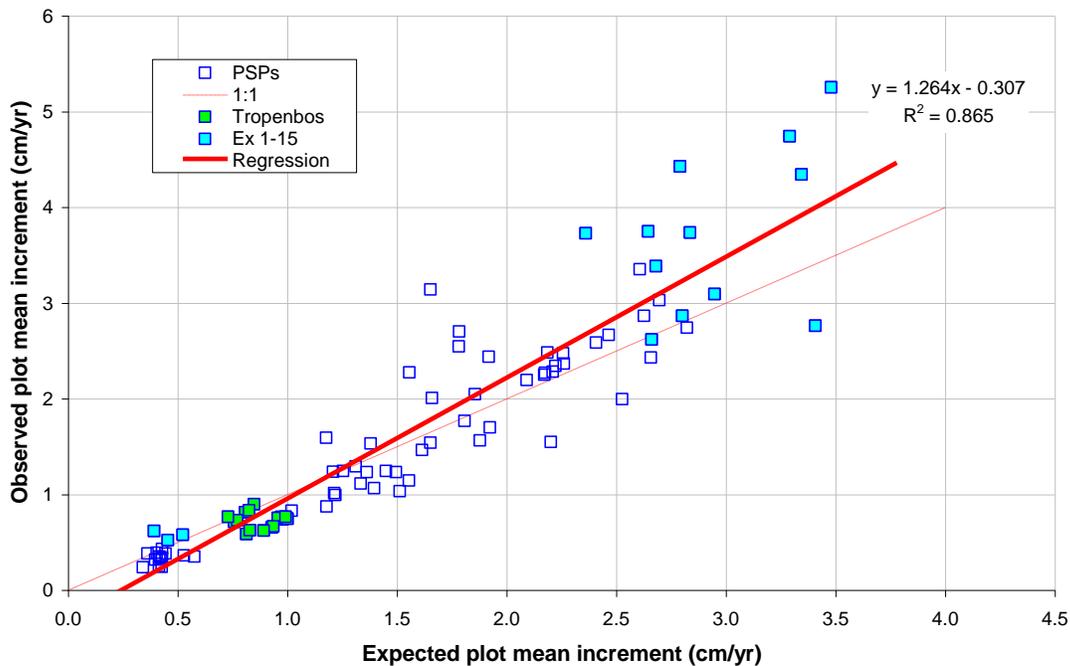


Figure 4 : Performance of the Guyana cohort model with the stand density effect incorporated

Both models use a constant diameter increment for each species group within the model, and a constant annual mortality rate. Neither model has any density dependent growth effect. They differ in their basic design. MYRLIN is a diameter class model, whereas GEMFORM uses the cohort modelling concept.

Comparing the efficiency of the models directly with some 35 years of measurement on a Greenheart stand in Guyana, it appears the cohort approach is substantially more accurate than the diameter class model. The reasons for this are evident. A diameter class model loses information about the resource data as the trees are grouped into classes. This detail is retained in a cohort model. The diameter class model also requires an assumption to relate the diameter increment rate to the actual transition frequencies for outgrowth from a class. This assumption is not required in a cohort model.

Programmatically, cohort models can cope better than diameter class models with additional layers of complexity. A diameter class model represents its data as a matrix. In the simplest case, this is species by diameter classes. However, additional factors such as crown class, defect, form add additional dimensions to the matrix in a way that is both demanding of computer memory and time, and also greatly complicates the programming by requiring additional levels of looping and indexing. A cohort model on the other hand stores the cohort as a list, and can easily accommodate additional variables without any important complication of the basic algorithms.

The validity of a very simple model has also been evaluated by testing the precision of its predictions. This has suggested that for the Guyana PSP data, for example, the simple cohort model could explain 80% of the variation in PSP basal area increment over the periods of measurement (which ranges from 2 to 6 years). With the best practicable stand density measure added ( $N/ha > 30$  cm diameter), this improved to 86%. However adding this additional factor

would have precluded applying GEMFORM to incomplete data sets, where non-commercial trees were not be recorded.

A similar consideration applies to the design of MYRLIN. In order to allow its application to the broadest possible range of data, no density-dependence has been incorporated into the model. This class of simple model is useful for developing basic forest management plans, and providing a first-order estimate of annual allowable cut from a natural forest. For this purpose, the tests suggest that they are not likely to deviate too far from actuality over a 100-year period if the increment and mortality rates supplied are approximately correct. However, such models are clearly of no use for deciding on many other issues in forest planning and management, such as the effect of heavy fellings on growth, regeneration and succession, or whether liberation thinning or refining might be sensible policies.

The author believes that the use of partial forest inventories and stock surveys, emphasising currently commercial species and large size classes, is a mistake, and should be regarded as an obsolete approach. It limits modelling and stand projection to the class of simple models presented here. To collect data on all species, down to a 10-cm diameter limit by sub-sampling, is not very much more expensive with good planning, and provides data that can be used for management and projection with a much higher degree of confidence and utility.

However, given the existence of many such incomplete data sets, and of the likelihood that they will continue to be gathered in this way for some time to come, tools such as MYRLIN and GEMFORM have a useful and necessary role to play. This paper has presented and compared them, and given indicators of their likely precision. The tools themselves and their documentation can be downloaded freely from the internet<sup>2</sup>.

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<sup>2</sup> See <http://www.bio-met.co.uk/myrlink> and <http://www.bio-met.co.uk/gemform>.

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