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# Biometric Models

Southern CRA Region

A project undertaken as part of the NSW Comprehensive Regional Assessments

July 2000

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# **BIOMETRIC MODELS**

**SOUTHERN CRA REGION  
(SOUTH COAST AND TUMUT  
SUB REGIONS)**

**State Forests of New South Wales**

A project undertaken for  
the Joint Commonwealth NSW Regional Forest Agreement Steering Committee  
as part of the  
NSW Comprehensive Regional Assessments  
project number NA13/FRA

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The project was principally developed and implemented by the Forest Resources Branch, Forest Policy and Resources Division, State Forests of New South Wales.

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# CONTENTS

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## Project Summary

1.	<b>Background</b>	1
1.1	Growth Models	1
1.2	Taper and Volume Equations	2
1.3	Base Growth Data	2
2.	<b>Scope of Work</b>	3
3.	<b>Methods and Results</b>	5
3.1	Diameter Increment Models for Native Eucalypt Forests	5
3.2	Height Prediction Models for Native Eucalypt Forests	7
3.3	Recruitment Models for Native Eucalypt Forests	8
3.4	Mortality and Degrade Models for Native Eucalypt Forests	9
3.5	Taper Functions	10
4.	<b>Key Products</b>	13
	<b>References</b>	15

## Figures

Figure 4.1	Native Forest Log Product Proportion Table Derivation
Figure 4.2	Native Forest Growth and Yield Model Relationships in Yield Simulation Process

## Appendices

Appendix 1	Diameter Growth in Native Regrowth Forests – Southern CRA
Appendix 2	Height Prediction Models in Native Regrowth Forests – Southern CRA
Appendix 3	Recruitment in Native Regrowth Forests – Southern CRA
Appendix 4	Mortality in Native Regrowth Forests – Southern CRA



# PROJECT SUMMARY

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This report describes a project undertaken as part of the Comprehensive Regional Assessments of forests in New South Wales. The Comprehensive Regional Assessments (CRAs) provide the scientific basis on which the State and Commonwealth Governments will sign Regional Forest Agreements (RFAs) for major forest areas of New South Wales. These agreements will determine the future of these forests, providing a balance between conservation and ecologically sustainable use of forest resources.

This project is one of four modules of the Forest Resource and Management Evaluation System (FRAMES), which was the tool used in CRA/RFA negotiations to calculate sustainable wood flows over time.

## **Project Objectives**

- To develop diameter increment and height functions for building a native eucalypt forest growth model;
- To develop mortality and recruitment functions for the growth model; and
- To develop volume and taper functions for key commercial tree species.

## **Methods**

A database of native forest growth information was collated from State Forests' Permanent Growth Plot (PGP) System and Research Experimental Plots. A total of over 600 plots with over 45,000 individual tree growth measurements were used for the development of biometric model functions.

Statistical analysis and modelling work was undertaken with the SAS statistical analysis software.

## **Key Results**

The project provided taper and volume equations for estimating timber volumes in the FRAMES Strategic Inventory and Yield Simulator, and growth functions (diameter increment, stand basal area increment, height prediction, mortality and recruitment functions) for predicting future yield and woodflow through the FRAMES Yield Simulator and Strategic Yield Scheduler.





# 1. BACKGROUND

Biometric models were developed to enable predictions of future tree growth and yield to be made for the northern NSW uneven-aged native forests and even aged hardwood plantations. The biometric models comprise two major categories:

(a) growth (diameter and stand basal area), height, mortality and recruitment models. These are used to reflect the expected future growth and composition of stands, and the response to forest management; and

(b) taper and volume equations. These are used to predict the total standing and merchantable volume of the resource.

The ultimate product arising from application of the biometric models is a series of yield tables. A yield table presents estimates of the anticipated future yields of merchantable volume of log products from a forest of a given type, productivity class, condition and silvicultural management history or intent. The yields are tabulated in cubic metres per hectare over time for uneven aged native forests. Yield tables are one of the primary inputs to the yield scheduling process, which are discussed separately in the FRAMES Yield Simulator and Strategic Yield Scheduler reports.

## 1.1 GROWTH MODELS

A growth model is an abstraction of the natural dynamic processes that take place in a forest stand. These encompass growth (diameter and height increment), mortality, recruitment and changes in stand composition and structure (Vanclay, 1994).

There are three classes of growth model. Selection of a particular approach depends on the objectives of the model, but is often constrained by data availability.

Whole Stand Models use population parameters such as stocking (number of stems per ha), stand basal area per hectare, and standing volume are used to predict the growth or yield of the entire stand or forest. These are typically simple and robust (Vanclay, 1994).

These models have limited application in multi-aged forests where tree size distributions are not easily predicted. However, these models are commonly used for modelling even-aged plantations and they were developed for the northern NSW CRA region hardwood plantations. Since State Forests of NSW (SFNSW) does not have hardwood plantations in the Southern CRA region, whole stand models were not used and are not be described any further.

Size Class Models predict the future condition of parts of the stand, and provide more detail on the structure of the stand than whole stand models. The size class modelling approach is a compromise between whole stand and single tree models. When the size class is infinitely large and only one class exists, then the method is a whole stand approach. When the class width is infinitely small and each tree is considered a single class, then the method becomes a single-tree approach. Sub-classes of this general type include stand table approaches, transition matrices

and cohort models. The stand table is the most common example of the size class models projection (Vanclay, 1994).

Individual Tree Models are the most detailed approach to growth modelling where single trees are used as the basic unit of modelling. The minimum requirement is a list of all trees specifying the size of each tree in the stand. Some models also require the spatial distribution of the trees. Individual tree models may be simple or can be very complex by modelling branches and internal stem characteristics (Vanclay 1994).

Individual tree growth models provide the most reliable growth predictions in uneven aged native forests, but are dependent on extensive datasets. The availability of a large dataset permitted individual tree diameter growth models to be developed for the native forests of the southern NSW CRA region.

## **1.2 TAPER AND VOLUME EQUATIONS**

Tree volumes are estimated with volume and taper equations. Tree taper functions reflect the diameter profile (shape) of the tree from its base to tree tip. Taper functions can be used on their own or in conjunction with volume equations to determine total volume and composition of log products obtainable from a tree.

A taper equation is used to predict the underbark stem diameter at known heights in the tree for a given tree species, dbhob and height. The information from the taper equation, together with assumptions about the stem shape between two predicted points, is used by the volume equation to calculate the total volume and volume between any two heights on a tree. Log product length and diameter specifications are used with the taper and volume equations to determine the total merchantable volume and volume by product type which can be recovered from a given tree.

Taper varies between trees of different species, diameter, dominance class, and silvicultural history (stocking/density). Taper and volume models developed for other projects (Bi and Hamilton (1998); Bi (2000)) were used. These included taper and volume for Alpine Ash, Blackbutt, Blue Gum, Brown Barrel, Messmate, Silvertop Ash, Spotted Gum, Yellow Stringybark, and a general equation for all other species. The source of these taper and volume functions is provided in the 'Strategic Inventory' for Southern CRA region report.

## **1.3 BASE GROWTH DATA**

The base growth data were obtained from SFNSW PGP and Research Experimental plots which were set up for monitoring growth, assessing the effects of different thinning and spacing intensities, and some for effect of burning. The PGP program contains an extensive database representing a broad range of site and stand conditions while Research experimental data provide long time series data in different Forest Management Areas. Permanent Growth Plot data were between 1978 and 1999, while the Research experimental data were established as far back as 1945. The Research Experimental data are good for supplementing PGP data because they have a range of silvicultural options that are not available in the PGPs. However, each of these datasets has particular strengths, needed for growth model development, pointed out above. The datasets were designed for different purposes so it was necessary to transform the datasets in a consistent format suitable for use in biometric model development. To strengthen the base data, a program of increased PGP measurements was undertaken similar to that implemented in for North East of NSW CRA.

## 2. SCOPE OF WORK

The first stage of the biometrics project included the collation and verification of PGP, CFI and relevant research data. In addition to the review of existing datasets, PGP's that had not been measured within the last 4 years were remeasured or had been measured once and were at least 3 years since measurement. This re-measurement exercise provided over 40 extra plot measures to the growth database.

The second stage of the project involved the development of biometric models for broad forest types at the stratum level. This stage was split into two sections, one for the UNE/LNE Regions and one for the Southern CRA Region. The current report addresses development of models relevant to the Southern CRA Region. A similar report was completed for the UNE and LNE CRA Regions.

The biometric models project was divided into the following sub-projects:

1. Diameter increment functions for native eucalypt forests;
  - (a) tree diameter increment models; and
  - (b) stand basal area models
2. Height prediction functions for native eucalypt forests;
3. Recruitment functions for native eucalypt forests;
4. Mortality and degrade functions for native eucalypt forests; and
5. Volume and taper functions.

This report provides an overview of the development of the biometric models for the Southern NSW CRA. Detailed biometric model reports for individual modules are contained in the appendices. Implementation of the models into the MARVL inventory system and native forest Yield Simulator are addressed in separate project reports.



# 3. METHODS AND RESULTS

The subprojects are briefly outlined below. Detailed reports are appended.

## 3.1 DIAMETER INCREMENT MODELS FOR NATIVE EUCALYPT FORESTS

A total of 10 tree level Diameter Increment Models (DIMs) were developed for the Southern CRA region compared to 52 DIMs developed for UNE and LNE CRAs. These models predict tree diameter increment for a wide range of environmental, tree and plot variables, and represent the best available functions for Southern NSW CRA for the available database. The variables used included:

- Species group (10 groups identified);
- Tree size (dbhob);
- Environmental variables (collectively as a measure of site productivity) - rainfall, temperature, slope, soil depth, soil fertility, topographic position, solar radiation and soil moisture index; and
- Tree competition (stand basal area, stand overtopping basal area, relative dominance).

A full description of these models by Muhairwe (2000a) is provided in Appendix 1.

The DIMs were developed for 10 broad tree species groups based on similarities in growth potential. The number of models were reduced from 52 to 10 compared to UNE and LNE because the further classification based on the applicability of tree dominance (3 three classes) and the availability of soils data (2 classes) were replaced. Tree dominance (a categorical variable with four classes) in the models for Southern CRA was replaced with Relative Dominance (RD). RD is the ratio of basal area of overtopping trees to total stand basal area per hectare. This means that a tree which is dominant would have RD=0 or close to zero because very few or no trees would be overtopping it and a suppressed tree would have RD close to 1.0 because all the other trees in the plots would be overtopping it. Classification based on soil data was removed because all the plots in the Southern CRA had the same environmental variables.

The 10 broad species groups based on the dominating species can be classified as:

- Blackbutt/Blue Gum
- Brown Barrel
- Ironbarks
- Coastal and Tableland Peppermints

- Spotted Gum
- Silvertop Ash
- Stringybarks and Mahoganies
- Non-commercial species (including Apples, Oaks) for South Coast and Tumut Sub Regions
- Alpine Ash (Bago/Maragle)
- Gums and Peppermints (Tumut Sub Region)

### 3.1.1 Dataset Collation

The development of DIMs was based on data from SFNSW' PGP and Research Experimental data. Data were available from a total of over 600 PGPs have been established across the State since 1978, which have been remeasured on a 5-year cycle or before harvesting. In addition, data were available from over 190 Research Experimental plots established for various purposes. These experimental plots were remeasured at one interval at early stages and later at a 5-year cycle. All PGPs due for re-measurement were measured and the measurement of additional plots was brought forward one year, in order to have as much information as possible available for development of diameter increment models.

Existing and remeasured PGP and Research Experimental data (205 and 215 plot remeasurements respectively) for Southern CRA were checked, and where necessary, corrected. A preliminary analysis was conducted on each plot, based on individual tree data within the plot. Plot summaries contained mean diameter increment, mean basal area increment, stand basal area (ha), stems per hectare, overtopping basal areas (basal area of larger trees), quadratic mean diameter and stand density index. These variables were used to identify any suspect plots for review and elimination if necessary. As a result of this process over 30 plot remeasurements were removed from the dataset (see Muhairwe (2000a) for details).

The final number of plot remeasurements was:

PGP database	South Coast	159 Remeasurements
	Tumut	35 Remeasurements
Research database	South Coast	148 Remeasurements
	Tumut	48 Remeasurements
Total		<b>390 Remeasurements</b>

### 3.1.2 Dataset Analysis

A range of regression functions were fitted to the data according to methods of individual tree growth functions proposed by Zeide (1993). A series of statistical tests were used to assess and identify the most appropriate models. The best individual tree models were selected based on goodness-of-fit statistics (multiple coefficient of determination or  $R^2$  and standard error of estimate), prediction statistics (index of fit or  $I^2$ , mean bias and absolute bias, mean square residuals, and prediction sum of squares) and most importantly on the diagnostic analysis of residuals for model deficiency.

The DIM models were fitted using over 19,400 observations. Ten species groups were identified in the analysis as the predominant classes with similar diameter growth parameters.

Individual tree models requiring only the list of tree sizes, stand attributes and site productivity measure (similar to the approaches followed by Wykoff (1990), Monserud and Sterba (1996), Vanclay (1994)) were developed.

Full details are outlined by Muhairwe (2000a).

### 3.1.3 Stand Basal Area Models (Growth Model Modifier)

Predicted stand basal area is used to constrain the individual tree diameter models, where the sum of basal areas of projected individual trees after a growth simulation is found to be higher than the predicted stand basal area. This basal area growth modifier is necessary after many years of simulation (e.g., 30 years) because individual tree based recruitment and mortality models are less likely to accurately reflect the dynamics of the stand particularly following silvicultural operations (e.g., harvesting, thinning) or fires. Therefore, after 30 years of simulation or following silvicultural treatment of the stand, the individual tree diameter increment models would be tested by stand basal area model to check their consistency.

Stand basal area increment models are a function of:

- initial stand basal area;
- initial stocking;
- future stocking (initial stocking, plus recruitment minus mortality);
- stand density index (based on quadratic mean diameter of 30cm);
- future stand density index; and
- environmental variables (solar radiation, topographic position, and soil depth).

Stand basal area models were developed by Muhairwe (2000a) for yield association groups in Southern CRA similar to the ones developed for UNE and LNE CRA. However, a nonlinear (an exponential) function was used for Southern CRA, instead of using a linear model used for UNE and LNE CRA. Also three yield association groups were used for Southern CRA compared to seven yield association groups used for UNE and LNE CRA. Only two yield associations with sufficient data could be modelled individually. As a result, models were developed for the following three yield association groups:

- Yield association 3 (Spotted Gum) – YAG 1;
- All other yield associations – YAG 2;
- Yield association 8 (Alpine Ash from Bago/Maragle) – YAG 3.

A full description of the model by Muhairwe (2000a) is provided in Appendix 1.

## 3.2 HEIGHT PREDICTION MODELS FOR NATIVE EUCALYPT FORESTS

Functions were developed to estimate the total tree height of trees in the Strategic Inventory without total tree height measured and for predicting new total tree heights for each year of future growth simulation in the Yield Simulator. Similar functions were developed for UNE and LNE CRA.

Total height of a given tree for a given species is a function of:

- size of the tree (dbhob); and
- site productivity (plot site height).

A height prediction model, based on the relationship between tree diameter (dbhob) and tree height, rather than a height increment model, was developed because the PGP dataset which was used in modelling diameter increment did not contain tree height data. This meant that there was a lack of height remeasurement data from which to develop a separate height increment model.

As for UNE and LNE CRA, strategic inventory data were used for fitting height prediction models (using non-linear least squares regression - a Chapman-Richards function). Individual tree height was predicted using dbhob and plot site height (as a measure of site productivity). The height-diameter relationship model adopted the same 10 species groups used for the diameter increment models.

A full description of the height prediction models by Muhairwe (2000b) is provided in Appendix 2.

### **3.3 RECRUITMENT MODELS FOR NATIVE EUCALYPT FORESTS**

The recruitment model predicts the amount of regeneration (in this case the ‘ingrowth’ into the minimum size) in the forest stand over time by simulating the number of new trees that grow into the 10cm dbhob size class. The modelling approach used for Southern CRA was the same as that used for UNE and LNE CRA. This consisted of two parts, a probability function to predict the likelihood of recruitment and another one to predict the amount of recruitment given that recruitment will occur. The recruitment model is driven by the changes in stand structure. Stand structure changes as a result of growth, successive harvesting and mortality will affect recruitment. The recruitment model was developed using PGP data.

The modelling process was divided into two stages (similar to UNE and LNE CRA):

- (a) prediction of the probability that recruitment will not occur in a given period; and
- (b) prediction of the number of stems entering the threshold 10cm diameter class given that recruitment will occur.

The first stage model determines the probability of no ingrowth, which is a function of:

- Stand density (basal area per ha ( $m^2/ha$ ));
- Quadratic mean diameter (cm); and
- Prediction period used as the weight for the function.

The second stage of the model determines the number new recruits per hectare entering the plot population, which is a function of:

- Stand density (basal area per ha ( $m^2/ha$ ));
- Stand density index (a measure of stocking when quadratic mean diameter = 30 cm);
- Prescott index (a measure of site productivity); and
- Prediction period used as the weight for the function.

The composition (species mix) of the new recruits was based on the original plot composition. It was assumed that the new recruits have the same proportion as the parent plot population.



This assumption could be incorrect, but there were limited data to prove or disprove it. The number of new stems recruited per hectare are then distributed into the plot in the same species proportions of the existing trees within each plot. The species proportions were calculated separately for each Strategic Inventory plot. The same proportions are used to simulate the new trees entering the plot population over the modelling time horizon.

The recruitment model provided estimates of future ingrowth across a wide range of forest types. A full report on the development and analysis of the recruitment models for Southern CRA by Muhairwe (2000c) is presented in Appendix 3.

### **3.4 MORTALITY AND DEGRADE MODELS FOR NATIVE EUCALYPT FORESTS**

Tree mortality functions were derived to model the loss of trees arising from natural and human activity.

Natural mortality comprises ‘non-catastrophic’ (tree maturation, suppression, competition, pests and diseases) and ‘catastrophic’ (i.e. wildfires, windthrow, drought, flood and major disease outbreaks) mortality. Since catastrophic mortality is irregular, and data were very limited, it was not modelled in this project.

Human-induced mortality occurs as a result of a harvesting or silvicultural treatment event in which damage to the stem or crown of trees can eventually lead to tree death or susceptibility to other natural mortality agents (harvest mortality). Trees that are only damaged and not killed can also be subject to significant stem quality downgrade and a reduction in future high quality wood products (harvest degrade).

Due to lack of data for Southern CRA to model harvest mortality and degrade, the models developed for UNE and LNE CRA were used for Southern CRA. It was assumed that the effects of harvesting or any other silvicultural treatment would be similar for Southern CRA as for UNE and LNE CRA. Therefore, only single model for natural mortality was developed.

#### **3.4.1 Natural Mortality Model**

The four agents of ‘natural’ mortality were identified as:

- Fire;
- Insect attack;
- Wind; and
- Other causes (such as tree maturation, suppression and competition).

The natural mortality model was based on PGP and Research data. Analysis of these data showed that over 70% of natural stand mortality occurs in the smaller diameter classes (<15cm dbhob). Similar results were reported by Lawrence (1997) and Vanclay (1994). However, some big trees also die due to maturation.

Lawrence (1997) found no significant differences in mortality rates between yield associations or structure classes for UNE and LNE CRA. However, for Southern CRA some yield associations had more mortality than for others. Mortality rates are generally specific to the species composition of the forests. However, with very low mortality rates and limited data it was necessary to conduct the analysis on major species amalgamations, making it difficult to distinguish differences. Yield associations were amalgamated into three yield association groups. Still the data for some groups lacked consistency and finally a single model was used for species. The model selection was based on a combination of ‘fit’ statistics as provided in

the logistic procedure in SAS/STAT (SAS Institute, Inc., 1989). The probability of survival was modelled as a function of:

- Tree size (dbhob);
- Measures of competition:
  - a) stand basal area;
  - b) basal area of overtopping trees; and
- Prediction period used as a weight.

Mortality is a highly variable process, which occurs at a very low overall level in the regrowth forests of NSW. The mortality model presented here handles this process well and should be reliable under a wide variety of stand conditions. It is a general model, which needs further refinement as more data become available. A full report on the development and analysis of the mortality model by Muhairwe (2000d) is presented in Appendix 4.

### 3.5 TAPER FUNCTIONS

Tree taper functions and volume equations are used to determine (i) total tree volume, (ii) merchantable volume, and (iii) the sectional or log volume of individual trees. The taper and volume functions developed were used for the strategic inventory analysis and within the yield simulator.

The Method for Assessing the Recoverable Volume of Logs (MARVL) inventory analysis software (Deadman and Goulding, 1979) was used to determine the total and product volumes of trees measured in the CRA strategic inventory. MARVL uses compatible volume and taper equations to determine the volume of the entire stem and sections of the stem. The program has a log bucking optimising algorithm which calculates the optimal blend of log products cut from each log in order to maximise the value recovery which is based on a user-defined cutting strategy (log specifications and relative values). A full description of MARVL processing can be found in Carter (1998).

Taper functions used in MARVL and the Yield Simulator were fitted for estimating tree volume for native species in NSW. Two function types were used for:

1. Taper functions are used to predict underbark diameter at any point along a tree stem from the DBHOB and height for a given species group. Predicted stem diameters along the tree stem are used in determining the tree and log product volume by a volume equation, and the MARVL optimising algorithm uses these figures to identify the appropriate points at which to cut the stem to optimise the value of log products.
2. The volume functions are used to predict the total and product volumes for each tree.

The taper and volume functions were developed for the major commercial tree species harvested in the native forests of Southern CRA. The report on Strategic Inventory provides a description of the taper and volume functions used for Southern CRA (SFNSW, 2000). These models are based on the forms described by Gordon (1983), Muhairwe (1995, 1999), Bi and Hamilton (1998) and Bi (2000). Carter (1998) gives a detailed description of the model form and equations developed by Bi (2000).

The following taper and volume equations were constructed:

<b>Common name</b>	<b>Botanical name</b>	<b>Function form</b>
Alpine Ash	<i>Eucalyptus delegatensis</i>	Gordon 1983
Blackbutt	<i>Eucalyptus pilularis</i>	Muhairwe 1999
Blue Gum	<i>Eucalyptus saligna</i>	Bi 2000
Brown Barrel	<i>Eucalyptus fastigata</i>	Bi 2000
Messmate	<i>Eucalyptus obliqua</i>	Bi 2000
Silvertop Ash	<i>Eucalyptus sieberi</i>	Gordon 1983
Spotted Gum	<i>Corymbia maculata</i>	Bi 2000
Yellow Stringybark	<i>Eucalyptus muelleriana</i>	Gordon 1983
Composite species	various species	Muhairwe 1995

Data collection for taper functions involved the destructive sampling of trees from a mix of growth plots and current harvesting sites throughout Southern CRA region. A sample size of hundreds of trees for each commercially important native forest species was taken across various tree diameter sizes and site qualities (see reports by Bi and Hamilton (1998), Bi (2000), Gordon (1983), Muhairwe (1995, 1999), and Carter (1998)).

A full report on taper data collection procedures, and the development and analysis of the taper and volume equations can be found in the published papers by Bi and Hamilton (1998), Bi (2000), Gordon (1983), Muhairwe (1995, 1998), and Carter (1998) and references there in. No individual species taper models reports are attached as Appendices (see the Biometrics Report for UNE and LNE CRA for more details) because the methodology and results are presented in the references.



# 4. KEY PRODUCTS

The biometrics project generated the following products:

An updated and verified PGP and CFI database used for constructing and testing different components of biometric models.

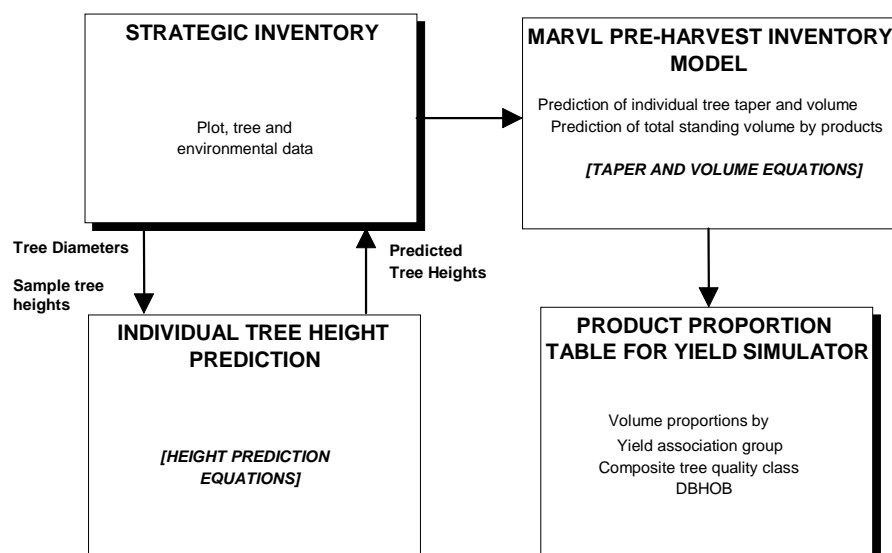
1. 10 Individual Tree Diameter Increment Models (ITDIMs) and 3 Stand Basal Area Models (SBAMs).
2. Total tree height prediction functions for the 10 groups selected for diameter increment modelling.
3. A single recruitment prediction model for all species.
4. A single natural mortality model for all species.
5. Several individual and composite tree species taper and volume equations.

These represent the best models and functions currently available for South Coast and Tumut Sub Regions of NSW given the limitations of the data used.

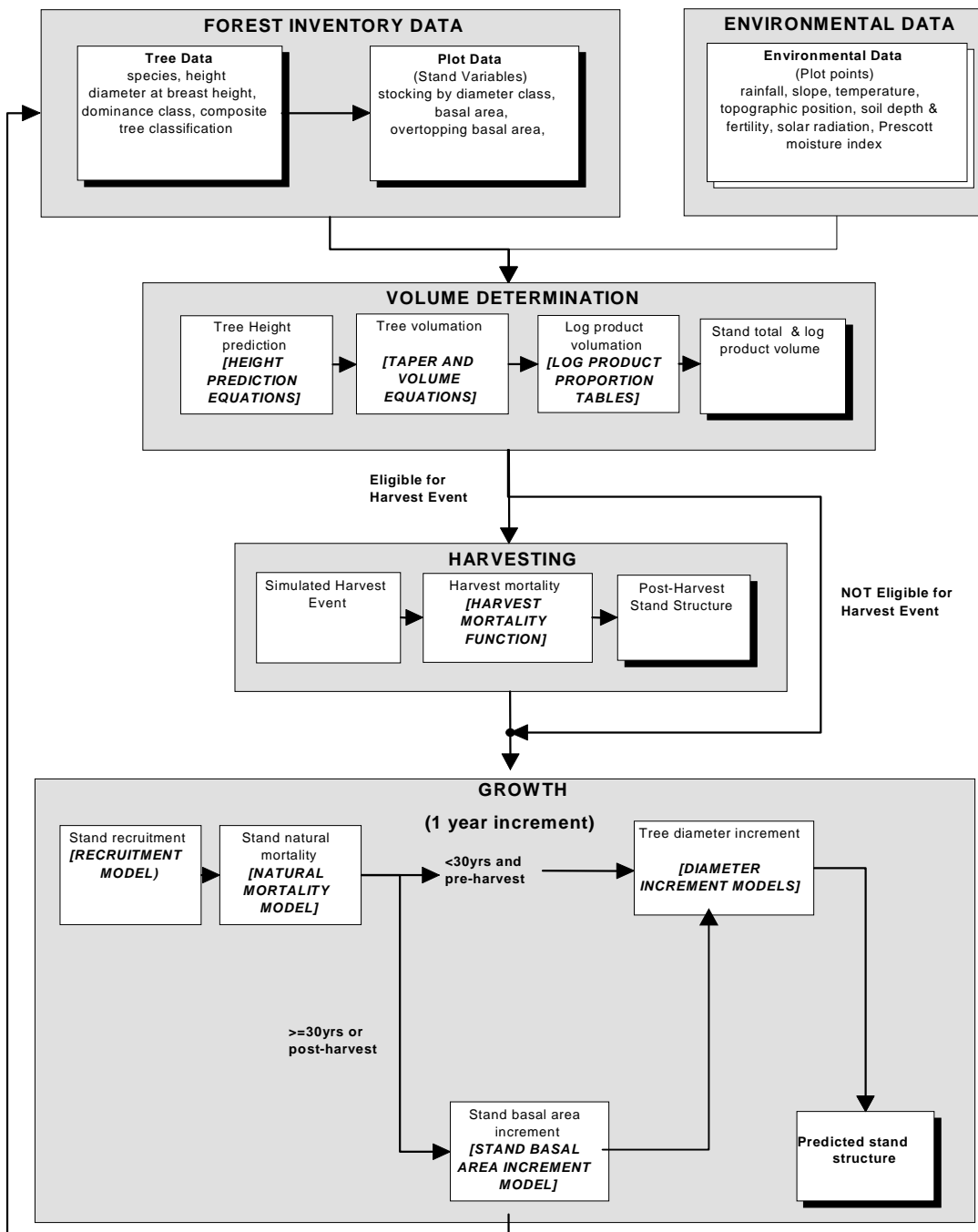
The biometric model predictions can only be verified and validated with independent data sets (data not used to estimate the model parameters). Supplementary inventory data collected through the ongoing post-RFA project and remeasurement of the existing Permanent Growth Plots and Continuous Forest Inventory system will be used for continual testing (cross-validation) and fine-tuning of the predictive models and functions developed.

The application of the biometric models and the relationships between them are illustrated in Figures 4.1 and 4.2 (similar figures produced for UNE and LNE CRA).

**Figure 4.1: NATIVE FOREST LOG PRODUCT PROPORTION TABLE DERIVATION**



**Figure 4.2: NATIVE FOREST GROWTH AND YIELD MODEL RELATIONSHIPS IN YIELD SIMULATION PROCESS**



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APPENDIX 1  
DIAMETER GROWTH IN  
NATIVE REGROWTH  
FORESTS - SOUTHERN  
CRA

**Diameter Growth in Native Regrowth Forests  
of  
South Coast and Riverina Regions of New South Wales**

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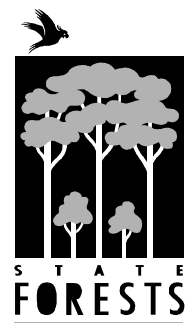
**A final report prepared for FRAMES Technical Committee  
CRA, South Coast and Riverina**

**by**

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## Summary

The biometrics component of the CRA/FRAMES process includes the development of a model to predict forest growth. The proposed growth model has five major components: individual tree diameter growth, height growth, mortality, recruitment, and harvest. This paper describes the development of an individual-tree growth (diameter increment) prediction model for native regrowth forest of South Coast and Riverina Regions of New South Wales, Australia.

Data from State Forests Permanent Growth Plot System and Research experimental plots were used to develop a set of equations for ten species groups based on a combination of individual tree and stand parameters. Due to data limitations for some species (most species with less than 100 tree observations), there was need to amalgamate most species into species groups with sufficient data. Species with enough data were modelled separately, as a result we have individual species models for spotted gum, alpine ash, brown barrel and silvertop ash.

The set of models developed were tested by simulation and found to behave in a manner compatible with the theory of growth. Therefore, it assumed that they should be able to reliably predict growth in diameter across a wide range of tree sizes, stand conditions and site productivity classes in both the South Coast and the Riverina Regions of New South Wales.

It should be noted, however, that we are not saying that the models developed for this study are the only possible models for modelling growth and we hope carry out an assessment of the models using validation data when it becomes available in the post-CRA process. If these models are to be deficient, we shall look at alternative model forms that are available in the literature. At the moment, we have happen with their predictions.

## Contents

<b>1. INTRODUCTION</b>	<b>1</b>
<b>2. METHODOLOGY</b>	<b>2</b>
2.1 Data Collation	2
2.2 Model Selection	10
<b>3. RESULTS</b>	<b>13</b>
3.1 Tree variables	14
3.2 Stand (plot) Variables	14
3.3 Locality variables	15
3.4 Environmental variables	15
<b>4. DISCUSSION</b>	<b>16</b>
4.1 Variation between DIMs	16
4.2 Confidence limits and parameter standard errors	17
4.3 Growth Model modifier	17
4.4 Diameter Increment Growth Model Evaluation	19
4.5 Diameter Increment Growth Model Implementation	21
<b>5. CONCLUSIONS</b>	<b>22</b>
<b>6. REFERENCES</b>	<b>23</b>
<b>APPENDICES</b>	<b>25</b>

## 1. Introduction

The Forest Resource and Management Evaluation System (FRAMES) being developed for the New South Wales CRA/RFA process provides a planning tool for that can determine sustainable wood flow for a range of management options and varying resource base. A key element in FRAMES is a series of biometric models that make up the growth model component of the Yield Simulator. Most growth models require the inclusion of many components, but the three major types of functions for native forest growth modelling include diameter increment, mortality, and recruitment. These models, based on a range of long term repeated measurement plots, predict diameter growth, mortality and recruitment of individual trees through time.

The Diameter Increment Models (DIMs) form the core of the FRAMES growth models. When applied to individual trees within each Strategic Inventory Plot, the DIMs are capable of predicting the growth in diameter at breast height over bark (dbhob) at yearly intervals. As for Upper and Lower North Coast, Distance-Independent Individual Tree Modelling approach was selected for diameter increment modelling in the FRAMES Yield Simulator. Distance-independent individual tree models were thought to be the most suitable diameter growth models given the nature of the base data available. Distance-dependent individual tree Models were not tried because of the lack of data on the spatial distribution of trees. Spatial data are not routinely collected in inventories. However, distance independent models, using overtopping basal area and crown competition factors as measures of density, have been found to be equally good if not better than distance dependent models (Vanclay 1994; Wykoff 1990; Huang and Titus 1995).

From the available literature (Vanclay 1994), there are many kinds of functions that can be used for modelling diameter growth. These models can predict annual or periodic growth of individual trees which is added to initial size to give future size, models can predict final size. Growth and yield can be modelled in terms of basal area or diameter. Some modellers prefer to use tree basal area increment instead of diameter increment because basal area is more directly related to volume. However, Wykoff (1990); Huang and Titus (1995) argue that there is no difference between the two model forms. It does not matter which variable is used, diameter or basal area. In order to use basal area, the units would have to be centimetres per year to avoid the small values associated with using metres per year.

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Since growth is nonlinear, a literature review was undertaken for a nonlinear model that could be used (see Zeide 1993; Vanclay 1994; Ratkowsky 1990). Given the general factors that can affect diameter growth, it is necessary to choose (i) the general structure of the model, (ii) the form of the dependent variable, (iii) the method for handling the error structure of the model during prediction, and (iv) the appropriate transformations of independent variables. After careful consideration and literature review, it was decided to predict the mean periodic diameter increment rather than mean annual increment because we do not remeasure our plots annually. Many researchers use periodic increments (Wykoff 1990; Huang and Titus 1995; Monserud and Sterba 1995). It should be noted that measurement periods varied from 2 to 10 years for our data, which makes using periodic growth more difficult. However, growth prediction was attempted by using the measurement period as an independent variable, but it produced poorer predicted diameters than using mean periodic increment and it was therefore abandoned.

Periodic Diameter Increment Models (DIMs), fitted for individual trees within species groups, were defined as a function of:

- **Species**
- **Tree size** (i.e., dbhob);
- **Site productivity** (rainfall, temperature, slope, soil depth, soil moisture index, topographic position and solar radiation); and
- **Tree competition** (plot basal area, plot overtopping basal area).

## 2. Materials and Methods

### 2.1 Data Collation

The growth models were developed from the data contained in the State Forests of NSW Permanent Growth Plots (PGP) and Research experimental plots (Research) databases. Some of the Research plots were established as far back as the 1940s, while the first PGPs were established in 1979.

#### 2.1.1 Plot Characteristics

All Research plots were fixed area plots. The plots varied in size from 0.1 to 0.8 hectares (ha). PGPs are concentric plots as shown in Table 1. From the table, it can be seen that dbhob measurement varied with the plot size. For the inner plot (0.1 ha plot) all trees were measured, while for 0.3 ha plot only trees bigger than 30 cm dbhob were measured and for

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the 0.5 ha plot only trees larger than 50 cm in dbhob were measured. As we shall see later, only the 0.1 ha plots can be used for modelling recruitment and mortality.

Table 1: Permanent Growth Plot Sizes

Size Class Dbhob (cm)	Plot radius (m)	Plot area (ha)
10+	17.84	0.1
30+	30.90	0.3
50+	43.70	0.6

The primary objective of the PGPs was to provide accurate and reliable growth data for the main productive forest types in areas which were to be managed on a long-term basis for wood production in coastal and tableland regions of the State.

PGPs were measured at establishment and subsequently at approximately five-year intervals, or at the time of harvesting. For Research plots, measurement was done at establishment, then at one-year intervals when the stands were young; the measurement interval was increased to five years as the stands matured. As a result, these plots have measurement intervals varying from one year to five years. Most of the PGP data has had at least two measurements, some with three and even a few with four measurements. Research data has up to 14 measurements. Tables 2 and 3 provide a description of the number of plots and measures for South Coast (SC) and Riverina (TT) CRA Regions.

Table 2: Number of plots and measurements for PGP Database

No. Measures	1	2	3	4
No of Plots (TT)	27	20	17	
No of Plots (SC)	108	95	70	3

Table 3: Number of plots and measurements for Research Database

No. Measures	1	2	3	4	5	6	7	8	9	10	11	12	13	14
No. Plots (TT)	7	7	7	6	6	6	5	5	5	2	1	1		
No. Plots (SC)	24	24	24	16	15	15	15	15	14	9	7	6	3	1

Note: SC stands for South Coast and TT stands for Riverina CRA Regions

### 2.1.2 Data Preparation

Data preparation methods used for Upper and Lower North Coast were equally applied to the South Coast and Riverina CRA Regions data (see the Report on Biometric Models for Upper and Lower North Coast CRA Regions for details). Research database was edited by using the same general approach applied to the PGP database.

### 2.1.3 Data Analysis

After data checking, some preliminary analysis was done, as was done for Upper and Lower North CRA Regions. This involved calculation of plot information from tree information. The plot information calculated included mean diameter increment, mean basal area increment, stand basal area in square metres per hectares ( $m^2/ha$ ), stocking density (stems per ha), basal of larger trees ( $m^2/ha$ ), and stand density index (stems per ha).

In calculating plot information, it was necessary to make the following corrections to the database in order to avoid bias (similar corrections were applied to the Upper and Lower North Coast CRA Regions Database).

(1) Some of the PGPs were originally established as 0.1ha plots instead of concentric plots. Analysis of such plots for plot information as if they were concentric would introduce some bias. Plots and measurement numbers for 0.1ha plots were separated from the normal concentric plots. These plots were then processed using the SAS code attached as Appendix 1. For research data, it was not necessary to apply the SAS code in Appendix 1 because the plots were either fixed (single) radius or square or rectangular.

(2) The problem of ‘missing trees’ – these are trees that were supposed to have been measured in the previous measure, but unfortunately were missed. This is a limitation with using concentric plots. Some trees on the border of two radii sometimes were considered to be too small for the large radius ‘outer’ plots and were not measured. Further, because some tree sizes were not supposed to be measured in some outer radii, the measuring crews would miss some trees that were supposed to be measured. This problem is very difficult to eliminate except through proper training. In some plots, some big trees were missed and such trees make plot information calculated for the previous measure an underestimation of the actual plot information. Therefore it was important to make some assumptions about these trees and give them some measure of dbhob and a special status code so that they are not included in the diameter increment calculation. Since these trees had no previous measurement, we could not assign them some increment based on their growth history. From data analysis we came up with some average increments within species groups and dbhob classes. These trees were assigned a new status code because they had to be excluded from diameter increment modelling. The code used to fix this problem is attached as Appendix 2

(3) Elimination of plots due to harvesting between measurements. Plots that were harvested within measurement interval have a similar problem to that caused by missing trees. Plot

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information at the second measurement underestimates the same attributes recorded at the first measure. The easiest choice would be to eliminate all such plots. However, this choice might not be a wise decision given the fact that data is limited and expensive to collect, and some plots could have been subjected only to light harvesting. Therefore, the following rules were used to eliminate some of the harvested plots.

- a) All harvested plots were marked.
  - b) Number of trees harvested were calculated.
  - c) If the harvested tree had no dbhob measured, then the number of harvested trees with missing dbhob as a proportion of the total was calculated. The plot was excluded if more than 10% of stocking or more than three trees had no dbhob measurement. For example a plot with 10 trees and having 2 trees harvested with missing dbhob would not be included while a plot with 80 trees with three trees harvested with missing dbhob would be included.
  - d) This routine has a bias in that plots with a few trees were hardly dropped compared to plots with many trees. For example a 30-tree plot with 3 harvested trees would be retained while a 100-tree plot with 4 trees harvested would be dropped. This routine was used because it was thought that compensating for lack of data on more than 10% or 3 trees would lead to biased plot information.
  - e) A new dbhob was calculated for the missing trees for harvested plots retained as:  $\text{Previous dbhob} + (\text{growth interval (years)} \times \text{previous mean periodic increment})$ . By doing this, it is assumed that the tree maintained the same growth rate in this growth period. This is not necessarily true because climatic conditions could vary or the tree could have changed status (e.g., changed dominance class). No obvious alternative was available.
  - f) All plots with more than three trees or more than 10% of stems harvested were excluded from any further calculations. This resulted in dropping **7** plot measures in the PGP database (2 plot measures in Riverina and 5 plot measures in South Coast) and **13** plot measures in Research database (3 plot measures in Riverina and 10 plot measures in South Coast). Trees given a new dbhob because they were harvested, had to be assigned a new status code because they were not included in the database for diameter increment modelling.
- (4) Trees with negative periodic mean increments. According to the analysis done by Carter (1994), periodic mean increments in dbhob between  $-0.5$  to  $2.2$  cm per year were genuine increments. Increments outside this range are probably measurement and/or rounding errors. For example, we know that eucalyptus trees shed their bark. If measured when they have just shed their bark, those trees might have a negative increment if the growth period is short. Also, fire will burn off the bark and cause the trees to have negative increments. However, very big increments would be difficult to explain, particularly if they occur in plots that are
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located on very productive sites. For every plot, diameter increments were plotted against dbhob for every measurement period. All trees with increments outside band of -0.5 to 2.2 cm were examined critically. Individual trees were examined by serial measurements. Some of these trees were found to have been mistaken entries. These were corrected where possible, either by the technician or for differences that were consistent with the plot sheets, by the district (to be field checked if possible). However, not all increments outside the range could be resolved in this way. These remained in the database (see Table 4). From the plots of mean periodic diameter increments against tree dbhob for these plots, a trend was seen. The trend indicated that plots with short remeasure periods (particularly less than 2 years) tended to have bigger negative and positive increments compared to plots with higher remeasure periods. This is because a small mistake in measurement of 2 or 3 cm for a remeasure period of 0.6 years would result in an error of 3.3 or 5 cm in periodic mean increment. An error of the same magnitude for 1.5-years period would result in an error of 1.3 or 2 cm in periodic mean increment. The error of the same magnitude for 3 years period would result in an error of 0.7 or 1 cm in periodic mean increment. It was decided that all plots with remeasure periods less than 2 years that had negative plot increments, or plots with persistent big negative or big positive values were dropped from the PGP database. This resulted in losing **4** plot measures from PGP database and **6** plot measures from Research database, all from South Coast.

Table 4: The distribution of measured diameter increments before exclusions and editing

Measured dinc (cm/yr)	DBHOB (cm)			
	10-30	30-50	50-70	70+
>0	9847	7728	4395	1383
0	353	185	139	65
-0.25 to 0	537	259	205	121
-0.5 to -0.25	22	26	25	15
< -0.5	21	9	14	22

(5) After editing, checking and dropping some plots, the database that remained is summarised in Tables 5 and 6 for the PGP and Research Databases. Table 7 shows the distribution of periodic mean increments by dbhob.

Table 5: Number of plots and measurements for PGP Database

No. Measures	2	3	4	Total
Riverina	18	17		35
South Coast	91	65	3	159
Total	109	82	3	194

**Note:** Measure 1 was excluded from Tables 5 and 6 because plots with only one measure cannot be used in growth modelling.

Table 6: Number of plots and measurements for Research Database

No. Measures	2	3	4	5	6	7	8	9	10	11	12	13	14
Riverina	7	7	6	5	6	5	4	5	2	1	1		
South Coast	22	23	15	13	14	14	13	11	7	6	6	3	1

(6) Although most of the plots with negative increments were dropped, a few remained. From Table 7, it can be seen that some trees with periodic mean increments below  $-0.25$  cm/yr were retained because the plots involved had positive mean periodic increments.

Table 7: The distribution of measured tree diameter increments after exclusions and editing

Measured dinc (cm/yr)	DBHOB (cm)			
	10-30	30-50	50-70	70+
>0	7444	6451	3713	1187
0	278	89	32	14
-0.25 to 0	120	52	33	16
-0.5 to -0.25	5	2	1	2

#### 2.1.4 Data Representativeness

The data used for growth modelling can be grouped as shown in Tables 8 and 9 by yield association groups (YAG) to show how representative these data would be in terms of area and number of plots, and number of measures. Yield association grouping is an aggregation of forest types based on their productivity. Yield association grouping is explained elsewhere. Table 10 shows the distribution of environmental variables available for growth modelling. The range for both the PGP data used for modelling and the strategic inventory data to which the growth models are applied tend to be similar.

Table 8: Growth Modelling Data by Yield Association

Yield Association Grouping Label	YAG	Number Of Plots	Plot Remeasures	Harvestable Net Area (ha)
Blackbutt/Blue Gum	1	6(1)	12(2)	7713.6
Spotted Gum	2	30(22)	48(109)	33714.1
Silvertop Ash	3	16	26	20829.2
Stringybark/Coast Grey Box/Forest Red Gum/Wollybutt	4	15(1)	25(6)	24625.6
Brown Barrel/Messmate	5	9	18	20043.1
Gum	6	10	16	19554.9
Apples/Peppermint/Scribbly Gum	7			525.8
Alpine Ash (Bago/Maragle)	8	16(7)	30(49)	
Bago/Maragle Hardwoods, Beucleuch Alpine Ash and Hardwoods	9	3	4	
Non-commercial/Unproductive Types	99	10	15	Not Harvestable

**Note:** The numbers in the brackets refer to Research database. Yield association groupings (YAG) are defined elsewhere (see the Report on the ‘Strategic Inventory for Southern CRA regions’).

Table 9: Number of measurements for Growth Modelling Data by Yield Association Groups

YAG	1	2	3	4	5	6	7	8	9
Remeasure No.									
2	6	29(8)	14	14(1)	9	10		14(7)	3
3	6(1)	17(12)	11	11	9	6		16(7)	1
4	(1)	2(13)	1	(1)				(6)	
5		(8)		(1)				(5)	
6		(10)		(1)				(6)	
7		(13)		(1)				(5)	
8		(12)		(1)				(4)	
9		(11)						(5)	
10		(7)						(2)	
11		(5)						(1)	
12		(6)						(1)	
13		(3)							
14		(1)							

**Note:** The numbers in the brackets refer to Research database. Yield association groupings (YAG) are defined elsewhere.

Table 10: The Environmental Variables by Yield Association

YAG	Environmental Variable	PGP		Strategic Inventory	
		Minimum	Maximum	Minimum	Maximum
1	Rainfall	996(1224)	1212(1224)	996	1272
	Mean Monthly Temperature	14.6(15.3)	15.7(15.3)	14.5	16.3
	Slope	2(7)	16(7)	2	30
	Topographic Position	0(59)	80(59)	0	100
	Mean Monthly Solar Radiation	14013(16063)	16423(16023)	11286	16611
	Soil Fertility	2	2	1	2
	Soil Depth	740(1510)	1230(1510)	505	1506
	Moisture Index	62(63)	87(63)	55	164
2	Rainfall	960(948)	1272(1272)	960	1272
	Mean Monthly Temperature	14.2(14.6)	16.5(15.6)	13.0	16.4
	Slope	2(1)	28(15)	0	30
	Topographic Position	0(0)	100(100)	0	100
	Mean Monthly Solar Radiation	11774(13605)	16999(16869)	11865	17284
	Soil Fertility	1(2)	3(2)	1	3
	Soil Depth	610(720)	2010(1510)	605	1506
	Moisture Index	48(53)	161(98)	49	194
3	Rainfall	912	1188	852	1284
	Mean Monthly Temperature	9.9	14.8	8.7	15.4
	Slope	6	23	2	29
	Topographic Position	0	100	0	100
	Mean Monthly Solar Radiation	11588	17607	10179	17569
	Soil Fertility	1	3	1	3
	Soil Depth	410	1000	405	1505
	Moisture Index	48	96	46	195
4	Rainfall	960(1032)	1236(1032)	936	1272
	Mean Monthly Temperature	13.6(14.9)	15.9(13.9)	12.8	16.0
	Slope	5(10)	26(10)	0	29
	Topographic Position	0(59)	100(59)	0	100
	Mean Monthly Solar Radiation	12431(16393)	17155(16393)	10740	17567
	Soil Fertility	2(2)	2(2)	1	3
	Soil Depth	700(950)	1230(950)	600	1506
	Moisture Index	52(60)	208(60)	47	195
5	Rainfall	816	1104	804	1140
	Mean Monthly Temperature	9.4	11.4	8.0	14.6
	Slope	4	23	2	30
	Topographic Position	0	68	0	100
	Mean Monthly Solar Radiation	14038	16574	9843	17559
	Soil Fertility	1	3	1	3
	Soil Depth	550	1510	405	1505
	Moisture Index	50	118	51	174
6	Rainfall	876	1104	852	1152
	Mean Monthly Temperature	10.5	15.0	7.7	15.2
	Slope	2	24	3	30
	Topographic Position	0	67	0	100
	Mean Monthly Solar Radiation	13199	16777	10646	17248
	Soil Fertility	2	3	1	3
	Soil Depth	950	1510	535	1505
	Moisture Index	57	105	46	203

Table 10: Continued

YAG	Environmental Variable	PGP		Strategic Inventory	
		Minimum	Maximum	Minimum	Maximum
7*	Rainfall			1056	1212
	Mean Monthly Temperature			14.3	15.4
	Slope			2	10
	Topographic Position			41	100
	Mean Monthly Solar Radiation			14602	15670
	Soil Fertility			1	3
	Soil Depth			735	735
	Moisture Index			56	79
8	Rainfall	1392(1416)	1560(1536)	1140	1596
	Mean Monthly Temperature	8.3(8.6)	9.7(9.5)	7.7	9.9
	Slope	1(2)	15(8)	2	23
	Topographic Position	18(0)	100(55)	14	100
	Mean Monthly Solar Radiation	14494(15399)	16877(16750)	13315	17070
	Soil Fertility	1(2)	3(2)	1	4
	Soil Depth	680(680)	2010(1790)	305	2269
	Moisture Index	63(92)	125(104)	55	166
9	Rainfall	1272	1584	1020	1500
	Mean Monthly Temperature	8.1	10.3	8.5	11.6
	Slope	8	12	2	22
	Topographic Position	20	50	0	100
	Mean Monthly Solar Radiation	16528	17073	13559	17745
	Soil Fertility	2	3	1	4
	Soil Depth	920	2010	305	2005
	Moisture Index	70	88	51	127

**Note:** The data in brackets are for Research, \*For YAG=7 only 2 plots were measured for the strategic inventory so there isn't much bias because of not having any PGP/Research plots in this yield association group. Yield association groupings (YAG) are defined elsewhere.

## 2.2 Model Selection

Three general forms of the dependent variable were used. These included using (1) the natural logarithmic mean periodic diameter increment, (2) the natural logarithmic mean periodic tree basal area increment ( $\text{cm}^2$ ), (3) remeasured breast height diameter (dbhob at next measure). Model forms [1] and [2] were similar (Wykoff 1990, Vanclay 1994), but it was easier to stabilise the residuals of model form [1] than model form [2]. The model form [3] had very high fit statistics as expected (Huang and Titus 1995), but the resulting residuals were biased and the inclusion of stand and site variables tended to have no improvement. As a result model forms [2] and [3] were not used. Model form [1] was selected as the best for the given database.

Within each species group, independent variables selection was based on a number of statistics. The independent variables selection was done in two steps:

1. A subset of models was selected from all possible models using a given set of independent variables. The SAS procedure called RSQUARE was used to select the best model for each species group. This involved models with highest  $R^2$  and adjusted  $R^2$ , minimum square error (MSE) and minimum Mallows'  $C_p$  statistic ( $C_p$ ). For each species group three best variable combinations were selected and then refitted using REG procedure to select the final model.
  2. The PRESS (Predicted Sum of squares) statistic, MSE and  $R^2$  were used to select the final models. The PRESS statistic is a good measure of the predictive abilities of a given model and useful for detecting the presence of outliers (see Draper and Smith 1981, Quan 1988) within the data range.
  3. In addition to the above statistics used to assess the models, the models were assessed for multicollinearity. Multicollinearity refers to the existence of high intercorrelations (near-linear dependencies) among the independent variables in the multiple linear regression. It is very important to check the models for independent variables that are highly correlated when using a large number of variables. When severe multicollinearity exists, the following problems will occur (Myers 1990). (1) Small changes in the data can produce significant changes in the parameter estimates, leading to unstable parameter estimates. (2) Parameter estimates have inflated standard errors, which affect the significance level of the corresponding independent variable. And (3) the parameter estimates may have the wrong sign and/or an unreasonable magnitude. The severity of multicollinearity among independent variables is indicated by others the correlation matrix, variance inflation factors, and the eigenvalues of the covariance matrix. For detailed discussion of multicollinearity, the reader is referred to Myers (1990). The SAS procedure REG has options for assessing multicollinearity by calculating the variance-inflation factors (VIF) and tolerance values for parameter estimates (TOL), and requesting a detailed analysis of collinearity among the independent variables. The option called COLLIN produces eigenvalues, condition indices, and decomposition of the variances of the estimate parameters with respect to each eigenvalue.
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### 2.2.1 Explanation of the Statistics used in assessing the Models

**R<sup>2</sup>** ⇒ Coefficient of multiple determination is defined as sum of squares regression divided by sum of squares total, which is proportion (percentage) of the total variation in the dependent variable explained or accounted for by the fitted regression. A model with a higher R<sup>2</sup> is preferred to a model with lower R<sup>2</sup> given all other factors being the same.

**MSE** ⇒ Mean Square Error (residuals) is defined as the sum of square error (SSE) divided by the degrees of freedom. This is a measure of unexplained variation. Therefore, a model with lower MSE value is better than a model with higher MSE.

**C<sub>p</sub>** ⇒ Mallows' statistic is defined as:  $(SSE_p/MSE) - (N - 2 \times p)$  where MSE is mean square error for the full model, SSE<sub>p</sub> is the error sum of squares for the model with p parameters including the intercept. If C<sub>p</sub> is plotted against p, Mallows recommends the model where C<sub>p</sub> first approaches p. When the right model is selected, the parameter estimates are unbiased, and this is reflected in C<sub>p</sub> near p (see Daniel and Wood (1980)).

**ADJRSQ** ⇒ Adjusted R<sup>2</sup> statistic is an alternative to R<sup>2</sup> that is adjusted for the number of parameters in the model. It can be calculated as:  $ADJRSQ = 1 - [(n-i)(1 - R^2)] / (n-p)$ , where n is the number of observations used to fit the model and i is an indicator variable that is 1 if the model includes an intercept or 0 otherwise. With one parameter R<sup>2</sup> = ADJRSQ. While R<sup>2</sup> increases with an increase in the number of parameters, ADJRSQ will increase to a maximum and reach a stage when it starts to decrease as the effect of p in the denominator increases.

**PRESS** ⇒ Predicted Residual Sum of Squares is defined as:  $PRESS = \sum(Y_i - Y_{(i)})^2$  where Y<sub>i</sub> is the ith measured observation of the dependent variable, Y<sub>(i)</sub> is the estimator of E(Y<sub>i</sub>) excluding the ith observation. The PRESS statistic estimates the squared differences between observed and predicted data points (sum of squares of discrepancies for a given model), as if the data point came from an independent data set. The lower the PRESS statistic, the better the model is in predicting new data. The 'best' regression model will have a comparatively small PRESS value. Quan (1988) has indicated that the PRESS statistic, in addition to being a cross-validation measure, can be good general measure of regression diagnostics for detecting outlier and influential observations. Therefore, with limited data sets the PRESS statistic will suffice instead of data splitting (Quan 1988).

**TOL** ⇒ Tolerance for a variable is defined as  $1 - R^2$ , where R<sup>2</sup> is obtained by regression of the variable on all other independent variables in the model.

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**VIF**  $\Rightarrow$  Variance inflation is the reciprocal of tolerance. Most statisticians generally agree that if the VIF exceeds 10, then there is reason for concern. On the other hand, if the model contains some polynomial and cross-product terms, VIFs up to some higher level can be tolerated for these terms.

### 3. Results

The final form of the dependent variable used was the natural log mean periodic diameter increment (Ldi). The model form used for Southern was the same form used for Upper and Lower North East, except that some variables were dropped from the model (see Equation 1) used for Southern. One major difference between the Southern model (Equation 1) and the model used for Upper and Lower North Coast is that dominance (a categorical variable) was replaced with relative basal area (BAL/BA). In addition, the variable called location was dropped from the model. However, as was done for Upper and Lower North Coast a constant value was added to all diameter increments to make all values positive. This is important because negative and zero values are undefined when logarithmic transformations are applied to the data. However, for North Coast a single value of 1.0 was added for all species groups. This value was found appropriate to remove negative and zero values as well as normalising the residuals. However, for Southern different values were used to compensate for both native and zero and normalise the residuals. The constant values of 0.1 to 0.6 depending on the species group were found to produce normally distributed dependent variables and the residuals. Thus, the dependent variable used was  $(Ldi) = \ln(\text{dinc} + \text{CF2})$ ; where dinc is the mean periodic diameter increment (cm/yr),  $\ln$  is the natural logarithm and CF2 is the constant. All the DIMs developed for the Yield Simulator have the following standard form:

$$Ldi = G_0 + G_1 dbhob + G_2 (10 / dbhob) + G_3 \ln(dbhob) + G_4 \ln(totba) + G_5 totba + G_6 dba + (1) \\ G_7 bal + G_8 balr + G_9 bal2 + G_{10} rain + G_{11} temp + G_{12} slope + G_{13} solar + G_{14} position + \\ G_{15} sdepth + G_{16} m\_index$$

where: **Ldi** = the natural log of (mean periodic diameter increment+CF2) and the predicted diameter increment (DIM) is calculated as:  $[\text{Exp}(\text{Ldi}) * \text{CF1}] - \text{CF2}$ ;  
**CF1** = the correction factor for the bias associated with logarithmic transformation,  
**CF2** = the correction factor used to normalise the residuals and compensate for negative and zero diameter increment values (as explained above), and

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Exp is the exponential value (approximately 2.71828183).

The models were fitted to over 19400 observations, which implicitly recognised that the 10 species groups share varying diameter growth parameters. Estimated parameters ( $G_0$  to  $G_{16}$ ) and standard errors (in brackets) for the individual diameter increment (DIM) projection equation are presented in Appendix 3.

**Note:** Since we are using a transformed variable (Ldi), a bias results when back-transforming to the original variable dinc (periodic mean diameter increment), because the logarithmic transformed variable estimate the median, not the mean value. Therefore, we need to correct the predicted values for this systematic bias. There are numerous correction factors (see Flewelling and Pienaar 1981). However, the correction factor used in this case will be the simple one suggested by Flewelling and Pienaar (1981), which is just multiplying the predicted diameter increment with exponent of mean square error (MSE) divided by 2 ( $\exp(\text{MSE}/2)$ ). This simple correction factor (CF1) will suffice because Flewelling and Pienaar (1981) stated that if the  $\text{MSE} < 0.5$  and the number of independent observations  $> 30$  then the error in predicted values will be less than 1 %. All our species groups meet these conditions. For example, a tree of diameter 40cm with an annual increment of 2 cm would be approximated with an increment of over 1.98cm (less than 0.2mm in error).

The tree, stand and environmental variables used in modelling diameter increment include the following:

### 3.1 Tree variables

- dbhob** = diameter over bark at breast height. The individual tree' size is the most important variable in an individual tree increment model.
- Ln(dbh)** = Natural logarithm of dbhob.
- bal** = overtopping basal area (the total basal area of the trees in the plot larger than a given tree (bal)). A transformation of bal was found to improve the model fit for some species groups.
- balr** =  $\text{bal}/\text{totba}$ , this variable, which has values ranging from zero for a dominant tree to nearly one for a suppressed tree, was used to replace the use of dominance.
- bal2** =  $\text{bal}/(\log(\text{dbhob}))$ .

### 3.2 Stand (plot) Variables

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<b>totba</b>	=	Total stand basal area per plot (m <sup>2</sup> per ha).
<b>Ln(totba)</b>	=	Natural logarithm of total stand basal area.
<b>dba</b>	=	Interaction between tree size (dbhob) and stand density (totba) as $\ln(\text{dbhob}) * \ln(\text{totba})$ .

### 3.3 Locality variables

Since the data were already separated into Riverina and South Coast groups, it was thought that further separation based on location, as was done for Upper and Lower North East, into Coastal and Tablelands was not necessary. However, it came to our notice after modelling that separation of South Coast data into Coastal and Tablelands could have helped to separate species like coastal brown barrel and silvertop ash from tablelands species. Such analysis will be done later to check how significant location would be for all species groups in the post-CRA work.

### 3.4 Environmental variables

<b>rainfall</b>	=	total annual rainfall (metres) based on the NEFBS model
<b>temp</b>	=	average monthly temperature (degrees).
<b>slope</b>	=	topographic slope (degrees). Note for Upper and Lower North we used radians.
<b>solar</b>	=	average monthly solar radiation/10000; Note a change in solar radiation scale.
<b>position</b>	=	topographic position.
<b>sdepth</b>	=	Soil depth (metres).
<b>sfert</b>	=	Soil Fertility as a dummy variable. This variable is on an ordinal (class) scale, from 1 (low fertility) to 5 (high fertility). The PGP and Research data had soil fertility only as values of 1, 2, and 3, with almost all the data in class 2. As a result this variable was dropped because it was not significant due data deficiency. Also based on the classification for creating dummies used for Upper and Lower North Coast of grouping 4 and 5 together and 1,2 and 3 together would result in insufficient dummies.
<b>M_index</b>	=	Soil moisture index.

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## **4. Discussion**

### **4.1 Variation Between DIMs**

#### **4.1.1 Species Group**

DIMs were developed for 10 broad species groups. Because of the large number of species and limited data, it was important to find sensible groupings of species based on their growth potential. The PGP data were used to group individual tree diameter increments per species within a given site productivity class into groups of similar growth rates. The PGP data were classified into 4 site productivity classes using site height as a measure of site productivity. That is, site height < 25m as class 1, site heights of 25-35 as site class 2, site heights between 35 and 45 m as site class 3, and site heights above 45 m as site class 4. Then a computer software program called KnowledgeSEEKER was used to group species within a site class using Ldi. KnowledgeSEEKER examined the Ldi for each species within site classes and displayed a summary of statistically significant groups as a graphic decision tree. 8 groups within site classes were produced for South Coast and 3 groups within site classes for Riverina. However, Group 8 for South Coast and Group 3 for Riverina were composed of the species with the poorest growth and as a result they were combined into one group (Group 8). Expert knowledge of experienced internal staff was then sought to assign species with insufficient or no data into the existing groups. The species contained in each group are listed in Appendix 4.

#### **4.1.2 Availability of environmental parameters**

Tree diameter growth is dependent on a range of environmental factors, including rainfall, temperature, soil type, slope, topographic position and solar radiation. These environmental variables were used in the model as a measure of site productivity. GIS layers covering the South Coast and Riverina regions were consistent for all environmental variables. Apart from the Prescott Soil Index, all the other variables were available for all areas, therefore, the Prescott Soil Index was not used. Even though the Prescott Soil Index is thought to be a good measure of site productivity, it is highly correlated with rainfall, temperature and solar radiation because it is derived from these

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variables. Therefore, we think that, by using rainfall, temperature and solar radiation instead of Prescott Soil Index, we might not have missed much.

Compared to 52 diameter increment models developed for Upper and Lower North Coast, only 10 models were developed for South Coast and Riverina regions because we had the areas covered for environmental variables and we dropped the use of dominance as an independent variable. The reason for dropping dominance from the models was that, in the Research data, dominance was not recorded for all trees at all measurement periods. Yet Research data were needed, not only to increase the data set, but because of the silvicultural operations carried out on research plots. Vanclay (1994) notes the importance of both passive monitoring (PGPs) and active stand manipulations (research) in modelling databases. The variable (bal/totba) used to replace dominance is quantitative and representative of dominance, therefore we believe it improves the portability and precision of the models. Previous models depended on a qualitative variable (dominance) that was only subjectively estimated.

## **4.2 Confidence limits and parameter standard errors**

The standard errors (in brackets) associated with each coefficient ( $G_0$  to  $G_{16}$ ) are presented in Appendix 3. Using the standard error we can construct confidence limits for the model parameters. However, it should be noted that we are using PGP and Research data that are both serially and longitudinally correlated. Therefore, the variances associated with these coefficients are biased. Since the models will be used for prediction of future diameter increment only, the coefficient estimates are not affected by the bias in the coefficient variances. This means the predicted diameter increments will be unbiased because they are based on unbiased coefficient estimates. The variables found not significant at the usual levels of significance ( $\alpha=0.05$ ), have zero values the parameter estimates.

## **4.3 Growth Model modifier**

The longer the time of simulation (i.e. 30 years or more), the less likely the individual tree based recruitment and mortality models will capture the dynamics of the stand. Predicted stand basal area (the sum of individual tree basal areas) might reach unrealistically high levels. A parallel stand-based basal area model should be developed to constrain the individual tree growth model results if necessary. This model developed uses initial basal area, initial stocking, future stocking (initial stocking, plus predicted recruitment minus

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predicted mortality), stand density index based on DBHOB of 30 cm, and environmental variables for a given yield association grouping. Due to data limitation, only 3 yield association groups were used, which were:

Yield association 3 gives yield association group (YAG) of 1,  
 All other Yield associations give yield association group (YAG) of 2,  
 Yield association 8 gives yield association group (YAG) of 3,

The general model fitted for all YAGs was:

$$BA_2 = \exp[B_0 + B_1 \ln(BA_1) + B_2 \ln(sph_1) + B_3 (sph_1 / sph_2) + B_4 \ln(sdi_1) + B_5 (sdi_1 / sdi_2) + B_6 solar + B_7 position + B_8 sdepth] \quad (2)$$

where **BA<sub>2</sub>** = the predicted basal areas at future time 2,  
**Ln** = natural logarithm,  
**BA<sub>1</sub>** = total basal area in m<sup>2</sup> per ha at the beginning of the growth period,  
**sph<sub>1</sub>** = initial stocking (number of stems per ha),  
**sph<sub>2</sub>** = the stocking at future time t,  
**sdi<sub>1</sub>** = initial stand density index, calculated as  $(\text{plot weight} \times \sum\{30/\text{dbhob}\}^{1.605})$  per plot,  
**sdi<sub>2</sub>** = stand density index at future time t, calculated as **sdi<sub>1</sub>**. The environmental variables are as defined for diameter increment models:

The environmental variables are as defined for diameter increment models:

**solar** = average solar radiation (MJ per day),  
**position** = topographic position (ranges from 0 for the valley and 100 for top of the ridge),  
**sdepth** = soil depth (m).

Stand density index, a stand density measure usually associated with even-aged stands was found to be a useful measure of stocking for uneven-aged stands by Long and Daniel (1990) and therefore was used here. A quadratic mean diameter of 30 cm was used because it was assumed that at this size, an average stand would be in its prime growth period.

The predicted basal area is used to constrain the diameter growth model predictions where the sum of basal areas of projected individual trees after the growth period is found to be higher than the predicted basal area. The constraint is:

- (1) Adjusted diameters:  $\text{dbhob}(\text{adjusted}) = \text{square root} \{ (BA_2 / \sum ba) \} * \text{dbhob}(\text{unadjusted})$
- (2) Adjusted Basal Area of individual trees =  $(BA_2 / \sum ba) * ba$ .

where *ba* is the future basal area of individual trees based on the diameter increment model.

The basal area models were fitted using about 398 plot observations for the 3 yield association groups. Estimated parameters (B<sub>0</sub> to B<sub>8</sub>) and standard errors (in brackets) are

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presented in Appendix 5. The variables found not significant at the usual levels of significance ( $\alpha=0.05$ ), have zero values the parameter estimates.

#### **4.4 Diameter Increment Growth Model Evaluation**

To evaluate the model it is necessary to use simulation studies because no independent data set was available. It can be seen from Equation 1 that the model is dependent on individual tree size, total stand basal area, overtopping basal area, and an array of soil, climatic and topographic factors (referred to as 'environmental variables'). Assuming that environmental variables are substitutes for site productivity index, it is difficult to allow them vary for any simulation. Therefore, all environmental variables were maintained constant (assuming a given a site). That leaves the important variables as current tree size (dbhob), total basal area (BA) or stand density, and Overtopping basal area (BAL) or measure of competition. Individual tree diameter is the most significant factor to tree growth, modified by stand density, competition and the environment it is growing in. Therefore, dbhob will be used as continuous variable in the simulation.

To get meaningful evaluation of the model, three or four dominance classes (dominant or codominant, subdominant and suppressed) and four stand density classes (low density, BA=10; medium density, BA=20; high density, BA=40 and very high density stands, BA=60) were used. It was assumed that a suppressed tree would have 95% of total stand basal area overtopping it, a subdominant with 50%, a codominant with 5% and dominant with 0% or none overtopping it.<sup>1</sup> These percentages were translated into actual values of overtopping basal area and used in the model. The results are presented in Appendix 6.

Appendix 6 shows that maximum growth for a tree occurs when the diameter at breast height is between 30 and 50cm. The Figure also demonstrates that optimum diameter increment is obtained where there is minimal total basal area and trees have less overtopping basal area (dominant or codominant trees). These growth rates drop by approximately 20% and more if the tree is in a subdominant or suppressed position in the same stand. The effect of doubling basal area from 20 to 40m<sup>2</sup>/ha is roughly the same as dropping a dominance class.

Appendix 6 demonstrates that a suppressed tree growing in a very dense stand with 60m<sup>2</sup>/ha total basal area will be have barely any growth compared to a suppressed tree growing in a

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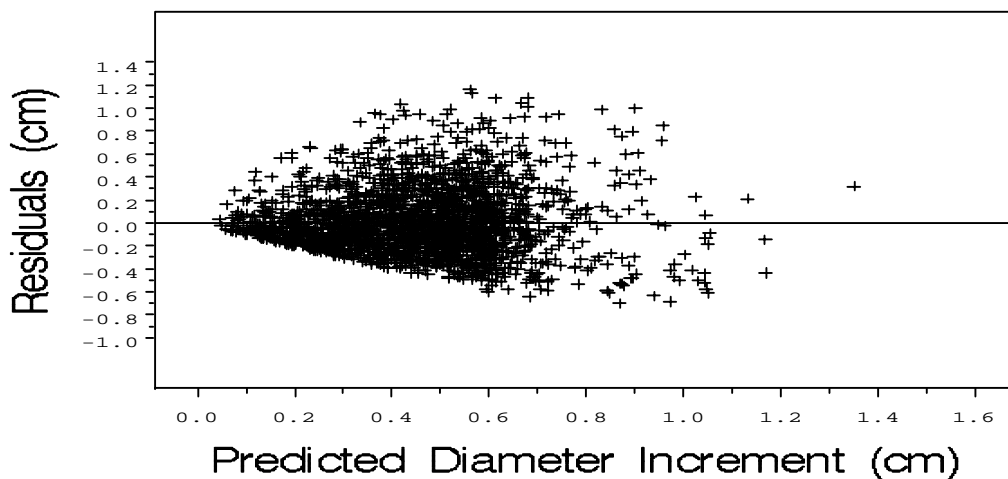
<sup>1</sup> For the light density stands (BA=10 and BA=20), the subdominant class was dropped for figure clearness.

less dense stand with  $40\text{m}^2/\text{ha}$  of total basal area. This difference can be explained by the fact that in a less dense stand there is still some gaps that can allow the tree to get more light. Also there will be less competition for the nutrients compared to trees in the denser stand. Figures similar to Figure 1 for all other nine species groups are available but not presented here. All figures have the same trend except that they have different growth rates for different species groups.

Appendix 6 shows that the diameter increment model (Equation 1) behaves in the expected manner and will allow some different growth rates to take place among trees of different sizes growing in different stand densities. Even though the model is general for some species (many species grouped together), it is expected to give reasonable predictions for all species. In future this model will be improved by modelling individual species or groups of a few species with similar growth characteristics. This will depend on data availability.

Due to the request by BRS that we present the plot of residuals, two figures are presented below. Figure 1 shows the plot of residuals against the periodic predicted diameter increment and Figure 2 shows the plot of residuals against the measured diameter at breast height overbark (DBHOB).

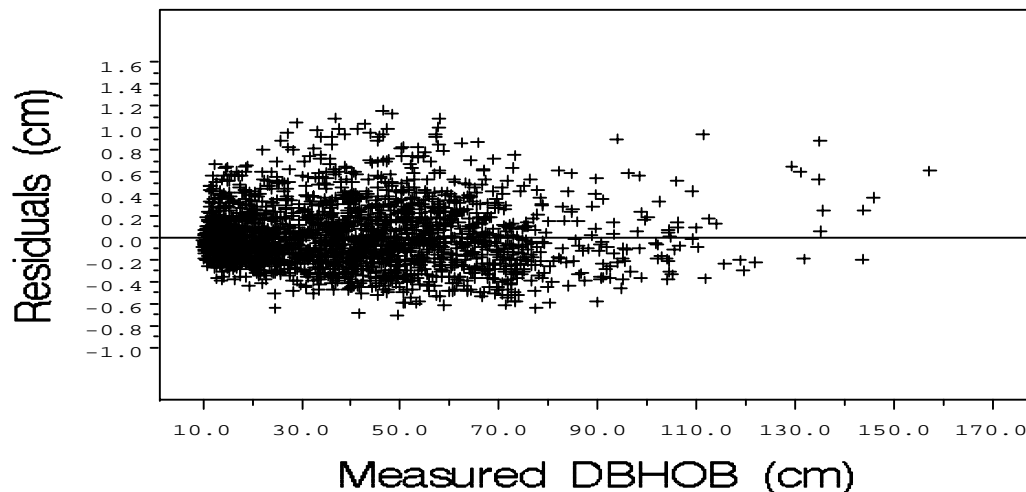
Figure 1: Plot of residuals against predicted diameter increment for species group one





From Figures 1 and 2, it is seen that no systematic biases resulted from model 1 for species group one. For all other species groups similar graphs are available from the author. It should be pointed out that because they are all similar in trend there was no reason to present them all here. The lower 'cut' in Figure 1 is due to data censoring at DBHOB=10 cm, which is the minimum DBHOB measured.

Figure 2: Plot of residuals against measured DBHOB for species group one



#### 4.5 Diameter Increment Growth Model Implementation

The growth model has been formulated to use one set of diameter increment models. The pseudo code presented below demonstrates how the models are linked and how the growth simulation fits into the greater context of the Growth and Yield System (the Yield Simulator). The code sequence that the Yield Simulator uses for implementing a full individual tree growth modelling that is driven by tree and plot variables is shown in diagram in Figure 3. This is a pseudo-English code sequence that describes the flow of data through the Yield simulator. The actual programming was done in Visual Basic.

Since our knowledge of stand dynamics is limited, it is assumed that the mortality and recruitment models, which are a general in nature, might not capture the drastic changes in the stand over time. After so many years, a basal area prediction model would be used to check on the diameter increment models to make sure that the predicted values do not give unrealistic values. This basal area growth model adjusts the individual tree growth based on

predicted overall basal area change. This stand basal area constraint provides an overall stand conditioning input in a way that is not possible with a tree growth alone.

Figure 3: The diagram showing control sequence for the Yield Simulator

```

For Simulation Year = 1 To 100
  Output the plot status and stand statistics every fifth year
  Grow the stand one year
    The growth module sequence includes
      Determine the level of Recruitment and insert recruits into the stand
      For each tree in the plot
        Determine if the mortality model kills the tree
        If the tree has not died then
          Grow the trees diameter for one year using the
            dominance constrained model and no dominance
            factor
        End If
      Select the next tree in the plot
    Calculate plot level statistics that determine the level of basal area and volume present
    If stand condition suitable for harvest then Undertake Harvest Simulation
  Next Simulation Year
  
```

## 5. Conclusions

The Diameter Growth Models project generated 10 DIMs for the FRAMES Yield Simulations for South Coast and Riverina regions. The results presented here, modelled diameter increment successfully under a wide range of environments and stand conditions, and represent the best available functions for the NSW CRA/RFA process for the South Coast and Riverina regions. These models will be progressively improved as more repeated measurement data comes to hand during post CRA. However, there is concern by BRS that this model (Equation 1) is not flexible in terms of shape and scale. This concern will be investigated in the post CRA work and if found true then a variety of other model forms (e.g., Huang and Titus 1995; Zeide 1993) will be tried to replace the existing model form.

However, the prediction abilities of the model for long serial measurements (such as hundreds of years) are not known. Such long serial measurements were not included the database for the model might not be predicted as accurately as short serial measurements. This was a concern of the BRS. However, the database contains both short serial measurements and a few long serial measurements from Research database. The short serial measurements are

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based on very many plots representing a big range of sites, stand densities and harvesting regimes. We anticipate that if our model can simulate these conditions well, then it should be able to predict future stand changes and growth of our forests equally well. This assumption will be tested in the post CRA work.

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## **Appendices**

**Appendix 1 SAS code to calculate plot weights**

**Appendix 2 SAS code to assign dbhob values to missing trees**

**Appendix 3 DIM coefficients and standard errors**

**Appendix 4 Species Group Aggregations**

**Appendix 5 Basal Area bases Growth Model Modifiers**

**Appendix 6 Diameter Increment Models for Species Group 1**

**Appendix 1 SAS code to calculate plot weights**

```
*****  
***** Calculating number of stems per plot and Basal Area*****  
*****  
/* For Measurements 2 and 3 */  
  
%let alpha=1;  
%let omega=2;  
  
data incr&omega&alpha;  
set incr&omega&alpha ..master;  
  
if dbhob_&alpha<10.0 then do;  
  weight&alpha=.; wba&alpha=.; end;  
else if (dbhob_&alpha<10 and dbhob_&omega<10) then delete;  
else if plotname in ('PAB101','PAB102','PAB103','PAB104','PAB105','PAB106') then do;  
  weight&alpha=10;  
  weight&omega=10;  
  wba&omega=(1/0.1)*ba&omega;  
  wba&alpha=(1/0.1)*ba&alpha;  
end;  
else if plotname='PAB113' then do;  
  if 10.0<=dbhob_&alpha<30 then do;  
    weight&alpha=10;  
    weight&omega=10;  
    wba&omega=(1/0.1)*ba&omega;  
    wba&alpha=(1/0.1)*ba&alpha;  
  end;  
  else do;  
    weight&alpha=1/0.3;  
    weight&omega=1/0.3;  
    wba&omega=(1/0.3)*ba&omega;  
    wba&alpha=(1/0.3)*ba&alpha;  
  end;  
end;  
else do;  
  if 10.0<=dbhob_&alpha<30 then do;  
    weight&alpha=10;  
    weight&omega=10;  
    wba&omega=(1/0.1)*ba&omega;  
    wba&alpha=(1/0.1)*ba&alpha;  
  end;  
  else if 30<=dbhob_&alpha<50 then do;  
    weight&alpha=1/0.3;  
    weight&omega=1/0.3;  
    wba&omega=(1/0.3)*ba&omega;  
    wba&alpha=(1/0.3)*ba&alpha;  
  end;  
  else do;  
    weight&alpha=1/0.6;
```

---

```
    weight&omega=1/0.6;
    wba&omega=(1/0.6)*ba&omega;
    wba&alpha=(1/0.6)*ba&alpha;
    end;
end;

if (dbhob_&alpha>10 and dbhob_&omega<10) then do;
    weight&omega=.; wba&omega=.;
    diam&omega&alpha=.;
    baha&omega&alpha=.;
    ba&omega&alpha=.;
    muhair&omega&alpha=.;
end;
run;

/* For Measurements 2 and 3 */
%let alpha=2;
%let omega=3;

data incr&omega&alpha;
    set incr&omega&alpha ..master;
if dbhob_&alpha<10.0 then do;
    weight&alpha=.; wba&alpha=.; end;
else if (dbhob_&alpha<10 and dbhob_&omega<10) then delete;
    else if plotname in ('PAB101','PAB102','PAB104','PAB106') then do;
        weight&alpha=10;
        weight&omega=10;
        wba&omega=(1/0.1)*ba&omega;
        wba&alpha=(1/0.1)*ba&alpha;
        end;
else do;
    if 10.0<=dbhob_&alpha<30 then do;
        weight&alpha=1/0.1;
        weight&omega=1/0.1;
        wba&omega=(1/0.1)*ba&omega;
        wba&alpha=(1/0.1)*ba&alpha;
        end;
    else if 30<=dbhob_&alpha<50 then do;
        weight&alpha=1/0.3;
        weight&omega=1/0.3;
        wba&omega=(1/0.3)*ba&omega;
        wba&alpha=(1/0.3)*ba&alpha;
        end;
    else do;
        weight&alpha=1/0.6;
        weight&omega=1/0.6;
        wba&omega=(1/0.6)*ba&omega;
        wba&alpha=(1/0.6)*ba&alpha;
        end;
end;

if (dbhob_&alpha>10 and dbhob_&omega<10) then do;
```

---

```
weight&omega=.; wba&omega=.;
diam&omega&alpha=.;
baha&omega&alpha=.;
ba&omega&alpha=.;
muhair&omega&alpha=.;
end;
run;

/* All measurements after third measure came from tri-radii plots. Therefore this code is
the same for all measures after 3rd measure.*/

%let alpha=3;
%let omega=4;

data incr&omega&alpha;
set incr&omega&alpha ..master;

if 10.0<=dbhob_&alpha<30 then do;
    weight&alpha=1/0.1;
    weight&omega=1/0.1;
    wba&omega=(1/0.1)*ba&omega;
    wba&alpha=(1/0.1)*ba&alpha;
end;
else if 30<=dbhob_&alpha<50 then do;
    weight&alpha=1/0.3;
    weight&omega=1/0.3;
    wba&omega=(1/0.3)*ba&omega;
    wba&alpha=(1/0.3)*ba&alpha;
end;
else do;
    weight&alpha=1/0.6;
    weight&omega=1/0.6;
    wba&omega=(1/0.6)*ba&omega;
    wba&alpha=(1/0.6)*ba&alpha;
end;

if (dbhob_&alpha>10 and dbhob_&omega<10) then do;
    weight&omega=.; wba&omega=.;
    diam&omega&alpha=.;
    baha&omega&alpha=.;
    ba&omega&alpha=.;
    muhair&omega&alpha=.;
end;
run;
```

---



**Appendix 2 SAS code to assign dbhob values to missing trees**

```
*****
                                *Calculations for Missing trees for all remeasures**
*****
%let alpha=1; /* or 2,3,4 */
%let omega=2; /* or 3,4,5 */

*STEP 1 - Re-assigning TSC value to all TSC_&omega='11' trees;

data data4 (drop=species2 dbhob);
set incr&omega&alpha..master;

if species in ('BBT','SBG','MMT','MAG','FAS','SHG','STA','WHA','ALA')
    then species2='FAT'; /* FOR FAST GROWING SPECIES */
else species2='SLO'; /* FOR SLOW GROWING SPECIES */

*** STEP 3 - Re-assigning dbhob_&alpha NEW values for the purposes of
of calculating 'LESS' BIASED stand density (total stand basal areas
and number of stems per ha);

%let MAXFAST=1.2; /*Fast growing trees */
%let MAXSLOW=0.8; /*Slow growing trees */

if tsc_&omega='11' then do;
if 40<=dbhob_&omega<=60 then do;
if species2='FAT' then do;
    dbhob=dbhob_&omega-(peri&omega&alpha*&MAXFAST);
end;
else if species2='SLO' then do;
    dbhob=dbhob_&omega-(peri&omega&alpha*&MAXSLOW);
end;
end;

%let MAXFAST=1.0; /*Fast growing trees */
%let MAXSLOW=0.6; /*Slow growing trees */

if (30<=dbhob_&omega<40 or 60<dbhob_&omega<=70) then do;
if species2='FAT' then do;
    dbhob=dbhob_&omega-(peri&omega&alpha*&MAXFAST);
end;
else if species2='SLO' then do;
    dbhob=dbhob_&omega-(peri&omega&alpha*&MAXSLOW);
end;
end;

%let MAXFAST=0.8; /*Fast growing trees */
%let MAXSLOW=0.5; /*Slow growing trees */

if (20<=dbhob_&omega<30 or 70<dbhob_&omega<=80) then do;
if species2='FAT' then do;
    dbhob=dbhob_&omega-(peri&omega&alpha*&MAXFAST);
end;
else if species2='SLO' then do;
    dbhob=dbhob_&omega-(peri&omega&alpha*&MAXSLOW);
end;
end;

%let MAXFAST=0.6; /*Fast growing trees */
%let MAXSLOW=0.4; /*Slow growing trees */
```

---

```
if (dbhob_&omega;<20 or 80<dbhob_&omega;<100) then do;
if species2='FAT' then do;
  dbhob=dbhob_&omega-(peri&omega&alpha*&MAXFAST);
end;
else if species2='SLO' then do;
  dbhob=dbhob_&omega-(peri&omega&alpha*&MAXSLOW);
end;
end;
```

```
%let MAXFAST=0.3; /*Fast growing trees */
%let MAXSLOW=0.2; /*Slow growing trees */
```

```
if (dbhob_&omega=>100) then do;
if species2='FAT' then do;
  dbhob=dbhob_&omega-(peri&omega&alpha*&MAXFAST);
end;
else if species2='SLO' then do;
  dbhob=dbhob_&omega-(peri&omega&alpha*&MAXSLOW);
end;
end;
```

```
END;
```

```
/* Assigning TSC to missing trees */
```

```
IF tsc_&omega='11' then do;
if distance<=18 then do;
  if 0<dbhob<10 then tsc_&omega='10';
end;
if (18<=distance<=31 and dbhob_&omega>30) then do;
  if 20<dbhob<30 then tsc_&omega='10';
end;
if (distance ge 31 and dbhob_&omega=>50) then do;
  if 40<dbhob<50 then tsc_&omega='10';
end;
```

```
END;
```

```
/* Assigning diameter and new tsc to missing trees so that they are not used in dinc calculations*/
```

```
if dbhob ge 10 then do;
  dbhob_&alpha=dbhob;
  tsc_&alpha='15';
end;
if 0<dbhob<10 then dbhob_&alpha=.;
if tsc_&omega='10' then do;
  dbhob_&alpha=.;
  tsc_&alpha=";
end;
run;
```

---

### Appendix 3 DIM coefficients and standard errors Parts 1 and 2

#### Part 1

SPECIES GROUP	CF1	CF2	INTERCEPT G0	DBHOB G1	10/DBHOB G2	LOG(DBHOB) G3	LOG(TOTBA) G4	TOTBA G5
01	1.0644	0.3	2.506053(0.285047)	-0.008952(0.001529)	-0.542829(0.171968)	0.000000	-1.14879(0.152437)	0.022036(0.004394)
02	1.0761	0.2	-2.60835(0.980006)	-0.022134(0.002460)	0.000000	0.791277(0.081171)	-0.450142(0.186659)	0.000000
03	1.0571	0.2	-2.085476(0.198085)	-0.012632(0.001576)	0.000000	0.642612(0.054903)	-0.260306(0.032892)	0.000000
04	1.0531	0.2	-2.51344(0.361858)	-0.02705(0.002001)	0.000000	1.196686(0.074255)	-0.140702(0.063960)	0.000000
05	1.0742	0.2	0.942825(0.329964)	-0.014133(0.001013)	0.000000	0.486372(0.031447)	-0.51195(0.086968)	0.012630(0.003641)
06	1.0394	0.3	-2.173831(0.405757)	-0.018070(0.002052)	0.000000	0.662633(0.075247)	0.425466(0.064006)	0.000000
07	1.0752	0.2	1.021256(0.297346)	-0.018259(0.002303)	0.000000	0.661693(0.072333)	-0.261793(0.053352)	0.000000
08	1.0582	0.1	0.000000	-0.038432(0.006702)	0.000000	1.355281(0.221687)	-1.639763(0.22389)	0.047599(0.008977)
09	1.0317	0.6	1.922657(0.276618)	-0.007287(0.001232)	-0.233846(0.114451)	0.000000	-0.653357(0.084411)	0.000000
10	1.0473	0.2	-9.027433(3.906492)	-0.012497(0.003206)	0.000000	0.836725(0.097210)	0.206516(0.198900)	0.000000

#### Part 2

SPECIES GROUP	CF1	CF2	DBA G6	BAL G7	BALR G8	BAL2 G9	RAINFALL G10	TEMP G11
01	1.0644	0.3	0.095024(0.034907)	-0.009685(0.001627)	0.000000	0.000000	0.613229(0.086831)	-0.055531(0.006260)
02	1.0761	0.2	0.000000	0.005406(0.001098)	-1.051407(0.256883)	0.000000	-1.237762(0.583928)	0.065142(0.026804)
03	1.0571	0.2	0.000000	0.000000	0.000000	0.000000	0.550055(0.125103)	0.000000
04	1.0531	0.2	0.000000	-0.005104(0.002125)	0.000000	0.000000	0.000000	0.010289(0.003404)
05	1.0742	0.2	0.000000	-0.019599(0.000968)	0.000000	0.000000	0.485883(0.053589)	-0.103322(0.017890)
06	1.0394	0.3	0.000000	0.011172(0.001908)	0.000000	0.000000	-1.045633(0.194049)	0.074325(0.008203)
07	1.0752	0.2	0.000000	-0.010846(0.002213)	0.000000	0.000000	0.000000	-0.149283(0.016708)
08	1.0582	0.1	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
09	1.0317	0.6	0.097104(0.022525)	0.000000	-0.456627(0.031541)	0.057334(0.026274)	-1.207305(0.136890)	0.000000
10	1.0473	0.2	0.000000	-0.007959(0.006851)	0.000000	0.000000	2.306945(1.302200)	0.254862(0.214684)

**Appendix 3 DIM coefficients and standard errors Part 3**

SPECIES GROUP	CF1	CF2	SOLAR G12	SLOPE G13	POSITION G14	SDEPTH G15	M_INDEX G16
01	1.0644	0.3	0.000000	0.003933(0.001309)	0.000000	0.000000	0.000000
02	1.0761	0.2	1.595738(0.795396)	0.024281(0.008934)	0.005088(0.001463)	0.000000	0.000000
03	1.0571	0.2	0.000000	0.000000	-0.001145(0.000326)	-0.237415(0.045499)	0.002008(0.000386)
04	1.0531	0.2	-0.361804(0.137889)	0.000000	0.000000	0.000000	0.000000
05	1.0742	0.2	-0.140928(0.066247)	0.000000	-0.001118(0.000182)	-0.066547(0.023923)	0.002555(0.000355)
06	1.0394	0.3	-0.560795(0.085551)	0.000000	0.000000	0.000000	0.000000
07	1.0752	0.2	0.000000	-0.008916(0.001916)	0.000000	-0.074685(0.046856)	0.001278(0.000511)
08	1.0582	0.1	0.000000	0.000000	-0.002793(0.001240)	0.000000	0.000000
09	1.0317	0.6	1.146127(0.097390)	0.000000	-0.000863(0.000224)	-0.050471(0.050471)	-0.000901(0.000439)
10	1.0473	0.2	0.000000	-0.021228(0.012496)	0.000000	0.000000	0.000000

## Appendix 4 Species Group Aggregations

Growth Group	Species Group	Common Name	Botanical Name	Species Code
Blackbutt/ Gums	<b>1</b>	Blackbutt	<i>Eucalyptus pilularis</i>	BBT
		Gum, Blue	<i>Eucalyptus saligna</i>	SBG
		Ash, White	<i>Eucalyptus fraxinoides</i>	WHA
		Bangalay	<i>Eucalyptus botryoides</i>	BAN
		Gum, Big Badja	<i>Eucalyptus badjensis</i>	BBG
		Gum, Manna	<i>Eucalyptus viminalis</i>	MAG
		Gum, Ribbon	<i>Eucalyptus viminalis</i>	MAG
		Gum, Monkey	<i>Eucalyptus cypelloarpa</i>	MKG
		Gum, Maidens	<i>Eucalyptus globulus</i> ssp. <i>maidenii</i>	MDG
		Gum, Shining	<i>Eucalyptus nitens</i>	SHG
		Peppermint, River	<i>Eucalyptus elata</i>	RPM
		Peppermint, Gully	<i>Eucalyptus smithii</i>	GPM
		Stringybark, Yellow	<i>Eucalyptus muelleriana</i>	YSB
Brown barrel	<b>2</b>	Brown barrel	<i>Eucalyptus fastigata</i>	FAS
Ironbarks	<b>3</b>	Ironbark, Grey	<i>Eucalyptus paniculata</i>	GIB
		Gum, Forest red	<i>Eucalyptus tereticornis</i>	FRG
		Box, Grey	<i>Eucalyptus moluccana</i>	GBX
		Ironbark, Mugga	<i>Eucalyptus sideroxylon</i>	RIB
		Gum, Grey	<i>Eucalyptus propinqua</i>	GYG
		Gum, Grey	<i>Eucalyptus punctata</i>	GYG
		Box, Coast grey	<i>Eucalyptus bosistoana</i>	CBX
		Woollybutt	<i>Eucalyptus longifolia</i>	WBT
		Turpentine	<i>Syncarpia glomulifera</i>	TRP
		Ironbark group	<i>Eucalyptus</i> spp.	IBK
		Bloodwood, Red	<i>Corymbia gummifera</i>	RBW
		Bloodwood group	<i>Corymbia</i> spp.	BLW
		Peppermints	<b>4</b>	Peppermint, Sydney
Peppermint group	<i>Eucalyptus</i> spp.			PPM
Other commercial Eucalypt	<i>Eucalyptus</i> spp			OCE
Box, Appletopped	<i>Eucalyptus angophoroides</i>			TBX
Messmate	<i>Eucalyptus obliqua</i>			MMT
Gum, Mountain	<i>Eucalyptus dalrympleana</i>			MTG
Peppermint, Broadleaved	<i>Eucalyptus dives</i>			BPM
Peppermint, Narrowleaved	<i>Eucalyptus radiata</i>			NPM
Spotted gum	<b>5</b>	Gum, Spotted	<i>Corymbia maculata</i>	SPG
Silvertop Ash	<b>6</b>	Ash, Silvertop	<i>Eucalyptus sieberi</i>	STA
Stringybarks	<b>7</b>	Stringybark, Brown	<i>Eucalyptus capitellata</i>	BSB
		Stringybark, Red	<i>Eucalyptus macrorhyncha</i>	RSB
		Stringybark, Blueleaved	<i>Eucalyptus agglomerata</i>	ASB
		Stringybark, White	<i>Eucalyptus globoidea</i>	WSB
		Stringybark group	<i>Eucalyptus</i> spp.	SBK
		Mahogany, Red	<i>Eucalyptus resinifera</i>	RMY
		Mahogany, Largefruited Red	<i>Eucalyptus scias</i>	RMY

**Appendix 4 Continued**

Growth Group	Species Group	Common Name	Botanical Name	Species Code
Non - Commercial	<b>8</b>	Apple, Roughbarked	Angophora floribunda	RAP
		Apple, Smoothbarked	Angophora costata	SAP
		Box, Apple	Eucalyptus bridgesiana	ABX
		Cherry, Native	Exocarpus cupressiformis	NCH
		Gum, Scribbly	Eucalyptus sclerophylla	SCG
		Stringybark, Red	Eucalyptus macrorhyncha	RSB
		Unknown species		UNK
		Wattle group	Acacia spp.	WAT
		Sallee, Black	Eucalyptus stellulata	BSA
		Gum, Snow	Eucalyptus pauciflora	SNG
		Non-commercial Eucs	Eucalyptus spp	NCE
		Non-commercial others	(Various)	NCO
		Oak, Forest	Allocasuarina torulosa	FOK
		Oak group	(Various)	OAK
		Palm, Cabbage tree	Livistona australis	CTP
Yertchuk	Eucalyptus consideniiana	YER		
Alpine ash	<b>9</b>	Ash, Alpine (Bago/Maragle)	Eucalyptus delegatensis	ALA
<b>Riverina</b> Gums and Peppermints	<b>10</b>	Ash, Alpine (Tumut)	Eucalyptus delegatensis	ALA
		Gum, Manna	Eucalyptus viminalis	MAG
		Gum, Ribbon	Eucalyptus viminalis	MAG
		Gum, Monkey	Eucalyptus cypellocarpa	MKG
		Messmate	Eucalyptus obliqua	MMT
		Gum, Mountain	Eucalyptus dalrympleana	MTG
		Brown barrel	Eucalyptus fastigata	FAS
		Peppermint, Broadleaved	Eucalyptus dives	BPM
		Peppermint, Narrowleaved	Eucalyptus radiata	NPM
		Other commercial Eucalypt	Eucalyptus spp	OCE
		Candlebark	Eucalyptus rubida	CBK
		Eurabbie	Eucalyptus bicostata	EUR

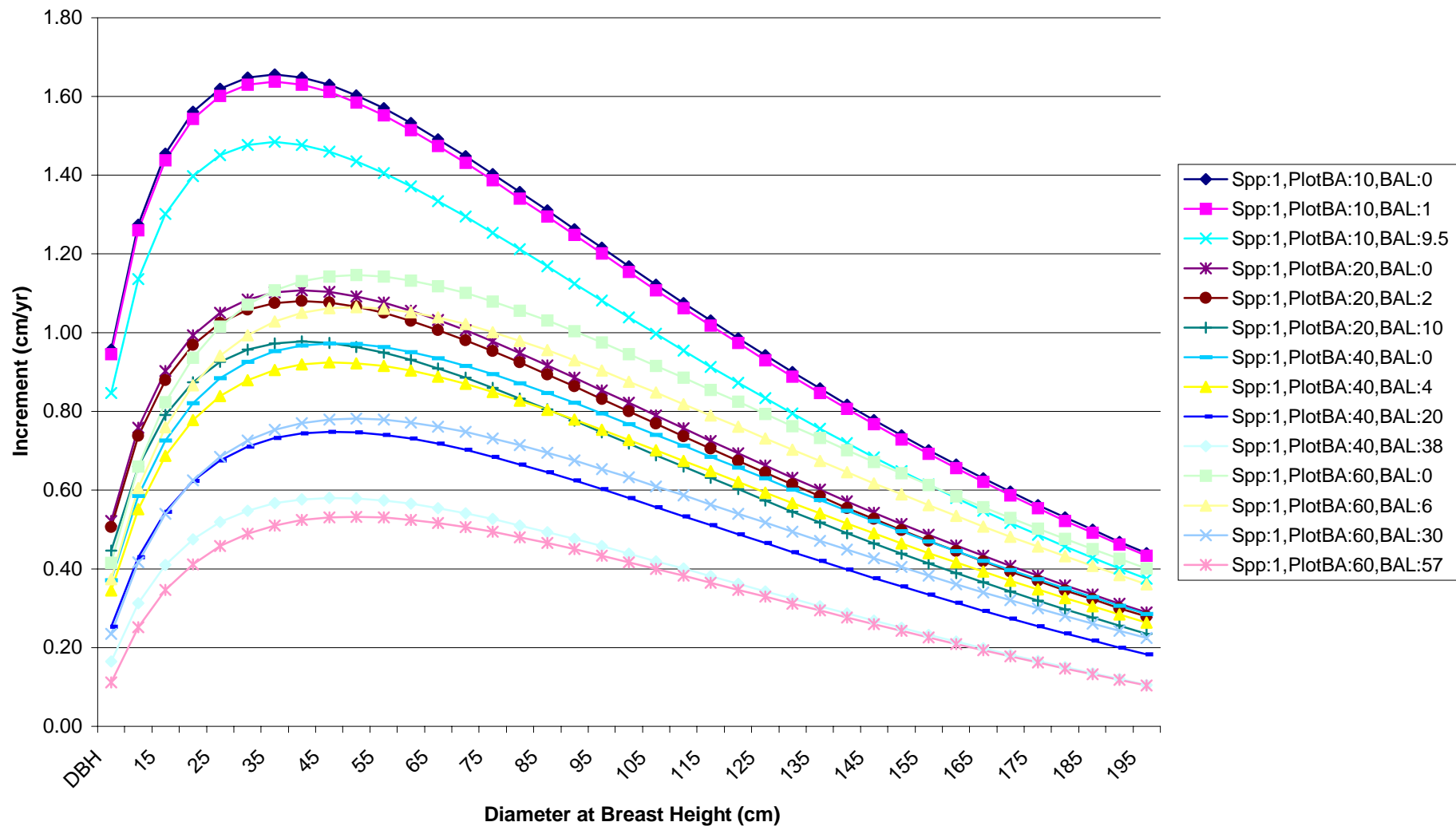
**Appendix 5 Basal Area bases Growth Model Modifiers****Part 1**

YEILD ASSOCIATION GROUP(YAG)	INTERCEPT B0	LBA B1	LOG(SPH) B2	SPHRATIO B3	LOG(SDI) B4	SDIR B5
SPG(YAG=2)	1.038168(0.010388)	0.979670(0.002316)	-0.004145(0.000576)	0.136130(0.0.00484)	0.026221(0.002867)	-1.232527(0.009774)
OTH(ALL OTHER YAs)	0.929355(0.011092)	0.977497(0.002515)	-0.004561(0.000717)	0.140755(0.007822)	0.028214(0.003352)	-1.132913(0.014130)
ALA(YAG=8)	0.941851(0.026626)	0.963983(0.007176)	-0.002527(0.001370)	0.083827(0.007802)	0.039375(0.008183)	-1.114782(0.025356)

**Part 2**

YEILD ASSOCIATION GROUP(YAG)	SOLAR B6	POSITION B7	SDEPTH B8
SPG(YAG=2)	-0.002685(0.000896)	-0.001073(0.000314)	0.000890(0.000293)
OTH(ALL OTHER YAs)	0	0	0
ALA(YAG=8)	0	0	-0.001170(0.000555)

### Appendix 6: Diameter Increment Models for Species Group 1







APPENDIX 2  
HEIGHT PREDICTION  
MODELS IN NATIVE  
REGROWTH FORESTS  
- SOUTHERN CRA

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**Height Prediction Models in Native Regrowth Forests  
for  
South Coast and Riverina Regions of New South Wales**

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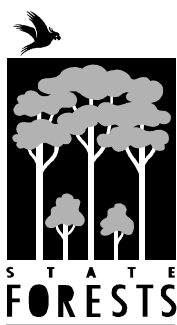
**A final report prepared for FRAMES Technical Committee  
CRA, South Coast and Riverina**

**by**

**Dr C.K. Muhairwe**

**Forest Resources  
State Forests of New South Wales**

**March 2000**



## Summary

The biometrics component of the CRA/Frames process includes the development of a model to predict forest growth. The proposed growth model has five major components: individual tree diameter growth, height growth, mortality, recruitment, and harvest. This paper outlines the fitting of total height prediction models using diameter at breast height and site productivity measure for native regrowth forest of South Coast and Riverina Regions of New South Wales, Australia.

Data from Strategic Forest Inventory for the CRA was used to fit nonlinear models for ten species groups used for diameter increment modelling.

The models are expected to reliably predict total height of a given tree for a given site. How good the models are depends on the data used to fit them. We assume that the models will be unbiased for application to any strategic inventory from the same regions. Since the strategic inventory database was used, with improvement and increase in this database we shall update our models accordingly.

## Contents

<b>1.</b>	<b>Introduction</b> .....	1
<b>2.</b>	<b>Materials and Methods</b> .....	2
	<i>3.1 Data source</i> .....	2
	<i>3.1 Data analysis</i> .....	3
<b>3.</b>	<b>Results and Discussion</b> .....	4
<b>4.</b>	<b>References</b> .....	4

## 1. Introduction

The Forest Resource and Management Evaluation System (FRAMES) being developed for the New South Wales CRA/RFA process provides a planning tool that can be used to determine sustainable wood flow for a range of management options and varying resource base. FRAMES includes a series of biometric models that make up the Growth Model component of the Yield Simulator. Growth models may include many components; however, the major components for native forest growth model are models for: diameter increment, height increment, mortality, recruitment, and harvesting. These models are mainly derived from a range of long term repeated measurements on permanent plots or research experiments to predict recruitment, diameter and height growth, mortality, and merchantability of individual trees through time. However, special inventories (pre and post harvest) and continuous forest inventories can be designed to supplement permanent growth and research experimental data.

Sometimes height increment or prediction model is included. Since height was not measured on all trees in the plot during the strategic inventory, there was a need to develop height increment model. To develop a height increment model we needed to remeasured data from permanent growth plots and/or research experimental plots (used for diameter increment models). However, majority of the PGP and all Research data had no height measurements. We were left with using the available data, which was the strategic inventory. Since the strategic inventory data is single time measure, height increment could not be modelled, but we could predict tree height based on measured tree, stand and site variables. The site variable (site productivity measure) measured during the strategic inventory was site height. Site height is defined in the Forest Inventory Manual as 'the average height of three tallest trees on site for a mature stand or near the site for immature stands'. The advantages and disadvantages of site height as a measure of site productivity will not discussed because they are discussed elsewhere. Site height measurement during the strategic inventory was assumed to be more precise than its measurement on permanent growth plots. Research data did not have site height measured or estimated.

In predicting height from diameter and site productivity, we are assuming that tree height for a given diameter will not change within a given site class. This assumption could be untrue because native forest trees stop putting on height when they are still putting on diameter. However, for regrowth forests this assumption might not be very incorrect because there seems to be a very high correlation between height and diameter with a given site.

## **2. Materials and Methods**

### **2.1 Data Source**

Data used for fitting height prediction models were the Strategic Inventory (a component of the FRAMES projects) data collected by stratified sampling for both South Coast and Riverina Regions (see the Report on Strategic Inventory for details on data collection). All data were based on 0.1ha plots. For each plot, not all tree heights were measured as opposed to DBHOB (diameter at breast height over bark). At least a minimum of five tree heights was measured for each plot distributed from the small to the big trees. For the same plot site height was measured if the plot was in mature forest. For immature stands, an adjacent forest was used to estimate site height for the plot assuming that the site productivity is not going to vary from the plot to the adjacent forest. Else with no near mature forest in site, the foresters used their experience to approximate the height mature stands that existed on the plot.

To obtain height estimates, individual tree height was predicted using DBHOB (diameter over bark at breast height in cm) and site height a measure of site productivity. Stand density (basal per hectare) was not tried because it was found marginally significant in one out of 14 species groups for Upper and Lower North Coast (see 'Height Modelling Report for Upper and Lower North Coast' prepared for the FRAMES Technical Committee). From the definition of site height, it can be seen that site height is a difficult variable to measure in the field especially for young stands. Also for mature and overmature stands or for stands that have residual trees left harvest harvesting, the definition of site height as measure of site productivity will give erroneous results. Site height does not take into account age of the tree and previous history of the tree/stand. With such difficulties and problems that plague site height, it was not used for diameter increment modelling. At present for all PGP remeasures tree height is measured and with the availability of the GIS environmental layer some measure of site productivity like Prescott Index and/or rainfall, temperature and other variables available will be used in future.

For this study, the data available from the PGP and Research was insufficient to carry out any meaningful height prediction modelling. However, it is important to remember that height is highly correlated with DBHOB for most trees in the regrowth forests. Table 1 shows data summary for the strategic inventory data used to predict total tree height from DBHOB and site height.

Table 1: Summary Statistics for the data

Variables	SPG	N	Minimum	Maximum	Mean	SD
Total Height(m)	1	1255	10.1	52.0	26.5	7.7
	2	460	8.3	54.4	27.2	8.3
	3	745	6.0	51.2	22.7	7.4
	4	555	9.4	45.4	22.5	6.9
	5	653	9.6	66.3	26.9	7.8
	6	552	8.3	42.0	23.5	5.9
	7	717	8.3	36.2	21.0	5.3
	8	192	9.6	41.4	18.3	5.7
	9	252	9.5	64.7	26.9	9.9
	10	430	5.6	53.4	24.4	8.6
DBHOB (cm)	1	1255	10.0	176.0	48.5	26.1
	2	460	10.4	194.0	55.7	27.5
	3	745	10.0	202.0	42.8	22.6
	4	555	10.0	165.1	45.1	25.1
	5	653	10.2	255.8	43.7	21.8
	6	552	11.5	137.4	47.7	22.8
	7	717	10.0	97.8	37.1	16.9
	8	192	10.2	104.6	31.8	17.2
	9	252	10.4	178.5	44.9	30.3
	10	430	10.0	200.0	48.8	31.9
Site Height (m)	1	368	25	60	34	7
	2	54	25	54	35	6
	3	151	25	51	30	6
	4	64	25	40	28	4
	5	36	25	60	31	7
	6	39	25	40	28	4
	7	10	25	35	27	3
	8	40	25	49	36	6
	9	46	27	60	40	7
	10	67	25	54	39	6

SPG = species group (10 groups), N = number of observations, SD = standard deviation, DBHOB = diameter at breast height over bark. Note site height is a plot variable while height and dbhob are tree variables.

## 2.2 Data Analysis

The model selected for Upper and Lower North Coast was used for South Coast and Riverina Regions. This non-linear equation based on the Chapman-Richards function (Clutter *et al.*, 1983) is shown below:

$$PHT = 1.3 + SH[(1 - \exp(-b_1 DBHOB))^{b_2}] \quad (1)$$

where PHT is the predicted total tree height, SH is site height a measurement of site productivity (see elsewhere for definition of site height), DBHOB is diameter at breast height over bark (cm) and



$b_1$  and  $b_2$  are parameter estimates.

Equation 1 was fitted using the nonlinear least squares method - the NLIN procedure in SAS/STAT (SAS Institute Inc, 1989). The parameter estimates for blackbutt species group in the Upper and Lower North Coast report were used as the initial values for parameter estimates  $b_1$  and  $b_2$ . The ten diameter increment models groups were used for modelling height growth as well. The philosophy behind using the same species groups as for diameter increment is that diameter and height growth are equally dependent on site productivity. Therefore, we growth dbhob and then use new dbhob to predict the new tree height.

### 3. Results and Discussion

The coefficient estimates and their standard errors are given in Table 2 below

Table 2: The coefficient estimates and their standard errors for the 14 groups

SPPCODE	$b_1$	$b_2$
O1	0.031098(0.001116)	0.908162(0.036023)
O2	0.024699(0.001276)	0.942319(0.051059)
O3	0.029681(0.001333)	1.007675(0.048425)
O4	0.024607(0.001464)	0.793720(0.045539)
O5	0.038571(0.001542)	1.057617(0.052890)
O6	0.023122(0.001727)	0.582058(0.041734)
O7	0.027195(0.001298)	0.783588(0.036485)
O8	0.020479(0.002175)	0.829765(0.068203)
O9	0.027932(0.002093)	0.961421(0.069717)
O10	0.019310(0.001196)	0.839912(0.043757)

SPPCODE = species group codes used for diameter increment modelling.

Table 2 shows that all parameter estimates were significant at the usual levels of significance ( $\alpha=0.05$ ). Detailed discussion on the height-diameter models developed here was presented in the report for Upper and Lower North Coast NSW.

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APPENDIX 3  
RECRUITMENT IN  
NATIVE REGROWTH  
FORESTS -  
SOUTHERN CRA

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**Recruitment in Native Regrowth Forests  
of  
South Coast and Riverina Regions of New South Wales**

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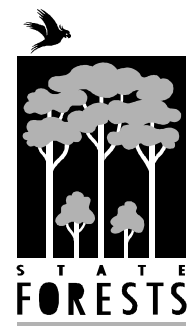
**A final report prepared for FRAMES Technical Committee  
CRA, South Coast and Riverina**

by

**Dr C.K. Muhairwe**

**Forest Resources  
State Forests of New South Wales**

**March 2000**



## Summary

The biometrics component of the CRA/FRAMES process includes the development of a model to predict forest growth. The proposed growth model has five major components: individual tree diameter growth, height growth, mortality, recruitment, and harvest. This paper describes the development of a recruitment prediction model for native regrowth forest of South Coast and Riverina Regions of New South Wales, Australia.

Data from State Forests Permanent Growth Plot System and Research experimental plots were used to develop a model to predict the number of stems reaching a threshold diameter of 10cm at breast height (1.3 m). Due to data limitations (only 391 plot measurements available), a single model was fitted for all yield association groups. This model consists of two parts, a probability function to predict the likelihood of recruitment to occur and then an equation to predict the amount of recruitment given the fact that recruitment will occur.

The model developed is expected to reliably predict recruitment across a wide range of forest types and stand conditions reflected in South Coast and Riverina Regions of New South Wales.

## Contents

<b>1.</b>	<b>Introduction</b> .....	1
<b>2.</b>	<b>Data</b> .....	2
<b>3.</b>	<b>Methods</b> .....	3
	3.1 <i>Yield association</i> .....	3
	3.2 <i>Silviculture</i> .....	4
	3.3 <i>Threshold diameter</i> .....	4
	3.4 <i>Species composition</i> .....	4
	3.5 <i>Explanatory variables</i> .....	4
<b>4.</b>	<b>Results</b> .....	6
	4.1 <i>Probability of recruitment model</i> .....	6
	4.2 <i>Amount of recruitment model</i> .....	7
	4.3 <i>Model evaluation</i> .....	8
	4.4 <i>Model implementation</i> .....	11
<b>5.</b>	<b>Discussion</b> .....	12
<b>6.</b>	<b>Conclusions</b> .....	13
<b>7.</b>	<b>References</b> .....	14

## 1. Introduction

The development of a growth model for uneven-aged mixed species regrowth forests must address changes in forest structure and composition and reflect responses to silvicultural operations. Vanclay (1994) identified the components of such a model as: growth, ingrowth (regeneration and recruitment), mortality (natural and catastrophic) and harvest. With selective harvesting systems practised in our native forests, ingrowth is an essential component of long term management and yield forecasting (Vanclay 1994, Moser 1972). Prediction of ingrowth can be approached in three stages: modelling seed production and germination, then regeneration modelling, which attempts to predict the development of trees from seed or seedlings, followed by recruitment (ingrowth) modelling, which predicts the number of stems attaining some pre-determined threshold size. In this report, we shall be concerned with modelling recruitment into 10cm dbh class as the threshold diameter size. We are assuming that there are enough seeds and seedlings in the stands and that seedlings grow into saplings, which in turn are recruited into the threshold diameter size within any limiting factors. It would be better to model the regeneration and followed by recruitment. However, this would mean collecting data for smaller (less than 10 cm diameter) trees, which increases the cost of both PGP and inventory measurements and, at present, such data are scarce.

Regeneration and subsequently recruitment is known to be sporadic, with some years with no or very little ingrowth and then in some years large amounts occur, especially after years after some silvicultural operation like thinning or harvesting. Such data are very difficult to model without knowing the trend of recruitment. According to Vanclay (1994, p.193-4), there are two approaches to modelling recruitment: static and dynamic approaches (see Vanclay 1994 for discussion). To overcome problems mentioned above, two-stage modelling (dynamic approach) was used for this study. The same approach was used for Upper and Lower North Coast (Lawrence 1997). This approach involves first predicting the probability of recruitment and then predicting the number of recruits, given that recruitment will occur. For more details about recruitment modelling approach taken, please consult the report by Lawrence (1997) and a good section in Vanclay (1994).

Recruitment is a highly variable process and the approach adopted by Vanclay (and then used by Lawrence) of dividing the modelling process into two stages has much merit, allowing more precise quantification of recruitment numbers by separating the probability of recruitment from the prediction of numbers of stems. The first stage consists of a logistic model which predicts the

probability that recruitment will occur in a given period. The second stage then predicts the number of stems (and species composition of recruits if necessary), given that recruitment occurs.

## 2. Data

The recruitment model was developed from data contained in State Forests' Permanent Growth Plot (PGP) system and the Research Division experimental plot data (Research data). The PGP system consists of a series of permanent plots located throughout NSW in a range of forest types at pre-determined intensities and in areas managed for long term timber production. Their primary objective is to provide growth data for individual trees in productive forest types. The Research experimental plots were aimed at giving State Forests of NSW the information on spacing, thinning and stocking levels. Details on "Data Preparation" are presented in the report on "Diameter Increment Models".

The PGP system use concentric plots, consisting of three circular plots on a common centre, designed to measure trees in a range of size classes (see Table 1 or refer to the Report on "Diameter Increment Models"). All trees 10cm diameter and above at breast height are measured in the interior 0.1ha plot, trees 30cm and above are measured in the 0.3ha plot, and trees 50cm and above are measured in the exterior 0.6ha plot.

Table 1: PGP plot design

<b>Size class Diameter (cm)</b>	<b>Plot radius (m)</b>	<b>Plot area (ha)</b>
10+	17.84	0.1
30+	30.90	0.3
50+	43.70	0.6

Since only the inner 0.1 ha plot had all trees measured, the dynamics of the stand (ingrowth and mortality) were better captured in this plot size. As a result, modelling mortality and recruitment was based on only this 0.1 ha plots for the PGP data. The Research data were based on fixed area plots, therefore all the data were used in modelling mortality and recruitment. The rest of data editing and preparations were the same for diameter increment modelling and are presented in the report on "Diameter Increment Models".



### 3. Methods

The recruitment model forms part of a cohort-based growth model driven by the strategic inventory data. The PGP and Research databases contain tree diameters and species, a very broad array of environmental variables (rainfall, temperature, solar radiation, topographic slope and position, and soil factors (soil depth, fertility, and moisture content). Environmental factors were estimated with ANUCLIM (Hutchinson 1989, 1991); soil factors were obtained from a combination of existing soil landscape maps and ANUCLIM data. The Research database has no height data on silvicultural information. The strategic inventory data consists of tree lists (including dbh, total height, and species), and the same environmental variables as the PGP and Research data.

Based on Research and PGP databases and knowing where the models are to be applied, a list of possible variables and their transformations used in modelling are show in Table 2.

Table 2: Individual tree and stand variables

<b>Variables</b>	<b>Description</b>
Ingrowth	Ingrowth (stems/ha)
Years	Period between measurements
Totba	Stand basal area (m <sup>2</sup> /ha)
Sph	Stand stocking (stems/ha)
Qmd	Quadratic mean diameter (cm)
Sdi*	Stand density index (stems per ha when Qmd=30)
Rainfall	Annual rainfall (m)
Temp	Mean monthly temperature (degrees)
Solar	Average daily solar radiation (MJ/m <sup>2</sup> )
Slope	Topographic slope (degrees)
Position	Topographic position
Sdepth	Soil Depth (m)
Sfert	Soil Fertility (Categorical values - 1 to 5)
M_index	Soil Moisture Index

\* Stand density index (Sdi) is calculated as:  $\sum(\text{dbhob}/30)^{1.605}$  (Long and Daniel 1990)

#### 3.1 Yield association groups

Yield associations (YA) are amalgamations of forest types representing broad species and site quality differences (Baur *et.al.* 1989). Plots were assigned to a yield association based on their forest type classification. Then yield associations were grouped into broad classes because some yield associations did not have enough data. As a result, nine yield association groups (YAG) were formed (see the 'Report on Diameter Increment Models' Table 8). These YAGs are defined elsewhere (see a report on 'Strategic Inventory' for definition of Yield Association Groups).

### *3.2 Silviculture*

The treatment records in the PGP system contain limited information on their silvicultural history. The deficiency in silvicultural history in the PGPs is compounded by the short history of remeasurement. The oldest PGPs were established in 1979. However, the shortcoming of the PGPs was reduced by inclusion of the Research Database. Research data had plots, which had long history of remeasurement up to 15 measurements, established as early as 1942. Many silvicultural operations have taken place in the research database, including thinning, spacing, harvesting, etc.

The effects of silvicultural operations on ingrowth should be included in any model so as to enable it handle ingrowth induced by silvicultural operations (Vanclay 1992, 1994). Vanclay used years since treatment as one of the explanatory variables. Unfortunately such a variable was not available for the PGP and Research data used in recruitment modelling. A spatial layer indicating forest disturbance was merged with the PGP and Research databases to get time since disturbance. However, the results showed inconsistencies and it was dropped. Future analyses would require a better logging history layer.

### *3.3 Threshold diameter*

Trees in the PGP system are first recorded when their diameter reaches 10cm. For most this diameter is slightly above 10 cm. Since the model is applied annually, we are assuming that even for good site trees will be recruited at 10 cm. This means that on a good site plot, a tree of 9.8 cm will put on only 0.2 cm in a year. This might be a conservative approach, but it is expected that not many young trees can put on more than 0.2 cm in a year.

### *3.4 Species composition*

Species composition of the recruited trees was assumed to be the same as the existing stand. This approach is conservative because some plots might change species composition. For example, following fires, some species might be given a better chance of growth. Lawrence (1997) tried to determine whether the species composition of stands changed over time and found no appreciable trends.

### *3.5 Explanatory variables*

Because the model is to be used for projecting the strategic inventory data for yield predictions, all driving variables should be readily obtainable in routine resource assessment. Basic stand variables

such as site quality and stand basal area are obvious candidates for explanatory variables. The presence of a species in the existing stand should also be an important variable. However, it is not necessary that a species exist in near a stand for regeneration to occur.

Many of the plots used in this study were logged or silviculturally treated, and the time since such a disturbance may provide a useful explanatory variable. Analyses indicated that time since major disturbance (excluding fire) explained only a little of the variation observed in the data, but time since last silvicultural treatment offered greater potential. Unfortunately, time since silvicultural treatment was highly correlated with stand basal area, and both variables could not be used in the model without causing instability in the estimated parameters. In this case, stand basal area was preferred to years since silvicultural treatment as an explanatory variable.

Species grouping and yield associations were also screened as possible indicators. Even though there were nine yield association groups (see 'Strategic Inventory Report or Diameter increment Modelling Report'), the data limitation could not allow modelling for each YAG. There was a need to further aggregate YAGs into fewer groups. Three groups were selected: group one (YAG=2 or spotted gum YAG), group two (all other YAGs excluding YAGs 2 and 8), group three (YAG=8 or Bago/Maragle Alpine ash YAG). Even with three broad groups, during modelling the data proved to be limited and it was decided to abandon groups and fit a single function for all stands. Table 3 shows the summary statistics for the variables used in the modelling.

Table 3: Summary Statistics for the data

<b>Variables</b>	<b>N</b>	<b>Minimum</b>	<b>Maximum</b>	<b>Mean</b>	<b>SD</b>
Ingrowth	214	1	310	39	49
Years	391	0.7	8.4	4.3	1.7
Totba	391	1.57	65.72	27.08	11.61
Sph	391	10	1560	323	128
Qd	391	11.9	74.3	35.2	11.0
Sdi	391	21	749	335	128
Rainfall	382	0.816	1.584	1.177	0.178
Temp	382	8.2	16.5	13.7	2.5
Solar	382	11588	17607	15395	1091
Slope	382	1	28	10	6
Position	382	0	100	44	27
Sdepth	382	0.41	2.01	1.11	0.38
M_index	382	48	208	77	18

N is number of observations, SD = standard deviation and all the variables are defined in Table 1. Note that nine plots didn't have environmental variables.

## 4. Results

In some plots, a weak relationship was found between the rate of recruitment and the number of years since silvicultural treatment. In these plots, the rate of ingrowth peaked between four to six years after treatment and declined thereafter. Experience suggests that silvicultural treatment will affect both regeneration and recruitment (Vanclay 1992, 1994). However, for this study the data were inconsistent because a number of plots had year of disturbance unrecorded yet it could be seen in the data that the stands were disturbed recently. As a result, if time since disturbance was used as an explanatory variable, the number of plots in database would have been reduced to less than 300. So we had to sacrifice the improvement in prediction that could have been achieved by using time since disturbance as an explanatory variable for model portability and parameter stability that comes from an increased number of observations.

### 4.1 Probability of recruitment model

Data measured at varying time intervals present difficulties in formulating the probabilities for modelling the occurrence of recruitment, and for the implementation of a model (in this case) on an annual basis. Although it is known that recruitment has occurred between successive measurements, it is not known exactly when the event occurred, or if it occurred uniformly over all of the intervening years.

Conversely, it is possible to state with certainty if recruitment has not occurred over a period of time, simply because if there is no recruitment after the measurement period, then it cannot have occurred in any of the intermediate years. As a result, we can build a model to predict the probability of no ingrowth ( $p$ ), and then obtain the probability of ingrowth ( $q$ ) as:  $q = 1 - p$ . This allows the probabilities to be derived with certainty. The varying measurement intervals in the PGP and Research data sets to be taken into account by incorporating the number of years between measurements as an exponent to the model (Hamilton and Edwards 1976; Monserud 1976, Lawrence 1997) or as weights (Vanclay 1992, 1994). The weighting approach involves fitting the models using the inverse of the measurement interval as a weight to compensate for the differing measurement intervals and provide annual probabilities of recruitment. For this study, the inverse of the measurement interval was used as the weight to compensate for the differing measurement intervals.

The logistic model selected for predicting the probability of no ingrowth was:

$$P(\text{No\_ingrowth}) = [1 + \exp(-(b_0 + b_1 BA + b_2 \ln(BA) + b_3 QD))]^{-1} \quad (1)$$

where:  $BA$  = total plot basal area (m<sup>2</sup>/ha)  
 $\ln$  = natural logarithm of  
 $QD$  = quadratic mean diameter (cm)  
 $years$  = measurement interval (years) - used as weight (inverse of years)

and  $b_0$  = -8.4626(1.1763)  
 $b_1$  = -0.0796(0.0186)  
 $b_2$  = 3.0027(0.5101)  
 $b_3$  = 0.0156(0.00528)

The numbers in brackets are the standard errors for the parameter estimates.

The inclusion of both BA and natural logarithm of BA was justified because it ensured that low stand density had higher probabilities of recruitment than high stand stands which was consistent with the data available. Stand density index was used even though it highly correlated with BA because it is good measure of stocking in uneven-aged multi-species stands (Long and Daniel 1990). Equation 1 lacks a measure of site productivity because all the environmental variables tried were found not significant. Lack of significance for the environmental variables could be due to data limitations.

#### 4.2 Amount of recruitment model

Once the probability of recruitment occurring has been calculated, the second stage of the model is to determine the number of recruits. As for stage one, candidate variables were identified by first using all combinations procedure (PROC RSQUARE) in SAS/STAT (SAS, 1989) to give all combinations for variables using all the data for natural logarithm of the annual rate of recruitment as the dependent variable. After examination of the data, the natural logarithm of the number of stems recruited (number of stems/ha) was selected as the dependent variable. The number of years between measurements was used to weight the regression analysis (as an inverse) on the basis that longer measurement intervals not only increase the likelihood of recruitment but also provide more reliable estimates of the true rate. The selected model was fitted as nonlinear using the MODEL procedure in SAS/ETS (SAS, 1993). The selected model was:

$$\text{No\_of\_Recruits} = \exp[b_0 + b_1 BA + b_2 \ln(BA) + b_3 \ln(SDI) + b_4 PI] \quad (2)$$

where  $PI$  = estimated Prescott Index and the rest of the variables are as defined for Equation 1.

And	$b_0$	=	-10.579544(2.454638)
	$b_1$	=	-0.035371(0.028840)
	$b_2$	=	-4.642827(0.899159)
	$b_3$	=	4.631009(0.843980)
	$b_4$	=	0.018889(0.009107)

The numbers in brackets are the standard errors for the parameter estimates. The parameter estimate for BA is slightly not significant at the usual levels of significance ( $\alpha=0.05$ ), but has been retained in the model for 'completeness'. That is, to ensure that the model would cover all situations in terms of stand density and site productivity.

The Prescott Index is here as simple measure of site quality which is an estimate of the soil-water balance (Prescott 1948; Phil J. Ryan 1998 Personal Communication). Since no GIS layer for the Prescott Index was provided from National Parks and Wildlife Services, an approximate of the same was calculated using the formulae provided by Prescott (1948) and McKenzie *et al.* (1996) using rainfall, temperature and solar radiation.

#### 4.3 Model evaluation

To evaluate the model it is necessary to use simulation studies because no independent data set was available. From Equation 1, the model is dependent on total stand basal area and quadratic mean diameter (QMD). To get meaningful evaluation of the model using simulations, one of the two variables (BA and QMD) has to be fixed and allow the other to be continuous. For this study, fixed values of QMD were used while BA was allowed to be continuous. QMD values were fixed a young stand (QMD=10), medium-age stands (QMD=20, 30 and 40) and old stands (QMD=50, 60 and 70). In another simulation, QMD could become continuous while stand density becomes fixed at low light density BA=10; medium density BA=20; high density BA=40; and very high density BA=60. For this study, BA was allowed to vary and seven classes of QMD were used (see Figure 1). From Figure 1, it can be seen that the probability of recruitment of any trees into the stand decreases as the stand density (BA) increases for a given QMD to a minimum value of BA at 35-40 m<sup>2</sup>/ha and starts to increase. (Some of these results are theoretical because in real situations when BA changes QMD changes too). The increase with increasing BA can be explained by saying that for large BA stands (old stands) above 40 m<sup>2</sup>/ha, the stands start to allow some ingrowth because they are degenerating. Another explanation could be that data combination goes outside the range of the fit data and starts to behave poorly.

Further evaluation was carried out using Equation 2. Since the model is dependent on total stand basal area, stand density index (SDI) and the Prescott Index (PI), to get meaningful evaluation of Equation 2 some variables would have to be used as constant values or classes. For simplifying the test, an average PI value of all plots (PI=75) and SDI classes of 50, 100, 200, 300, 400, 500, 600, 700, and 800 were used while BA was allowed to be continuous.<sup>1</sup> Small SDI values correspond to light stocked stands and high SDI values correspond to heavily stocked stands (see Figure 2). Figure 2 shows that the number of trees recruited decreases as the stand BA increases for a given SDI. (The situation is more complicated that is shown in the figure because, as BA increases, SDI will also increase for a given stocking density.)

However, Figures 1 and 2 have shown that the recruitment model (Equations 1 and 2) behave in the expected manner and will predict reasonable number of trees (recruits) into the stand for the given stocking, stand density and site quality.

#### *4.4 Model implementation*

The recruitment model should provide reliable estimates of future ingrowth across a wide range of forest types and yield associations. It can be implemented either as a stochastic process or deterministically. In our simulation system, which is used to growth the strategic inventory forward, the recruitment model routine is implemented as a stochastic process because we are modelling for individual trees as follows. After calculating the probability of recruitment, random numbers between 0 and 1 are thousand times and averaged. (This was a concern by BRS.) Then the average value is compared with the probability of recruitment. If the random number generated is greater than the probability of recruitment. This means recruitment will occur and Equation 2 is applied to calculate the number of recruits else no recruitment.

Some manual overrides, that enable the model to apply to all situations, have been included in the Yield Simulator. Such manual over-rides are employed when the stocking falls below critical values for a given yield association group. Without using manual over-rides, the recruitment model would give biased predictions especially for stands not represented in the modelling database. Therefore, it was necessary to restrain the Yield Simulator to deal with such cases (see the Report on the Simulator for more details).

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<sup>1</sup> We should note that some SDI and BA combinations give unrealistic predictions because they are outside the range actual situations in the field. So the SDI and BA combinations not realistic based on the fit data were not used. For example, when SDI=50 one cannot have BA of 70.

## 5. Discussion

The emphasis in this project has been to develop a robust recruitment model applicable to a wide range of situations, which would be applied to any strategic inventory. The available data were fairly limited and the absence of a single measure of site quality (like site index) meant that a variety of variables were used. This also restricted the modelling options. Research data provided more reliable long-term estimates of recruitment, but it was limited in number of plots and species diversity.

Although it could be expected that recruitment in some forest types (represented by yield associations), and on some sites, could be higher than others, the limitations by the data could not detect such differences. It is possible, however, that using one model for all species groups and yield associations is too broad to be able to explain the highly variable nature of recruitment and that at least species groupings like those used for diameter increment should have been used. However, this was not possible with the data that was available. It is expected that, in future, species will be separated into more homogeneous groups when more data and knowledge are acquired.

Predicting the probability of no ingrowth and incorporating the number of years between measurements in the model has made it possible to account for the varying measurement intervals in the data. The simulations by the model (Figs. 1 and 2) indicate that the model is behaving as expected. However, it could be a bit biased for stands with very low densities ( $BA < 2 \text{ m}^2/\text{ha}$ ) because such stand densities are outside the range of the data used to fit the model (see Table 2). That is why we have included restraints in the Yield Simulator, to handle situations, which are outside the range of the data.

The very slow growth rates of some species mean that using a single equations for all species (fast and slow growing) will allow all trees attain the threshold diameter (10cm) at the same time. However, it is known that slow growing species should take longer to reach the threshold diameter than fast growing species. It is acknowledged that the difference could be a major problem. The estimation of the number of years to reach the 10cm diameter will be put in the system manually.

The equation to predict the numbers of recruits is based on directly derived stand structural information, where the recruitment rate increases with decrease in stand basal area, numbers of



stems, and stand density index. Using small plots (0.1ha) like data from the PGP system means that not many large trees can be found in the 0.1ha inner plot and it is only by setting a low diameter class limit that meaningful trends can easily be identified. In future it is possible to either increase the size of the inner plot to 0.2 ha or lower the threshold diameter from 10 cm to 5 cm. The former suggestion might carry the day because presently all inventory used a minimum diameter of 10 cm.

The analysis of species composition by yield association over time was carried out by Lawrence (1997) indicated no significant changes. He found out that for most species, there was no change in composition over time. This study never looked at the same issue of change in species composition over time. It was expected that species do not change over time, which is the only conclusion that can be derived, given the data limitations.

## **6. Conclusions**

Separation of the recruitment model into two stages has proven a useful technique for analysing the highly variable data. Although a high proportion of the variance remains unexplained, the standard errors of the coefficients are low and there does appear to be a significant relationship between recruitment and stand density (see Fig. 1 and 2). We should not hold too much hopes on this model because the database was very limited. This model will be evaluated and if necessary replace or refit as soon as new data comes on hand.

BRS has concerns that the logistic function (Equation 1) that predicts the probability of recruitment needs to be revised to such a model form that changes both in shape and scale with different stand densities and site quality. By using the logistic function, it was thought that it is flexible enough and should be able to change in shape and scale with changes in stand density (Vanclay 1992, 1994; Lawrence 1997; Bushman *et al.* 1983). However, as indicated by BRS, we shall investigate the flexibility in shape and scale of Equation 1 and make changes accordingly. Equation 1 did not take site quality into account. This means that it was assumed that all sites will have the same recruitment rates for a given stand density. As new data becomes available in the post CRA phase, we shall rigorously test this function and if necessary change it to more flexible models. We shall also investigate the inclusion of a site quality measure in the model.

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## **Appendix 1: Recruitment Model for South Coast and Riverina Regions**

Figure 1: Probability of Recruitment

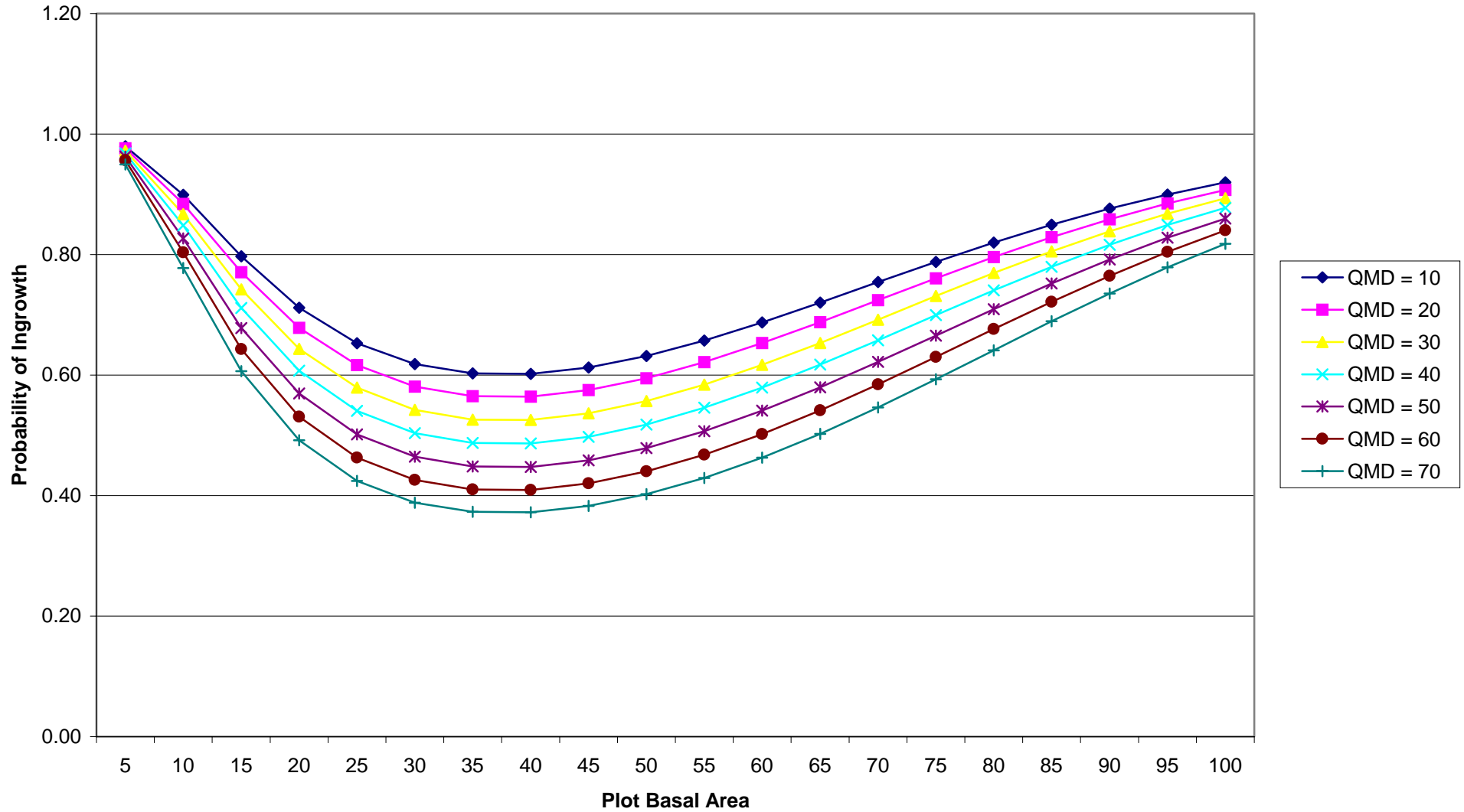
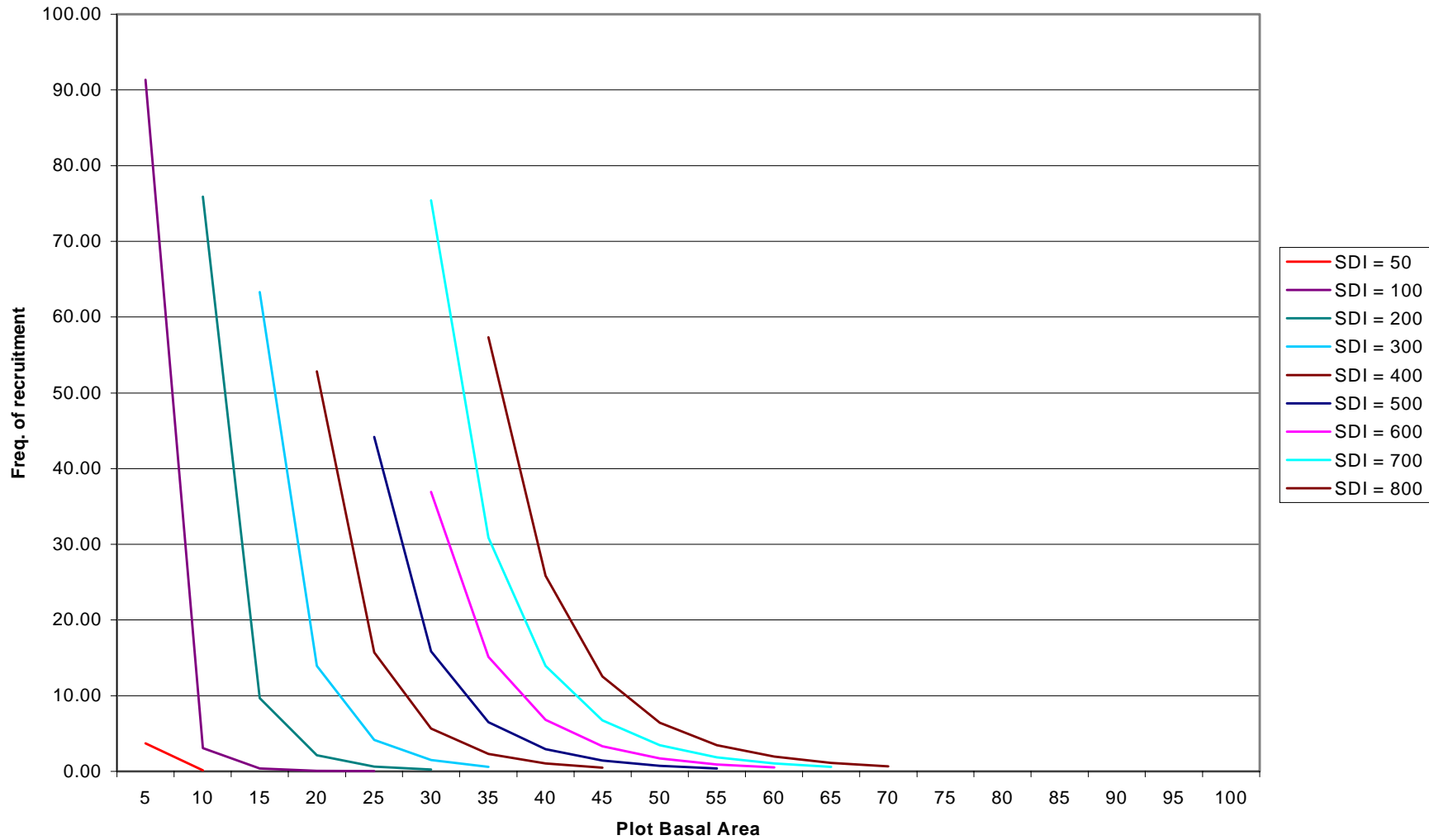


Figure 2: Number of Annual Recruits





APPENDIX 4  
MORTALITY IN NATIVE  
REGROWTH FORESTS  
- SOUTHERN CRA

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**Mortality in Native Regrowth Forests  
of  
South Coast and Riverina Regions of New South Wales**

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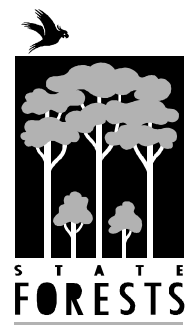
**A final report prepared for FRAMES Technical Committee  
CRA, South Coast and Riverina**

**by**

**Dr C.K. Muhairwe**

**Forest Resources  
State Forests of New South Wales**

**March 2000**





## Summary

The biometrics component of the CRA/FRAMES process includes the development of a model to predict forest growth. The proposed growth model has five major components: individual tree diameter growth, height growth, mortality, recruitment, and harvest. This paper describes the development of an individual-tree mortality prediction model for native regrowth forest of South Coast and Riverina Regions of New South Wales, Australia.

Data from State Forests Permanent Growth Plot System and Research experimental plots were used to develop a logistic function to predict mortality of individual trees based on a combination of individual tree and stand parameters. The varying measurement intervals in the data were modelled by predicting the probability of survival and incorporating the time between measurements as a weight to compensate for the differing measurement intervals and provide annual probabilities of survival.

Due to data limitations (only 942 dead trees out of over 15300 trees), a single model was fitted for all yield association groups. This model consists of modelling the probability of survival and then subtracting it from one to give the likelihood of mortality for a given tree.

The model will reliably predict mortality across a wide range of species groups and stand conditions in both the South and Riverina Regions of New South Wales. However, a model based on such a broad database for many species (shade tolerant and intolerant) is not expected to be the best for a given species. However, with availability of more data, the model will be tested and different species groups models could be adapted. All this will be done in the post CRA work.

## Contents

<b>1.</b>	<b>Introduction</b> .....	1
<b>2.</b>	<b>Data</b> .....	2
<b>3.</b>	<b>Methods</b> .....	4
	3.1 <i>Yield association and species grouping</i> .....	4
	3.2 <i>Explanatory variables</i> .....	5
<b>4.</b>	<b>Results</b> .....	5
	4.1 <i>Mortality model</i> .....	5
	4.2 <i>Model evaluation</i> .....	7
	4.3 <i>Model implementation</i> .....	8
<b>5.</b>	<b>Discussion</b> .....	10
<b>6.</b>	<b>Conclusions</b> .....	11
<b>7.</b>	<b>References</b> .....	11

## 1. Introduction

The development of a growth model for uneven-aged mixed species regrowth forests must address changes in forest structure and composition and reflect responses to silvicultural operations. Components of such a model have identified as: growth, ingrowth (regeneration and recruitment), mortality (natural and catastrophic) and harvest (Beers 1962; Moser 1972; Vanclay 1994). With selective harvesting systems practised in our native forests, mortality varies a lot and it is an essential component of long term management and yield forecasting (Vanclay 1994; Moser 1972).

Mortality is commonly classified as 'regular' or 'irregular' (catastrophic) (Lee 1971, Vanclay 1994). Most models attempt to simulate regular mortality over time, making allowance if necessary, for catastrophic mortality stochastically. Regular mortality is primarily attributed to ageing, competition and suppression, some due to 'chance', and some due to deaths induced by insects and diseases, which occur at low intensities over long periods of time. Catastrophic mortality is ascribed to major events such as epidemics (major disease and pest outbreaks), wildfires or severe weather conditions such as storms and cyclones.

Mortality is an important factor in uneven-aged natural forest. The longevity of suppressed stems is critical in determining mortality levels, and more importantly, the growth of other stand components. As a result, a number of methods have evolved for modelling the mortality of suppressed stems, most based on comparing individual tree diameter increments with a pre-determined threshold level, below which, trees are classified as dead (Botkin *et al.* 1972; Ek and Monserud 1974).

Mortality models are usually empirical or theoretical based, and use tree and stand variables such as stand density, competition (stand or individual tree) and/or tree vigour and sometimes age. Hamilton (1986) used both diameter and relative diameter (individual tree diameter/mean diameter), the latter a measure of competitive ability. Vanclay (1989, 1991) included a transformation of diameter to better model small trees, as well as the basal area of trees larger than the subject tree, as a proportion of total stand basal area, total basal area, and a site productivity variable. Monserud and Sterba (1999) used diameter, diameter squared, an inverse of diameter, crown ratio and basal area of larger trees to predict the probability of mortality. Lawrence (1997) used relative basal area, which he defined as basal area of trees greater than 30cm in diameter to total plot basal area instead of basal area of larger trees. He further stated that diameter increment and relative diameter increment were important factors. What he did not state was that predicted diameter increment is different from measured diameter increment and the usefulness of predicted diameter increment is very low (Monserud 1976). The use of predicted diameter increment as one of the explanatory variables reduces the portability of the model.

Buchman *et al.* (1983) predicted survival as a function of diameter and diameter increment, a measure of tree vigour. A similar approach had previously been used by Hann (1980) for ponderosa pine, where trees were categorised by vigour class based on their expected basal area growth. Hamilton (1990) extended the range of applicability of his 1986 mortality models by describing a number of factors. He found that the impact of diameter increment on mortality is best represented by the variable diameter increment/potential increment, where the potential increment is the maximum increment for a tree of that species. This makes intuitive sense, a low value implies that the tree is either suppressed or approaching senescence and will have a higher probability of mortality. In the absence of actual diameter increments the values can be predicted from tree and stand variables, although this approach has been shown to be slightly less effective (Monserud 1976).

Vanclay (1994) provides a good summary of the various approaches used to model mortality in both plantations and natural forests, including discussion of the relative merits of many of the common variables used. For additional information, one can consult Alder (1995). Lawrence (1997) outlines the mortality model developed for Upper and Lower North CRA Process. The same modelling philosophy will be used in this report.

## **2. Data**

The mortality model was developed from data contained in State Forests' Permanent Growth Plot (PGP) system and the Research Division experimental plot (Research) system. The PGP system consists of a series of permanent plots located throughout NSW in a range of forest types at pre-determined intensities and in areas managed for long term timber production. Their primary objective is to provide growth data for individual trees in productive forest types. The Research experimental plots were aimed at giving State Forests of NSW the information on spacing, thinning and stocking levels. Details on "Data Preparation" are presented in the report on "Diameter Increment Models".

The PGP system use concentric plots, consisting of three circular plots on a common centre, designed to measure trees in a range of size classes (see Table 1 or refer to the Report on "Diameter Increment Models"). All trees 10cm diameter and above at breast height are measured in the interior 0.1ha plot, trees 30cm and above are measured in the 0.3ha plot, and trees 50cm and above are measured in the exterior 0.6ha plot.

Table 1: PGP plot design

Size class Diameter (cm)	Plot radius (m)	Plot area (ha)
10+	17.84	0.1
30+	30.90	0.3
50+	43.70	0.6

Since only the inner 0.1 ha plot had all trees measured, the dynamics of the stand (ingrowth and mortality) were better captured in this plot size. As a result, modelling mortality and recruitment was based on only this 0.1 ha plots for the PGP data. The Research data were based on fixed-area plots therefore all the data were used in modelling mortality and recruitment. The rest of data editing and preparations were the same as for diameter increment modelling and are presented in the report on "Diameter Increment Models". Table 2 provided summary statistics for plot and tree variables.

Table 2: Summary statistics

Tree Variables (N=15342)	Mean	SD	Minimum	Maximum
Diameter at breast height (cm)	28.5	16.2	10.0	159.8
Diameter increment (cm/year)	0.37(0.43)	0.20(0.31)	-0.05(-0.34)	1.86(2.48)
Overtopping basal area (m <sup>2</sup> /ha)	22.1	11.7	0	65.6
Relative dominance	0.72	0.27	0	0.99
Stand Variables (N=391)				
Years	4.3	1.8	0.7	8.4
Stand basal area(m <sup>2</sup> /ha)	27.08	11.614	1.57	65.72
Stocking (Stems per ha)	323	128	10	1560
Quadratic mean diameter (cm)	35.2	11.0	11.9	74.3
Stand density index	335	128	21	749
Rainfall (m)	1.18	0.18	0.82	1.58
Temperature (degrees)	13.7	2.5	8.2	16.5
Solar radiation (MJ/m <sup>2</sup> )	15395	1091	11588	17607
Slope (degrees)	10	6	1	28
Topographic Position	44	27	0	100
Soil depth (m)	1.11	0.38	0.41	2.01
Soil fertility	2	0.5	1	3
Soil moisture index	77	18	48	208

N = number of observations, SD = standard deviation and nine plots have missing environmental variables. Note for diameter increment the numbers outside the brackets refer to predicted values and the ones in the brackets refer to measured values.

Mortality is identified in the PGP and Research data systems by a series of tree status codes. The categories of mortality recognised include:

- mortality due to fire
- mortality due to insect attack
- mortality due to wind
- mortality due to logging damage
- mortality due to silvicultural damage
- mortality due to other causes ('natural' or competition induced mortality).

Examination of the data indicates that mortality occurs heavily in the lower diameter classes and that most deaths attributed to fire and wind are effectively 'natural' mortality and not due to irregular or catastrophic events (see Lawrence 1997, Figure 1). It seems likely that tree deaths ascribed to fire, insect attack and wind may have been hastened by the events but are unlikely to have been primarily caused by them. For modelling purposes, four categories (fire, insect, wind and natural causes) were amalgamated to form regular mortality. Mortality due to logging or silvicultural damage was not included in the model, but modelled separately as harvest mortality and damage reported elsewhere.

### **3. Methods**

The mortality model forms part of a growth model driven by strategic inventory data. The PGP and Research databases contain tree diameters and species, a very broad array of environmental variables (rainfall, temperature, solar radiation, topographic slope and position, and soil factors (soil depth, fertility, and moisture content)). Environmental factors were estimated with ANUCLIM (Hutchinson 1989, 1991); soil factors were obtained from a combination of existing soil landscape maps and ANUCLIM data. The Research database has no height data on silvicultural information. The strategic inventory data consists of tree lists (including dbh, total height, and species), and the same environmental variables as the PGP and Research data (see Table 2).

#### *3.1 Yield Associations and Species Grouping*

Yield associations (YA) are amalgamations of forest types representing broad species and site quality differences (Baur *et al.* 1989). Plots were assigned to a yield association based on their forest type classification. Then yield associations were grouped into broad classes because some yield associations did not have enough data. As a result, nine yield association groups (YAG) were formed (see the 'Report on Diameter Increment Models' Table 8). These YAGs are defined

elsewhere (see a report on 'Strategic Inventory' for definition of Yield Association Groups). Even with nine yield association groups, the data limitation could not allow modelling for each YAG. Therefore, there was a need to further aggregate YAGs into fewer groups. Three groups were selected: group one (YAG=2 or spotted gum), group two (all other YAGs excluding 2 and 8), group three (YAG=8 or Bago/Maragle alpine ash).

### 3.2 *Explanatory variables*

Because the model is to be used for projecting the strategic inventory data for yield predictions, all driving variables should be readily obtainable in routine resource assessment. Basic stand variables such as site quality and stand basal area are obvious candidates for explanatory variables. The presence of a species in the existing stand should also be an important variable.

Individual tree measurement data were combined with estimates of stand parameters derived from each plot and plot environmental variables. An additional variable denoting tree status was added, if the tree was alive at the end of a measurement period, the tree 'status' = 1 and if the tree had died between measurements, the tree 'status' = 0.

The final data set contained 15342 individual tree observations with 912 trees labelled as dead. Due to data limitations (only 912 dead trees), it was not possible to split the data set into the fit and test data sets and use cross-validation technique to evaluate the model. All data were used in fitting the model and simulation was employed to check the behaviour and appropriateness of the model. Table 3 provides a list of possible tree and stand variables used in the modelling.

## 4. Results

### 4.1 *Mortality model*

Data measured at varying time intervals present difficulties in formulating the probabilities for modelling the occurrence of mortality, and for the subsequent implementation of the resulting model. This occurs because, although it is known that mortality has occurred between successive measurements, it is not known exactly when the event occurred, or if it occurred systematically or randomly over the intervening years.

Conversely, it is possible to state with certainty if mortality has not occurred over a period of time, simply because if there is no mortality after the next measurement, then it cannot have occurred in

any of the intermediate years either. As a result, the model was constructed to predict the probability of survival ( $q$ ), and the probability of mortality ( $p$ ) was obtained as:  $p = 1 - q$ . This allows the probabilities to be derived with certainty and the varying measurement intervals in the PGP and Research systems to be taken into account either as a weighting variable in the analyses, or more directly as an exponent in the mortality function. This involves fitting the models using the inverse of the measurement interval as a weight to compensate for the differing measurement intervals and provide annual probabilities of recruitment (Vanclay 1991, 1994). For this study the inverse of the measurement interval was used as the weight to compensate for the differing measurement intervals.

Table 3: Individual tree and plot variables

<b>Tree Variables</b>	<b>Description</b>
STATUS	Alive (1) or dead (0)
SPECIES	Species code (refer appendix in Diameter Inc. Report)
DBH	Diameter at breast height (1.30m) over bark (cm)
LD	Natural log of DBH
DI	Inverse of DBH
DD	DBH squared
DINC	Periodic diameter increment (cm/year)
RDINC	DINC/Potential increment (Maximum Increment by species group)
BAL	Overtopping basal area or basal area of larger trees (m <sup>2</sup> /ha)
BALR	'Relative dominance' = BAL/BA
<b>Stand Variables</b>	
Years	Period between measurements (years)
BA	Stand basal area (m <sup>2</sup> /ha)
LBA	Natural log of BA
SPH	Stand stocking (stems/ha)
QD	Quadratic mean diameter (cm)
SDI	Stand density index (per ha)
Rainfall	Annual rainfall (m)
Temp	Mean monthly temperature (degrees)
Solar	Average daily solar radiation (MJ/m <sup>2</sup> )
Slope	Topographic slope (degrees)
Position	Topographic position
Sdepth	Soil Depth (m)
Sfert	Soil Fertility (Categorical values - 1 to 5)
M_index	Soil Moisture Index

Model selection options in the LOGISTIC procedure in SAS/STAT (SAS Institute, Inc., 1989) were used to select the best model. These options include forward, backward, stepwise and score. The Score Option was used because it provides all combinations of models. Three models were selected and then fitted with all the testing options. The test statistics used included: Deviance (or



likelihood-ratio test), Akaike Information Criterion, and Schwartz Criterion (SAS Institute, Inc., 1989, Agresti 1996), Hosmer and Lemeshow goodness-of-fit test (Hosmer and Lemeshow 1989). As well, regression diagnostics provided for LOGISTIC procedure in SAS/STAT (SAS Institute, Inc., 1989, p. 1093-5) were used in selecting the final model.

Initially model selection was carried out for each of three mortality/recruitment species groups. However, even with three broad groups, the data proved to be limited and it was decided to abandon groups and fit a single function for all stands. The exercise of model selection was repeated with all data. The resulting logistic model, similar to the one for species group 1, is presented below:

$$P(\text{Survival}) = [1 + \exp(-(a_0 + a_1DBH + a_2LD + a_3BA + a_4LBA + a_5BAL))]^{-1} \quad (1)$$

where:  $DBH$  = diameter at breast height (1.30m) (cm)  
 $LD$  = natural log of DBH  
 $BA$  = stand basal area (m<sup>2</sup>/ha)  
 $LBA$  = natural log of BA (stand basal area)  
 $BAL$  = basal area of larger trees than a given tree or overtopping basal area

		<u>Estimate</u>	<u>Standard error</u>	<u>Wald Chi-Square</u>
and	$a_0$	= -2.3518	0.05845	16.1887
	$a_1$	= 0.1034	0.00678	232.9380
	$a_2$	= 5.1680	0.1439	1289.4865
	$a_3$	= 0.1483	0.0113	171.7582
	$a_4$	= -2.9567	0.2140	190.8494
	$a_5$	= -0.0921	0.00925	99.2117

The inverse of the measurement interval (1/years) was used a weight to compensate for the differing measurement intervals and provided annual probabilities of recruitment (Hamilton and Edwards 1976; Vanclay 1991, 1994). Then the probability of mortality is obtained as 1-probability of survival.

#### 4.2 *Model evaluation*

To evaluate the model it is necessary to use simulation studies because no independent data set was available. It can be seen from Equation 1 that the model is dependent on individual tree size, total stand basal area and overtopping basal area. To get meaningful evaluation of the model, four dominance classes (dominant, codominant, subdominant and suppressed) and four stand density

classes (low density, BA=10; medium density, BA=20; high density, BA=40<sup>1</sup> and very dense stands, BA=60) were used. It was assumed that a suppressed tree would have 95% of total stand basal area overtopping it, a subdominant with 50%, a codominant with 5% and dominant with 0% or none overtopping it. These percentages were translated into actual values of overtopping basal area and used in the model. The results are presented in Figure 1 of Appendix 1. Figure 1 shows that dominant trees (BAL=0) have very high chances of survival and the probability of survival drops as the tree becomes overtopped with the suppressed trees (BAL ratio of 95%). For example, a 10 cm suppressed tree has 50% chance of survival if growing a stand of BA=60 compared to 70% change of survival when growing in a stand of BA=20 and has 92% change of survival when growing in a stand of BA=10. This means mortality rates depend on tree size, the stand conditions (BA and BAL) will determine the tree's survival abilities.

Figure 1 shows that the mortality model (Equation 1) behaves in the expected manner and will allow some mortality to take place among small trees growing in dense stand and among big trees which are very old. Even though the model is general for all species, it is expected give reasonable predictions for all species. In future this model will be improved by modelling individuals species or groups of species with similar growth and mortality characteristics. This will depend on data availability in the post CRA work.

#### 4.3 *Model implementation*

The mortality model should provide reliable estimates of future mortality of individual trees across a wide range of forest types and yield associations. It can be implemented either as a stochastic process or deterministically. In our simulation system, which is used to grow the strategic inventory forward, the mortality model routine is implemented as a stochastic process as follows. After calculating the probability of survival for a given tree (one tree represent 10 trees per ha in 0.1 ha plots), random numbers between 0 and 1 are generated thousand times and an average obtained. Then on each occasion the average value is compared with the probability of survival. If the random number generated is greater than the probability of survival then that tree is killed. At the end of the simulation for one record (representing 10 trees), some trees might die and others remain. Thereafter the tree will carry a different weight. For example, if three times out of the ten average values the tree was killed, it will carry a weight of seven not ten into the next growth period (see the Report on the Yield Simulator for more details).

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<sup>1</sup> This class was dropped to reduce overcrowding in the figure.

Some manual over-rides which were incorporated into the Yield Simulator enable the model to apply to all situations. For example, it is known that some poor quality trees (trees that suffered some growth impediment), which are coded in the strategic inventory as pulp or waste, will be growing slowly and should have higher chances of death than trees of the same size (trees that have not suffered any growth impediment), which are coded in the strategic inventory as high or low quality. Since we never used the quality code as one of the explanatory variables in the mortality model, it was necessary to put a restraint in the Yield Simulator that gives different mortality rates for such cases (see the Report on the Yield Simulator for more details).

## **5. Discussion**

The aim of this project has been to develop a robust mortality model applicable in a wide range of conditions. Mortality models require a large amount of data, especially when the underlying mortality rate, as in this case, is very low. Ideally, these data should be collected over very long time periods if they are to provide reliable estimates of the stand dynamics. Even though we had some data with long serial measurements from Research experiments, they were limited because only two species (spotted gum and alpine ash) were involved in these experiments. The PGP data, which formed the major bulk of the data, were very limited in terms of serial measurements; the maximum number of repeated measures was only 3. However, we believe that we shall be able to improve on the mortality model as more data become available from our PGP re-measurement program. It is also hoped that the availability of Research data might have improved the mortality process for South Coast and Riverina Regions compared to Upper and Lower North Coast whose mortality model was based purely the restrictive PGP data.

Mortality generally occurs in proportion to the species compositions and characteristics of the forests. For example, it is expected that shade intolerant species would have higher rates of mortality than shade tolerant species growing the same stand. However, with very low mortality rates and limited data it was necessary to resort to major amalgamations of species, making it difficult to discern differences between the species. This limitation must be addressed as soon as more data becomes available because it is expected that this model just gives only an average and it might be imprecise for all but a few of the most abundant species.

Predicting the probability of survival allows the variable measurement interval to be taken into account directly in the model. It also enables the probabilities to be estimated over varying time

intervals in the future. However incorporating the period between successive measurements indirectly, as a weighting variable (Hamilton and Edwards 1976; Vanclay 1991), contributed little to improving the 'fit' of the model. The primary benefit is in the structure of the function and its subsequent application because it is used to predict annual mortality.

Measured and predicted diameter increment and related variables were tried as explanatory variables for predicting the probability of mortality. It was found that measured diameter increment is good indicator of mortality. This is consistent with the findings of Hamilton (1986). However, using measured diameter increment (previous diameter increment) resulted in losing more than half of the data because mortality at second measure had no previous diameter increment. We could not afford to lose any data as we were already suffering data limitation. Therefore, measured diameter increment was not used. Predicted actual and relative diameter increments were included in the model selection procedure but none proved useful. Overtopping basal area seemed to have displaced them in the model. The model developed is more portable and flexible because it uses easily measured tree and stand variables during routine strategic and operational inventories.

Finally, catastrophic mortality due to wild fires, insect or pathological epidemic or storms has not been taken into account in this model. It has to be accounted for in the growth model for long term growth prediction. This can be included as a stochastic function of time which randomly kills a certain number of trees.

## **6. Conclusions**

Mortality is a highly variable process, which occurs at a very low overall level in regrowth forests of South Coast and Riverina where selective logging is used. The results presented here simulate this process as well as it could, given the data limitations, and should be reliable under a wide variety of stand conditions. However, this model will need to be evaluated and be refitted if necessary for individual species or species groups of importance when data become available in the post CRA process.

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## Appendix 1: Mortality Model for Southern CRA - South Coast and Riverina Regions

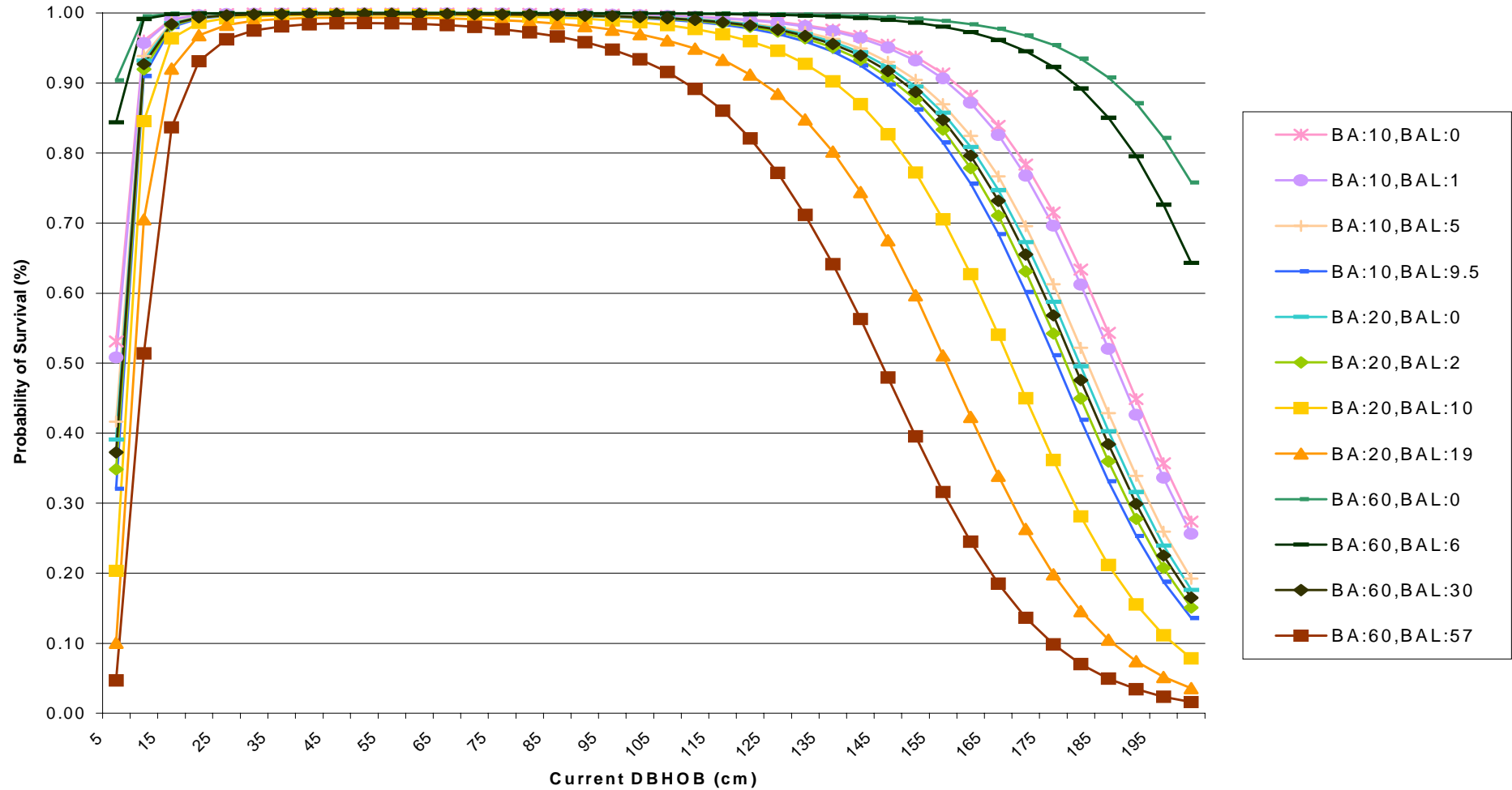


Figure 1: Revised "All Species Combined" Mortality Model - SCRA

