



An Australian Government Initiative



Modelling the potential productivity of commercial farm forestry species



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A report for the RIRDC/L&W Australia/FWPRDC
Joint Venture Agroforestry Program

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May 2007

RIRDC Publication No 05/175

RIRDC Project No CSF-56A
(Sub-project of CSF-56A)

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ISBN 1 74151 238 7
ISSN 1440-6845

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Publication No. 05/175

Project No. CSF-56A

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Published in May 2007
Electronically printed and published to www.rirdc.gov.au

Foreword

Assessing potential productivity is an important part of evaluating the commercial viability of farm forestry operations. The purpose of this sub-project was to assess the potential of general regions and specific sites for farm forestry within southeastern Australia. This included collating available field data and calibrating models available in 2001.

Three methods were used to relate tree growth to environmental conditions. The ProMod simulation model was used to provide evaluations of potential productivity for *Eucalyptus globulus*, *Eucalyptus nitens* and *Pinus radiata*, which are all species important in existing plantations as well as for farm forestry. The Plantgro simulation model was used to provide evaluations for lesser-known species important for farm forestry including *Corymbia maculata*, *Eucalyptus grandis*, *Eucalyptus saligna* and *Eucalyptus camaldulensis*. A statistical approach using multiple regression equations, including factors generated by a simple growth model called Growest, was also tried for comparative purposes.

The project evaluated the capability of models to predict productivity for key farm forestry species, including in low to medium rainfall zones. While improved predictions were demonstrated, future analysis of data from more uniformly-managed trials with species better suited to low rainfall environments is recommended. By using models and their analyses, farm foresters, extension workers and investors can assess the potential of different regions and specific sites for growing key species.

The work described here was a sub-project of project CSF-56A “Seed and Information Support for Commercial Farm Forestry” funded by the Joint Venture Agroforestry Program (JVAP) and the Natural Heritage Trust. The JVAP is supported by three R&D Corporations — Rural Industries Research and Development Corporation (RIRDC), Land & Water Australia, and Forest and Wood Products Research and Development Corporation (FWPRDC), together with the Murray-Darling Basin Commission (MDBC). These agencies are funded principally by the Australian Government.

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Acknowledgements

We are grateful to the following:

The project sponsors which are the Joint Venture Agroforestry Program and the Natural Heritage Trust (through the Department of Agriculture, Fisheries and Forestry – Australia); and the many organisations and individuals who allowed access to their trials and provided information on growth. In particular we thank Ian Hollingsworth and Don McGuire for their work in collecting samples from South Australia, Randall Falkiner, Julie Davis, Wanda Pienkowski and Rae Lowther for chemical and physical analysis of soil samples and Tom Baker and Des Stackpole for access to the Trees for Profit trial sites. In addition Dale Percival, Angela Robinson, Cressida Wilson, David Gritton, Adrian Beech, Scott Jaensch, Charles Hajeck, Stuart Sizer, Rod Bird, John Fenton, Brian Myers, Michael Pisasale, John Scott, John Davidson, Clive Hackett and Andrew Hamlett all assisted the project in various ways. Adrian Bugg provided helpful comments on the manuscript. Many people assisted the project and we apologise to any relevant individuals we have omitted.

Abbreviations

3-PG	Physiological Principles in Predicting Growth – growth model
CSIRO	Commonwealth Scientific and Industrial Research Organisation
ESOCIM	Climate estimation package
Growest	Growth estimation program
MDB	Murray-Darling Basin
MDBSIS	Murray-Darling Soil Information System
Plantgro	Plant growth simulation program
PROMOD	Tree growth simulation program
RPC	Regional Plantation Committee (since renamed as Private Forestry Development Committees)

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Executive Summary

What the report is about

This report outlines the prediction of productivity of several key farm forestry species, using available data and three modelling approaches. Generalised growth of five species in response to climate and soils was modelled, and mapped for three species. The models have since been used in other projects, and this report provides useful background.

Who is the report targeted at?

This report will help familiarise farm foresters, extension workers and researchers with species productivity models, and the potential for estimating growth and productivity of key species in different regions and specific sites in southeastern Australia. The excel version of ProMod and the site description methods reported here are suitable for use by extension officers.

Background and Aims

The work described here was one of 14 parts of a project on “Seed and Information Support for Commercial Farm Forestry” (JVAP Project CSF-56A). The overall objective of this project was to assist farm forestry growers and investors to select and make the best use of native and exotic species. The whole project included compilation of a species directory, development of a handbook for designing trial and demonstration plantings, preparation of an updated version of “Trees for Saltland” (now published as “Trees for Saline Landscapes”, Marcar and Crawford 2004) as well as workshop, field day and conference contributions. The aim of the subproject described here was to provide improved predictions of potential productivity for several commercially important farm forestry species at particular sites and across broad regions in southeastern Australia.

Methods

The first section of the report describes some alternative methods, which have been used in the past to relate tree growth to environmental conditions. These include statistical methods, such as multiple regression, and the use of computer simulation models. Three growth models were used in this study: Growest, Plantgro and PROMOD. Growest is a very simple model, which evaluates the effects of climate, but not soil, on plant growth. Plantgro is a general plant growth model, which is designed to be relatively easy to calibrate for different species. PROMOD was designed especially to simulate tree growth, but is more difficult to calibrate for different species.

The second section describes the collection of tree growth, climate and soils data from a wide range of farm forestry sites across southeastern mainland Australia. Over 200 plots growing *Corymbia maculata* (spotted gum), *Eucalyptus globulus* (blue gum), *Eucalyptus grandis* (flooded gum), *Eucalyptus saligna* (Sydney blue gum) and *Eucalyptus camaldulensis* (river red gum) at more than 80 locations were assessed including both irrigated and rainfed sites.

The third section describes the use of statistical regression analysis to relate the growth of the five species mentioned above to environmental conditions. To provide an adequate number of observations for analysis, data from all five species mentioned above were pooled together. Indices generated by a simple computer growth model (Growest) were used along with other climate and soil factors to improve the quality of the predictions.

The fourth section describes the use of the Plantgro model to predict the growth of the same five species used in the regression analysis. Soil and climate files were created for 50 sites from the “hills” subset of data used in the regression analysis. Initial Plantgro simulation runs were then made using plant files which had been created using information from other sources.

The fifth section of the report describes the use of the PROMOD model to develop regional predictions for the growth of *E. globulus* (blue gum), *E. nitens* (shining gum) and *P. radiata* (radiata pine), which

are all species important in commercial plantations as well as farm forestry, with available data more suited to broadscale analysis. Climate and soils grids (at a resolution of 0.025 degrees (approximately 2.8 km) were prepared which enabled the PROMOD model to be run for areas of the Murray-Darling Basin which receive more than 400 mm mean annual rainfall.

Results/key findings

In the past the most reliable predictive relationships relating tree growth to environmental conditions have usually been obtained when data have been collected from similar trees grown using similar establishment and management practices. These relationships have often also come from relatively small areas, such as individual plantation forests. In contrast, the data used here had to come from varied sources over a vast region. Data came from existing trials of different provenances of different species, established and managed in different ways and measured at different ages at sites across a vast region. This is because farm forestry is extending into areas where plantation forests have not been established in the past. Appropriate species are still being identified and suitable silvicultural systems are still being developed. Despite the difficulties in collecting and analyzing such a diverse dataset, the project objective of providing improved predictions of potential productivity for several commercially important farm forestry species at particular sites and across broad regions was successfully fulfilled.

The key results and findings were:

Soil and climatic data (existing and newly collected within this project) were used to derive a regression equation for site index, and relate this to species growth. Outputs from simple growth models used in the regression analysis accounted for the considerable differences in climatic conditions. The predictive relationship for sites from locations in “hills” was found to be much better than that using data from locations in “plains”.

However, the predictions using Plantgro were not as good as those made using the regression analysis including model data, so further simulations were not performed. Plantgro had not, in 2001, been adapted for such datasets with large numbers of sites, but is still well worth applying with smaller and more uniform datasets.

The ProMod analyses extended assessments of plantation potential into low rainfall areas which are a high priority for farm forestry development. These analyses successfully indicated broad patterns of productivity for the three target species. More detailed maps were also prepared for particular regions, such as the Lachlan Catchment, for use by extension staff.

Recommendations

1. Analysis and data collection from more recent trials is recommended, particularly from comparable trials with use similar establishment methods and the same genetic material over a wide range of conditions. Newer trials such as those from the Australian Low Rainfall Tree Improvement Group and low rainfall sites of State Forests NSW will provide more uniform data and information on lesser known species. This will allow improved calibration of models for species better suited to low rainfall environments.
2. Site sampling methods used in this study were kept relatively simple so extension officers can easily take samples. However future studies should sample soil to depths greater than 2m, to improve prediction of growth on ‘plains’ sites.

1. Introduction

1.1. Background and objectives

The success of farm forestry in Australia depends to a large extent on opportunities being taken up by large and small investors. Providing improved estimates of potential productivity is important not only to identifying general regions worth considering for investment, but also to select specific sites within these regions for planting. The objective of this subproject was to produce improved predictions of potential productivity for several commercially important farm forestry species at particular sites and across broad regions in southeastern Australia. This was achieved by using both statistical analyses and tree growth simulation models.

Priority species for analysis were identified following discussions with individuals concerned with farm forestry, including representatives of Regional Plantation Committees (RPCs). The species were major species, such as *Eucalyptus globulus*, *Eucalyptus nitens* and *Pinus radiata* as well as lesser-known species such as *Corymbia maculata*, *Eucalyptus grandis*, *Eucalyptus saligna* and *Eucalyptus camaldulensis*. The specific sites and general regions for analysis were selected from locations in southeastern Australia (including New South Wales, Victoria and South Australia). As described in Section 5, emphasis was given to lower rainfall environments (400-800 mm) in the Murray-Darling Basin. This was a result of the increasing interest in the potential of this region (Consortium 2001). The need for information on the potential of higher rainfall regions had also been reduced as a result of analyses produced as part of the Comprehensive Regional Assessment/Regional Forest Agreement process (see, for example, Bureau of Rural Sciences 2000a,b). It was originally intended to also include sites in Tasmania, but analyses of sites in this State were carried out before this project began (see Section 5).

1.2 Predicting tree growth

Inions (1992) has reviewed previous studies relating tree growth to environmental conditions, and previous broad-scale studies of plantation potential in Australia have been reviewed by Stephens et al. (1998). In the past the potential productivity of forest plantations has often been related to simple classifications of factors including climate, soil, topography and/or natural vegetation (see, for example, the site evaluation chart on pages 24 and 25 of Lewis et al. 1976). These systems were often based on just expert knowledge, but in some cases statistical methods such as multiple regression analysis, have been used to relate potential growth to environmental conditions (see, for example, Turvey et al. 1990 and Inions 1992).

Reviews of regression and classification studies suggest that the most reliable predictive relationships usually come when data are collected from the same provenances of the same species established under similar conditions across a range of environments within a relatively small area, such as a forest or small region. The analysis attempted here was very difficult as it had to use data from different provenances of several species, which had been established using different techniques (site preparation, fertilization, spacing), managed using different methods (including irrigation in some cases) and measured at different ages. This is because farm forestry is extending into areas where plantation forests have not been established in the past. Appropriate species and provenances are still being identified and suitable silvicultural systems developed.

The very large area analysed posed a further problem. Both classification and regression can work well in areas where there are already many existing plantations, which can be used to develop predictive relationships. However, empirical relationships developed in one region may not be reliable in predicting growth in another region because they are not based on any fundamental understanding of growth processes. Simple linear relationships, such as those used in multiple regressions, often work well in small areas such as individual forests. Non-linear relationships, such

as complex interactions between rainfall and evaporation, become more important when data from sites from areas with winter, uniform and summer rainfall regimes are combined. This is a major problem for farm forestry as estimates of growth are often required in regions where there are few existing plantations of high priority species.

In the late 1980s and early 1990s a great deal of effort began to go into developing process-based models, for predicting plant growth in general and tree growth in particular. All of these models simulate important processes such as responses to temperature, light and soil water balance i.e. the interaction between factors such as rainfall, evaporation and run-off. Growest, which was one of the earliest and most simple models uses just light, temperature and moisture indices to estimate a growth index (Nix et al. 1977). The more complex models simulate other important plant processes such as light interception, photosynthesis, and respiration. Early process-based models such as BIOMASS (McMurtie et al. 1990) were designed primarily as research tools. They provided valuable insights into factors affecting tree growth, but were too complex to be useful for site evaluation. However, during the 1990s three models, named Plantgro, ProMod and 3-PG were developed by CSIRO, which were designed to be relatively simple to use.

In this study, completed in 2002, the Growest model was used to provide simple indices to assist the regression analysis, whilst the Plantgro and ProMod were used for more detailed modeling studies. ProMod was used for evaluations of well established plantation species, including *Pinus radiata*, *Eucalyptus globulus* and *Eucalyptus nitens*, whilst Plantgro was used for lesser-known species, such as *Corymbia maculata* and *Eucalyptus camaldulensis*, as it is easier to calibrate. The origins and structure of Growest, Plantgro, ProMod and 3-PG are briefly outlined in the following sections, as each has been used for evaluating site suitability for plantations.

1.2.1 Growest

The Growest (Fitzpatrick and Nix 1970, Nix et al. 1977) model was one of the first computer models to be used for assisting land evaluation in Australia. The model calculates a weekly growth index ranging between zero (no growth) and one (maximum growth) by multiplying light, temperature and moisture indices (each ranging between zero and one) together. The light index is zero if there is no light. It increases as light increases up to an optimum level above which increasing light no longer increases the light index. The temperature index is the main factor that can be changed for different species. Minimum, optimum, and maximum temperatures for growth define a bell-shaped temperature response. The temperature index is zero below the temperature minimum, the index increases to unity at the optimum and is zero above the maximum. The relationship for the moisture index uses a simple water balance calculation, which estimates the amount of soil water based on rainfall, evaporation and estimated plant water use. The weekly growth indices can be summed to give an annual index, which can be related statistically to actual growth at different sites.

For example, the Growest growth index accounted for growth measured in terms of site index (ie mean height growth) across 18 *Pinus radiata* (radiata pine) sites much better than simply using mean annual rainfall (Booth 1980). Its capacity to account for annual variations in *P. radiata* growth was tested using annual data for more than forty years from 85 permanent plots in four ACT forests. The index was far superior to either total rainfall or seasonally effective rainfall when accounting for annual variations in growth, reducing the total residual sum of squares by almost 20%. The model was also used in the late 1970s to produce maps showing the potential growth of *P. radiata* at about 200 locations across southeastern Australia. Though the Growest model is useful for accounting for the effects of climate on growth, it does not assess the effects of soil fertility.

1.2.2 Plantgro

The Plantgro model (Hackett 1991) was originally developed to assist the selection of plants for growing in village gardens in Papua New Guinea. The developer recognised that a small number of highly detailed models were available for the dozen or so crops which dominate world agricultural trade. However, no general system existed to simulate the growth of the hundreds of other lesser-known plant species including trees. The aim was therefore to develop a system for which preliminary descriptions could easily be created for lesser-known species. The program comes with data for about fifty mainly agricultural and horticultural species.

The program uses relatively simple relationships to assess the effects of solar radiation, temperature, and soil water conditions on plant growth. Plantgro also evaluates 11 soil factors, including nitrogen, phosphorus, potassium, pH, and salinity. These are evaluated along with the climatic factors using “notional relationships”, which are simple graphs representing what are often best guesses for likely responses. For example, Figure 1.1 shows the notional response for soil pH (ie soil acidity/alkalinity) for a particular species. If a particular site had a soil pH of 5 then Figure 7.2 would indicate a limitation rating of 6. Plantgro’s limitation ratings are constrained between zero and nine. As they are limitations, a rating of zero indicates ideal conditions and a rating of nine indicates totally unsuitable conditions (ie. plant death). Factors are combined using Liebig’s Law of the Minimum. This simply means that the most limiting factor determines the growth rate. In other words the presence of a factor in luxurious quantities does not compensate for limitations in another factor.

Plantgro has been used by consultants carrying out a multimillion dollar National Masterplan for Forest Plantations in Indonesia (Pawitan 1996). Plantgro climate and soil files were developed in a geographic information system (GIS) for numerous areas in Indonesia. Plantgro plant files were then prepared for about twenty species. Plantgro-derived limitation ratings were linked to tree growth curve data, so that actual tree volumes could be predicted for particular areas and suitable areas could be mapped. Plantgro has also been used for a JVAP-sponsored study of farm forestry potential in southern Queensland and northern New South Wales (Harrison and Herbohn, in press).

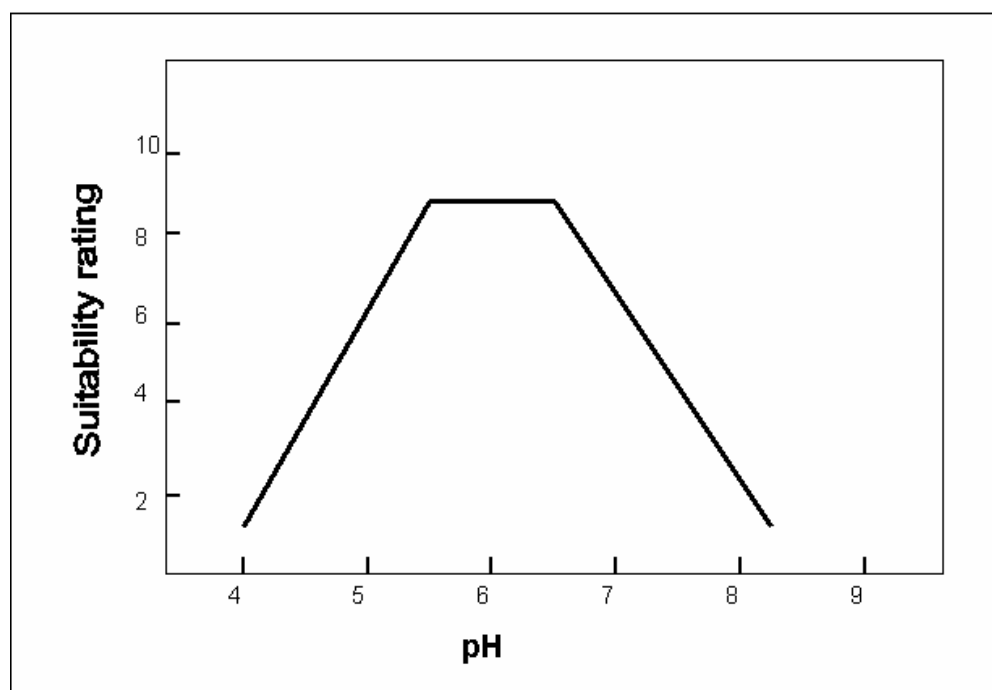


Figure 1.1 An example of a Plantgro notional relationship for soil pH for a particular species. The optimum soil pH for this species is between 5.5 and 6.5.

Plantgro is reasonably easy to understand. Users are encouraged to make preliminary estimates of notional relationships, so the program is relatively easy to set up for lesser-known species. However, it was designed as a general plant growth model and was not especially designed to simulate tree growth as were the ProMod and 3-PG models.

Though the first two versions of the Plantgro package were well documented and sold as commercial packages (Hackett 1991, Iris Media 1994) with MS DOS-based software, there have been long-running problems with producing an updated third version for Windows operating systems. A prototype Windows-based version 3.0 was prepared in 1997 at about the time the current project was being developed, but it was never finished. A company in New Zealand was developing a completely rewritten version 3.0 (see www.topoclimate-south.co.nz), but this was not completed in time to be used in this project.

1.2.3 ProMod

Unlike Plantgro, PROMOD was designed from the outset as a tree growth model. A 1995 workshop was held in Hobart to identify the needs of forest managers for simulation models and PROMOD was developed to meet these needs (Battaglia and Sands 1997).

PROMOD calculates closed-canopy leaf area index from mean annual rainfall and temperature at a site, and a simple index of site fertility. Day/night temperature variations are taken into account in a similar way to Plantgro, but possible seasonal adjustments of photosynthesis to current conditions are also assessed. A simple water balance calculation is made, and this includes a relationship to take into account vapour pressure deficit effects. The main output from the model is peak annual increment, which can be used to estimate site index. An analysis of the relative limitations of various environmental factors on growth can also be produced. PROMOD can be used to provide predictions of potential growth for individual sites or for a grid of sites across a region (see Figure 5.3).

The input data required by PROMOD are simpler than Plantgro, as detailed soil chemical analyses are not required. The aim in developing PROMOD was to use only data that would be readily available to forest managers or data which could be cheaply obtained. Site factors include the latitude, longitude and elevation of the site and the number of trees per hectare. Soil factors include texture, stoniness, depth of soil, presence/absence of any features impeding root development and a salinity measure. PROMOD 2001 only uses a simple 0-4 index of soil fertility. In this system 0 = fully fertilised sites, 1 = the most fertile sites and 4 = least fertile sites. Climatic factors include monthly mean values of daily maximum temperature, daily minimum temperature, solar radiation, precipitation, pan evaporation and number of rain days. These can be obtained from local records or estimated from the site location data using ESOCIM (McMahon 1996). For land evaluation purposes the program is usually run with monthly mean data, but actual daily measurements can be used for detailed growth studies at specific sites.

PROMOD has been calibrated to predict the growth of *Eucalyptus globulus*, *Eucalyptus nitens* and *Pinus radiata* using data from research sites in Tasmania and Western Australia (Sands et al. 2000). Developing appropriate settings for other species (parameterisation) requires detailed information on factors such as canopy development. The parameterisation process is much more complex than the notional relationship approach of Plantgro, but should provide more reliable growth predictions.

PROMOD is well suited to site evaluation studies involving species of major importance. It has been used for studies of small numbers of sites as well as evaluating thousands of sites to provide maps of growth potential for a 1000 m grid across the whole of Tasmania (Mummery and Battaglia 1999). As it concentrates on predicting peak annual increment it does not include predictions of stand development, but linking the program's outputs with conventional forest growth models can provide these estimates. It has also been used to predict the effects of irrigation on the growth of farm forestry

plantations (Sands et al. 1999). A simplified version, suitable for use by extension workers and farmers in Tasmania, has been circulated on the Farm Forestry Toolbox CD-ROM (Private Forests Tasmania 1999, and more recent versions).

1.2.4 3-PG

Although it was not used in the present study the 3-PG model has become widely used for tree growth modelling in recent years, so it's useful to understand its relationship to Plantgro and PROMOD. The 3-PG (Physiological Principles in Predicting Growth) model was developed by Landsberg and Waring (1997). Gross primary production is predicted by adjusting light interception for the effects of soil moisture, vapour pressure deficits and stand age. Two major differences from ProMod are the treatment of respiration and stand development. The 3-PG model does not make separate calculations for respiration, assuming that the ratio between net and gross primary production is constant. In contrast to PROMOD, which concentrates on the prediction of peak mean annual increment, 3-PG simulates stand development over time. 3-PG requires calibration to provide species specific estimates of tree growth.

Input data requirements are similar to PROMOD. The original version of 3-PG had no temperature response relationship apart from a frost factor. However, a temperature response has been added to later versions. Key soil attributes required to run 3-PG are similar to PROMOD and include plant available soil water holding capacity and a fertility index.

Like PROMOD, 3-PG is well suited to site evaluation either for small numbers of sites or for broadscale assessments using geographic information systems. In collaboration with CSIRO the Bureau of Rural Sciences (BRS) has written a version of 3-PG for use within the ARC/INFO geographic information system (Tickle *et al.* 2001a,b). This enables the model to be run for thousands of locations and maps to be generated indicating potential productivity across particular regions. BRS have used this version of 3-PG in several studies of broadscale plantation potential as part of Comprehensive Regional Assessments carried out as part of the process of developing Regional Forest Agreements (e.g. Bureau of Rural Sciences 2000a,b) and recently for an assessment across New South Wales (Bugg *et al.* 2002). The Forest Science Centre at Creswick has also developed a version for broadscale assessment (Morris, J. personal communication). CSIRO and the Cooperative Research Centre for Sustainable Production Forestry have developed a version of 3-PG called 3-PGpjs, for Microsoft Excel spreadsheets (Sands 2000).

2. Site sampling and spatial data

2.1. Site selection

Tree growth, soil and climate data were collected from a wide range of sites across southeastern mainland Australia, mainly for the following five species which have potential for use in farm forestry: *Eucalyptus camaldulensis* Dehnh., *Eucalyptus globulus* Labill. subsp. *globulus*, *Eucalyptus grandis* Hill ex Maiden, *Corymbia maculata* (formerly *Eucalyptus maculata* Hook) and *Eucalyptus saligna* Smith. The location of the sample sites is shown in Figure 2.1. Summary information on the trial name, region, latitude, longitude, elevation, species planted and age at growth measurement are given in Appendix 1. The data described in Appendix 1 were subsequently used in analyses described in sections 3 and 4 of this report.

Locational details for 31 *E. globulus* sites in the Greater Green Triangle area, around Mt. Gambier, are not included in Appendix 1. Though some additional sampling was carried out at these sites they were not included in the regression or modeling analyses reported here as the trees were too young to provide reliable growth data (only two years when sites sampled). However, the sites are of particular interest to the Greater Green Triangle Regional Plantation Committee and the information collected will be used when later growth data are available.

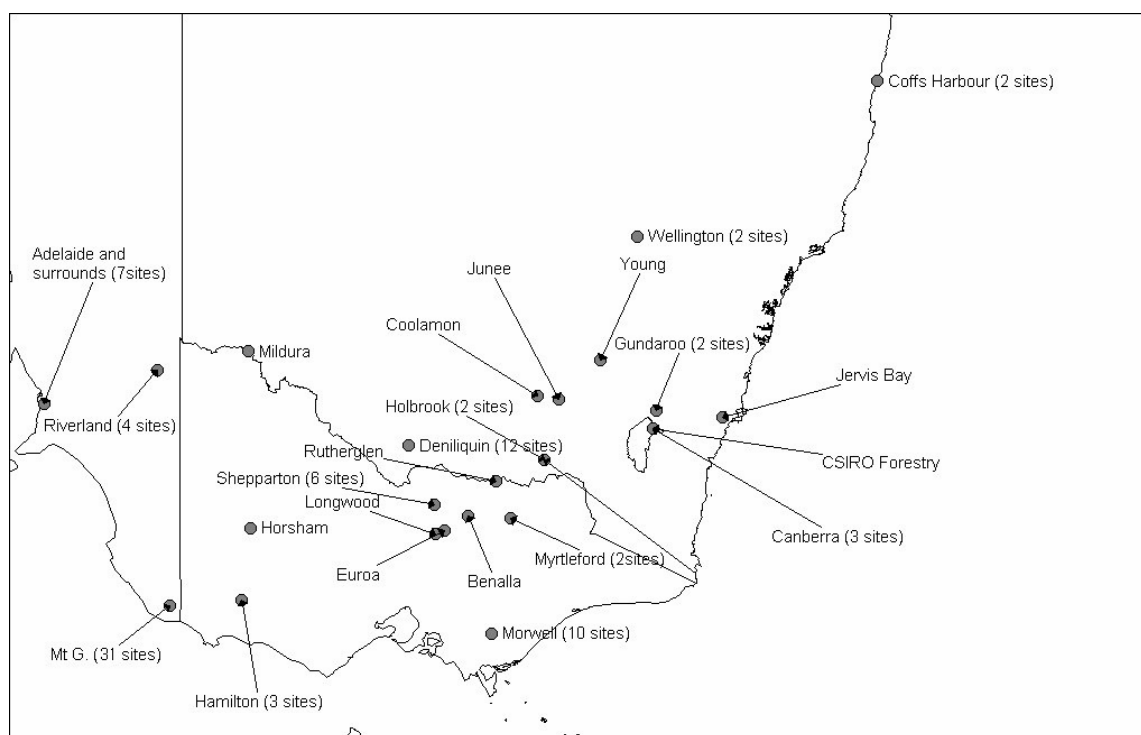


Figure 2.1 Location of sample sites

The site sampling carried out for this project built on a previous set of data collected from about 30 sites. When selecting sites, preference was given to well maintained replicated trials of at least three years of age, which included examples of known genetic origin of at least one of the selected target species. The trials included irrigated as well as rainfed sites.

Stocking rates varied according to the type of planting. They were mainly species/provenance trials, but the stocking rates ranged from about 700 to 1600 trees/ha. The number of trees per plot varied from 16-70.

2.2. Tree growth measurement

In some cases appropriate height and diameter measurements were already available. However, additional measurements of diameter at breast height and predominant height (mean height of the 100 largest diameter trees per hectare) were made in many cases. Where possible growth measurements were taken in winter, when the trees were not actively growing. Tree heights were measured using height poles or the Vertex optical height measurement system (Forestor Vertex, GRUBE KG Forstgerätestelle), whilst diameter measurements were made with a diameter tape.

Growth measurements were made on sites of varying age, so it was necessary to adjust measurements to a standard age, so that growth on different sites could be compared. A site index measurement related to predominant height (i.e. mean height of the largest 100 trees per hectare) was used as this measure is relatively insensitive to changes in stocking rate. Site index estimates were related to tree height measurements at 10 years of age as most of the trials were quite young. Height growth relationships described by Wong et al. (2000) were used to estimate tree heights at 10 years from measurements made at other ages.

2.3. Soil sampling and laboratory analyses

At each site twenty soil samples were taken at random with a soil auger from 0-20 cm soil depth and three samples from 50-70 cm. If the site had been mounded, samples were taken on the mound between the trees. Soil textures were assessed in the field. The samples from within each layer were bulked, air-dried and sieved through a 2 mm sieve. Total nitrogen (%) was determined after digestion (Nelson and Sommers 1972) using an automated colorimetric method (Bran+Luebbe 1986). For South Australian samples, the combustion furnace method (Leco Corporation 1991) was used to analyse samples for total nitrogen. Available phosphorus (ppm) was determined using a sodium bicarbonate extractant method followed by colorimetric determination with molybdenum blue (Olsen et al. 1954). Exchangeable cations including sodium, potassium, calcium, magnesium and aluminium were determined by barium chloride extraction followed by inductively coupled plasma optical emission spectrophotometry (Perkin Elmer P2000). Cation exchange capacity (CEC - meq/100 g soil) in samples from South Australia was estimated directly by saturation with ammonium ions. For other samples CEC was calculated by summing the individual cations. The exchangeable sodium percentage (ESP - %) was derived from estimates of exchangeable sodium and CEC. Electrical conductivity (dS/m) was determined by 1:5 soil/water dilution and multiplied by a constant depending on the soil texture of the sample (Rayment and Higginson 1992). The same dilution was also used for pH determination.

If possible, at least one of the 50-70 cm auger holes was extended up to a maximum depth of 2 m to determine effective soil depth and the presence of any hard pans. Watertable depth and groundwater salinity were determined from bore logs (bore characteristics and depths), published information or from the farmers or local district soils/irrigation officers' knowledge. Irrigation application rates, if applicable, were obtained from similar sources.

2.4 Estimation of mean climatic conditions

Mean monthly climatic conditions at individual sites were estimated using the ESOCIM climate prediction software (McMahon et al. 1996). The program uses latitude, longitude and elevation data to provide reliable estimates for monthly mean values of precipitation, maximum temperature, minimum temperature, evaporation and solar radiation for any location by accessing interpolated climate surfaces. Mean errors for precipitation are usually below 10 mm or less than 10 per cent of the monthly mean in southeastern Australia, whilst mean temperature estimates are less than 0.5°C. Mean errors for solar radiation are also around 5 per cent (Hutchinson et al. 1984).

ESOCLIM was also used, together with elevation estimates from the national digital elevation model of Australia (9 second DEM) (www.auslig.gov.au), to produce gridded estimates of climatic data used for the regional analyses described in section 5.

2.5 Spatial data

Gridded soil data used in section 5 were obtained from the Murray-Darling Basin Soil Information System (MDBSIS). The MDBSIS project is a collaborative project between MDBC, CSIRO Land and Water (managing agency), sections of the Bureau of Rural Sciences (BRS) of the Department of Agriculture, Fisheries and Forests (formerly Department of Primary Industries and Energy), NSW Department of Land and Water Conservation, Victorian Department of Natural Resources and Environment, Primary Industries SA, SA Department for Transport, Urban Planning and the Arts and Queensland Department of Primary Industries. The project collated existing digital spatial soil and geology data from relevant Australian State and Federal sources, and subsequently developed new data on soil-landforms and geology (Bui 1999). A major output from the project has been the preparation by a company called Georeality of ARC/INFO coverages for the MDB of soils, landforms, relief simplified lithology, structural vegetation, climate, hydrogeology, socio-economic and satellite Landsat TM imagery in a multiple CD-ROM product called "Basin-in-a box". We were fortunate to have access to a pre-release test copy of this product for this study.

Gridded data at a 0.025 degree resolution (approximately 2.8 km) was prepared for 161 271 locations within the region with greater than 400mm rainfall in the MDB. Information for soil depth, soil texture, salinity, fertility, depth to groundwater and groundwater salinity were derived from the surfaces available in the MDBSIS CD-ROM database (see also Bui et al. 1998) taking mid-points of the categories for each class in the dataset. These data were 1:250,000 for the Murray Basin and 1:1,000,000 for the Darling Basin. Classes used in MDB PROMOD analysis were derived as follows:

Soil Depth

1	<0.5 m	Shallow
2	0.5 - 1.5 m	Moderate
3	>1.5 m	Deep

For all PROMOD runs these soil depth classes were set to (1)= 0.5 m, (2) = 1.0 m and (3) = 2.0 m except where depth to groundwater was greater than these values, then soil depth was set to groundwater depth.

Soil Texture

1	Uniform Coarse
2	Uniform Medium
3	Uniform Fine
4	Uniform Cracking
5	Gradational calcareous
6	Gradational
7	Duplex

These texture classes were combined in an attempt to match PROMOD texture classes. The four PROMOD soil textures were defined as : 1 = (3) + (4), 2 = (2) + (5), 3 = (6) + (7) and 4 = (1) PROMOD is known to be relatively insensitive to soil texture inputs.

Groundwater salinity

1	0-500 mg/L
2	500-1000 mg/L
3	1000-1500 mg/L
4	1500-3000 mg/L
5	3000-7000 mg/L
6	7000-14000 mg/L
7	14000-35000 mg/L
8	>35000 mg/L

Salinity values were set to the midpoint of each of the above classes (> 35000 mg/L class was set to 35000 mg/L) and all values converted to mS/m.

Fertility

1	Low	Major responses to N, P and K along with most micronutrients
2	Moderate	Responses to N, P and K with occasional response to some micronutrients
3	High	Responses to N and P uncommon except after intensive farming

Fertility ratings were inverted to match PROMOD sequencing (where 1 = high fertility) and assigned as follows: 1 (PROMOD) = High (MDBSIS), 2.5 = Moderate and 4 = Low fertility.

Depth to groundwater

1	0-2 m
2	2-5 m
3	5-10 m
4	>10 m

Depth to groundwater values were set to midpoint of each class (>10 m set to 10 m).

3. Regression model

3.1 Multiple regression analysis for complete dataset

Soil and climatic data described in Section 2 were used to derive a regression model for site index (at 10 years) using the multiple regression module in the GENSTAT statistical package (Lawes Agricultural Trust 2001). Growth data from five tree species, *E. grandis*, *E. globulus*, *E. saligna*, *E. camaldulensis* and *C. maculata*, were combined in the regression model to provide an adequate number of observations. Maximum, minimum and mean values for variables used in the regression analysis are shown in Table 3.1. Available phosphorus was input as a ramp function (extpx) as preliminary analysis indicated that sites with phosphorus levels greater than 12 ppm were adequate in terms of P supply.

Table 3.1 Summary statistics for factors used in the regression analysis

	Min	Mean	Max
Growth measure			
SI (m)	2.6	14.7	29.7
Soil variables			
EC (dS/m)	0.00	0.27	2.87
pH	3.7	5.5	8.9
N (%)	0.010	0.128	0.442
P (ppm)	0.007	18	204
K (meq/100g)	0.01	0.50	2.42
CEC (meq/100g soil)	1.12	7.45	26.97
Climate variables			
evaporation (mm)	910	1421	1893
temperature (°C)	11.4	14.3	17.8
rainfall (mm)	227	745	1830
Growest indices (see text)			
index[1] sum of temperature index	20.73	28.08	35.02
index[2] sum of radiation index	41.12	42.87	45.84
index[3] sum of moisture index	9.88	32.32	50.65
index[4] sum of the growth index	4.54	13.83	26.00
index[5] Leibig index	9.20	18.12	29.01
index[6] sum of evapotranspiration index	258	670	1452
index[7] sum of temp by radiation indices	17.95	24.46	29.61
index[8] sum of most limiting indices	19.84	26.80	32.99

3.2 Growest modelling

As well as environmental factors described in Section 2 several indices from the Growest growth model (Nix et al. 1977) were included in the analysis to account for the wide range of climatic conditions experienced at the trial sites. These included the following (see indices 1-8 in Table 3.1):

- 1) SUMT - Sum of the temperature index over the year (i.e. sum of individual weekly values between 0 and 1 with a theoretical maximum value of 52).
- 2) SUMR - Sum of the radiation index over the year.
- 3) SUMM - Sum of the moisture index over the year.
- 4) SUMG - Sum of the growth index over the year (i.e. sum of weekly temperature, radiation and moisture indices).
- 5) SUML - Leibig index – sum of the most limiting value for the three indices (i.e. temperature, radiation and water) for each week over the year.
- 6) SUMTR- sum of weekly estimates of evapotranspiration through the year.
- 7) SUMIR- sum of weekly multiple of temperature and radiation indices i.e. assuming site experiences no water stress.
- 8) LIRR – sum of the most limiting of two indices (ie temperature and radiation) for each week over the year i.e. assuming site experiences no water stress.

3.3 Regression analysis

A stepwise multiple regression analysis was carried out using the GENSTAT statistical analysis package using an F-value of 4 to determine inclusion or rejection of variables.

Incorporating irrigation into the analysis was difficult because few of the irrigation trial sites had detailed records of the amount and timing of irrigation applications. A simple three level qualitative variable (irrigated/not irrigated/effluent irrigated) was found to be as useful as a quantitative one, which was based on presumably unreliable estimates of irrigation applications. Coefficients for the best regression relationship including the irrigation factor are shown in Table 3.2. This model accounted for 58.8 % of the variance in the data and had a root mean square error of 3.31 m (n=189). The constant in Table 3.2 relates to the performance of *E. grandis* when used along with the other factors. The species factors indicate the relative performance of the other species. So, for example, the analysis indicated that on average the *E. globulus* sites were 2.69 metres higher than the *E. grandis* sites at 10 years of age.

Table 3.2 Multiple regression coefficients of environmental variables (including irrigation factors) related to site index

	Coefficient	Standard error	t (177)
Constant	-57.30	15.3	-6.1
species <i>E. globulus</i>	2.69	0.65	4.1
species <i>E. saligna</i>	-0.94	0.70	-1.4
species <i>E. camald.</i>	-3.94	0.87	-4.6
species <i>C. maculata</i>	-4.92	1.05	-4.7
temperature	2.89	0.39	7.4
evaporation	-0.0184	0.0026	-6.9
EC	-2.83	0.49	-5.8
Irrig 2	3.96	1.25	3.2
Irrig 3	8.31	1.32	6.3
N	12.05	2.90	4.2
index[2] SUMR	1.32	0.43	3.1

The final model of site index developed using stepwise regression accounted for 64.9% of the variance and had a root mean square error of 3.05 metres (n = 189) with all terms in the model significant at the 5% level (see Table 3.3). The model included the following 13 independent variables :

- Four qualitative factors (dummy variables) to account for differences in site index of *E. globulus*, *E. camaldulensis*, *E. saligna*, and *C. maculata* compared to *E. grandis*, which was used as the control species.
- Two climatic variables including mean annual temperature (temp) and mean annual evaporation (evap);
- Four growth indices derived from the Growest model. These were the yearly sums for the temperature index (index 1), the radiation index (index 2), the overall growth index (index 4) and the evapotranspiration index (index 6).
- Three continuous soil variables, including electrical conductivity (EC), pH and its square, pH².

Table 3.3 Multiple regression coefficients of environmental variables related to site index - best model.

	Coefficient	Standard error	t (175)
Constant	-133.10	21.70	-6.1
species <i>E. globulus</i>	2.20	0.61	3.6
species <i>E. saligna</i>	-1.03	0.65	-1.6
species <i>E. camald.</i>	-4.67	0.83	-5.7
species <i>C. maculata</i>	-5.17	0.97	-5.3
temperature	3.07	0.36	8.6
evaporation	-0.0129	0.0026	-5.0
EC	-0.85	0.40	-2.1
pH	-10.83	1.93	-5.6
pH ²	0.77	0.16	4.8
index[1] SUMT	-0.81	0.13	-6.1
index[2] SUMR	4.32	0.57	7.5
index[4] SUMG	2.17	0.27	7.9
index[6] SUMTR	-0.0474	0.0054	-8.8

Two separate multiple regression analyses were also completed, the first including just soil factors, and the second using only climate factors. Incorporating the climate factors, temperature and evaporation (with the species terms and Growest indices [2], [3], [4], [6], [7]) accounted for 55.1% of the variance in the multiple regression analysis. Using the soil factors N, CEC, P, K, pH and pH² (with the species terms) in a multiple regression analysis accounted for only 33.6% of the variance in the regression.

3.4 Calibration-validation procedure

A calibration/validation exercise was carried out on the data set. The independent factors used were those which had been determined from the stepwise analysis of the complete data set. The data set was split into two halves, with 97 in the calibration set and 92 in the validation dataset. Regression parameters were fitted for the calibration set (see Table 3.4 and Figure 3.1). This model accounted for 69.6 % of the variance in the data and root mean square error was 2.74. This model was used to estimate site index values for the independent validation data set (see Figure 3.2). The root mean square error for the validation data set was 3.45 m.

Table 3.4 Estimates of parameters - Calibration data

Factor	Estimate	Standard error	t(83)	t(probability)
Constant	-140.00	29.10	-4.8	<.001
species <i>E. glob.</i>	2.74	0.80	3.4	<.001
species <i>E. salig.</i>	-0.03	0.90	-0.03	0.977 ns
species <i>E. camal</i>	-3.48	1.23	-2.8	0.006
species <i>C. mac.</i>	-4.36	1.16	-3.8	<.001
temperature	3.65	0.46	7.98	<.001
evaporation	-0.0144	0.0031	-4.6	<.001
EC	-0.13	0.52	-0.26	0.796 ns
pH	-9.20	2.50	-3.7	<.001
pH2	0.61	0.21	2.9	0.004
index[1] SUMT	-0.64	0.17	-3.7	<.001
index[2] SUMR	4.11	0.76	5.4	<.001
index[4] SUMG	2.07	0.35	5.9	<.001
index[6]SUMT R	-0.0454	0.0070	-6.5	<.001

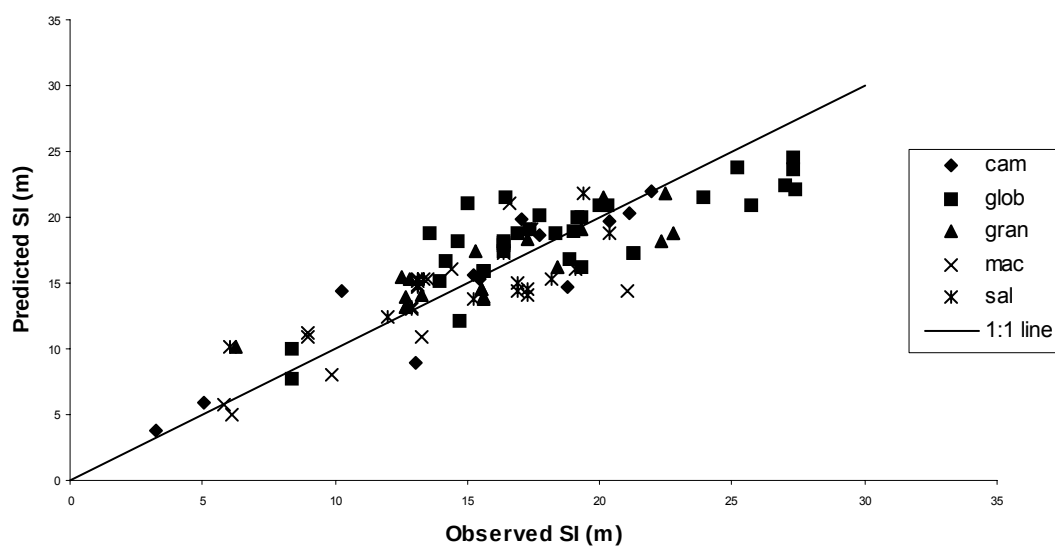


Figure 3.1 Observed and fitted site index for calibration relationship described in Table 3.3
Abbreviations: cam = *E. camaldulensis*, glob = *E. globulus*, gran = *E. grandis*, mac = *C. maculata*, sal = *E. saligna*

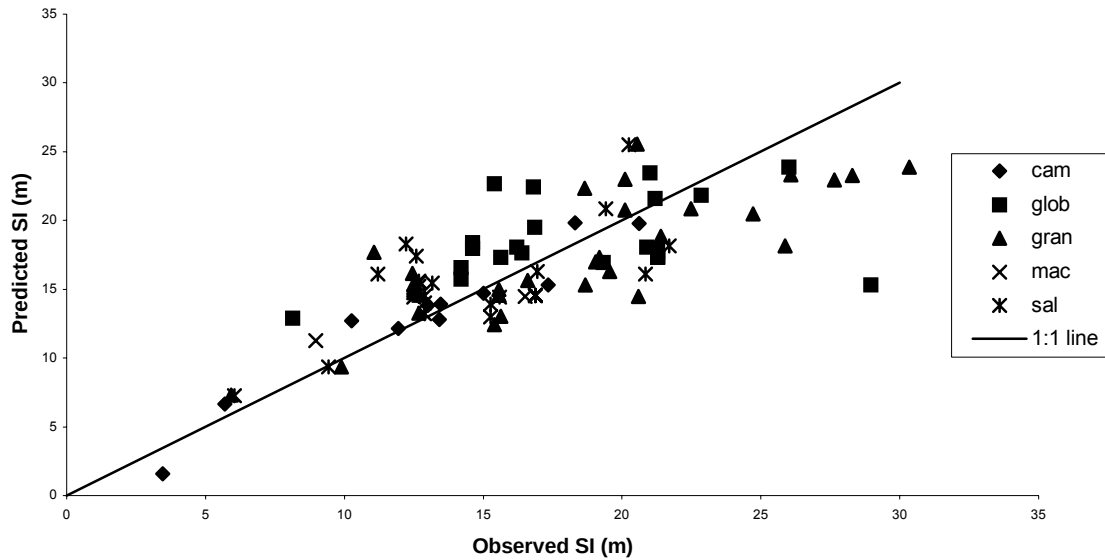


Figure 3.2 Observed and fitted site index for validation data set

3.5 Hills and plains sites analysis

An analysis was performed on separate landform types, breaking the site data into ‘hills’ and ‘plains’ groups. Plains sites have soils mainly derived from alluvial deposition or unconsolidated sands derived from marine deposits, both of which are potentially deep and have a watertable. In contrast, hills sites tend to be shallow and do not have access to a permanent watertable.

The multiple regression analyses showed that site index had a much higher correlation with environmental variables on hills sites than on plains sites. The relationship for the hills sites accounted for 88.0% of the variance in the site index data with a root mean square error of 1.59 ($n = 77$), whilst the best relationship for the plains sites accounted for only 54.7 % of the variance with a root mean square error of 3.65 ($n = 105$)(see Table 3.5 and Figures 3.3 and 3.4). Plains sites incorporated some sites that were irrigated with different types and amounts of irrigation including saline and effluent irrigation. As mentioned above, reliable records of irrigation amounts were not available for several sites so the effects of irrigation on site index could not be reliably determined. In addition, some plains sites may have had access to groundwater, whereas others did not.

Table 3.5 Coefficients from multiple regressions for hills and plains sites.

Factor hill sites	Estimate hills sites	s.e hill sites	t(65)	Estimate Plains sites	s.e plains sites	t(96)
Constant	2.92	3.61	0.81	-80.9	21.9	-3.69
species <i>E. globulus</i>	3.039	0.499	6.10	3.417	0.985	3.47
species <i>E. saligna</i>	0.109	0.533	0.20	-1.77	1.03	-1.73
species <i>E. camal.</i>	-3.483	0.972	-3.59	-4.31	1.15	-3.76
species <i>C. maculata</i>	-3.301	0.766	-4.31	-3.92	1.99	-1.97
N	10.74	4.17	2.58			
EC				-3.529	0.681	-5.18
K	-6.756	0.993	-6.80	2.75	1.24	2.23
P				0.324	0.118	2.74
Temp	3.111	0.316	9.85			
index[1]	-0.469	0.157	-2.99			
index[2]				2.242	0.526	4.26
index[4]	5.559	0.612	9.08			
index[5]	-4.287	0.515	-8.32			
index[6]	-0.02515	0.00371	-6.79			

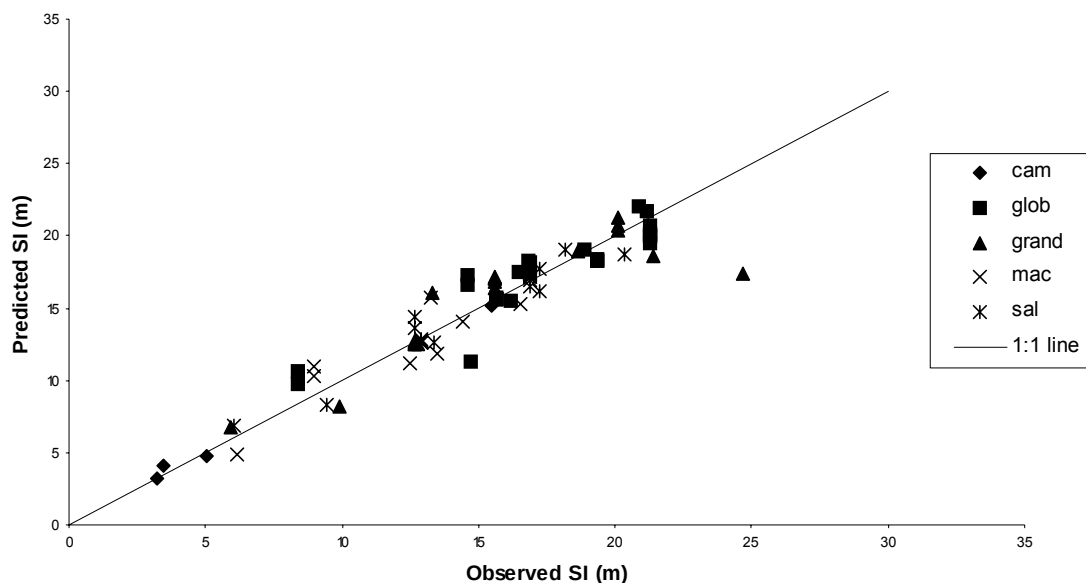


Figure 3.3 Observed and fitted site index for the hills data set using environment variables and Growest indices.
 Abbreviations: cam = *E. camaldulensis*, glob = *E. globulus*, grand = *E. grandis*, mac = *C. maculata*, sal = *E. saligna*

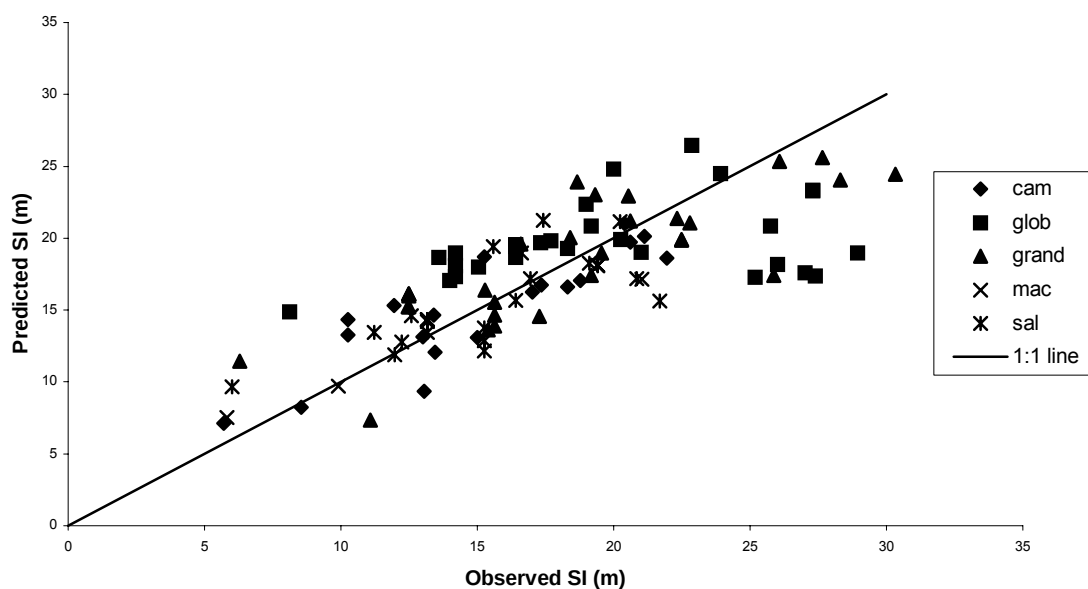


Figure 3.4 Observed and fitted site index for plains data set

4. Plantgro model

4.1 Calibration

As mentioned in section 2 the Plantgro model uses plant files which describe a particular plant's responses to environmental conditions. The plant files for *E. grandis*, *E. globulus*, *E. saligna*, *E. camaldulensis* and *C. maculata* used here were created using the methods described by Hackett (1991, 1996a) and Davidson (1996). These files were essentially first estimates of tree responses to environment variables based on published information. They provided a starting point, which can be improved by calibration comparisons.

The regression analysis in the previous section had shown that the “hills” subset of data was a more coherent set of data than the entire dataset described in section 2. Accordingly, Plantgro soil and climate files were created so that simulation runs could be made for these sites.

Initial simulation runs were made for a total of 50 sites including 12 *E. grandis*, 15 *E. globulus*, 11 *E. saligna*, 8 *C. maculata* sites and 4 *E. camaldulensis*. Not surprisingly, the initial model runs using the uncalibrated plant files produced poor relationships between observed and predicted site index ($r^2 = 0.29$ and root mean square error of 7.7 m). It was decided to use the data from the 50 sites for further calibration and adjustment of the Plantgro plant files with the intention to then use the other data points from the “plains” group as a validation set.

For example, changes for *E. grandis* included lowering the minimum temperature for growth from 11°C to 9°C and extending the optimum from just 25°C to include temperatures from 20°C to 25°C (see temperature responses in Hackett 1996b) and switching off the nitrogen response factor, as samples from several sites showed very low soil nitrogen levels but reasonable growth as fertiliser was added some years ago.

Calibration was a slow process, as the 2001-2 version of the Plantgro program did not support batch runs, so the program had to be run 50 separate times to complete each set of predictions. Figure 4.1 shows results from one set of simulation runs following various calibration adjustments to the plant files. Though the relationship between growth and environmental conditions was considerably improved ($r^2 = 0.58$ and mean square error of 3.9 m) it was still poor in comparison to the regression relationship shown in Figure 3.3. The relationship was not sufficiently good to warrant carrying out validation runs using sites from the “plains” dataset.

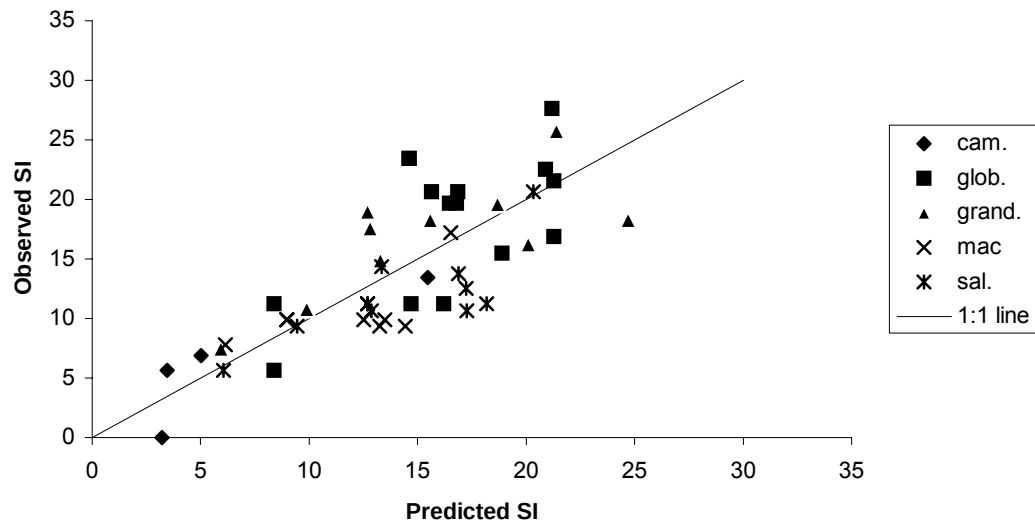


Figure 4.1 Comparison of predicted site index (m) generated by the Plantgro model and observed site index from 50 sites in the “hills” dataset.
 Abbreviations: cam = *E. camaldulensis*, glob = *E. globulus*, grand = *E. grandis*, mac = *C. maculata*, sal = *E. saligna*

5. PROMOD

5.1 Calibration

Initial calibrations of the PROMOD model had been completed by Sands et al. (2000) before this project began for *Eucalyptus globulus*, *Eucalyptus nitens* and *Pinus radiata*. Example comparisons between observed and predicted mean annual increments are shown in Figure 5.1.

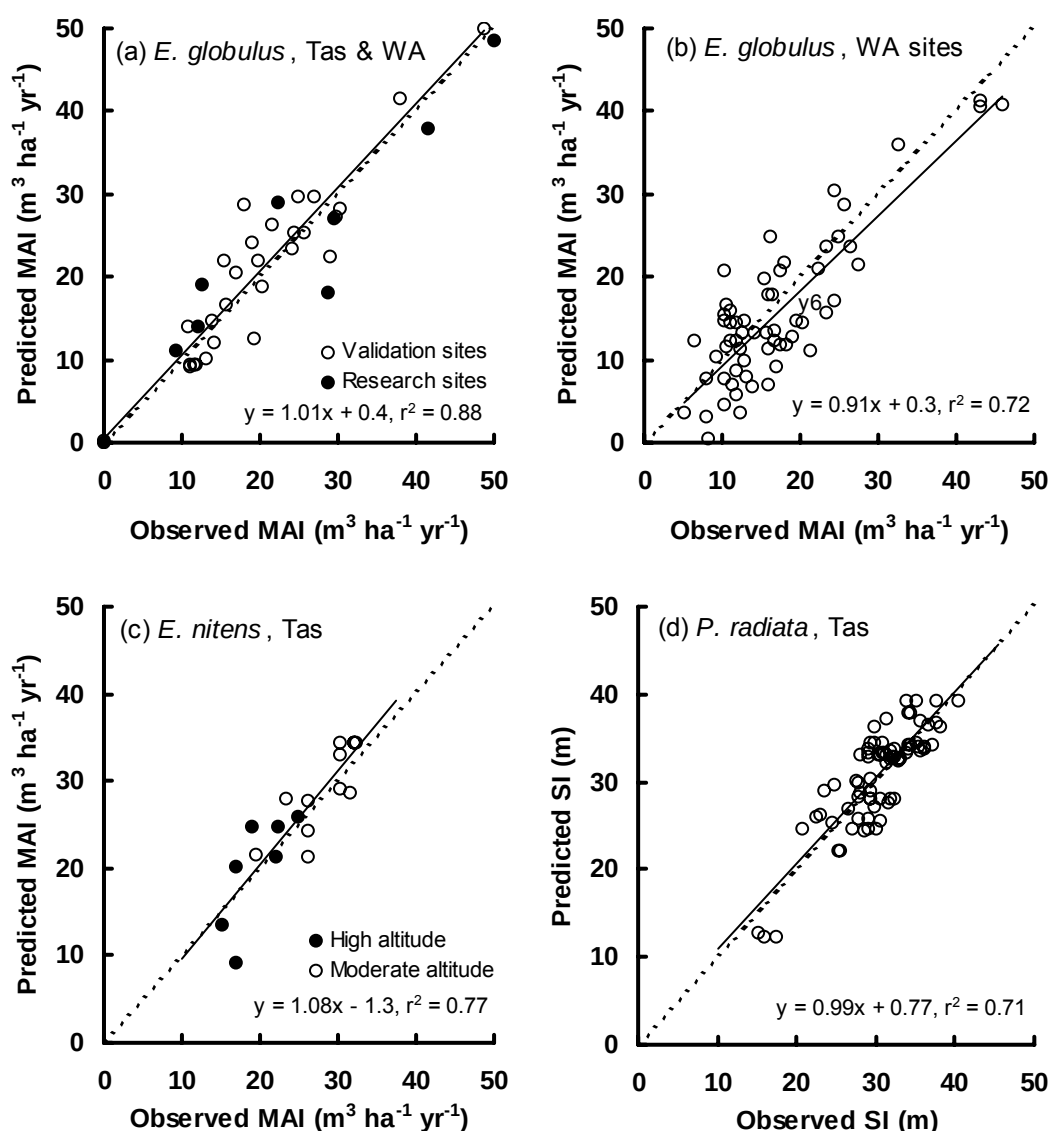


Figure 5.1 Observed mean annual increment and predicted values generated using PROMOD for *E. globulus* in Tasmania, *E. globulus* in W.A., *E. nitens* in Tasmania and *P. radiata* in Tasmania (from Sands et al. 2000)

The model calibrations have proved to be quite robust and all predictions for *E. globulus*, for example, are now run with one set of parameters. Both individual site and broadscale analyses were used to check the suitability of the models developed using data from Tasmania and Western Australia, and also to generate predictions for areas of interest to Regional Plantation Committees.

5.2 Simulations for individual sites

5.2.1 *E. globulus* in the Greater Green Triangle

Figure 5.2 shows PROMOD predictions made against harvested volumes from 10 year old *E. globulus* plantations in the Greater Green Triangle (GGT) area around Mt. Gambier, South Australia. These prediction runs were carried out by Dr Michael Battaglia (CSIRO/CRC for Sustainable Production Forestry). The predictions were made for about 70 old plots with unknown silviculture, depth to groundwater had to be inferred and soil properties were not defined in detail. Although these predictions were not carried out as part of this project they demonstrate that PROMOD makes reasonable predictions of *E. globulus* growth on the basis of limited information from sites within the GGT area.

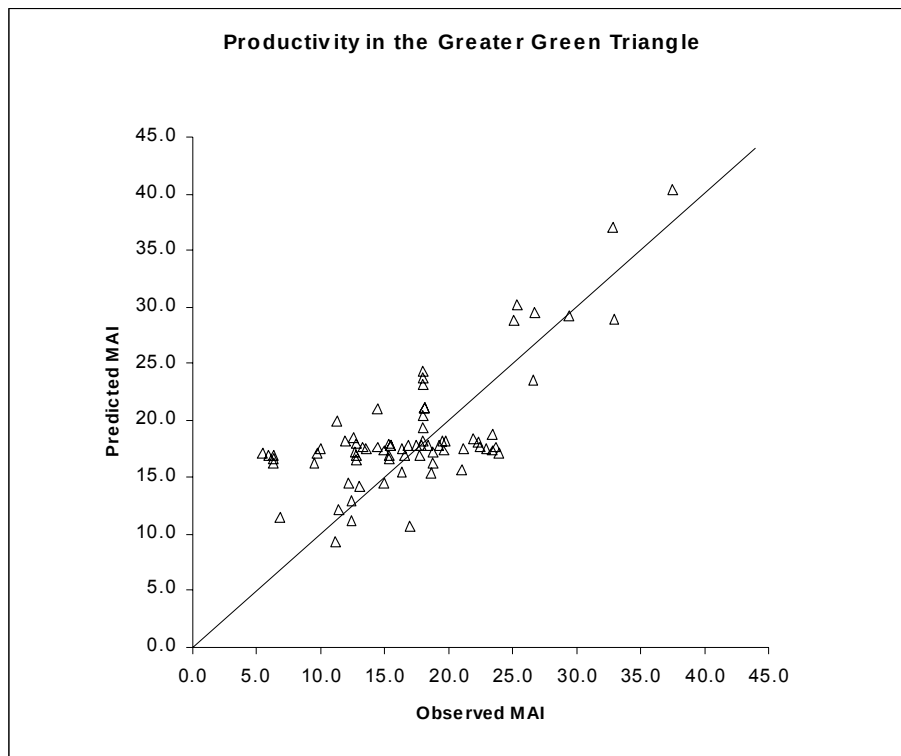


Figure 5.2 Observed and predicted mean annual increment of 10 year old *E. globulus* sites within the Greater Green Triangle

The area of *E. globulus* plantations in the GGT has expanded rapidly in recent years, with about 7000 ha of new plantations established in 1998 and over 40 000 ha in 2000. Plantations are expanding out into drier areas, which are further from processing facilities. Predicting the likely productivity of these sites is of particular interest to the GGT Regional Plantation Committee. Mr David Fife (CSIRO Forestry and Forest Products, Plantation Forest Research Centre, Mt Gambier) set up a series of 31 trial sites across a range of *E. globulus* sites in the GGT. Early growth measurements made at two years of age indicated a fourteen fold difference in volume increment across the sites, with the slowest growing sites recording less than one $\text{m}^3\text{ha}^{-1}\text{yr}^{-1}$ whilst the fastest growing had recorded nearly $14 \text{ m}^3\text{ha}^{-1}\text{yr}^{-1}$.

As part of this project PROMOD simulation runs were made for all these 31 sites. However, lack of detailed information on soil depth was a limitation in estimating growth at the 30 sites, so additional measurements were made as part of this project to determine effective soil depth up to 4 metres at 13 sites. Simulation runs were repeated using PROMOD model. The trees at the sites are still too young to provide a reliable test of the model, but it is planned to compare the model predictions with tree growth at five years of age.

5.3 Broadscale analyses

An objective of this study was to select broadscale areas within southeastern Australia and show their potential for several major farm forestry species. Broadscale analyses of Tasmania for *E. globulus*, *E. nitens* and *P. radiata* using were completed before this project began (Mummery and Battaglia 2001). Example output for *E. globulus* is shown in Figure 5.3.

Prior to the start of this project there had been few attempts to assess broadscale potential for farm forestry (see, for example, the work of Booth and Walker described in Booth and Jovanovic 1991). However, several other broadscale evaluations of plantation potential were completed between the time that the proposal for this project began initial development in 1997 and the time when the broadscale analyses for this project were undertaken in 2001. In particular, the Bureau of Rural Sciences carried out studies as part of the Comprehensive Regional Assessment/Regional Forest Agreement process. These studies included the Central Highlands of Victoria (Bush et al. 1998), Northeastern Victoria (Wareing and Baker 1998), Gippsland (Borschmann et al. 2000), Southern New South Wales (Bureau of Rural Sciences 2000a) and Upper and Lower North East New South Wales (Bureau of Rural Sciences 2000b).

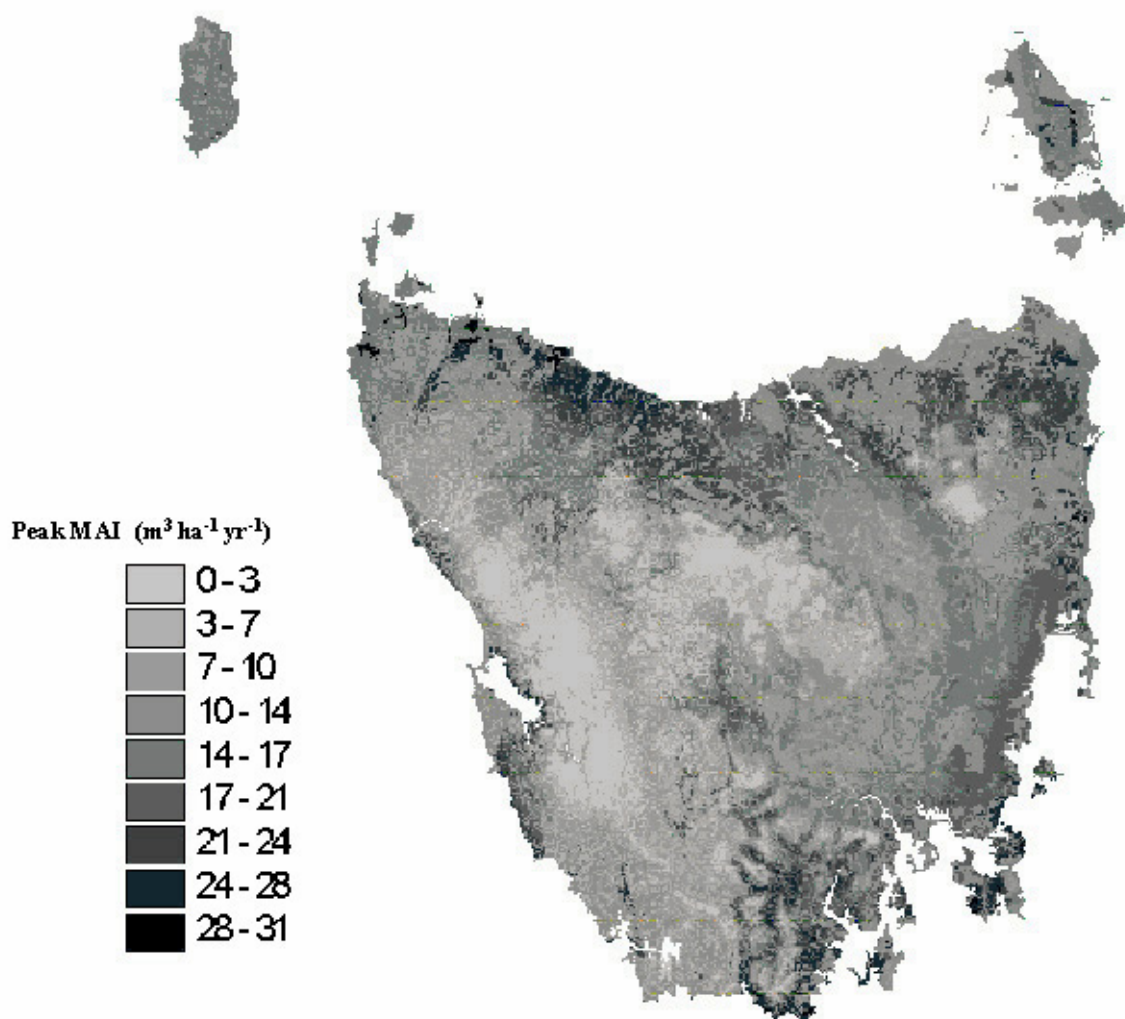


Figure 5.3 Predicted mean annual increment for *E. globulus* (Mummery and Battaglia 2001)

At the same time that the plantation potential of these relatively high rainfall areas of southeastern Australia was being assessed there was increasing interest in the potential of low to medium rainfall areas for farm forestry (Consortium 2001). For the purposes of this report these areas are considered to be the 400-800 mm mean annual rainfall zone. Rather than repeat analyses already carried out for Tasmania and the relatively well-watered areas of mainland southeastern Australia it was decided to concentrate the analysis of the broadscale plantation potential on the 400-800 mm rainfall zone. As soil information was also required for the analysis the study was restricted to the Murray-Darling Basin to take advantage of the Murray-Darling Basin Soil Information System (MDBSIS) study. Areas of the MDB receiving more than 400mm annual rainfall are shown in Figure 5.4.

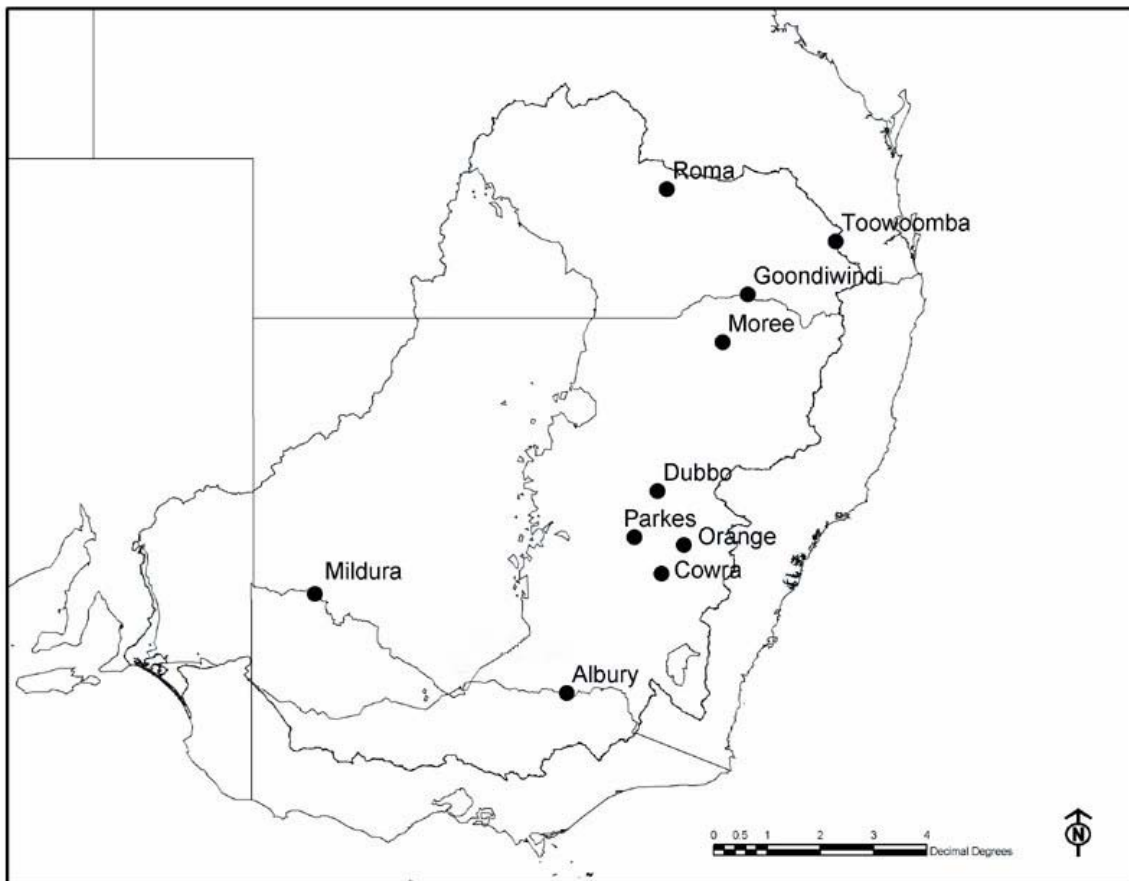


Figure 5.4 Regions of the Murray Darling Basin receiving more than 400 mm mean annual rainfall include locations such as Albury, Cowra, Orange, Parkes, Dubbo, Moree, Goondawindi, Toowoomba and Roma, as well as limited areas around the mouth of the Murray. Drier locations, such as Mildura, are mainly located in the western part of the basin.

The PROMOD model was run for three species, *Eucalyptus globulus*, *Eucalyptus nitens* and *Pinus radiata* for the gridded MDB dataset using data that has been described in Sections 2.3 and 2.4. The model was run with the model calibrations used to produce the data shown in Figure 5.1 and described by Sands et al. (2000). Figure 5.5 shows the output for *E. globulus*, Figure 5.6. the output for *E. nitens* and Figure 5.7 the output for *Pinus radiata*.

The PROMOD model used to generate Figure 5.5 was calibrated for Tasmanian blue gum (*E. globulus* spp. *globulus*). This sub-species is not generally suitable for New South Wales and Queensland as it is sometimes affected by diseases in uniform and summer rainfall environments (see “Improved species climatic profiles” Jovanovic and Booth 2002, produced as another subproject of CSF-56A), so only the predictions for Victoria are relevant.

The PROMOD predictions of potential productivity for blue gums in north-eastern areas of Victoria show a similar general pattern to maps included in reports prepared by Wareing and Baker (1998) and Margules Poyry (1998), both of which were based on evaluations of soil and rainfall conditions in relation to observed growth described by Borschmann (1998). They all show a generally suitable region running in an arc mainly south of the Hume highway through Kilmore, Seymour, Benalla, Wangaratta and Albury with some suitable areas extending south towards areas around towns such as Mansfield and Myrtleford. Low rainfall is the major limitation on the northern side of this arc, whilst cooler temperatures restrict suitable areas for blue gums in higher elevation areas below the arc.

However, the predicted productivity rates in the Wareing and Baker (1998) and Margules Poyry (1998) report are generally higher than those estimated in this report, with 37 per cent of the area rated in the 10-20 MAI class, 41% in the 21-30 class and 22% in the 30–40 class, whereas about 80 per cent of the sample locations in Figure 5.4 are in the 10-20 class and only about 20 per cent in the 20-30 MAI class.

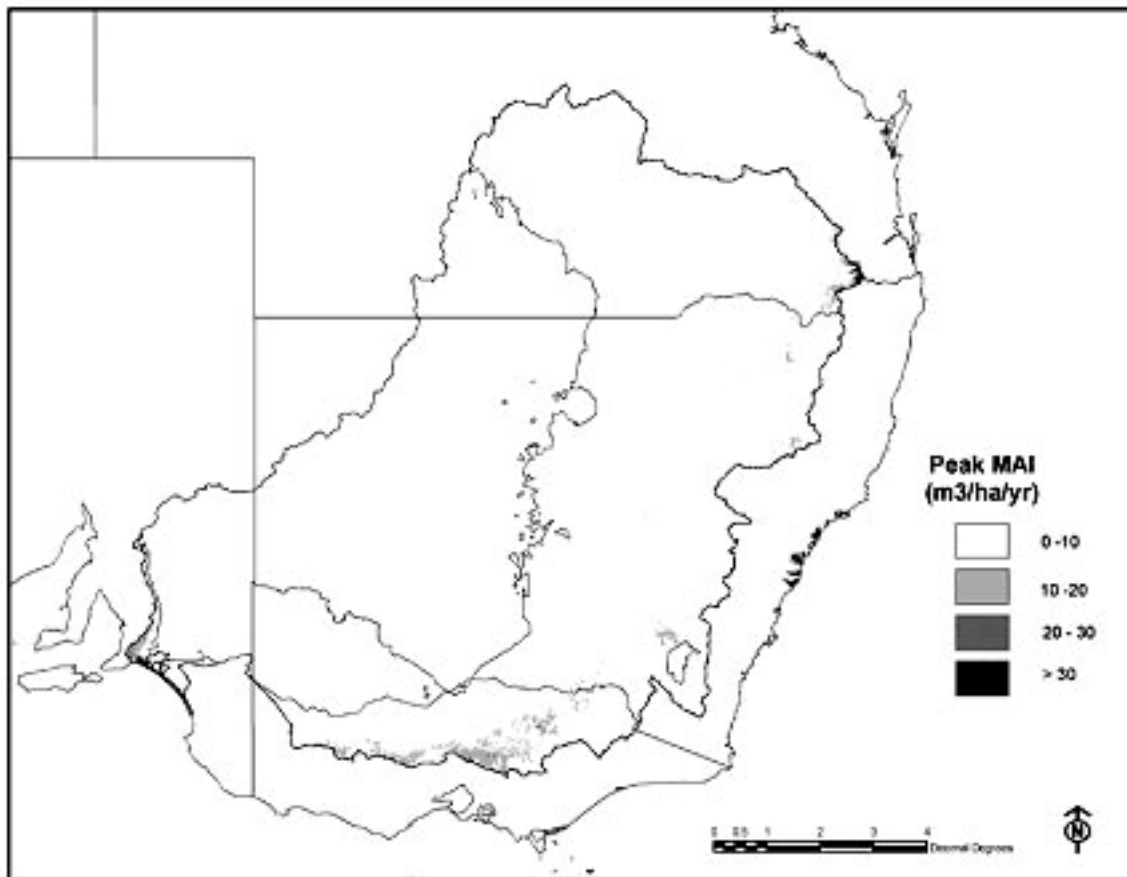


Figure 5.5 PROMOD peak MAI predictions for *E. globulus* for locations within the Murray Darling Basin receiving mean annual rainfall between 400 and 800 mm per annum. Note *E. globulus* spp. *globulus* is not generally suitable for growing in New South Wales and Queensland (see text).

Figure 5.6 shows predictions of potential productivity of *E. nitens* made using the ProMod model. New plantations in northeastern Victoria are more likely to use *E. globulus* (Margules Poyry 1998), so the reliability of the predictions in this area are not particularly important. However, the Bureau of Rural Sciences in conjunction with State Forests of New South Wales and the Australian Bureau of Agricultural and Resource Economics (2000a) evaluated plantation opportunities in southern New South Wales for *E. nitens* using the 3-PG model, which is described in section 2 of this report. Model output, together with the opinions of expert validators, was used to identify areas of low, medium and high potential productivity for *E. nitens*. Figure 5.6 is generally similar to the plantation potential map in the BRS report with the highest productivity areas in high rainfall sites to the east of Gundagai, Tumut, Batlow and Tumbarumba. Figure 5.6 and the BRS report both also showed good growth rates in the Bathurst region. Another BRS report (Bureau of Rural Sciences in conjunction with State Forests of New South Wales and Australian Bureau of Agricultural Economics 2000b) using the 3-PG Spatial model shows medium potential productivity areas for hardwood species (including *E. grandis*, *E. pilularis* as well as *Corymbia maculata* and *C. variegata*) in the region east of Tenterfield and Glen

Innes. These areas are shown as being more extensive in Figure 5.6. This is not surprising as *E. nitens* may be better adapted to cool high elevation sites along the Great Dividing Range at the edge of the Murray-Darling Basin.

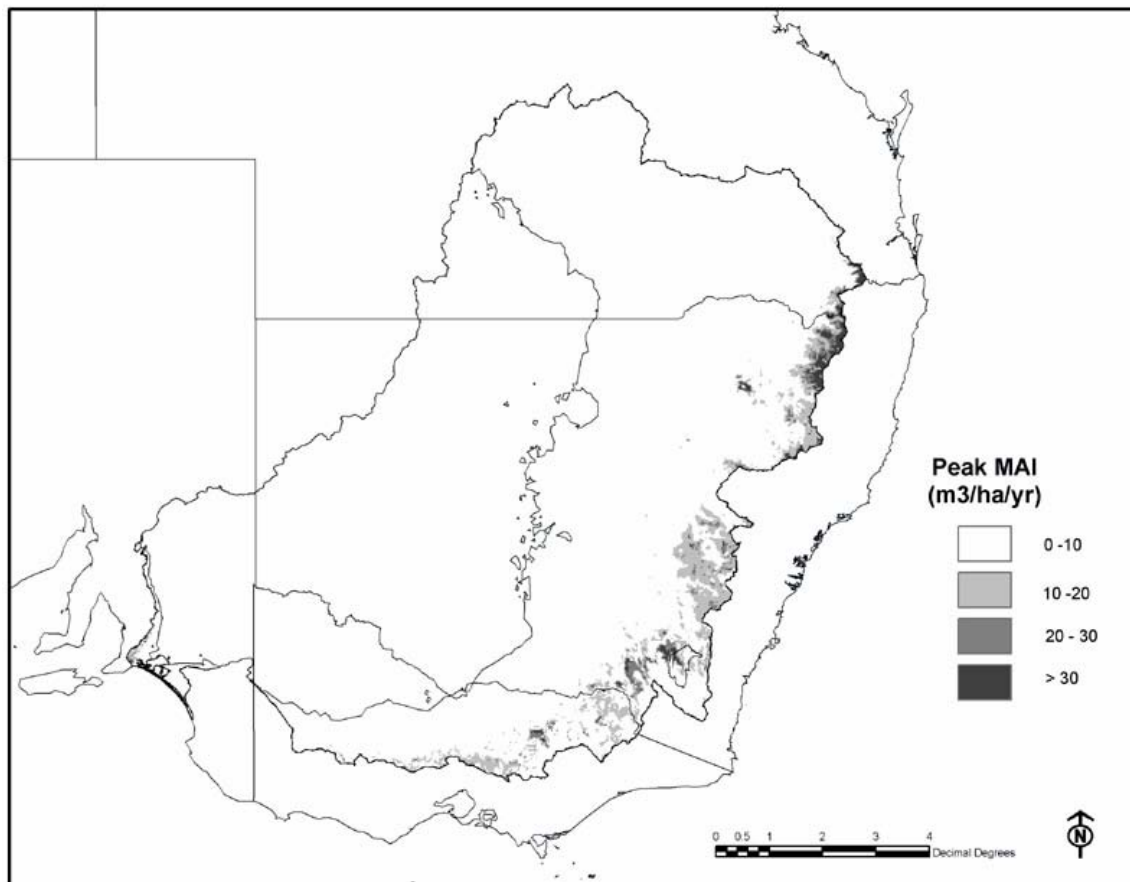


Figure 5.6 PROMOD peak MAI predictions for *E. nitens* for locations within the Murray-Darling Basin receiving mean annual rainfall more than 400 mm per annum.

Figure 5.7 shows predictions of potential productivity for *P. radiata* made using the PROMOD model. Potential productivity is shown in terms of site index (mean dominant height at 20 years of age)(Candy 1989) rather than mean annual increment. The Murray-Darling Basin includes many major *P. radiata* plantations in areas such as Bathurst-Orange, Tumut-Tumbarumba and northeastern Victoria (Booth 1984, Wood *et al.* 2001). The Margules Poyry (1998) report differs in that it shows a similar general area of *P. radiata* suitability in northeastern Victoria to that shown for *E. globulus*, with suitable areas in this case being generally south of the Hume highway and again extending to areas around towns such as Mansfield and Myrtleford. Figure 5.7 indicates that the suitable area for *P. radiata* is greater than that shown in Figure 5.5 for *E. globulus* because suitable areas for the pine extend into higher cooler areas. The main reason why similar differences are not shown by the Margules Poyry (1998) maps is that they evaluated only cleared private land, whereas the PROMOD analysis described here extended into areas such as National Parks, which though suitable for *P. radiata* would not be available for plantation establishment. Some caution should also be used in interpreting the *P. radiata* productivity estimates for northern New South Wales and southern Queensland. Although it is grown commercially in these regions, it is reaching its environmental limits.

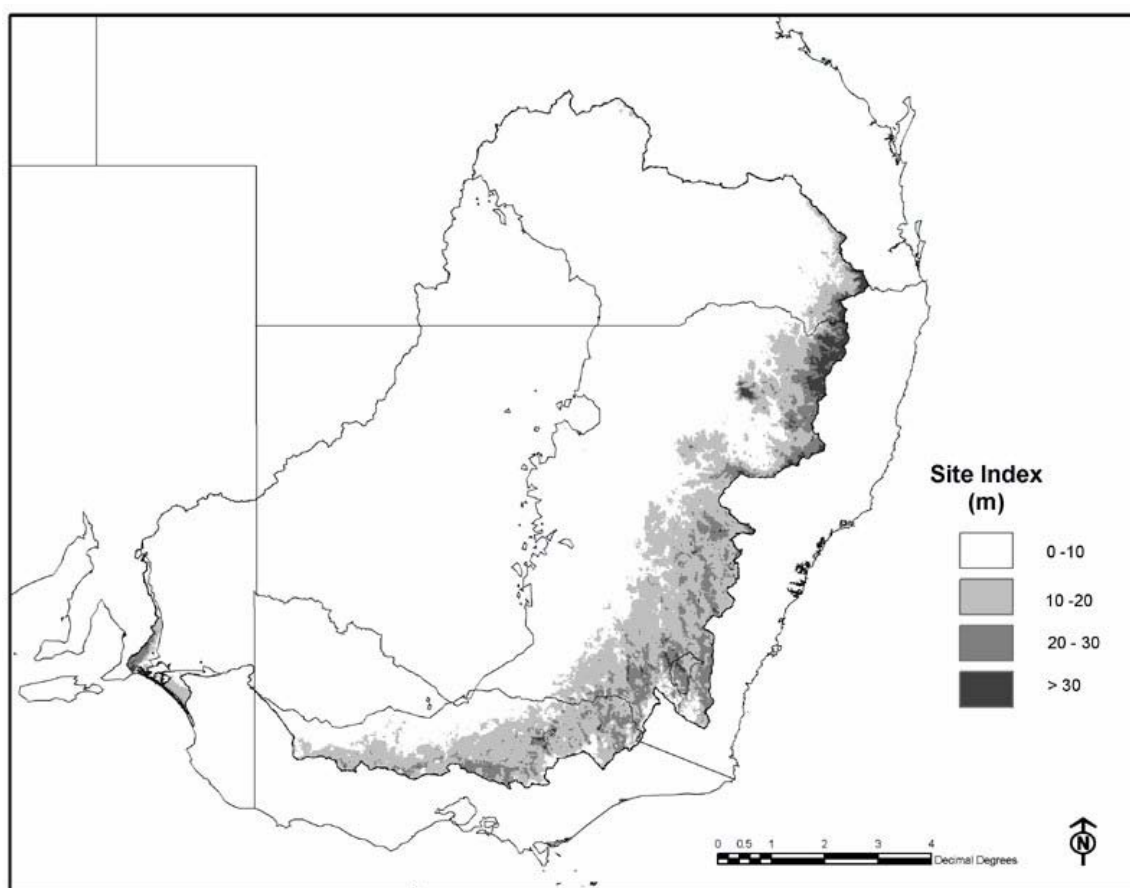


Figure 5.7 PROMOD site index predictions for *P. radiata* for locations within the Murray-Darling Basin receiving mean annual rainfall more than 400 mm per annum.

5.4 Lachlan case study

Although the maps shown in Figures 5.5, 5.6 and 5.7 provide a useful overview it's obviously difficult to estimate predicted productivity at specific locations. To assist the validation process and to provide output more useful for particular areas, detailed maps of PROMOD predictions were extracted for the Lachlan and Murray-Riverina regions and circulated for comment to appropriate people involved in farm forestry in these regions. For example, Figure 5.8 shows output for *P. radiata* in the Lachlan valley region. Comments indicated that the maps provided useful summaries of general productivity patterns, but also indicated a need for means to assess particular sites.

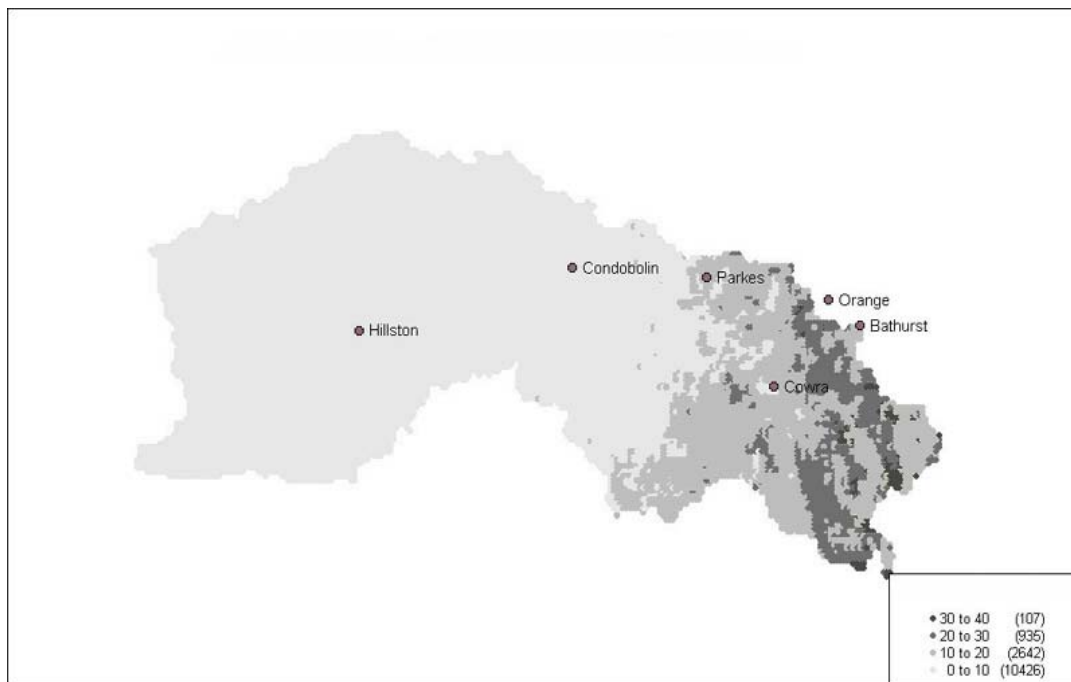


Figure 5.8 Estimated site index (mean dominant height in m at 20 years of age) for *P. radiata* for 14 110 locations in a 1 km grid across the Lachlan valley, New South Wales.

5.5 ProMod – Excel version

An Excel version of PROMOD is available to allow extension staff to assess the potential of particular sites (contact Peter.Sands@csiro.au). Climatic data necessary to run the model can be obtained from farm records, published sources (Bureau of Meteorology 1988) or the gridded data used for the analyses described in the previous section. Site factors, which must be provided, include soil texture, stoniness, depth of soil, presence/absence of any features impeding root development and a salinity measure. The model can be run for *E. globulus*, *E. nitens* and *P. radiata* and predictions indicate peak annual increment ($\text{m}^3 \text{ha}^{-1} \text{yr}^{-1}$) or site index (m).

6. Discussion and recommendations

The objective of this subproject was to provide improved predictions of potential productivity for several commercially important farm forestry species at particular sites and across broad regions in southeastern Australia. Making use of data from existing trials presented some difficulties.

In the past the most reliable relationships between tree growth and environmental conditions have generally been developed when data have been gathered from the same species established and managed under similar conditions. Regression relationships in particular tend to have been more successful when also developed using data from relatively small areas, such as within individual forests. In this case data from different species and provenances grown under different conditions over a vast area had to be used.

Considering these limitations the analyses were reasonably successful. The inclusion of outputs from a simple growth model in the regression analysis accounted for the considerable differences in climatic conditions much better than the simple climatic factors initially used. It was also very interesting that the regression relationship for the “hills” dataset was much better than that for the “plains” dataset. These differences may in part be due to the inclusion of several irrigated sites in “plains” dataset and the frequent lack of detailed information on irrigation applications. Another factor may be that the “hills” sites generally had shallower soils and that soil depths were therefore determined more reliably on these sites.

Results from the Plantgro analyses were disappointing. Plantgro was difficult to use with this very complex and quite large dataset, as the Plantgro program has not been updated to allow batch runs for large numbers of sites. Including outputs from a growth simulation model in the regression analysis overcame some of the usual limitations of a purely statistical approach. It was much quicker and easier to fit the hybrid statistical model than adjust the Plantgro plant files to produce improved predictions. Though Plantgro results were not very encouraging here the model has performed well in the past with other datasets (e.g. Sands 2001) and is still well worth applying particularly with smaller and more uniform datasets.

The broad-scale PROMOD analyses extended assessments of plantation potential into low rainfall areas, which are a high priority for farm forestry development. The predictions corresponded well with local knowledge of productivity and with predictions made by others when areas assessed overlapped in higher rainfall (>700 mm) areas. A limitation of the broad-scale analyses was the lack of calibrations for species better suited to low rainfall environments. Strengths of the PROMOD analysis are that the available data combined in the process-based model give an indication of the interactive effect of some of the major growth determining factors on the production of the target species (i.e. salinity, soil water holding capacity, temperature, rainfall, evapotranspiration and fertility). Scale studies of the model’s broad area predictions when made with this type of data in other areas have shown that the results are plausible (see, for example, Mummery and Battaglia 2001). A potential weakness is that some key factors (waterlogging, hardpans and soil structure) have not been considered. Volumes or yield averaged over broad areas are likely to be reasonably accurate, but point estimates may be highly inaccurate (see Mummery and Battaglia 2001). Classifications of soil characters, such as soil depth, included in “Basin-in-a-box” indicate general trends across thousands of locations. These estimates can provide inputs into PROMOD, but are not sufficiently accurate to make predictions as reliable as those based on actual measurements at particular sites. However, the availability of the Excel version of PROMOD allows extension staff to collect detailed information for particular sites, to further validate existing models and also make assessments for specific locations.

Future developments, which could complement this work, include analyses of more recent trials. Probably the greatest limitation of this study was the lack of comparable trials planted using similar establishment methods and the same genetic material over a wide range of conditions. Recent trials such as those established by the Australian Low Rainfall Tree Improvement Group (ALRTIG)

(www.ffp.csiro.au/alrtig) and the 49 low rainfall trial sites established by State Forests of New South Wales (B. Royal, personal communication) will provide a much better basis for analysis as they mature. These newer trials will provide a more uniform basis for developing predictive relationships. They will also provide information on lesser-known species suited to low rainfall environments, such as *Eucalyptus cladocalyx* (sugar gum), *Eucalyptus occidentalis* (swamp yate) and *Pinus pinaster* (Maritime pine).

Climatic variability, particularly rainfall, is likely to be important in determining establishment success and plantation growth in the low-medium (400-800mm) rainfall zone. However, more data on survival and early growth are needed before the effects of rainfall variability can be reliably simulated.

The site sampling methods used in this study were kept relatively simple, so extension officers could easily take samples. However, it is recommended that samples should be taken to depths greater than 2 m in future studies. The regression results suggested that lack of information on effective soil depth may have been a problem in developing the predictive relationship for the “plains” sites. Another recent CSIRO study for JVAP (Polglase et al. 2002), which involved detailed studies of root distributions and tree water use, has clearly shown the importance of sampling to depths greater than the 2 m limit used here. It also highlighted the need to understand important differences in the ways that particular species can or cannot make use of groundwater.

It is recommended that all future farm forestry projects should, where appropriate, take account of the minimum data set recommendations made in the manual “Site Evaluation for Farm Forestry” (Harper et al. in press), which has been prepared for JVAP.

Despite the difficulties in collecting and analyzing a very diverse dataset, the project objective of providing improved predictions of potential productivity for several commercially important farm forestry species at particular sites and across broad regions was successfully fulfilled. The information provided here will assist those involved with farm forestry to identify broad areas suitable for particular species as well as the potential of specific sites.

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8. Appendix 1 – Sample sites

Sites used in site productivity analysis.

gr= *E. grandis*, ca=*E. camaldulensis*, sa=*E. saligna*,

ma=*C. maculata*, gl=*E. globulus*

Note : Samples were also taken from an additional 31 *E. globulus* sites in the Greater Green Triangle area, but were not used in the development of regression relationships as all sites were very young.

Region	Trial name H = Hills P = Plains	Latitude (decimal degrees) South	Longitude (decimal degrees) East	Elevati on (m)	Species planted	Tree growth measure -ment age (yrs)
ACT	Stromlo H	35°16'	149°02'	510	ca,sa,gr ,ma,gl	12
ACT	Kowen H	35°20'	149°20'	650	ca,sa,gr , ma,gl	12
ACT	Urriara H	35°18'	148°52'	720	ca,sa,gr ,ma,gl	12
Riverland, SA	Berrivale P	34°15'	140°36'	50	ca	10
Myrtleford VIC	Buffalo River H	36°70'	146°68'	300	gl,gr,sa	3
Coffs Harbour NSW	Cascade H	30°30'	152°78'	600	gl,gr,sa	14
Shepparton VIC	Cobram TFP site P	35°59'	145°37'	110	ca,gr,gl ,sa	4
South East SA	Cope P	37°42'	141°12'	60	gr	6
South East SA	CSIRO trial, dune crest P	37°44'	140°46'	60	gl sa gr	5
South East SA	CSIRO trial, dune swale P	37°44'	140°46'	55	gl	13
Adelaide Hills SA	Cudlee Creek, Fox Creek road H	34°52'	138°50'	360	gr,ma,s a	10
Adelaide Hills SA	Cudlee Creek, Springkeld H	34°53'	138°50'	500	gl,gr,m a,sa.	27
South East SA	Derrymore P	37°35'	140°38'	70	gl	3
South East SA	Fartch P	37°44'	140°33'	40	gl	5
Deniliquin NSW	Greendale P	35°49'	144°36'	110	ca,gr	4

Region	Trial name H = Hills P = Plains	Latitude (decimal degrees) South	Longitude (decimal degrees) East	Elevati on (m)	Species planted	Tree growth measure -ment age (yrs)
Adelaide Hills SA	Gumeracha, Bennett's block H	34°49'	138°50'	380	gl,ma	5
Adelaide Hills SA	Gumeracha, Weir block H	34°49'	138°52'	330	gl,ma	3
Adelaide Hills SA	Handiside, Meadows (crest) P	35°10'	138°46'	420	gl	8
Adelaide Hills SA	Handiside, Meadows (footslope) P	35°10'	138°46'	410	ca	8
Adelaide Hills SA	Handiside, Meadows (footslope) P	35°10'	138°46'	410	sa	8
Adelaide Hills SA	Handiside, Meadows (valley flat) P	35°10'	138°46'	410	gr	6
South East SA	Heath P	37°34'	140°55'	70	gl	8
Hamilton VIC	Hensley Park P	37°35'	142°03'	225	ca,gl,gr,ma	11
Adelaide SA	Hiat P	34°46'	138°33'	5	gl,gr,ma,ca	6
Horsham VIC	Horsham P	36°43'	142°12'	130	gl,gr,ma,sa,ca	20
South East SA	Johnsons Glencoe P	37°43'	140°37'	60	gl	6
Adelaide Hills SA	Kuitpo H	35°12'	138°42'	340	gl,sa	13
Shepparton VIC	Kyabram P	36°19'	145°03'	110	ca,gr,gl	20
Bransholme VIC	Lanark P	37°52'	141°48'	150	gr,sa,ca	7
Riverland SA	Leake's Waikeri P	34° 11'	139°56'	50	gr	10
Euroa VIC	Longwood H	36°80'	145°42'	192	gl,ma,sa	5
Riverland SA	Lox 1 P	34°26'	140°38'	40	ca	4
Riverland SA	Lox 2 P	34°26'	140°38'	40	ca	4

Region	Trial name H = Hills P = Plains	Latitude (decimal degrees) South	Longitude (decimal degrees) East	Elevation (m)	Species planted	Tree growth measure- ment age (yrs)
Shepparton VIC	Mangalore TFP site P	36°54'	145°10'	140	ca,gl,gr ,sa	4
Gippsland VIC	Mt Worth 140 P	38°30'	145°97'	450	gl	12
Gippsland VIC	Silver Crk 141 H	38°28'	146°27'	100	gl	12
Gippsland VIC	Silver Crk 142 H	38°30'	146°30'	100	gl	12
Gippsland VIC	Maryvale 143P	38°20'	146°47'	50	gl	12
Gippsland VIC	Mt Worth 145H	38°32'	145°98'	400	gl,gr,sa	11
Gippsland VIC	Silver Crk 146 H	38°33'	146°22'	200	gl,gr,sa	11
Gippsland VIC	Flynn 147 P	38°25'	146°65'	150	gl,gr,sa	11
Gippsland VIC	Glencoe 148 P	38°27'	147°05'	80	gl,gr,sa	11
Gippsland VIC	Stockdale 149 H	37°85'	147°18'	100	gl,gr,sa	11
Hamilton VIC	Melville Forest P	37°30'	141°52'	250	gr	7
Mildura VIC	Mildura P	34°11'	142°10'	130	gr,ma,c a,sa	20
Riverland SA	Moore's 1P	34°28'	140°36'	50	gr,ca	12
Riverland SA	Moore's 2 P	34°28'	140°36'	50	gr	12
Riverland SA	Moore's 3 P	34°28'	140°36'	55	gr,ca	12
Riverland SA	Moore's 4 P	34°28'	140°36'	60	gr,ca	12
South East SA	Mt. Edward P	37°37'	140°36'	120	gl	5
South East SA	Mt. McIntyre H	37°33'	140°33'	70	gl	4
Shepparton VIC	Nathalia TFP site P	35°57'	145°13'	100	ca,gl,gr ,sa	4
Deniliquin NSW	Norwood P	35°28'	145°21'	110	gr	4
Rutherglen VIC	Rutherglen 1 P	36°05'	146°46'	167	ca	9
Young NSW	Springview H	34°00'	148°18'	475	gl,ca	11
South East SA	Strath P	37°42'	141°09'	50	gl	11
Shepparton VIC	Tatura TFP site P	36°24'	145°13'	110	ca,gl,gr ,sa	4

Region	Trial name H = Hills P = Plains	Latitude (decimal degrees) South	Longitude (decimal degrees) East	Elevati on (m)	Species planted	Tree growth measure -ment age (yrs)
Shepparton VIC	Timmering TFP site P	36°18'	144°55'	100	ca,gl,gr ,sa	4
Myrtleford NSW	Villela 1 P	36°34'	146°44'	200	gl,gr,sa	3
Wagga NSW	Wagga effluent trial H	35°07'	147°22'	190	gl,ca,gr ,ma,sa	3
Wake	P	34°07'	139°37'	50	gr	11
Coffs Harbour NSW	Wedding Bells 1 H	30°18'	153°08'	50	gr	9