



Forecasting Growth of Key Agroforestry Species

in south-eastern Australia

**A report for the
RIRDC/LWRRDC/FWPRDC Joint
Venture Agroforestry Program**

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Foreword

To obtain a better understanding of the growth and yield of agroforestry *Eucalyptus* species, the Joint Venture Agroforestry Program (RIRDC/LWRRDC/FWPRDC) commissioned the project, “Forecasting tree growth and yield and financial returns of key agroforestry species across southern Australia”. This project was designed to:

- improve the reliability of forecasting tree growth and yield of key agroforestry species on cleared agricultural land across southern Australia, by developing height, basal area and volume predictions according to grouped site productivity classes;
- investigate relationships between tree growth rates and site factors, and construct mathematical models of tree growth which could be incorporated into financial models such as FARMTREE; and
- improve landholders’ knowledge of the relative economic returns and benefits from adopting different agroforestry regimes.

This report presents growth data for a number of *Eucalyptus* species from a range of sites, and models growth using “site types” based on rainfall and soil classes. The growth functions are suitable for use by extension providers and farm foresters.

RIRDC's involvement in this project and in the Joint Venture Agroforestry Program, is part of the Corporation's Agroforestry and Farm Forestry Research Program which aims to foster integration of sustainable and productive agroforestry within Australian farming systems. It was funded by three R&D Corporations — RIRDC, LWRRDC and FWPRDC which are principally funded by the Federal Government.

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Peter Core

Managing Director

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Executive Summary

Accurate estimates of tree growth rates are essential to reliably forecast agroforestry returns and benefits. Landholders and investors need such data to evaluate alternative species and silvicultural regimes. Data from long-standing research trials provides the most immediate basis for this information.

Utilising long-established trials across south-eastern Australia, this project collected and collated tree growth data and site and soil characteristics to:

- improve the reliability of forecasting tree growth and yield of key agroforestry species on cleared agricultural land across southern Australia, by developing height, stand basal area and volume predictions according to grouped site productivity classes;
- investigate relationships between tree growth rates and site factors, and construct mathematical models of tree growth which could be incorporated into financial models such as FARMTREE; and
- improve landholders' knowledge of the relative economic returns and benefits from adopting different agroforestry regimes.

Six *Eucalyptus* species were studied in detail, and based on actual data, growth predictions of height, basal area and volume were made for a range of sites. Site productivity classes for the different species were developed based on "site types" grouped by climatic and soil information. These productivity classes allow growth rates to be estimated for any site, provided that annual rainfall and general soil characteristics are known. Predictions of growth can also be made by inputting measurements of an actual stand at a known age.

The growth modelling functions used are easy to apply and require minimal actual growth measurement information. The growth predictions based on site productivity classes could be used as a general guide to tree growth on similar sites. The predictions are only indicative of the rates of growth expected and only with the presence of actual long-term data can the predictions be verified.

By providing a tool for forecasting tree growth this project has improved landholders' and investors' ability to estimate the returns and benefits of agroforestry regimes. Further work to continue with the extension of this material in a more accessible format could include shorter publications or fact sheets. After further development and testing, the modelling methodologies could be incorporated into FARMTREE or a similar package for use by owners and managers of small farm forests with the expectation of providing improved growth predictions. (See Appendix 1 for a discussion on FARMTREE).

The project was managed by the Victorian Department of Natural Resources and Environment (NRE) and Primary Industries and Resources of South Australia (PIRSA), with the work collaboratively undertaken principally by the Centre for Forest Tree Technology (CFTT), ForestrySA, the Department of Forestry University of Melbourne, NRE and PIRSA.

1. Introduction

Traditionally, the majority of Australia's wood needs have relied upon the harvesting of *Eucalyptus* hardwood forests. Farm forestry plantations represent a chance to create a significant new wood resource. State and Federal Governments have recognised this opportunity and determined a need to significantly expand the plantation resource in all commercial tree-growing regions of Australia, with the major aims of:

- creating a new wood resource; and
- encouraging tree planting to rehabilitate agricultural land, improve water quality, and meet other environmental objectives.

A major expansion of eucalypt plantations is occurring in some areas of Australia. While most of the older eucalypt plantation programs were undertaken by the state forest services or private companies, since 1980, large areas of *Eucalyptus globulus* have been planted in south-western Western Australia, south-eastern South Australia, south-western Victoria and Tasmania. Eucalypts used in other significant plantation programs include *E. nitens* (Tasmania), *E. grandis*, *E. dunnii*, *E. maculata* (north coast New South Wales), *E. grandis* and *E. cloeziana* (Queensland).

Recent Federal Government initiatives such as the 2020 Vision have promoted wider interest in forestry as a commercial venture, both for wood yield and carbon credits. The proposed trebling of the area of private plantations by 2020 would reduce Australia's dependence upon imported wood products, offer landholders an economically viable alternative that would compliment existing agricultural activities, and provide environmental benefits.

Tree growth rates are one of the key determinants of agroforestry financial returns and benefits. Landholders and investors need to be able to forecast growth rates of prospective agroforestry species on particular sites.

The main objectives of this project were:

- 1) To improve the reliability of forecasting tree growth and yield of key agroforestry species on cleared agricultural land across southern Australia, by developing height, basal area and volume predictions according to grouped site productivity classes.
- 2) To investigate relationships between tree growth rates and site factors, and construct mathematical models of tree growth which could be incorporated into financial models such as FARMTREE.
- 3) To improve landholders' knowledge of the relative economic returns and benefits from adopting different agroforestry regimes.

To achieve these objectives, the project has focussed on gathering growth data from older field experiments, and a range of *Eucalyptus* species potentially suitable for agroforestry in south-eastern Australia. These data were then analysed to identify relationships between growth and site. The growth data have been collected by numerous forestry organisations over the past 10 to 15 years, and provide an immediate opportunity to improve current estimates of tree performance.

Six eucalypt species were selected for further modelling work based on the availability of data, and an indicated preference for these species among forest growers. These species were:

- | | |
|------------------------------|-------------------|
| • <i>Eucalyptus globulus</i> | Southern Blue Gum |
| • <i>E. nitens</i> | Shining Gum |
| • <i>E. viminalis</i> | Manna Gum |
| • <i>E. botryoides</i> | Southern Mahogany |
| • <i>E. grandis</i> | Flooded Gum |
| • <i>E. saligna</i> | Sydney Blue Gum |

This report characterises the sites from which growth data were collated, and details statistical summaries of tree growth performance and mathematical growth functions relating tree size to other variables for these six species. The report produces predictions of tree growth based on measurements of standing trees or on site information of soil groups and annual rainfall.

The project, originally proposed by Mr B. Loane, was managed by the Victorian Department of Natural Resources and Environment (NRE) and Primary Industries and Resources of South Australia (PIRSA). The project was principally undertaken by the Centre for Forest Tree Technology (CFTT), ForestrySA, Department of Forestry University of Melbourne, NRE and PIRSA. Forest Essentials Pty Ltd, Margules Poyry Pty Ltd, Australian Paper Plantations Pty Ltd (APP), Ian Sargeant and Associates, and the Victorian Resource Atlas Project also collaborated on various tasks within the project.

2. Site Characterisation

Climatic and soils information was collected variously for experimental trial sites and is presented mainly in the form of tables and figures for use in describing site productivity classes. The site information may assist extension providers to classify sites and therefore make predictions of growth for their local site. It is important that site constraints are identified prior to planting so that trees are planted where they will survive and grow well (Harper and McGrath, 1997).

2.1 Gippsland

Twelve eucalypt species trials were established across the major soil types in Gippsland, Victoria between 1986 and 1989 (Figure 1). The site characteristics for the species trials at Tostaree, Waygara and the 10 trials established by APP (VRV140-149) are presented in Table 1. Soil classification, texture profiles, and surface and subsoil characteristics were determined according to the conventions of Northcote (1979), Turvey (1987) and McDonald *et al.* (1990), and are presented in Tables 2-4 and Figure 2. Root abundance was assessed in most soil pits and is presented in Figure 3.

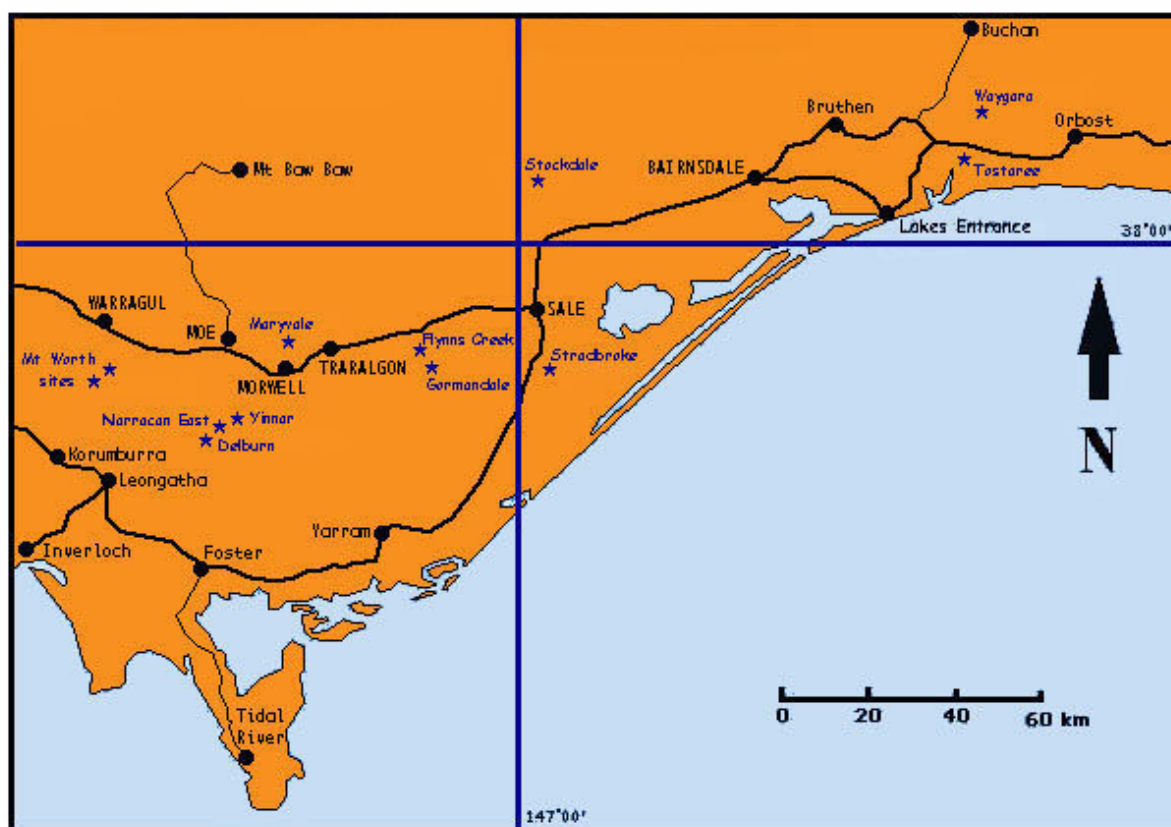


Figure 1. Location of the 12 eucalypt species trial sites in Gippsland, Victoria.

The trial sites range in altitude from approximately 40 to 400 m, and except for the Mt Worth sites have gentle slopes. Average annual rainfall ranges from 600 to 1220 mm, average annual pan evaporation ranges from 1010 to 1260 mm, and average daily maximum and minimum temperatures range from 22-26 and 10-13°C in January, and 9-14 and 2-5°C in July.

The Tostaree, and Mt Worth East and West sites were previously improved pasture, while the Waygara site was previously degraded native forest. All other sites were previously *Pinus radiata* plantations.

The soils at Waygara, Mt Worth East and West, Narracan East and Delburn have a Gradational Primary Profile Form (PPF; Northcote, 1979), while the soils at Gormandale and Stradbroke have a Uniform PPF, and the soils at Tostaree, Yinnar, Maryvale, Flynn's Creek and Stockdale have a Duplex PPF. While the soil at the Waygara trial was classified in this study as having a Gradational PPF, it behaves as a Duplex soil in that it has impeded drainage. Indeed, a previous, more comprehensive soil sample at this variable site classified the soil as having a Duplex PPF, with a distinct texture contrast between the hard-setting A horizon and the clayey B horizon of low hydraulic conductivity and high bulk density (Hopmans, pers. comm.). Therefore, in this report the soil at Waygara has been treated as having a Duplex PPF.

Root abundance decreased with increasing depth, but the rate varied within and between sites. The soil at Yinnar (VRV142) had fewer and smaller roots than all other sites, especially at depth. The soil at Yinnar is characterised by having a shallow A horizon over yellow or grey clay. The clay B horizon inhibits root development and retards the root system from fully exploring the nutrient potential of the soil (Turvey, 1980). A perched watertable often forms in winter, and the surface soil is hard-setting in summer.

Table 1. Location and site characteristics for the 12 eucalypt species trials in Gippsland, Victoria ^[1].

Character	Tostaree	Waygara	VRV140 ^[2] Mt Worth West	VRV141 Narracan East	VRV142 Yinnar	VRV143 Maryvale	VRV144 Gorman- dale	VRV145 Mt Worth East	VRV146 Delburn	VRV147 Flynn's Creek	VRV148 Stradbroke	VRV149 Stockdale
Location												
Longitude (E)	148°11'	148°19'	145°59'	146°16'	146°18'	146°28'	146°42'	145°59'	146°14'	146°36'	147°03'	147°11'
Latitude (S)	37°47'	37°41'	38°18'	38°17'	38°18'	38°12'	38°16'	38°19'	38°21'	38°16'	38°16'	37°51'
Altitude (m)	40	80	380	180	100	40	200	400	200	110	60	90
Annual rainfall (mm)	819	870	1212	963	930	768	830	1224	1002	765	598	693
Annual pan evap. (mm)	1259	1263	1018	1116	1153	1195	1138	1011	1099	1173	1217	1182
Ave. temperature (°C)												
maximum: January	24.2	24.6	22.2	24.1	24.7	25.7	23.7	22.0	23.6	24.5	24.0	25.3
July	14.1	13.7	10.0	11.7	12.4	13.2	11.8	9.8	11.4	12.5	13.0	13.2
minimum: January	12.3	12.1	10.5	11.7	12.2	12.4	11.7	10.5	11.7	12.1	12.2	11.8
July	3.1	2.6	3.6	4.1	4.4	4.1	3.8	3.6	4.4	4.0	3.7	2.7
Slope (%)	3-6	0-1	24-28	2-3	0-5	0-2	0-5	5-28	0-8	0-1	2-7	0-1
Soil parent material	Tertiary sediments	Tertiary sediments	Cretaceous sediments	Mid- Tertiary sediments	Cretaceous or Mid- Tertiary sediments	Late Tertiary sediments	Late Tertiary sediments	Cretaceous sediments	Mid- Tertiary sediments	Late Tertiary sediments	Pleistocene aeolian sediments	Late Tertiary sediments
Previous land use	Improved pasture	Native forest	Improved pasture	<i>Pinus radiata</i>	<i>Pinus radiata</i>	<i>Pinus radiata</i>	<i>Pinus radiata</i>	Improved pasture	<i>Pinus radiata</i>	<i>Pinus radiata</i>	<i>Pinus radiata</i>	<i>Pinus radiata</i>
Month/year planted	8/1988	8/1989	8/1986	8/1986	8/1986	8/1986	8/1986	8/1987	8/1987	8/1987	8/1987	8/1987

[1] Climatic data (annual rainfall, annual pan evaporation and average temperatures) were estimated using ESOCIM (Hutchison *et al.*, 1999).

[2] APP trial code.

Table 2. Classification of soils in the 12 eucalypt species trials in Gippsland.

Site	Pit	PPF ^[1] Subdivision	Tech. Class. of Soils	Great Soil Group	ASC Order ^[2]	APP soil type
Tostaree	1	Dg	052-6-50/2-1-3-32	Soloth	Grey Kurosol	Stockdale loamy sand
	2	Db	052-6-50/2-1-3-32	Soloth	Brown Kurosol	Stockdale loamy sand
	3	Db	052-6-50/2-1-3-32	Soloth	Brown Kurosol	Stockdale loamy sand
Waygara	1	Gn	052-5-50/4-1-3-32	Yellow podsolic	Brown Dermosol	Boolara loam
	2	Gn	052-5-50/4-1-3-32	Brown podsolic	Yellow Dermosol	Boolara loam
VRV140	1	Gn	051-5-43/4-1-1-32	Brown podsolic	Brown Dermosol	Balook clay loam
Mt Worth West	2	Gn	051-5-00/4-1-1-32	Brown podsolic	Brown Dermosol	Balook clay loam
VRV141	1	Gn	112-5-50/4-1-2-32	Brown podsolic	Brown Dermosol	Silver Creek loam
Narracan East	2	Gn	112-5-50/4-1-2-32	Brown podsolic	Yellow Dermosol	Silver Creek loam
VRV142	1	Dy	021-6-42/4-1-2-32	Yellow soloth	Brown Kurosol	Maryvale sandy loam ^[3]
Yinnar	2	Gn	000-5-33/2-1-3-33	Grey podsolic	Grey Dermosol	Maryvale sandy loam ^[3]
VRV143	1	Dg	052-6-23/2-1-2-32	Grey soloth	Grey Kurosol	Maryvale sandy loam
Maryvale	2	Gn	052-5-23/4-1-2-32	Brown podsolic	Brown Dermosol	Maryvale sandy loam
VRV144	1	Uc	022-2-43/1-2-3-12	Podsol	Podosol	Flynn sand ^[4]
Gormandale	2	Uc	022-2-43/1-2-3-12	Podsol	Podosol	Flynn sand ^[4]
VRV145	1	Gn	051-5-50/4-1-1-32	Brown podsolic	Black Dermosol	Balook clay loam
Mt Worth East	2	Gn	051-5-50/4-1-1-32	Brown podsolic	Black Dermosol	Balook clay loam
	3	Gn	051-5-50/4-1-1-32	Brown podsolic	Brown Dermosol	Balook clay loam
VRV146	1	Gn	112-5-50/4-1-1-32	Brown podsolic	Brown Dermosol	Silver Creek loam
Delburn	2	Gn	112-5-50/4-1-1-32	Yellow earth	Brown Dermosol	Silver Creek loam
	3	Gn	112-5-50/4-1-1-32	Yellow earth	Brown Dermosol	Silver Creek loam
VRV147	1	Dy	052-6-50/2-1-3-32	Soloth	Grey Chromosol	Stockdale loamy sand ^[5]
Flynns Creek	2	Dg	052-6-50/2-1-3-32	Soloth	Grey Chromosol	Stockdale loamy sand ^[5]
VRV148	1	Uc	022-2-43/1-2-3-12	Podsol	Podosol	Gormandale sand ^[6]
Stradbroke	2	Uc	022-2-50/1-2-3-11	Podsol	Podosol	Gormandale sand ^[6]
	3	Uc	022-2-43/1-2-3-12	Podsol	Podosol	Gormandale sand ^[6]
VRV149	1	Dy	052-6-50/2-1-3-32	Soloth	Brown Kurosol	Stockdale loamy sand
Stockdale	2	Dy	052-6-50/2-1-3-32	Soloth	Brown Kurosol	Stockdale loamy sand

[1] Primary Profile Form (PPF) Subdivision (Northcote, 1979).

[2] Australian Soil Classification (Isbell, 1996).

[3] Previously described as Boolara loam by APP.

[4] Previously described as Gormandale sand by APP.

[5] Previously described as Maryvale sandy loam by APP.

[6] Previously described as Glencoe sand by APP.

Table 3. Key surface soil characteristics in the 12 eucalypt species trials in Gippsland.

Site	Pit	Texture	Colour	Condition	Pedality	A2 bleaching
Tostaree	1	loamy sand	10YR3/2 very dark greyish brown	structured	weak	pale
	2	loamy sand	10YR3/2 very dark greyish brown	structured	weak	pale
	3	loamy sand	10YR3/2 very dark greyish brown	structured	weak	pale
Waygara	1	sandy clay loam	10YR4/1 dark grey	structured	weak	pale
	2	sandy clay loam	10YR4/1 dark grey	structured	weak	pale
VRV140	1	clay loam	10YR3/3 dark brown	structured	strong	no A2
Mt Worth West	2	clay loam	10YR2/2 very dark brown	structured	strong	no A2
VRV141	1	sandy clay loam	10YR4/2 dark greyish brown	structured	moderate	pale
Narracan East	2	sandy clay loam	10YR4/2 dark greyish brown	structured	moderate	pale
VRV142	1	clay loam	10YR5/3 brown	structured	weak	pale
Yinnar	2	sandy loam	10YR3/2 very dark greyish brown	structured	weak	pale
VRV143	1	sandy loam	10YR3/2 very dark greyish brown	structured	weak	pale
Maryvale	2	clay loam	10YR4/2 dark greyish brown	structured	weak	pale
VRV144	1	loamy sand	10YR3/1 very dark grey	sand	grain	pale
Gormandale	2	loamy sand	10YR3/1 very dark grey	sand	grain	no A2
VRV145	1	clay loam	10YR2/2 very dark brown	structured	strong	no A2
Mt Worth East	2	clay loam	10YR3/2 very dark greyish brown	structured	moderate	no A2
	3	clay loam	10YR4/2 dark greyish brown	structured	moderate	no A2
VRV146	1	clay loam	7.5YR3/4 dark brown	structured	moderate	no A2
Delburn	2	clay loam	10YR4/2 dark greyish brown	structured	moderate	no A2
	3	clay loam	7.5YR5/4 brown	structured	strong	no A2
VRV147	1	sandy loam	10YR3/3 dark brown	structured	weak	sporadic
Flynns Creek	2	sandy clay loam	10YR5/2 greyish brown	structured	weak	pale
VRV148	1	loamy sand	10YR3/2 very dark greyish brown	sand	grain	pale
Stradbroke	2	loamy sand	10YR3/1 very dark grey	sand	grain	pale
	3	loamy sand	10YR3/2 very dark greyish brown	sand	grain	pale
VRV149	1	sandy loam	10YR4/2 dark greyish brown	structured	weak	pale
Stockdale	2	sandy loam	10YR4/2 dark greyish brown	structured	weak	pale

Table 4. Key subsoil characteristics in the 12 eucalypt species trials in Gippsland.

Site	Pit	Fabric	Pedality	Texture	Colour	Mottles	
Tostaree	1	pedal	moderate	light medium clay	10YR6/2	light brownish grey	many
	2	pedal	moderate	light medium clay	10YR5/4	yellowish brown	many
	3	pedal	moderate	light medium clay	10YR4/6	dark yellowish brown	common
Waygara	1	pedal	moderate	light medium clay	2.5YR6/4	light yellowish brown	many
	2	pedal	weak	light medium clay	10YR6/1	light grey	many
VRV140	1	pedal	weak ^[1]	light medium clay	10YR3/3	dark brown	few
Mt Worth West	2	pedal	weak ^[1]	light medium clay	10YR4/3	dark brown	few
VRV141	1	pedal	weak	medium clay	10YR5/6	yellowish brown	common
Narracan East	2	pedal	strong	medium clay	10YR6/1	light grey	many
VRV142	1	pedal	moderate	medium heavy clay	10YR5/3	brown	many
Yinnar	2	pedal	strong	medium heavy clay	10YR6/2	light brownish grey	few
VRV143	1	pedal	strong	medium clay	2.5YR6/2	light brownish grey	many
Maryvale	2	pedal	strong	medium heavy clay	10YR4/6	dark yellowish brown	many
VRV144	1	none		sand	7.5YR3/4	dark brown	common
Gormandale	2	none		loamy sand	10YR6/4	light yellowish brown	none
VRV145	1	pedal	moderate	light medium clay	10YR4/3	dark brown	none
Mt Worth East	2	pedal	weak	light clay	10YR4/2	dark greyish brown	none
	3	pedal	weak	medium clay	10YR5/1	grey	common
VRV146	1	pedal	strong	medium clay	10YR5/4	yellowish brown	common
Delburn	2	pedal	strong	light medium clay	10YR5/8	yellowish brown	many
	3	pedal	moderate	light clay	10YR5/4	yellowish brown	few
VRV147	1	pedal	moderate	medium clay	10YR6/2	light brownish grey	common
Flynns Creek	2	pedal	weak	light clay	7.5YR6/2	pinkish grey	many
VRV148	1	none		sand	5YR3/3	dark reddish brown	many
Stradbroke	2	none		sand	5YR4/4	reddish brown	many
	3	none		sand	5YR2.5/2	dark reddish brown	many
VRV149	1	pedal	strong	medium heavy clay	10YR5/4	yellowish brown	many
Stockdale	2	pedal	moderate	medium heavy clay	10YR4/6	dark yellowish brown	common

[1] Estimated from auger borings.

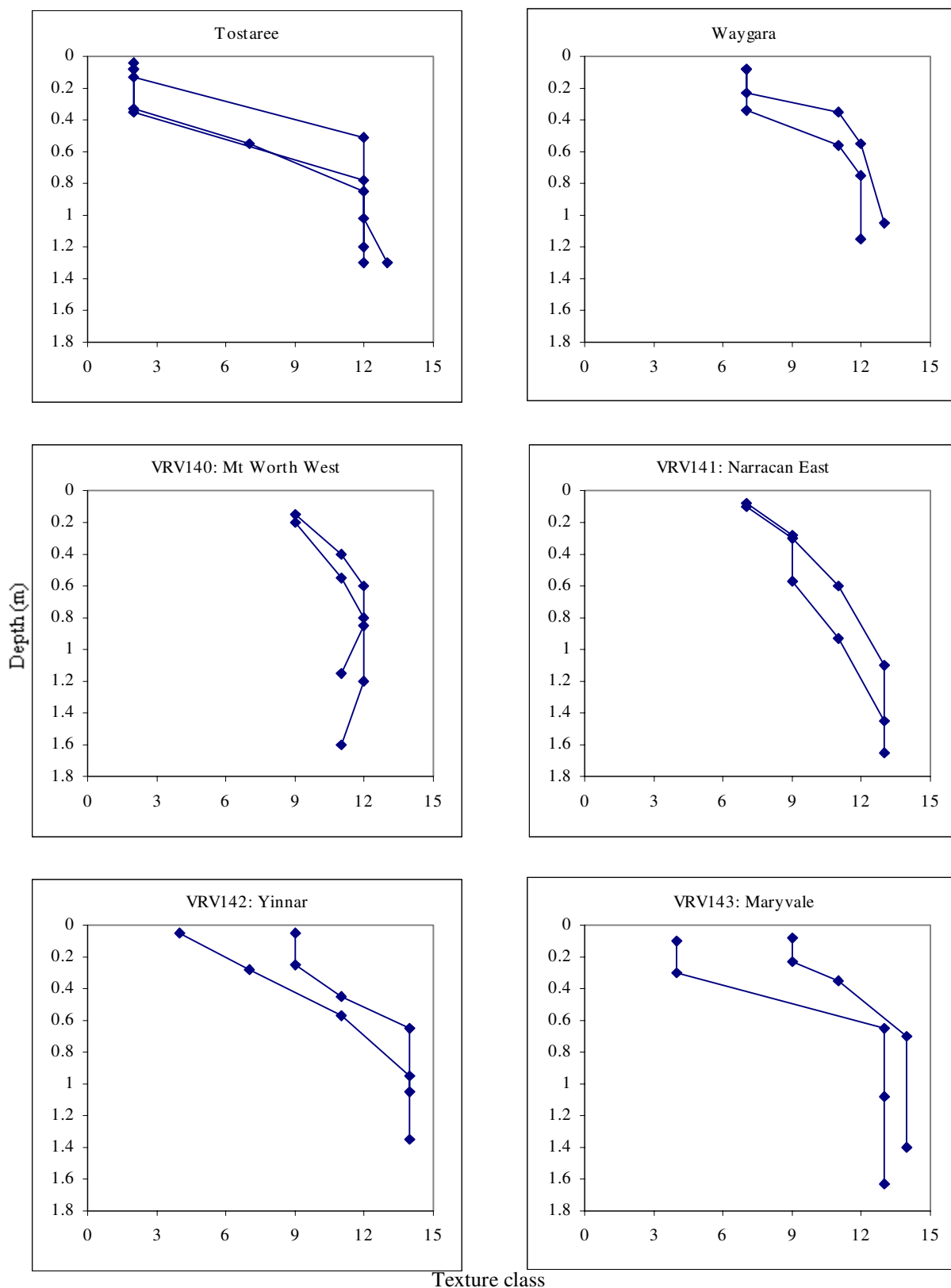


Figure 2. Texture profiles of soils in the 12 eucalypt species trials in Gippsland: 1 = sand, 2 = loamy sand, 3 = clayey sand, 4 = sandy loam, 5 = loam, 6 = silty loam, 7 = sandy clay loam, 8 = clay loam sandy, 9 = clay loam, 10 = silty clay loam, 11 = light clay, 12 = light medium clay, 13 = medium clay, 14 = medium heavy clay, 15 = heavy clay.

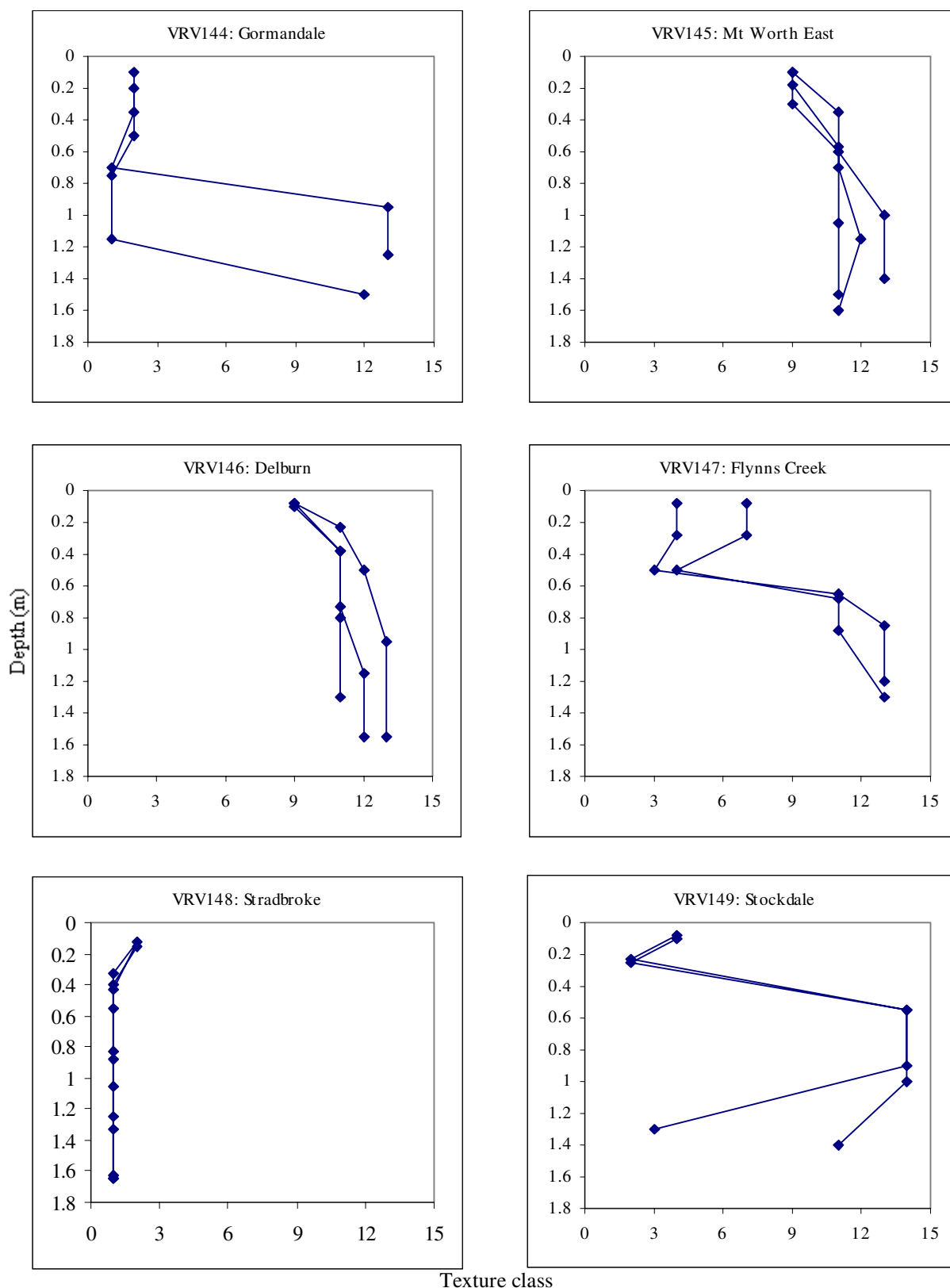


Figure 2. (continued) Texture profiles of soils in the 12 eucalypt species trials in Gippsland: 1 = sand, 2 = loamy sand, 3 = clayey sand, 4 = sandy loam, 5 = loam, 6 = silty loam, 7 = sandy clay loam, 8 = clay loam sandy, 9 = clay loam, 10 = silty clay loam, 11 = light clay, 12 = light medium clay, 13 = medium clay, 14 = medium heavy clay, 15 = heavy clay.

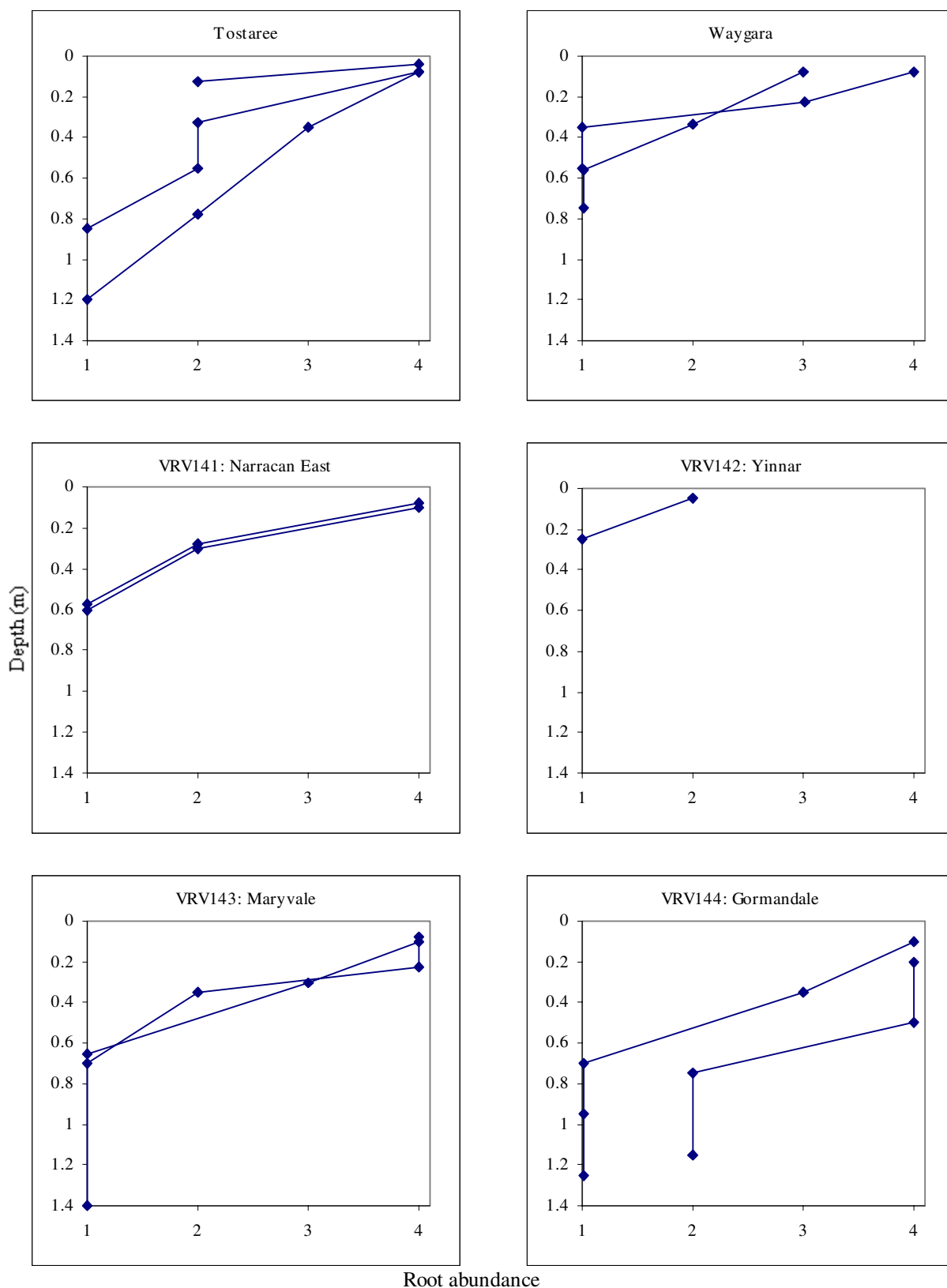


Figure 3. Root abundance in 11 eucalypt species trials in Gippsland: 1 = few, 2 = common, 3 = many, 4 = abundant. VRV140 (Mt Worth West) was sampled with auger borings and root abundance was not determined.

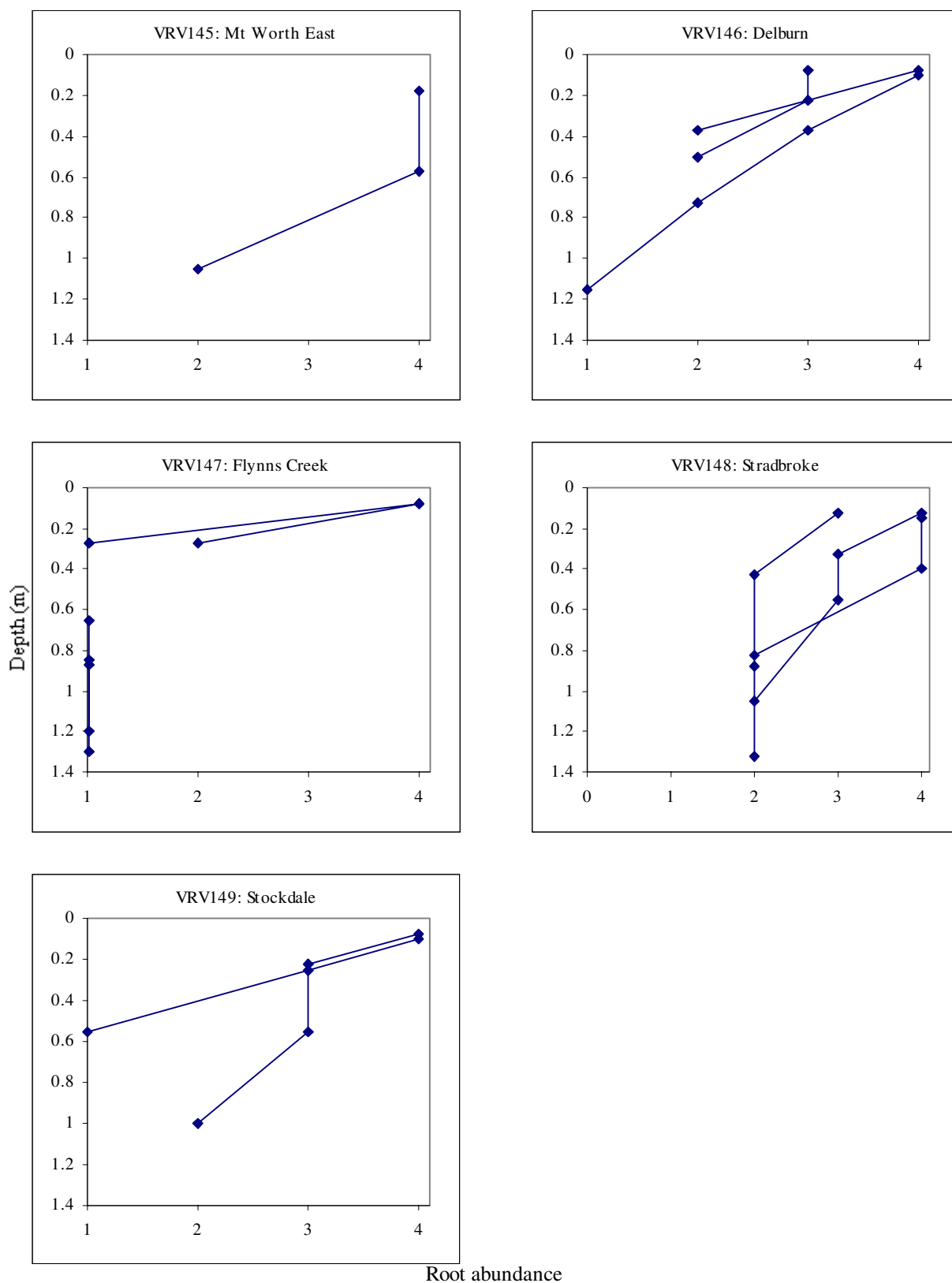


Figure 3. (continued) Root abundance in 11 eucalypt species trials in Gippsland: 1 = few, 2 = common, 3 = many, 4 = abundant. VRV140 (Mt Worth West) was sampled with auger borings and root abundance was not determined.

2.2 South Australia

Nine trials were established between 1982 and 1992 on sites representative of those suitable for afforestation within South Australia (Figure 4). Eleven single plot *E. globulus* sites were also established in South Australia between 1988 and 1992. Site characteristics for the 9 South Australian trials are presented in Table 5, and soil characteristics are summarised in Table 6.

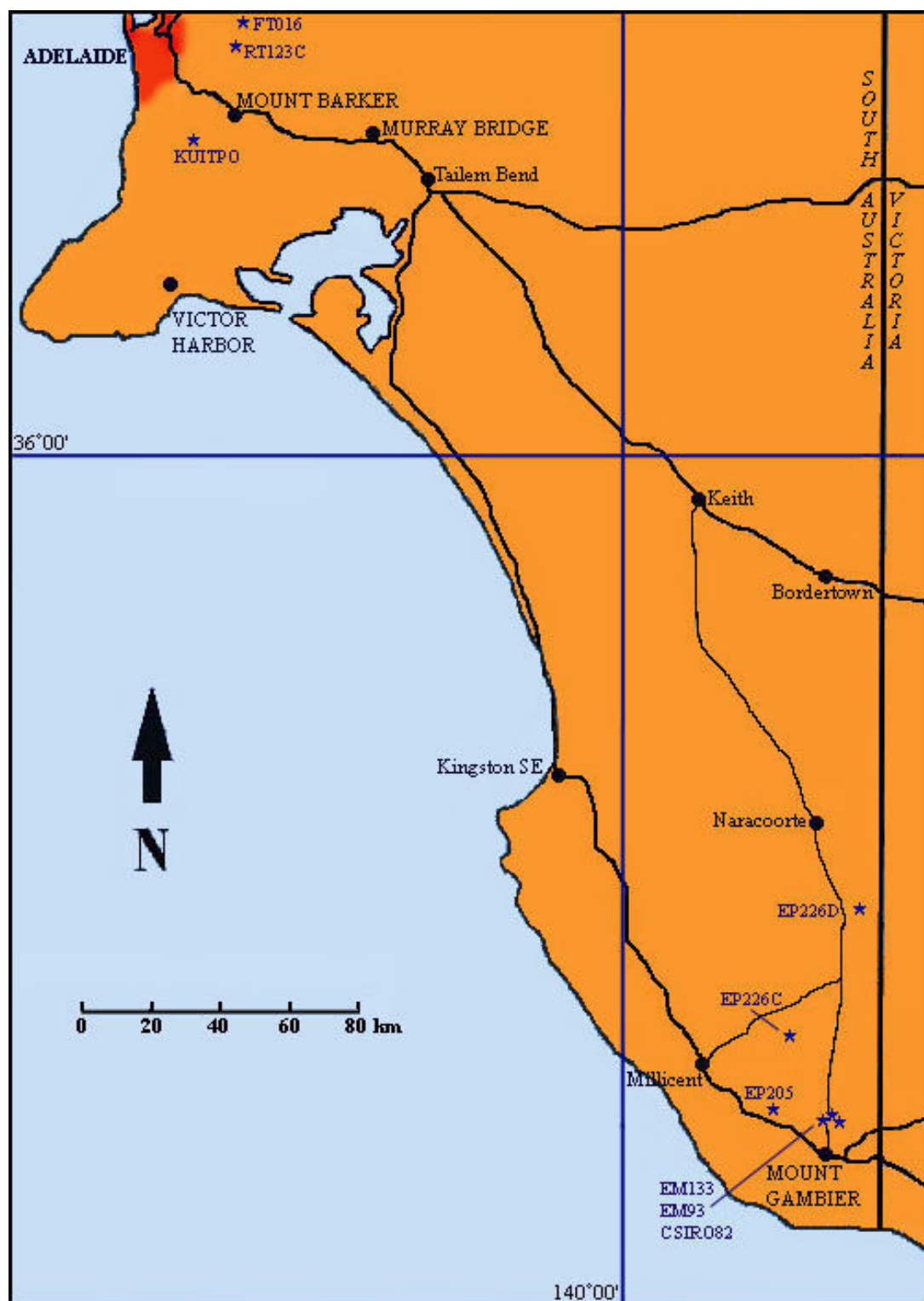


Figure 4. Location of the 9 eucalypt species trial sites in South Australia.

Table 5. Location and site characteristics for the 9 eucalypt species trials in South Australia ^[1].

Character	RT123C	EP205	EM133	EP226C	EP226D	FT016	EM93	KUITPO	CSIRO82
Location									
Longitude (E)	138°49'	140°37'	140°47'	140°39'	140°55'	138°51'	140°47'	138°43'	140°47'
Latitude (S)	34°53'	37°43'	37°45'	37°32'	37°12'	34°49'	37°44'	35°13'	37°44'
Altitude (m)	500	60	60	65	90	380	50	340	60
Annual rainfall (mm)	926	766	745	726	632	775	742	855	745
Annual pan evap. (mm)	1366	1262	1276	1295	1384	1432	1280	1434	1276
Ave. temperature (°C)									
maximum: January	25.4	23.7	23.8	24.8	26.8	26.7	23.9	25.1	23.8
July	10.8	12.9	12.9	13.1	13.1	11.9	13.0	11.8	12.9
minimum: January	11.6	11.4	11.2	11.1	10.9	12.5	11.2	12.1	11.2
July	4.2	5.1	4.9	4.8	4.2	4.3	4.9	4.7	4.9
Slope (%)	20		1			35	0	4	1
Previous land use	<i>Pinus radiata</i>	Pasture	Pasture	Improved pasture	<i>Pinus pinaster</i>	<i>Pinus radiata</i>	Pasture	<i>Pinus radiata</i>	Pasture
Month/year planted	8/1988	7/1988	5/1991	8/1990	8/1990	7/1992	8/1985	7/1984	8/1982

[1] Climatic data (annual rainfall, annual pan evaporation and average temperatures) were estimated using ESOCLIM (Hutchison *et al.*, 1999).

The trial sites in South Australia cover a smaller climatic range compared to the Gippsland sites. The trial sites range in altitude from approximately 50 to 500 m, and except for RT123C and FT015, have gentle slopes. Average annual rainfall ranges from 630 to 930 mm, average annual pan evaporation ranges from 1260 to 1430 mm, and average daily maximum and minimum temperatures range from 23-27 and 11-13°C in January, and 10-13 and 4-5°C in July.

The EP205, EM133, EP226C, EM93 and CSIRO82 sites were previously used for agriculture, while the other sites were previously pine plantations. RT123C, FT016 and KUITPO were previously planted with *P. radiata*, and EP226D was planted with *P. pinaster*. The EP226C trial site probably had improved pasture compared to the other pasture sites as evidenced by a history of phosphorous fertilisation.

Table 6. Soil characteristics for the 9 eucalypt species trials in South Australia.

Site	Soil type	Soil description	Depth to clay (cm)
RT123C	Cudlee Creek Loam	loam over medium clay	30
EP205	Mount Burr Sand	sand over medium clay	70
EM133	Mount Burr Sand	uniform sandy profile	200+
EP226C	Kalangadoo Sand	ND	ND
EP226D	Comaum White Sand	ND	ND
FT016	Cudlee Creek Loam	sandy loam over clay	40
EM93	Mount Burr Sand	uniform sandy profile	80+
KUITPO	Blackfellows Creek Loam	loam over clay loam	30
CSIRO82	Mount Burr Sand	uniform sandy profile	200+

ND = not determined.

The soils vary from loams over clays, to uniform sandy profiles. Most sites in the South East region were established on sandy, texture contrast soils, with a variable depth to clay, while the soils at the sites in the Mount Lofty Ranges were generally shallow loams over clay. Soil types for the various soils are representative of their principal local area of occurrence within the region (Stephens *et al.*, 1941; Rix and Hutton, 1953; Jackson, 1957; and Beckmann, 1964).

3. Tree Growth

Summaries of tree growth data for trials used in this study are presented in this chapter. For each trial, tree growth summaries are based on mean data for the better performing seedlots of each species. However, the seedlots and the number of seedlots varied between trials depending on the trial design and site characteristics.

Tree measurements followed the standard mensurational procedures for each state organisation with mean dominant height in Gippsland being the equivalent of the 200 largest-diameter, single-stemmed trees per hectare. In South Australia the height of the tallest 75 trees per hectare was used to calculate predominant height. Volumes in Gippsland are to a 2 cm small end diameter underbark, while the South Australian volumes are total underbark volumes.

3.1 Gippsland trials

Seven of the Gippsland trials contained the six selected species (*E. globulus*, *E. nitens*, *E. viminalis*, *E. botryoides*, *E. grandis*, and *E. saligna*), while the other 5 trials contained only *E. globulus* and *E. nitens*. All the trials were replicated, and treatment plots varied between 12 and 30 trees. A more detailed description of growth trends in these trials is presented in Duncan *et al.* (2000).

Tostaree

The Tostaree species trial was established by NRE/CFTT in 1988 on an ex-pasture site with a history of relatively high rates of fertiliser application. Tree growth was measured at age 2, 4, 6, 8 and 10 years. The tree growth summary data are based on the 2 best seedlots per species (Table 7).

Table 7. Tree growth data to age 10 years of six *Eucalyptus* species at Tostaree.

Age (years)	<i>E. globulus</i>	<i>E. nitens</i>	<i>E. viminalis</i>	<i>E. botryoides</i>	<i>E. grandis</i>	<i>E. saligna</i>
Density (tph)						
0	1000	1000	1000	1000	1000	1000
2	951	920	908	964	980	960
4	942	916	904	960	972	948
6	924	900	892	952	972	948
8	884	860	876	936	960	928
10	840	832	872	888	940	908
Height (m)						
2	6.8	6.8	7.5	6.0	5.9	5.9
4	13.1	12.6	13.4	10.0	9.8	9.5
6	17.9	17.5	18.0	13.4	13.7	13.1
8	24.6	23.9	23.6	18.5	18.5	16.9
10	27.3	26.1	25.0	20.4	21.1	18.8
Basal area (m ² /ha)						
2	4.7	4.8	4.0	3.3	3.3	3.4
4	15.1	16.0	16.2	13.3	11.7	12.6
6	23.3	22.0	24.4	19.7	17.8	19.1
8	28.3	25.9	29.5	24.9	22.3	23.7
10	33.4	30.0	34.3	28.4	26.9	27.5
Volume (m ³ /ha)						
2	13	13	12	8	8	8
4	74	76	81	49	45	46
6	157	147	166	103	93	95
8	262	237	262	171	161	154
10	334	287	319	216	215	195

Waygara

The Waygara species trial was established by NRE/CFTT in 1989 on degraded native forest. The previous vegetation at this site was low elevation mixed species forest of *E. sieberi* and stringybark species severely affected by the fungal pathogen *Phytophthora cinnamomi*. Tree growth was measured at age 2, 4, 6, 8 and 10 years. Tree growth summary data are based on the 2 best seedlots per species (Table 8).

Table 8. Tree growth data to age 10 years of six *Eucalyptus* species at Waygara.

Age (years)	<i>E. globulus</i>	<i>E. nitens</i>	<i>E. viminalis</i>	<i>E. botryoides</i>	<i>E. grandis</i>	<i>E. saligna</i>
Density (tph)						
0	1000	1000	1000	1000	1000	1000
2	938	695	713	963	911	954
4	938	685	696	963	911	946
6	917	662	688	958	911	921
8	892	643	683	938	894	904
10	858	656	679	938	886	896
Height (m)						
2	7.2	5.9	5.8	4.6	5.1	5.4
4	13.3	11.5	11.7	8.9	9.6	9.3
6	17.0	14.5	14.6	12.9	13.3	12.6
8	20.0	16.0	16.9	14.2	15.1	14.1
10	21.1	17.1	17.2	14.9	15.7	14.9
Basal area (m ² /ha)						
2	3.6	2.0	1.7	2.0	2.1	2.4
4	12.8	9.5	8.5	7.1	7.9	8.3
6	18.0	12.8	13.1	13.1	13.3	14.4
8	21.1	14.0	15.7	15.9	16.0	17.3
10	23.1	15.3	17.2	17.6	17.2	18.7
Volume (m ³ /ha)						
2	10	5	5	5	5	6
4	65	41	38	24	30	30
6	115	70	74	64	68	69
8	159	87	103	86	92	92
10	181	114	109	102	95	105

Australian Paper Plantation (APP) trials

Growth data were collected from 10 APP species trials. Five of the trials were established in 1986 (VRV140-144), and five in 1987 (VRV145-149). The 1986 trials were measured at age 3.5, 6 and 12 years and the 1987 trials were measured at age 3.5, 6 and 11 years. One trial (VRV140) was also measured at age 8.5 years. Tree growth summary data are based on the 2 best seedlots per species (Tables 9 and 10).

Table 9. Tree growth data to age 12 years of two *Eucalyptus* species at APP trials VRV140-144.

Age (years)	Density (tph)	Height (m)	Basal area (m ² /ha)	Volume (m ³ /ha)	Density (tph)	Height (m)	Basal area (m ² /ha)	Volume (m ³ /ha)
VRV140: Mt Worth West								
<i>E. globulus</i>					<i>E. nitens</i>			
0	1010				1010			
3.5	800	10.6	7.2	31	970	10.8	11.6	48
6	831	19.1	19.0	135	954	19.9	28.2	206
8.5	800	24.2	25.9	227	970	25.8	37.6	356
12	631	31.6	34.6	401	818	32.5	47.3	558
VRV141: Narracan East								
<i>E. globulus</i>					<i>E. nitens</i>			
0	1010				1010			
3.5	927	9.8	8.6	33	912	9.1	8.1	29
6	889	14.8	17.4	94	902	13.5	16.5	85
12	800	24.0	41.5	365	776	23.4	35.7	305
VRV142: Yinnar								
<i>E. globulus</i>					<i>E. nitens</i>			
0	1010				1010			
3.5	970	6.5	2.8	8	800	5.9	2.4	6
6	929	10.8	8.7	38	803	10.1	7.0	28
12	866	18.4	22.2	152	707	15.9	13.6	81
VRV143: Maryvale								
<i>E. globulus</i>					<i>E. nitens</i>			
0	992				992			
3.5	932	8.9	5.7	20	966	7.1	4.7	13
6	888	13.2	13.0	65	966	9.9	10.7	41
12	883	20.0	29.4	214	638	15.9	14.9	87
VRV144: Gormandale								
<i>E. globulus</i>					<i>E. nitens</i>			
0	992				992			
3.5	992	10.2	7.8	31	979	9.0	5.9	20
6	992	14.0	15.8	86	966	12.6	12.2	58
12	868	21.1	28.1	216	916	18.1	20.6	135

Because of the high productivity and small plot size at Mt Worth East, growth rates of *E. nitens* were unrealistically high at age 11 years and unrepresentative of broad-scale plantations. Therefore, these data were not used for growth modelling purposes (Chapter 4).

Table 10. Tree growth data to age 11 years of six *Eucalyptus* species at APP trials VRV145-149.

Age (years)	Density (tph)	Height (m)	Basal area (m ² /ha)	Volume (m ³ /ha)	Density (tph)	Height (m)	Basal area (m ² /ha)	Volume (m ³ /ha)
VRV145: Mt Worth East								
<i>E. globulus</i>					<i>E. botryoides</i>			
0	1010				1010			
3.5	884	7.4	8.5	27	884	6.7	5.2	15
6	876	12.5	23.1	114	857	11.4	17.5	77
11	828	19.8	45.3	340	764	17.1	33.4	212
<i>E. nitens</i>					<i>E. grandis</i>			
0	1010				1010			
3.5	952	9.0	15.5	56	846	6.0	4.2	11
6	927	15.3	42.9	248	856	9.5	11.3	44
11	922	NP	NP	NP	720	14.5	21.8	120
<i>E. viminalis</i>					<i>E. saligna</i>			
0	1010				1010			
3.5	960	8.0	9.5	32	918	7.3	7.7	23
6	961	13.2	27.1	138	901	12.4	21.2	101
11	938	20.3	56.7	435	838	18.1	40.3	281
VRV146: Delburn								
<i>E. globulus</i>					<i>E. botryoides</i>			
0	1010				1010			
3.5	935	8.0	4.6	15	972	6.4	3.0	8
6	935	14.5	15.7	84	943	11.7	12.4	57
11	917	22.3	38.0	316	926	18.3	31.0	211
<i>E. nitens</i>					<i>E. grandis</i>			
0	1010				1010			
3.5	817	6.9	3.8	11	951	6.5	3.5	9
6	817	13.4	13.8	70	935	11.2	12.6	54
11	817	20.5	33.3	259	892	17.0	28.5	183
<i>E. viminalis</i>					<i>E. saligna</i>			
0	1010				1010			
3.5	876	7.0	3.6	11	978	6.3	3.7	10
6	850	13.1	13.2	63	962	11.0	13.6	59
11	850	19.3	31.4	224	935	17.7	32.4	215

NP = not presented (see text).

Table 10. (continued) Tree growth data to age 11 years of six *Eucalyptus* species at APP trials VRV145-149.

Age (years)	Density (tph)	Height (m)	Basal area (m ² /ha)	Volume (m ³ /ha)	Density (tph)	Height (m)	Basal area (m ² /ha)	Volume (m ³ /ha)
VRV147: Flynn's Creek								
<i>E. globulus</i>					<i>E. botryoides</i>			
0	992				992			
3.5	919	7.0	4.4	13	910	5.5	3.7	9
6	910	11.2	11.9	52	902	9.6	10.8	40
11	884	17.2	27.8	179	885	14.0	25.7	136
<i>E. nitens</i>					<i>E. grandis</i>			
0	992				992			
3.5	744	6.3	3.9	10	886	5.5	3.5	8
6	695	11.4	10.3	44	877	9.0	9.6	34
11	678	16.4	22.9	139	860	13.1	19.5	98
<i>E. viminalis</i>					<i>E. saligna</i>			
0	992				992			
3.5	860	6.6	3.4	9	851	5.9	3.9	9
6	860	10.9	8.8	37	842	9.7	10.6	38
11	835	14.6	19.1	105	786	13.8	22.0	113
VRV148: Stradbroke								
<i>E. globulus</i>					<i>E. botryoides</i>			
0	992				992			
3.5	943	8.0	5.7	18	959	8.4	9.1	30
6	919	12.2	11.9	54	959	12.4	21.0	97
11	888	14.9	18.3	106	947	17.2	40.5	257
<i>E. nitens</i>					<i>E. grandis</i>			
0	992				992			
3.5	934	7.0	5.6	16	934	7.9	7.1	23
6	927	10.3	12.3	49	927	12.0	15.8	74
11	876	12.6	17.8	86	921	16.4	27.1	172
<i>E. viminalis</i>					<i>E. saligna</i>			
0	992				992			
3.5	951	7.7	6.1	20	935	8.6	8.3	28
6	943	11.3	13.4	59	927	12.0	17.2	78
11	898	13.2	20.8	107	924	16.0	30.3	183

Table 10. (continued) Tree growth data to age 11 years of six *Eucalyptus* species at APP trials VRV145-149.

Age (years)	Density (tph)	Height (m)	Basal area (m ² /ha)	Volume (m ³ /ha)	Density (tph)	Height (m)	Basal area (m ² /ha)	Volume (m ³ /ha)
VRV149: Stockdale								
<i>E. globulus</i>					<i>E. botryoides</i>			
0	992				992			
3.5	919	8.4	5.6	19	919	7.1	4.9	15
6	902	12.3	12.8	61	919	10.6	12.0	49
11	877	16.4	22.8	141	900	13.4	19.9	102
<i>E. nitens</i>					<i>E. grandis</i>			
0	992				992			
3.5	910	7.8	5.8	17	901	6.8	4.4	12
6	893	11.7	11.9	52	901	10.2	10.4	43
11	679	14.2	15.7	84	876	13.3	17.1	89
<i>E. viminalis</i>					<i>E. saligna</i>			
0	992				992			
3.5	959	7.9	5.4	18	911	7.6	4.9	15
6	934	12.1	12.9	59	893	10.6	11.5	48
11	883	14.4	21.4	117	829	13.5	18.4	96

The Gippsland sites were classified into a simple rainfall by soil group matrix (Table 11). In general, average growth rates increased with increasing rainfall, and increased from deep sands to gradational textured soils. The main exception to this pattern was the poor growth rates recorded at Yinnar (VRV142). Even though this site has relatively high rainfall (900-999 mm/year), growth rates were the lowest of all sites because of restricted root growth in a shallow surface soil (Figure 3).

Growth rates were very high at the sites that were previously improved pasture (Tostaree, Mt Worth East and Mt Worth West). The substantial fertiliser history at these sites has led to better tree nutrition, and hence better growth, compared to sites previously planted with trees.

Table 11. Classification of Gippsland eucalypt species trial sites based on soil and annual rainfall.

Soil group	Rainfall (mm/year)				
	600-699	700-799	800-899	900-999	1000+
Deep sands	Stradbroke VRV148		Gormandale VRV144		
Texture contrast soils	Stockdale VRV149	Maryvale VRV143 Flynn's Creek VRV147	Tostaree Waygara	Yinnar VRV142	
Gradational textured soils				Narracan East VRV141	Mt Worth West VRV140 Mt Worth East VRV145 Delburn VRV146

3.2 South Australian trials

All 9 South Australian trials included *E. globulus*. The other 5 species; *E. nitens*, *E. viminalis*, *E. botryoides*, *E. grandis*, and *E. saligna* were present at only 2 sites each, and 3 sites in total. Some unreplicated plots have been included in the study to provide a guide to tree growth but data from these should be treated with caution. Summaries of the South Australian trial data are presented in Tables 12 to 15.

RT123C

The RT123C demonstration was established in 1988 in a high rainfall area of the Mount Lofty Ranges previously planted with *P. radiata*. A wide range of provenances of eucalypt species were included, generally as unreplicated 25 tree plots. Tree growth has been measured 6 times to age 11 years (Table 12).

EP205

The EP205 species/provenance trial was planted in 1988 along an undulating sand dune ridge. The data summary is based on 4 replicates of the 3 best provenances measured in 25 tree plots. Tree growth for each species has been measured on 7 occasions to age 8.5 years, with *E. globulus* also being measured at age 11 years (Table 13).

EM133

This Scrimber Hardwood Trial (EM133) was established in 1991 to model relative initial growth rates of *E. globulus*, *E. grandis* and *E. saligna* in the South East region. Tree growth has been measured on 10 occasions to age 5 years. The growth data are from 3 replicates of 121 tree plots (Table 14). Detailed trial information is available in the RIRDC publication 98/004 (Sheriff, 1998).

Table 12. Tree growth data to age 11 years of six *Eucalyptus* species at RT123C.

Age (years)	Density (tph)	Height (m)	Basal area (m ² /ha)	Volume (m ³ /ha)	Density (tph)	Height (m)	Basal area (m ² /ha)	Volume (m ³ /ha)
<i>E. globulus</i>					<i>E. botryoides</i>			
0	1612				1612			
1.5	1526	2.8	0.2	ND	1612	2.7	0.2	ND
2.5	1526	5.0	1.7	4	1612	5.2	2.0	4
4.8	1526	11.2	11.3	42	1612	9.5	11.5	37
6.7	1505	15.8	21.3	108	1612	13.5	20.8	91
8.7	1505	20.1	31.8	200	1612	16.7	30.9	164
11.1	1440	23.4	43.4	320				
<i>E. nitens</i>					<i>E. grandis</i>			
0	1612				1612			
1.5	1548	3.2	0.3	ND	1548	2.2	0.1	ND
2.5	1548	6.5	2.6	5	1548	4.9	1.3	2
4.8	1419	12.8	15.8	65	1548	10.9	10.5	37
6.7	1419	18.2	26.9	151	1419	15.9	18.2	88
8.7	1419	21.7	39.6	268	1419	18.4	26.5	150
11.1	1354	24.6	50.8	390	1419	21.5	35.4	232
<i>E. viminalis</i>					<i>E. saligna</i>			
0	1612				1612			
1.5	1462	2.3	0.1	ND	1515	2.4	0.1	ND
2.5	1440	4.5	0.9	1	1515	4.8	1.2	2
4.8	1419	9.0	9.9	32	1515	10.4	10.1	35
6.7	1354	13.6	19.6	89	1483	14.5	18.4	85
8.7	1354	17.4	30.7	173	1520	17.9	28.8	162
11.1	1354	20.6	43.1	288	1493	20.7	37.1	240

ND = not determined.

Table 13. Tree growth data to age 11 years of four *Eucalyptus* species at EP205.

Age (years)	Density (tph)	Height (m)	Basal area (m ² /ha)	Volume (m ³ /ha)	Density (tph)	Height (m)	Basal area (m ² /ha)	Volume (m ³ /ha)
<i>E. globulus</i>					<i>E. viminalis</i>			
0	1000				1000			
0.3	999	0.5	0.0	ND	999	0.4	0.0	ND
1.3	979	2.4	0.1	ND	922	2.0	0.0	ND
2.4	979	6.8	4.2	11	916	5.6	1.9	4
3.4	969	10.7	10.1	37	912	8.7	6.3	20
4.3	966	12.6	14.1	60	912	10.3	10.0	37
6.4	962	17.0	23.1	130	882	13.4	17.3	80
8.5	946	20.3	29.8	196	852	15.9	22.6	123
10.9	936	23.5	37.1	279				
<i>E. nitens</i>					<i>E. botryoides</i>			
0	1000				1000			
0.3	999	0.3	0.0	ND	999	0.5	0.0	ND
1.3	946	2.0	0.1	ND	989	1.9	0.0	ND
2.3	932	5.4	2.1	5	989	5.2	2.1	5
3.4	922	8.7	6.3	20	986	8.4	6.5	20
4.3	922	10.3	10.3	39	986	9.6	10.0	35
6.4	906	13.7	18.9	93	982	12.9	19.8	92
8.5	872	16.7	25.0	147	959	15.4	26.9	147

ND = not determined.

Table 14. Tree growth data to age 5 years of three *Eucalyptus* species at EM133

Age (years)	Density (tph)	Height (m)	Basal area (m ² /ha)	Volume (m ³ /ha)	Density (tph)	Height (m)	Basal area (m ² /ha)	Volume (m ³ /ha)
<i>E. globulus</i>					<i>E. grandis</i>			
0	1739				1739			
0.6	1739	0.7	0.0	ND	1739	0.8	0.0	ND
0.9	1739	0.9	0.0	ND	1739	1.1	0.0	ND
1.5	1739	2.1	0.0	ND	1739	1.9	0.0	ND
1.8	1723	3.2	0.5	1	1739	3.3	0.3	ND
2.3	1723	4.7	1.6	3	1739	4.3	0.8	1
2.7	1690	6.8	4.6	11	1739	5.8	3.0	6
3.3	1690	8.3	7.5	21	1739	7.2	5.3	13
3.8	1690	10.3	11.3	39	1739	8.7	9.3	28
4.1	1690	10.8	13.3	48	1723	9.6	11.2	37
5	1642	13.1	16.6	69	1674	11.2	13.9	51
<i>E. saligna</i>								
0	1739							
0.6	1739	0.6	0.0	ND				
0.9	1739	0.7	0.0	ND				
1.5	1739	1.3	0.0	ND				
1.8	1723	2.3	0.0	ND				
2.3	1723	2.8	0.2	ND				
2.7	1690	4.0	1.0	2				
3.3	1674	4.7	2.1	4				
3.8	1610	5.6	4.1	10				
4.1	1610	6.8	5.7	15				
5	1545	7.9	8.1	24				

ND = not determined.

***E. globulus* trials with multiple plots**

Summary growth data for *E. globulus* at a range of trials in South Australia are presented in Table 15. The Kuitpo and FT016 sites are located in the Mount Lofty Ranges, while all other sites are in the South East region of the state. The trials were established between 1982 and 1992, and tree growth has been measured on several occasions with the latest measurements ranging from age 5 to 15 years.

Table 15. Tree growth data for *E. globulus* at various trials in South Australia.

Age (years)	Density (tph)	Height (m)	Basal area (m ² /ha)	Volume (m ³ /ha)	Age (years)	Density (tph)	Height (m)	Basal area (m ² /ha)	Volume (m ³ /ha)
EP226C					EP226D				
0.0	1152				0.0	1201			
2.1	1152	8.3	5.1	14	2.1	1201	5.4	1.4	3
3.2	1137	11.5	9.9	37	3.2	1201	9.0	4.6	13
5.3	1107	16.4	17.6	89	5.3	1183	11.1	7.1	25
8.2	1126	22.9	27.6	188	8.2	1183	12.6	10.2	39
CSIRO82					KUITPO				
0.0	1110				0.0	791			
5.3	1043	16.6	10.3	54	12.0	666	22.9	18.8	131
7.1	952	21.6	27.5	180	12.8	661	23.9	20.0	146
13.4	941	31.3	48.3	452	13.7	656	25.7	21.5	166
					15.1	652	26.8	23.9	194
EM93					FT016				
0.0	1334				0.0	930			
0.7	1216	1.0	0.0	ND	0.4	920	0.7	0.0	ND
1.1	1216	1.6	0.1	ND	1.4	920	3.4	0.5	1
1.9	1093	3.8	0.8	2	2.3	920	6.3	2.7	6
2.9	1038	7.1	3.1	9	3.3	920	9.3	6.6	21
3.1	1032	7.5	4.1	12	5.4	920	13.9	15.5	72
4.2	1015	9.7	7.3	26					
5.2	987	12.7	11.9	52					
6.3	987	15.2	18.1	93					
7.4	970	17.7	24.3	145					
8.1	970	19.2	28.2	182					
10.4	970	22.9	37.2	277					

ND = not determined.

4. Growth Modelling

The growth modelling undertaken in this report is empirical, rather than mechanistic or process based, in that the selected equations and parameters are used without attempting to explain the physiological processes of tree growth. Empirical growth models form a continuum of complexity, but can be divided into three classes (Munro, 1974; Clutter *et al.*, 1983; Davis and Johnson, 1987; Rayner and Turner, 1990; Vanclay, 1994; and others).

- (i) Whole stand models use stand average values and are often simple and robust.
- (ii) Diameter class or size class models provide some information on the structure of the stand. The classes are used as the basic unit for modelling.
- (iii) Individual tree models are the most complex and use each tree as the basic unit of modelling. Single tree models can either be distance-dependent or distance-independent depending on whether spatial locations of the trees are required.

The data available to the present study (Chapter 3) are suitable for whole stand models.

The functions presented in this chapter have been used to develop growth curves. Where possible, the growth predictions are grouped by site productivity classes to improve the reliability of forecasting tree growth (see Chapter 5). The models have been derived from repeated measurements, using linear and nonlinear regression techniques to find the best fit to the observed data.

4.1 Height and basal area

Using replicate information of the data listed in Chapter 3, for each species at each site, height and basal area were modelled using several difference equations selected from the literature (e.g. West and Mattay, 1993; Candy, 1997; Tome *et al.*, 1997; and West, 1998). Difference equations predict a size value for a certain age based on a previous measurement. The most suitable equations, based on ease of convergence, fit and ease of use were:

$$H_{t_2} = a \frac{1 - \frac{\ln(1 - e^{bt_2})}{\ln(1 - e^{bt_1})}}{H_{t_1}} \quad [\text{Equation 1}]$$

$$BA_{t_2} = BA_{t_1} \left[\frac{1 - e^{at_2}}{1 - e^{at_1}} \right]^b \quad [\text{Equation 2}]$$

where: H = height (m);
BA = basal area (m²/ha);
t = age (years); and
a, b and c are parameters to be estimated.

While the predictions of growth followed the actual data well, extrapolations should only be considered as indicative of future growth.

Equations 1 and 2 were used to calculate initial basal area and height values. These values were then used to relate height and basal area growth to site indices. To group the sites into productivity classes, data for each species were combined within Gippsland and South Australia. The initial modelling indicated that *E. botryoides*, *E. grandis* and *E. saligna* had similar growth on the Gippsland sites, so these species were combined as one under the *Salignae* series. The 3 species of

the Viminalis series were modelled separately. The species data were modelled for height and basal area using:

$$H_{t_2} = H_{t_1} \left[\frac{1 - e^{a t_2}}{1 - e^{a t_1}} \right]^b$$

[Equation 3]

$$\ln(BA_{t_2}) = \left(\frac{t_1}{t_2} \right)^c \ln(BA_{t_1}) + \left(\frac{a}{c} + \frac{b}{c} SI \right) \left\{ 1 - \left(\frac{t_1}{t_2} \right)^c \right\}$$

[Equation 4]

where: H = height (m);
 BA = basal area (m²/ha);
 SI = site index (height at age 10 years);
 t = age (years); and
 a, b and c are parameters to be estimated.

Equations 3 and 4 are path invariant, that is, the same predicted values are obtained irrespective of the number of intermediate ages at which a height or basal area is predicted. Once the parameters have been determined, actual heights or basal areas can be input into the equations, with site index (SI), the height at age 10 years, being estimated using the height equation.

SI, if known, can be input into Equations 3 and 4 to obtain growth curves for a particular site index. In this case, for the basal area function, an initial basal area is also required. If a basal area measurement is not available, it can be obtained using the basal area initialisation equation (Candy, 1997) where:

$$\ln(BA) = a + b.SI^{-1}$$

[Equation 5]

where: BA = basal area (m²/ha) at age 10 years;
 SI = site index (height at age 10 years); and
 a and b are parameters to be estimated.

SI is the most common measure to quantify site differences in even-aged stands of a single species (Vanclay, 1994). While it is approximate in that it summarises several factors of the environment as a single index, it is useful in that it enables meaningful growth forecasts. SI is sensitive to differences in site quality, and strongly correlated to volume growth (Davis and Johnson, 1987). It is easy to measure and is relatively unaffected by stocking differences within the normal range of stand densities.

As SI is based on tree measurements, it cannot be used where suitable stands are not present. Without standing trees, a geocentric view is required, which assumes site productivity is dependent on soil and climatic factors. While geocentric methods are difficult to test, they are important for predicting possible tree growth on areas being considered for planting.

Based on the site details in Chapter 2 and replicate information of the growth data in Chapter 3, site indices for the Gippsland sites were estimated according to rainfall and soil groups. These site indices have been used in the above equations to provide predictions of tree growth (see Chapter 5).

4.2 Volume

A stand volume equation is required to calculate volume from basal area and dominant height. Seven linear volume functions suitable for the Gippsland data were chosen from Inions (1992) for investigation.

Model

- A $\ln V = a + b.(H) + c.(\ln BA)$
- B $V = a + b.(BA).H$
- C $V = a + b.(BA^2).H$
- D $\ln V = a + b.(\ln BA) + c.(\ln H)$
- E $V = a + b.(BA) + c.(H) + d.(BA).H$
- F $\ln V = a + b.(\ln BA)$
- G $\ln V = a + b.(\ln H)$

where: V = volume (m^3/ha);
 BA = basal area (m^2/ha);
 H = height (m); and
 a , b , c and d are parameters to be estimated.

A comparison of the volume data indicated that the data of different species were, for practical purposes, indistinguishable. Combining the data for all species, Model E provided the best fit for volume. F tests indicated that the intercept (' a ') was not significantly different from zero. The model used for all species was:

$$V = 0.3983.(BA) - 0.0661.(H) + 0.35366.(BA).H \quad \text{[Equation 6]}$$

adjusted $r^2 = 99.5$
standard error = 5.4

4.3 Comparison of modelling approaches

This section provides a general comparison of *Eucalyptus* growth modelling approaches found in the literature and the grouped modelling methods using the Gippsland species data. While there would be environmental, genetic, establishment, silvicultural, and possibly mensurational differences between the data, a comparison between the various functions and parameter estimates indicates that the predictions used in this report are valid.

Height and basal area models and parameter estimates were found for *E. globulus* (Inions, 1992), *E. nitens* (Candy, 1997; Coetzee, 1998) and *E. grandis* (West and Mattay, 1993; West, 1998). The *E. grandis* models have been compared to the Gippsland Salignae series data comprising *E. botryoides*, *E. grandis* and *E. saligna*.

Comparisons of the height models are presented in Figures 5 to 7, where age 5 year heights for the various functions for each species have been set to the same value (7, 10, 13 or 16 m). The two *E. globulus* height models remained very similar through time, while the Gippsland *E. nitens* and Salignae series height predictions were intermediate to the predictions from the literature using a reference age of 10 years, with the *E. nitens* predictions being more variable. The *E. nitens* predictions for South Africa should be treated with caution as the author has described them as interim, and stated that the study will have to be reviewed as more height growth data becomes

available. The fast growth of *E. nitens* in Tasmania and New Zealand can be partially explained by Candy (1997) setting the asymptote of his *E. nitens* height model at 60 m, which is larger than that for the Gippsland sites.

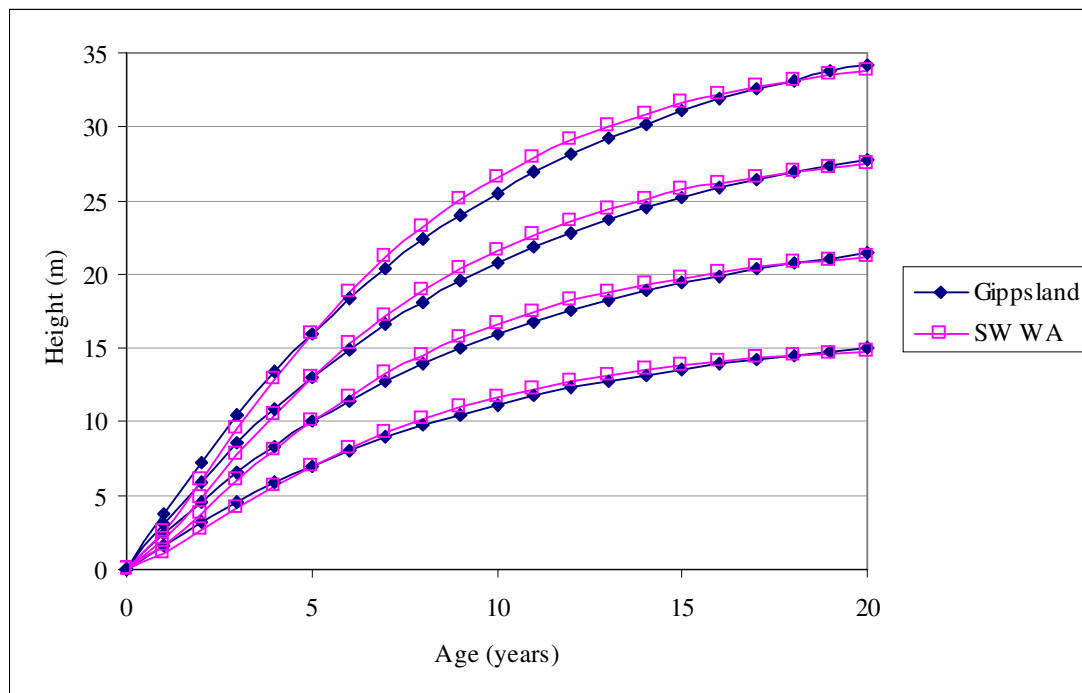


Figure 5. Modelled height growth of *E. globulus* in Gippsland and south-western Western Australia (Inions, 1992). Each pair of lines represents different productivity classes.

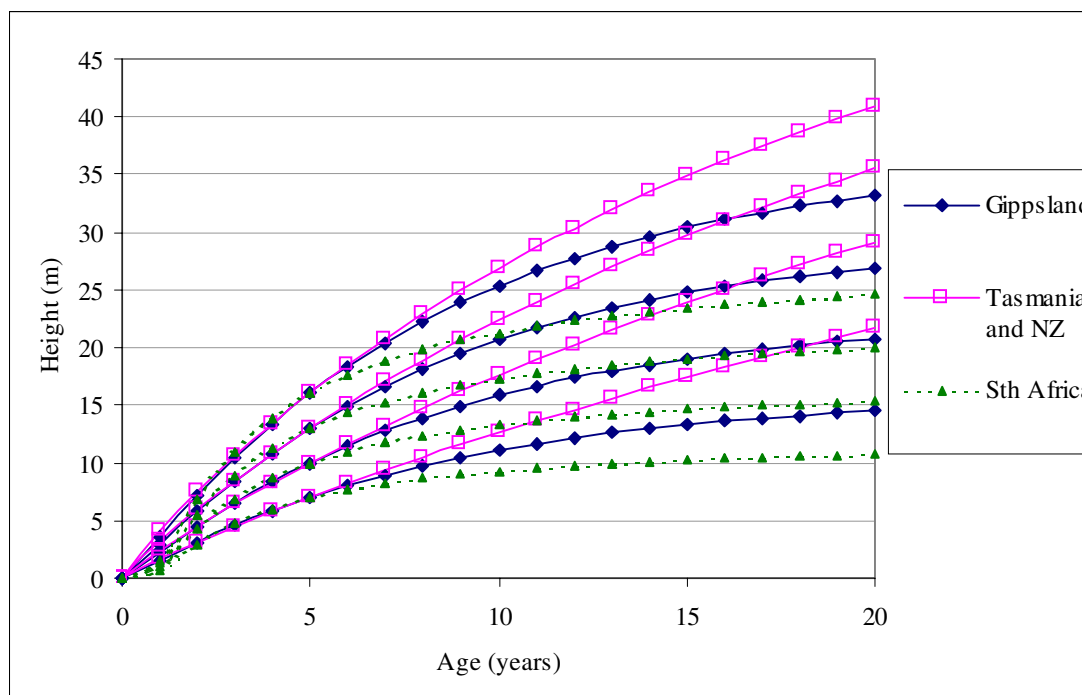


Figure 6. Modelled height growth of *E. nitens* in Gippsland, Tasmania and New Zealand (Candy, 1997), and South Africa (Coetzee, 1998).

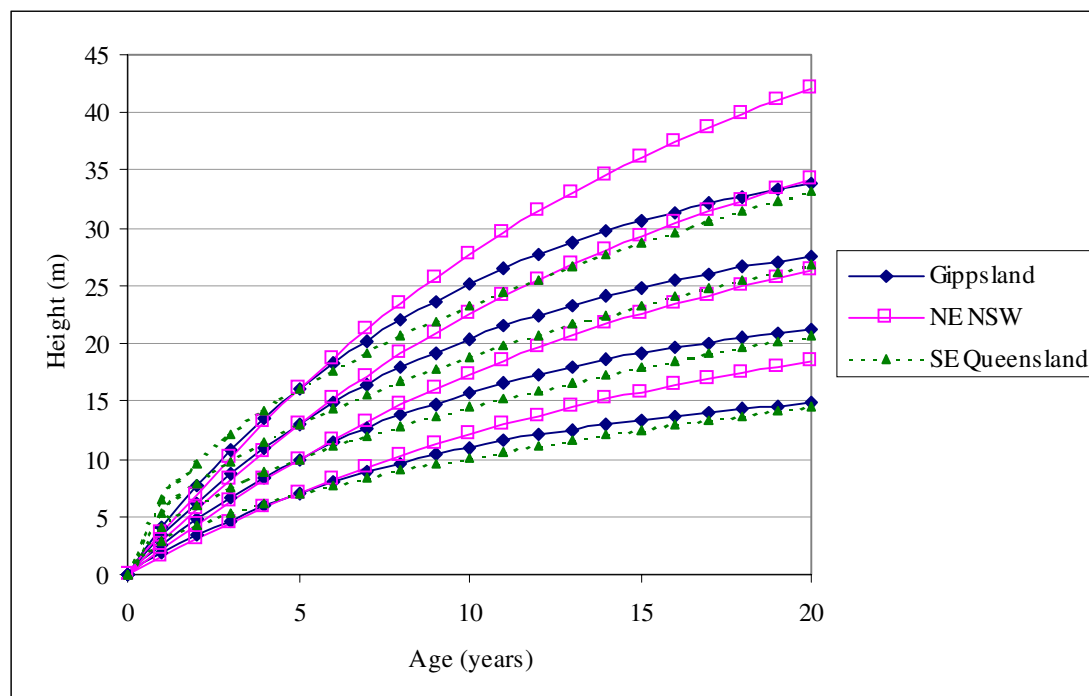


Figure 7. Modelled height growth of the *Salignae* series in Gippsland, and *E. grandis* in north-eastern New South Wales (West, 1998) and south-eastern Queensland (West and Mattay, 1993).

Basal area predictions based on the height estimates in Inions (1992) and Candy (1997) are presented in Figures 8 and 9. For the *E. grandis* basal area model (West, 1998), the predictions start at the same basal areas as the Gippsland *Salignae* series at age 5 years (Figure 10).

While there is little difference in the basal area predictions between the *Salignae* series in Gippsland and *E. grandis* in north-eastern NSW, the *E. globulus* and *E. nitens* predictions for Gippsland vary considerably compared to those found in the literature. The *E. globulus* curves from Western Australia indicate that the Gippsland predictions may not be decreasing at a fast enough rate at later ages. Later age data is necessary to determine if this is the case, as it would allow a comparison of the curves to real situations, and further modelling if required. The West Australian model was based on “unimproved lands”, so perhaps the differences between the models are exaggerated.

Basal area growth of *E. nitens* in Gippsland was predicted to be less than in Tasmania and New Zealand. The high basal areas predicted in Tasmania and New Zealand can be partly explained by the faster height growth on which the basal area curves are based (Figure 6).

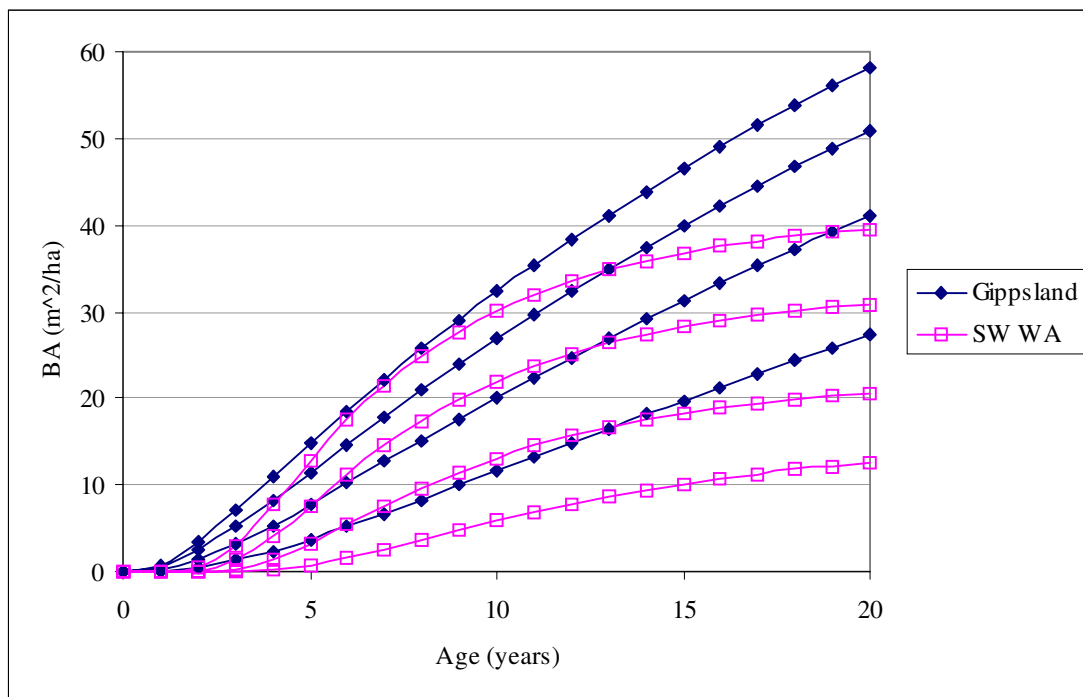


Figure 8. Modelled basal area growth of *E. globulus* in Gippsland and south-western Western Australia (Inions, 1992).

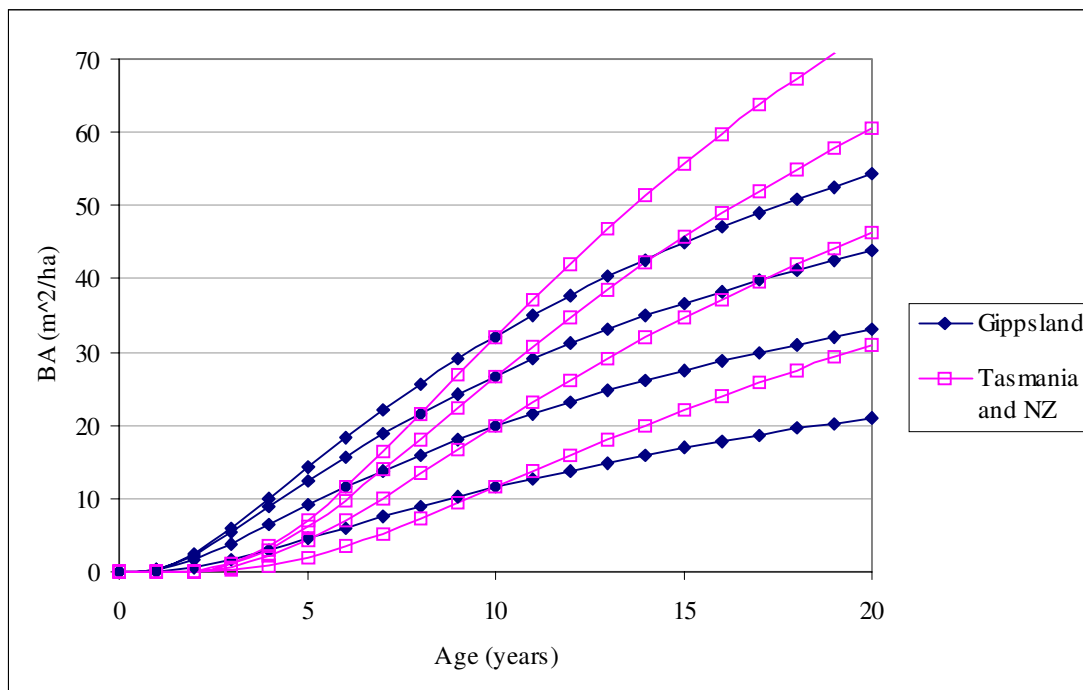


Figure 9. Modelled basal area growth of *E. nitens* in Gippsland, and Tasmania and New Zealand (Candy, 1997).

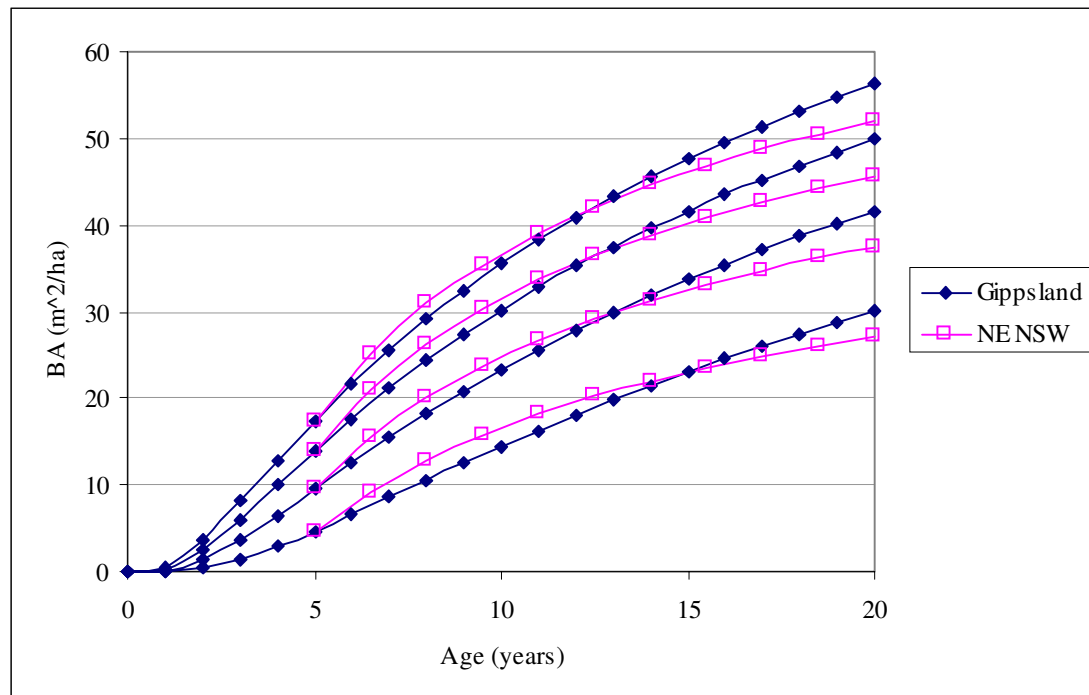


Figure 10. Modelled basal area growth of the *Salignae* series in Gippsland, and *E. grandis* in north-eastern New South Wales (West, 1998).

5. Relating Tree Growth to Site Productivity Classes

In this chapter the modelled tree growth is presented, and is related to site characteristics in Gippsland and South Australia. The sites have been grouped into site productivity classes for each species to assist in improving the reliability of forecasting tree growth.

The predicted growth rates beyond age 10 to 12 years involve considerable extrapolations given the relatively young age of the actual data available. Only with the presence of longer-term data will the predictions be verified. Amaro *et al.* (1998) suggested it is plausible that the asymptote of maximum growth be constrained physiologically and be constant for a species while Zhang *et al.* (1993) stated that generally, an estimate for the asymptote is not directly available from forest stand growth data typically used for model development. Extensive and careful validation should be conducted for the resulting models (Zhang, 1997). Therefore, predictions of growth presented in this report should only be used as a guide.

5.1 Gippsland growth predictions

Height

Using Equation 3 to model height, the following coefficient estimates were generated for each species (Table 16).

Table 16. Estimated coefficients, standard errors and fitted statistics for the height equation (Equation 3) using Gippsland data.

	<i>E. globulus</i>		<i>E. nitens</i>		<i>E. viminalis</i>		Salignae series	
	a	b	a	b	a	b	a	b
Coefficient	-0.1114	1.033	-0.1287	1.093	-0.1670	1.089	-0.1008	0.9568
S.e. of coefficient	0.0140	0.0542	0.0159	0.0643	0.0197	0.0727	0.0107	0.0365
Adjusted r^2	87.4		86.2		80.0		78.4	
$\sqrt{\text{MSE}}$	1.79		2.04		1.95		1.58	

$\sqrt{\text{MSE}}$ is the square root of the mean square error or the standard error of the observations.

With known heights, or assuming a given height at a given age, a set of height curves can be constructed. Figure 11 presents the actual height data for *E. globulus* at the 12 Gippsland sites, and modelled site index curves ranging from 12 to 30. The actual height data for the given sites tend to follow the fitted curves well. Similar curves resulted for the other species.

Using Equation 1, heights at age 10 years (SI) were obtained for each seedlot at each site. These heights were then grouped according to soil groups and annual rainfall. The matrix that resulted represents a general guide to relationships between various soil and rainfall conditions in Gippsland and possible height growth of various species (Table 17). Table 17 is based on over 100 seedlot observations and enables growth to be predicted on unplanted sites or for unmeasured stands.

The SI predictions suggest that *E. globulus* will have greater height growth than the other species at most sites in Gippsland. The exceptions are the very high rainfall, gradational sites where *E. nitens* will be superior, and the low rainfall deep sands where the Salignae series has better height growth. However, these low rainfall deep sands are not representative of sites for future plantation development in Gippsland (Baker *et al.*, 1995).

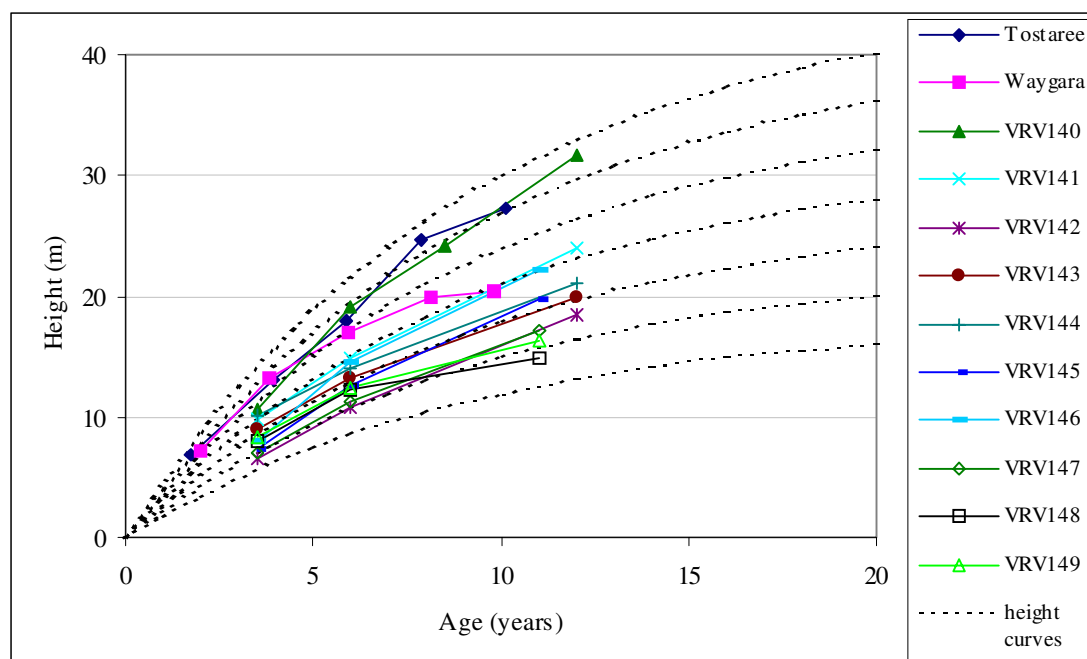


Figure 11. Actual and modelled (representing SI = 12 to 30) height growth for *E. globulus* in Gippsland.

Table 17. Possible SI range for *E. globulus*, *E. nitens*, *E. viminalis* and the Salignae (*E. botryoides*, *E. grandis*, *E. saligna*) series at age 10 years, on sites with various soil and rainfall combinations in Gippsland ^[1].

Soil group	Species	Rainfall (mm/year)				
		600-699	700-799	800-899	900-999	1000+
Deep sands	<i>E. globulus</i>	13-16		18-21		
	<i>E. nitens</i>	10-13		15-18		
	<i>E. viminalis</i>	11-14				
	Salignae series	14-18				
Texture contrast soils	<i>E. globulus</i>	14-17	16-19	19-22 (25-29)		
	<i>E. nitens</i>	12-15	14-17	16-19 (24-28)		
	<i>E. viminalis</i>	13-16	13-16	15-18 (23-27)		
	Salignae series	11-14	11-14	13-16 (18-22)		
Gradational textured soils	<i>E. globulus</i>				20-24	(26-30)
	<i>E. nitens</i>				19-23	(26-30)
	<i>E. viminalis</i>					17-20
	Salignae series					14-18

[1] Based on over 100 seedlot and 450 replicate observations.

The data in parentheses indicate SI for ex-pasture sites with a good fertiliser history.

Basal area

The coefficient estimates for Equation 4 for the Gippsland data are presented in Table 18. Using known or calculated basal areas for each site individually, basal area curves can be generated. Figure 12 presents the actual and predicted basal area growth for *E. globulus* at the 12 Gippsland sites, with the predictions being based on basal areas at age 10 years.

Table 18. Estimated coefficients, standard errors and fitted statistics for the basal area equation (Equation 4) using Gippsland data.

	<i>E. globulus</i>			<i>E. nitens</i>		
	a	b	c	a	b	c
Coefficient	2.443	-0.00193	0.4078	2.236	0.03516	0.6322
S.e. of coefficient	0.211	0.00647	0.0555	0.239	0.00783	0.0939
Adjusted r^2		82.9			76.4	
$\sqrt{\text{MSE}}$		4.31			5.38	

	<i>E. viminalis</i>			Salignae series		
	a	b	c	a	b	c
Coefficient	1.944	0.01947	0.3562	2.929	0.00591	0.6326
S.e. of coefficient	0.209	0.00778	0.0544	0.154	0.00708	0.0375
Adjusted r^2		86.6			81.0	
$\sqrt{\text{MSE}}$		4.48			3.79	

$\sqrt{\text{MSE}}$ is the square root of the mean square error or the standard error of the observations.

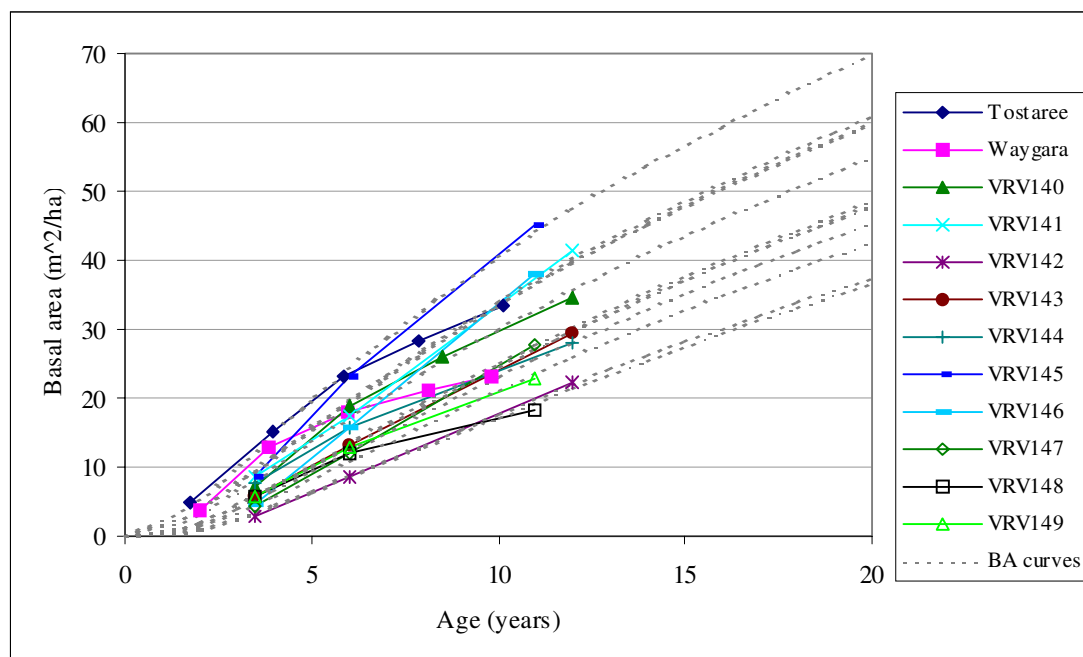


Figure 12. Actual and modelled (based on basal areas at age 10 years) basal area growth for *E. globulus* in Gippsland.

In the absence of actual basal area measurements, and where SI can be estimated from the matrix in Table 17 above, basal area at age 10 years can be derived using Equation 5. Statistical analysis indicated that two curves were necessary to best represent the data. Groupings were made based on the Salignae series and the Viminalae series (Figure 13). Covariance analysis showed that the groups shared a common asymptote (Table 19). While the basal area initialisation equation reduced the accuracy of the resulting basal area predictions, it still provided a good guide to basal area growth.

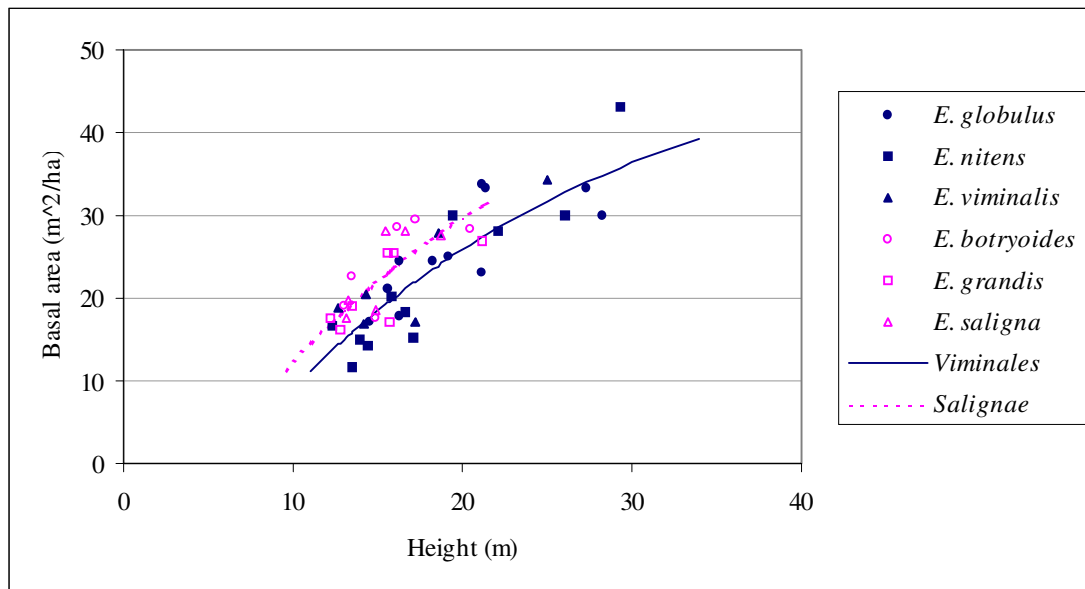


Figure 13. Relationship between basal area and height at age 10 years for *Eucalyptus* species in Gippsland.

Table 19. Estimated coefficients, standard errors and fitted statistics for the basal area initialisation equation (Equation 5) using Gippsland data.

	Viminalae series		Salignae series	
	a	b	a	b
Coefficient	4.271	-20.34	4.271	-17.62
S.e. of coefficient	0.119	2.06	0.119	1.85
Adjusted r^2	67.8			
$\sqrt{\text{MSE}}$	0.161			

$\sqrt{\text{MSE}}$ is the square root of the mean square error or the standard error of the observations.

Volume

Using predicted values of height (Table 20) and basal area (Table 21) for a range of site indices, volume was calculated using the stand volume equation (Equation 6). These estimates of volume are shown for *E. globulus* in Table 22 and Figure 14.

Table 20. Height (m) estimates for *E. globulus* for a range of site indices (height at age 10 years) based on trials in Gippsland.

Age (years)	Site index						
	14	16	18	20	22	24	26
0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1	2.1	2.4	2.7	3.0	3.3	3.5	3.8
2	4.0	4.6	5.1	5.7	6.3	6.9	7.4
3	5.8	6.6	7.4	8.2	9.0	9.9	10.7
4	7.3	8.4	9.4	10.5	11.5	12.6	13.6
5	8.8	10.0	11.3	12.5	13.8	15.0	16.3
6	10.1	11.5	12.9	14.4	15.8	17.2	18.7
7	11.2	12.8	14.4	16.0	17.6	19.2	20.8
8	12.2	14.0	15.7	17.5	19.2	21.0	22.7
9	13.2	15.1	16.9	18.8	20.7	22.6	24.5
10	14.0	16.0	18.0	20.0	22.0	24.0	26.0
11	14.8	16.9	19.0	21.1	23.2	25.3	27.4
12	15.4	17.6	19.8	22.0	24.2	26.4	28.6
13	16.0	18.3	20.6	22.9	25.2	27.5	29.7
14	16.6	18.9	21.3	23.6	26.0	28.4	30.7
15	17.0	19.5	21.9	24.3	26.8	29.2	31.6
16	17.5	20.0	22.4	24.9	27.4	29.9	32.4
17	17.8	20.4	22.9	25.5	28.0	30.6	33.1
18	18.2	20.8	23.4	26.0	28.6	31.2	33.8
19	18.5	21.1	23.8	26.4	29.1	31.7	34.4
20	18.8	21.5	24.1	26.8	29.5	32.2	34.9

Table 21. Basal area (m²/ha) estimates for *E. globulus* for a range of site indices (height at age 10 years) based on trials in Gippsland.

Age (years)	Site index						
	14	16	18	20	22	24	26
0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1	0.1	0.2	0.3	0.4	0.5	0.7	0.8
2	0.9	1.3	1.8	2.2	2.7	3.2	3.6
3	2.3	3.2	4.0	4.9	5.7	6.5	7.3
4	4.1	5.4	6.6	7.8	9.0	10.1	11.1
5	6.1	7.8	9.4	10.9	12.4	13.8	15.1
6	8.2	10.2	12.2	14.0	15.8	17.4	18.9
7	10.3	12.7	15.0	17.1	19.1	20.9	22.6
8	12.5	15.2	17.8	20.1	22.3	24.3	26.1
9	14.6	17.7	20.5	23.1	25.4	27.5	29.5
10	16.8	20.1	23.1	25.9	28.4	30.7	32.7
11	18.9	22.4	25.7	28.6	31.3	33.7	35.9
12	20.9	24.8	28.2	31.3	34.1	36.6	38.8
13	23.0	27.0	30.6	33.9	36.8	39.4	41.7
14	24.9	29.2	33.0	36.3	39.3	42.0	44.4
15	26.9	31.3	35.2	38.7	41.8	44.6	47.1
16	28.8	33.4	37.5	41.1	44.2	47.1	49.6
17	30.7	35.4	39.6	43.3	46.6	49.5	52.0
18	32.5	37.4	41.7	45.5	48.8	51.8	54.4
19	34.2	39.3	43.7	47.6	51.0	54.0	56.6
20	36.0	41.2	45.7	49.6	53.1	56.1	58.8

Table 22. Volume (m³/ha) estimates for *E. globulus* for a range of site indices (height at age 10 years) based on trials in Gippsland.

Age (years)	Site index						
	14	16	18	20	22	24	26
0	0	0	0	0	0	0	0
1	0	0	0	0	1	1	1
2	1	2	4	5	7	8	10
3	5	8	12	15	20	24	29
4	12	17	24	31	39	48	57
5	21	30	40	52	64	78	91
6	32	45	60	76	93	112	131
7	44	62	81	103	125	149	174
8	58	80	105	131	159	188	219
9	73	100	130	161	195	229	265
10	89	120	155	192	231	271	312
11	105	141	181	223	267	313	360
12	121	163	207	255	304	355	407
13	138	184	234	286	340	396	453
14	155	205	260	317	376	436	498
15	171	227	285	347	411	476	543
16	188	248	311	377	445	515	586
17	204	268	336	406	478	553	628
18	221	288	360	434	511	589	669
19	236	308	383	462	542	625	708
20	252	327	407	489	573	659	746

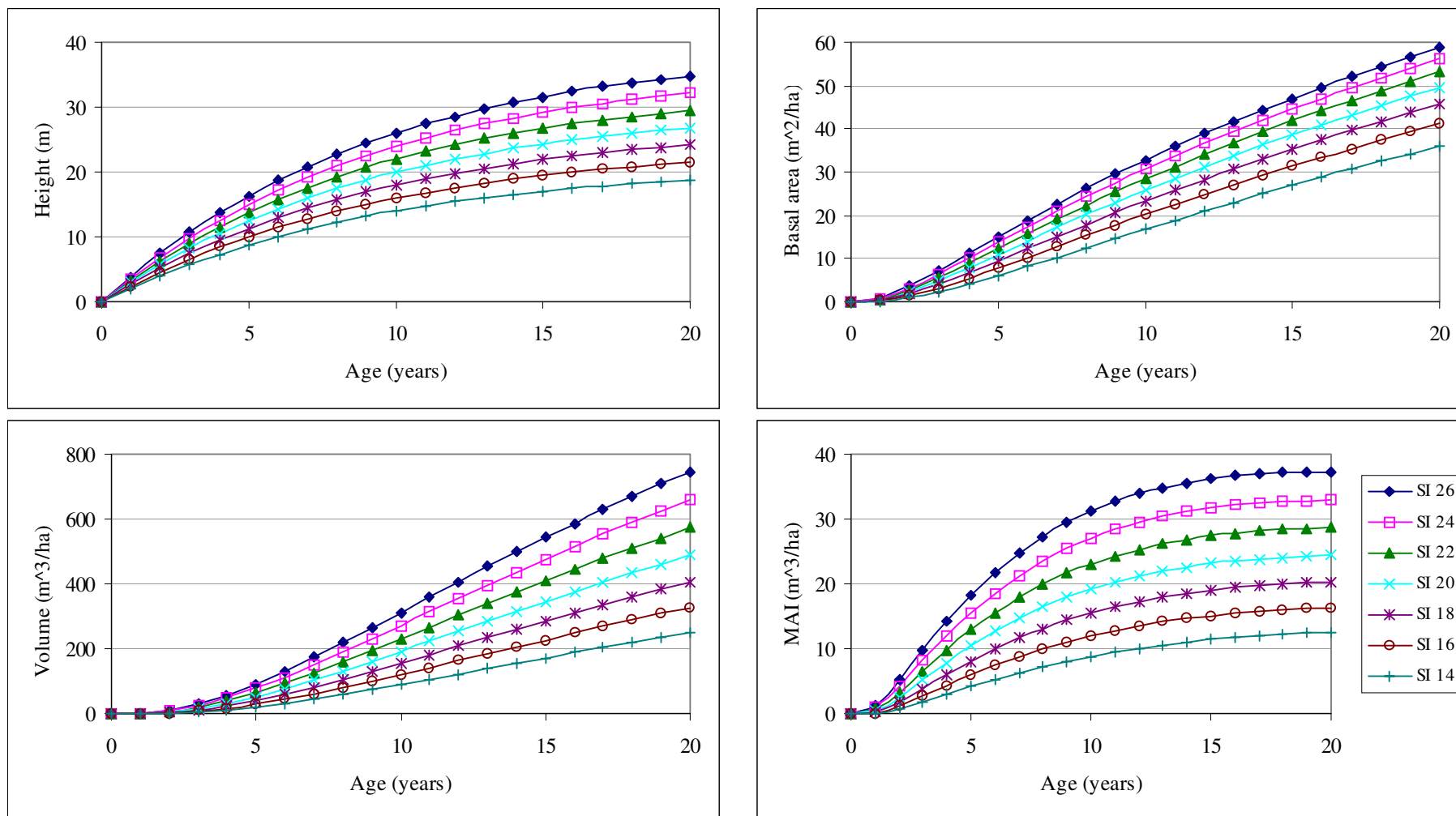


Figure 14. Modelled height, basal area, volume and volume mean annual increment (MAI) for *E. globulus* for a range of site indices (SI) in Gippsland.

5.2 South Australian growth predictions

Height

Using Equation 3 to model height, the following coefficient estimates were generated for each species (Table 23). Unlike the Gippsland data, *E. botryoides*, *E. grandis* and *E. saligna* could not be grouped together for the South Australian trials. Most South Australian data were for *E. globulus* (see Chapter 3) and actual *E. globulus* data are presented against modelled height curves in Figure 15. Similar curves resulted for the other species, with the actual data generally following the modelled height curves.

Table 23. Estimated coefficients, standard errors and fitted statistics for the height equation (Equation 3) using South Australian data.

	<i>E. globulus</i>		<i>E. nitens</i>		<i>E. viminalis</i>	
	a	b	a	b	a	b
Coefficient	-0.1207	0.9935	-0.2277	1.605	-0.2017	1.446
S.e. of coefficient	0.0071	0.0135	0.0203	0.0783	0.0227	0.0827
Adjusted r^2	95.2		96.9		95.6	
$\sqrt{\text{MSE}}$	1.32		0.98		1.11	

	<i>E. botryoides</i>		<i>E. grandis</i>		<i>E. saligna</i>	
	a	b	a	b	a	b
Coefficient	-0.1605	1.255	-0.2293	1.548	-0.1755	1.596
S.e. of coefficient	0.0201	0.0598	0.0180	0.1240	0.0174	0.0841
Adjusted r^2	96.1		99.3		98.7	
$\sqrt{\text{MSE}}$	0.91		0.88		0.78	

$\sqrt{\text{MSE}}$ is the square root of the mean square error or the standard error of the observations.

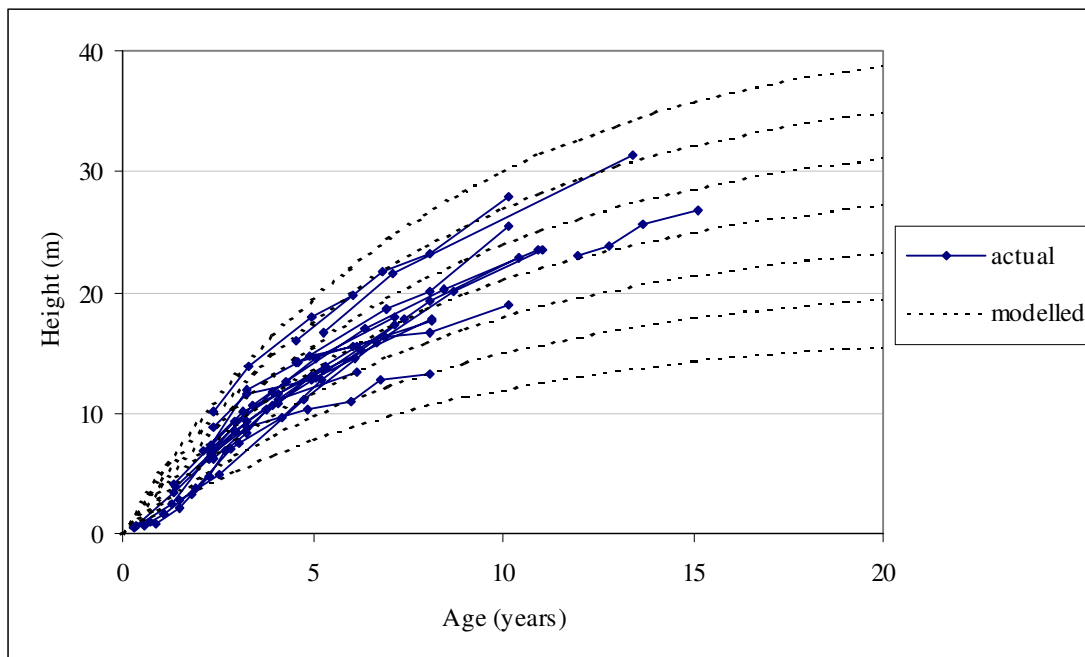


Figure 15. Actual and modelled (representing SI = 12 to 30) height growth for *E. globulus* in South Australia.

Heights (and basal areas) at age 10 years were estimated for each species at each site using Equation 1 (and Equation 2). Height growth in South Australia, based on annual rainfall and soil information, followed the same trends as in Gippsland, with more rapid height growth generally occurring in areas of higher rainfall on texture contrast soils rather than in areas of lower rainfall on deep sands. Gradational textured soils were not present at the South Australian trial sites.

A comparison of heights and basal areas between species on the same sites revealed similar rankings of the species to those in Gippsland (Table 24). *E. globulus* generally grew the fastest, with *E. nitens* growing well on the high rainfall RT123C site.

Table 24. Modelled height and basal area (BA) at age 10 years for eucalypt species at 3 South Australian sites.

Species	RT123C		EP205		EM133	
	Height (m)	BA (m ² /ha)	Height (m)	BA (m ² /ha)	Height (m)	BA (m ² /ha)
<i>E. globulus</i>	22.3	37.9	22.4	33.7	19.0	20.0
<i>E. nitens</i>	23.5	45.7	18.4	27.2		
<i>E. viminalis</i>	19.4	36.6	17.2	24.3		
<i>E. botryoides</i>	18.6	35.6	16.9	30.2		
<i>E. grandis</i>	20.1	30.7			17.1	16.4
<i>E. saligna</i>	19.6	33.1			12.8	10.7

Basal area

Basal area modelling for *E. nitens*, *E. viminalis*, *E. botryoides*, *E. grandis*, and *E. saligna*, based on SI, could not be undertaken because of the small number of sites on which they occurred (each species was present at only 2 sites).

Basal area initialisation using Equation 5 was constructed for all species. The South Australian basal areas tended to be smaller at smaller heights, and larger at larger heights compared to the Gippsland data, perhaps partially reflecting the differences in residual stockings at age 10 years and the species differences (Figure 16). For the South Australian data, not only were all the species data combined, but *E. globulus* was also modelled separately. The coefficient estimates and predictions are presented in Table 25 and Figure 17. For a given height, *E. globulus* trees generally had a smaller basal area than the other species. This was also the case in Gippsland.

Table 25. Estimated coefficients, standard errors and fitted statistics for the basal area initialisation equation (Equation 5) using South Australian data.

	All species		<i>E. globulus</i>	
	a	b	a	b
Coefficient	4.686	-27.02	4.563	-25.69
S.e. of coefficient	0.186	3.50	0.177	3.42
Adjusted r ²	67.6		76.6	
√MSE	0.197		0.150	

√MSE is the square root of the mean square error or the standard error of the observations.

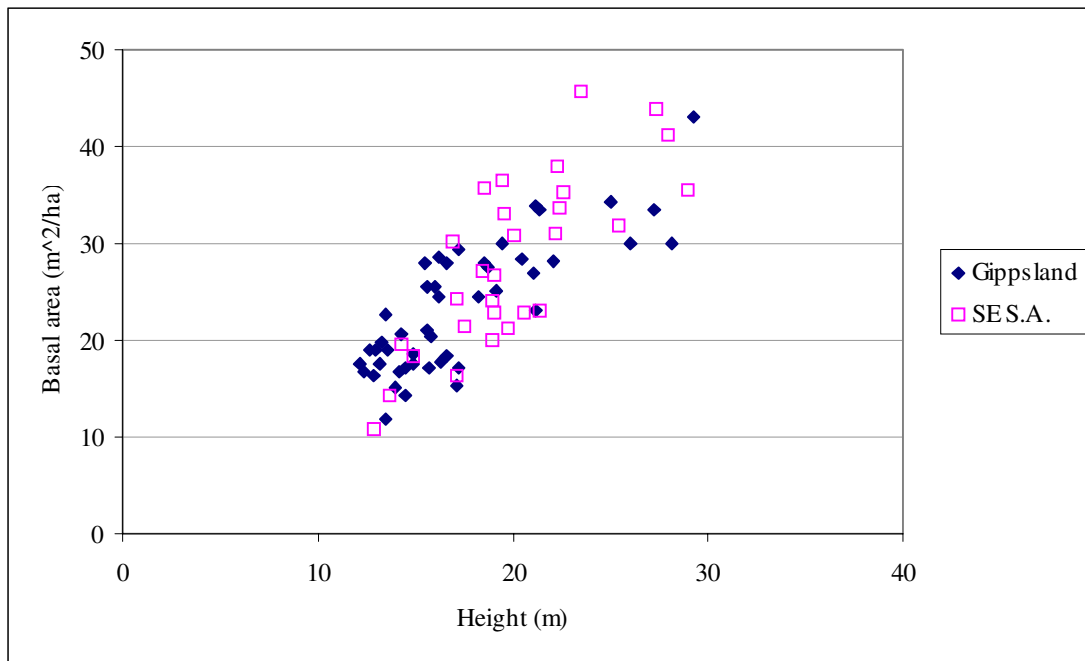


Figure 16. Relationship between basal area and height at age 10 years for *Eucalyptus* species in Gippsland and South Australia.

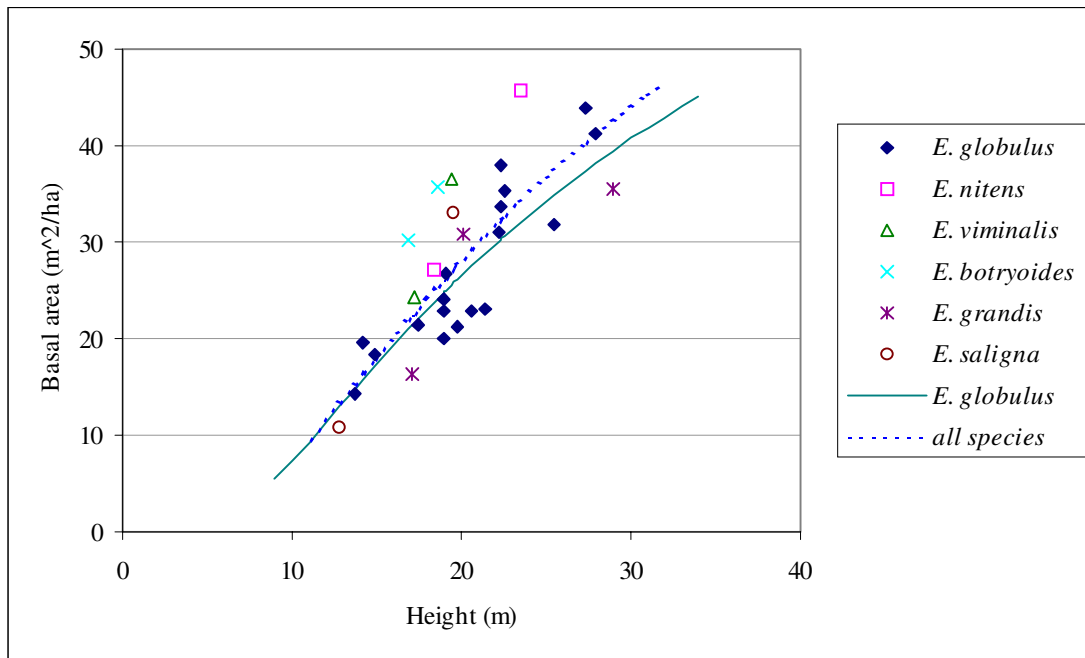


Figure 17. Relationship between basal area and height at age 10 years for *Eucalyptus* species in South Australia.

With an initial basal area value, basal area growth can be predicted with Equation 4, which had the following coefficient estimates for *E. globulus* in South Australia (Table 26). Actual basal areas were used as a starting value to predict *E. globulus* basal area growth (Figure 18). If basal area was unknown, but a SI was known, basal area at age 10 years could be estimated using Equation 5. Using the initialisation equation reduced the accuracy of the basal area predictions but it did provide a general guide to basal area growth.

Table 26. Estimated coefficients, standard errors and fitted statistics for the basal area equation (Equation 4) using South Australian *E. globulus* data.

	<i>E. globulus</i>		
	a	b	c
Coefficient	2.181	0.0681	0.8183
S.e. of coefficient	0.189	0.0102	0.0499
Adjusted r^2	96.5		
$\sqrt{\text{MSE}}$	2.30		

$\sqrt{\text{MSE}}$ is the square root of the mean square error or the standard error of the observations.

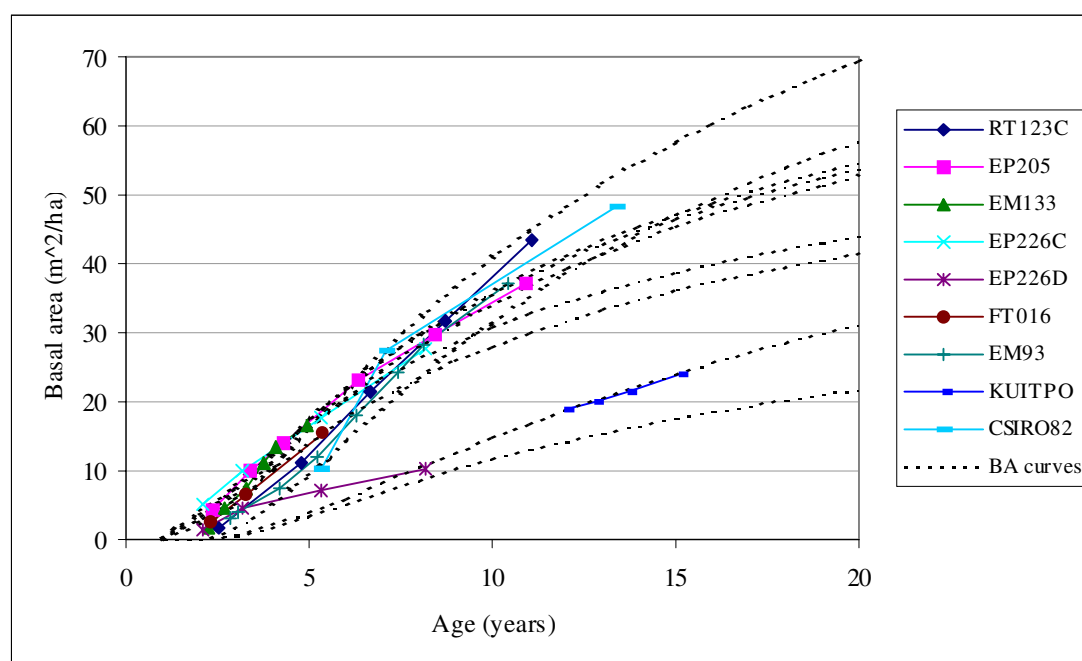


Figure 18. Actual and modelled (based on actual basal areas around the age of 10 years) basal area growth for *E. globulus* in South Australia.

Volume

Having predicted height and basal area, volume can be derived. The volume function used for the Gippsland data (Equation 6) was used to provide consistency between the volume predictions and assist in the comparisons between the regions.

Results of *E. globulus* growth for a range of site indices are presented in Tables 27 to 29, and Figure 19. The *E. globulus* growth predictions for South Australia and Gippsland are very similar, with the South Australian basal areas covering a wider range. The lower site indices in South Australia have lower basal areas, and growth slows more rapidly at later ages. The basal area differences are carried through to the volume estimates.

Table 27. Height (m) estimates for *E. globulus* for a range of site indices (height at age 10 years) based on trials in South Australia.

Age (years)	Site index						
	14	16	18	20	22	24	26
0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1	2.3	2.6	3.0	3.3	3.6	3.9	4.3
2	4.3	4.9	5.6	6.2	6.8	7.4	8.0
3	6.1	7.0	7.8	8.7	9.6	10.5	11.3
4	7.7	8.8	9.9	11.0	12.1	13.2	14.3
5	9.1	10.4	11.7	13.0	14.3	15.6	16.9
6	10.3	11.8	13.3	14.7	16.2	17.7	19.2
7	11.4	13.0	14.7	16.3	17.9	19.6	21.2
8	12.4	14.2	15.9	17.7	19.5	21.2	23.0
9	13.2	15.1	17.0	18.9	20.8	22.7	24.6
10	14.0	16.0	18.0	20.0	22.0	24.0	26.0
11	14.7	16.8	18.9	21.0	23.1	25.2	27.3
12	15.3	17.5	19.6	21.8	24.0	26.2	28.4
13	15.8	18.1	20.3	22.6	24.8	27.1	29.4
14	16.3	18.6	20.9	23.2	25.6	27.9	30.2
15	16.7	19.1	21.5	23.8	26.2	28.6	31.0
16	17.1	19.5	21.9	24.4	26.8	29.2	31.7
17	17.4	19.9	22.4	24.8	27.3	29.8	32.3
18	17.7	20.2	22.7	25.3	27.8	30.3	32.8
19	17.9	20.5	23.1	25.6	28.2	30.7	33.3
20	18.2	20.8	23.3	25.9	28.5	31.1	33.7

Table 28. Basal area (m²/ha) estimates for *E. globulus* for a range of site indices (height at age 10 years) based on trials in South Australia.

Age (years)	Site index						
	14	16	18	20	22	24	26
0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1	0.0	0.1	0.1	0.1	0.1	0.1	0.0
2	0.8	1.1	1.4	1.5	1.5	1.3	1.2
3	2.4	3.4	4.1	4.6	4.7	4.6	4.4
4	4.5	6.0	7.3	8.2	8.7	8.9	8.8
5	6.6	8.7	10.5	11.9	12.9	13.5	13.7
6	8.6	11.2	13.5	15.4	16.8	17.9	18.6
7	10.5	13.5	16.2	18.6	20.5	22.1	23.3
8	12.3	15.6	18.7	21.5	23.9	26.0	27.8
9	13.9	17.5	21.0	24.1	27.0	29.6	31.9
10	15.3	19.3	23.0	26.5	29.8	32.9	35.7
11	16.6	20.8	24.9	28.7	32.4	35.9	39.2
12	17.8	22.2	26.5	30.7	34.7	38.7	42.5
13	18.9	23.5	28.1	32.5	36.9	41.2	45.5
14	20.0	24.7	29.5	34.2	38.9	43.6	48.3
15	20.9	25.8	30.8	35.7	40.7	45.7	50.9
16	21.8	26.8	31.9	37.1	42.4	47.8	53.3
17	22.6	27.8	33.0	38.4	44.0	49.6	55.5
18	23.3	28.6	34.1	39.6	45.4	51.4	57.6
19	24.0	29.4	35.0	40.8	46.8	53.0	59.6
20	24.7	30.2	35.9	41.8	48.0	54.6	61.4

Table 29. Volume estimates (m³/ha) for *E. globulus* for a range of site indices (height at age 10 years) based on trials in South Australia.

Age (years)	Site index						
	14	16	18	20	22	24	26
0	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0
2	1	2	3	4	4	4	3
3	6	9	13	15	17	18	18
4	13	21	28	34	40	44	47
5	23	35	47	58	69	78	86
6	34	51	68	85	102	118	132
7	46	67	90	113	137	160	183
8	58	84	112	142	173	204	235
9	70	100	134	170	208	248	288
10	81	116	154	197	243	291	341
11	92	131	175	223	276	332	392
12	102	145	194	248	307	372	441
13	112	159	211	271	337	409	488
14	122	171	228	293	365	445	533
15	131	183	244	314	392	479	576
16	139	194	259	333	417	511	616
17	147	205	273	351	440	541	654
18	154	215	286	368	462	569	690
19	161	224	298	384	483	595	723
20	167	232	309	399	502	620	755

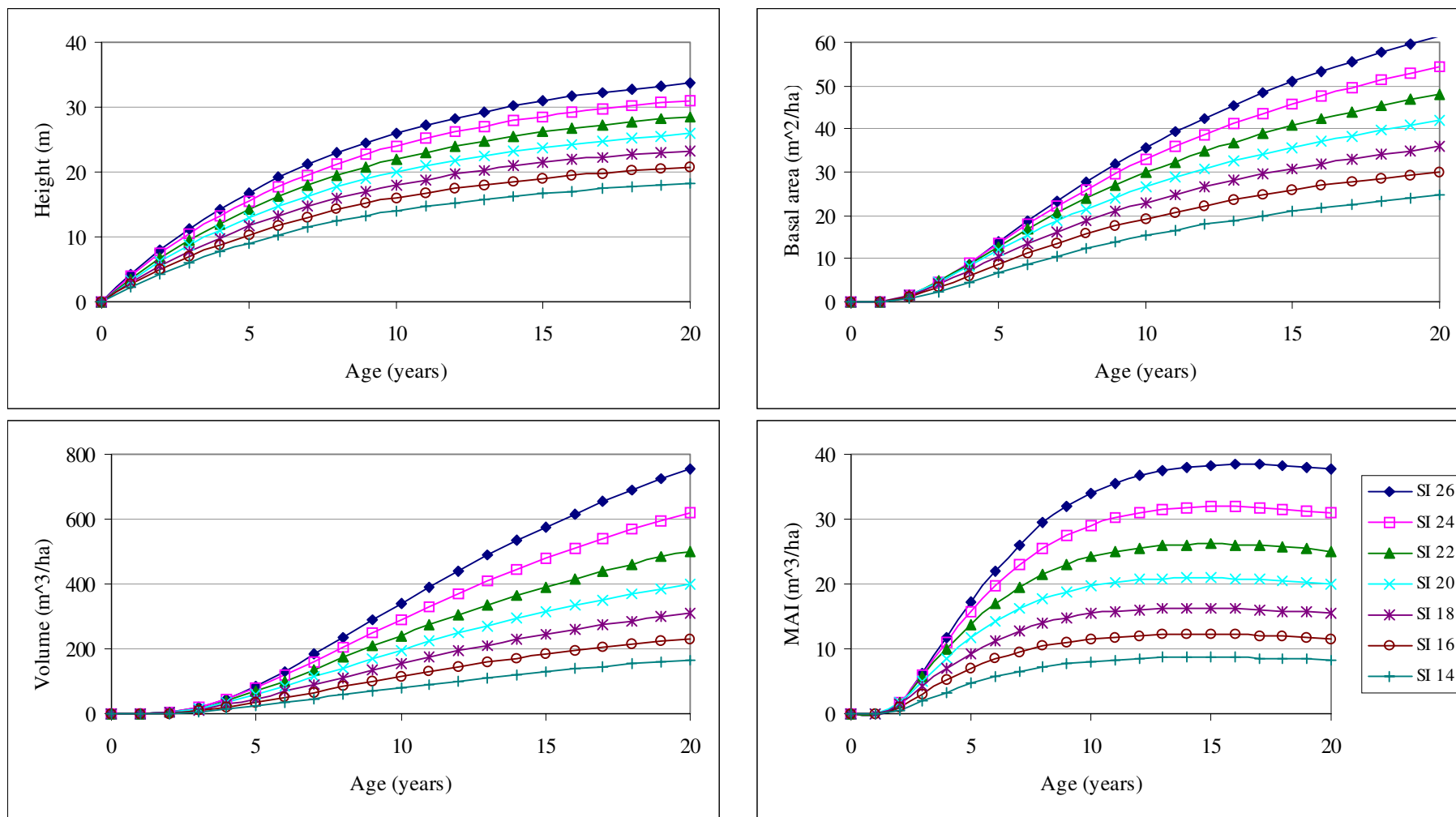


Figure 19. Modelled height, basal area, volume and volume mean annual increment (MAI) for *E. globulus* for a range of site indices (SI) in South Australia.

6. Implications for Farm Forestry

This report made use of data from long-standing trials to develop empirical models of height, basal area and volume growth. Six eucalypt species were studied; *E. globulus*, *E. nitens*, *E. viminalis*, *E. botryoides*, *E. grandis*, and *E. saligna*, with most data being for *E. globulus*. The tree growth data came from eucalypt field trials and some demonstration plantings in Victoria and South Australia established on sites representative of the climatic and edaphic conditions suitable for tree growth.

The growth models allow estimates of future (and past) growth to be made from stand measurements made at a particular time. Predictions of growth can also be made from estimates of site index based on a classification of annual rainfall and soils. The growth equations may be variously used to assist in the:

- selection of species for particular types of sites;
- estimation of yields, and therefore returns, from a stand at various times;
- prediction of potential tree growth on a site being considered for planting; and
- support of financial analysis of farm forestry.

Greater confidence in the determination of these factors will in turn encourage tree planting, and may also result in secondary, environmental benefits (e.g. salinity control).

The growth models in this report have generally been developed using data to age 12 years, and used to predict growth to age 20 years. Only with the presence of actual long-term data can these predictions be verified. Most of the data came from replicated experimental plots, established with considerable care to ensure valid comparisons of growth could be made. Actual yields achieved by landholders pursuing farm forestry may be higher or lower depending on site variation and the intensity of silvicultural practices, particularly for large scale plantation establishment over broad areas. Climatic variation is also important as drought, especially during establishment, may cause significant mortality and consequently reduced yields at rotation age.

There are a number of ways that the outcomes and products of this project could be summarised in the form of broader extension material. By making the summary forms of the data available, and by use of the models, landholders would have a valuable aid for agroforestry management. After verification and modification, if necessary, the functions could be used to develop or improve software analytical tools such as FARMTREE. The relationships between tree growth rates and site factors, and the construction of mathematical models of tree growth which could be incorporated into financial models such as FARMTREE have already been investigated (Appendix 1).

7. Appendix 1. FARMTREE

Introduction

FARMTREE was developed by the former Victorian Departments of Agriculture, and Conservation and Environment to estimate the financial returns from planting trees on farms. The main aim of this computer program is to provide extension officers, farmers and other landholders with an aid to make better informed choices about tree growing (Loane, 1994). FARMTREE allows an analysis of the costs and returns of a tree-growing enterprise, integrated with the costs and benefits to agriculture.

In the present study, analyses of FARMTREE's useability and the possibilities for improving the tree growth predictions in the program were undertaken using 2 consultant groups and as part of a postgraduate research program. The consultants' reports and a Master of Forest Science thesis have been provided separately to this report. This appendix summarises these.

Evaluation of FARMTREE's useability

Margules Poyry Pty Ltd were engaged to independently evaluate the FARMTREE computer model, particularly with respect to:

- the usefulness of outputs to users;
- the useability of the model;
- any required modifications; and
- the constraints to adoption.

Briefly, the consultants believe that there is an expanding requirement for a program such as FARMTREE to provide yield and financial data for farm forestry. While FARMTREE has substantial potential in this area, a large amount of work is required to improve the software to ensure that it will be readily adopted and be competitive with other products. This included improvements with respect to:

Operation - fix the current "bugs".

Output - revise the output to provide user choices and a clear presentation.

Instructions - produce a stand alone manual that describes FARMTREE's operation and methodology in detail.

User-support – to provide support, which can be accomplished in several ways, would probably require the most effort and expense.

Reprogramming - reprogram the operations into modules that provide options for varying levels of input.

The consultants also suggested a marketing strategy to get FARMTREE into the wider marketplace once the improvements had been made. This included maintaining a database and regular contact with the users of FARMTREE, providing training sessions and support, and advertising at forestry and agriculture organisational gatherings.

FARMTREE's growth modelling functions

Mr W. Incoll of Forest Essentials Pty Ltd was engaged in January 1998 to provide advice on research priorities for this project, including development of a suitable postgraduate research program.

The following is taken from Justin Wong's thesis titled "Tree growth modelling of *Eucalyptus delegatensis* and other *Eucalyptus* species utilising early-aged stand measurements". While it details possible improvements to FARMTREE, it should be noted that more work would be required for modelling of *Eucalyptus* species more suited to farm forestry. Further verification of the *E. delegatensis* functions with another more detailed data set could also be carried out.

Abstract

Growth modelling methods for *Eucalyptus* species that make use of minimal measurement information are scarce but necessary for those involved in small-scale forestry to make informed decisions about investment and management options. A computer program, FARMTREE, is available for evaluating the costs and benefits of trees on farms, but its growth modelling functions require significant improvement. This study provides a series of basal area, survival, diameter distribution and individual tree diameter increment models for *E. delegatensis* and other eucalypt species that could be incorporated into a FARMTREE-like program.

Comparing the predicted estimates of basal area, mortality and diameter distributions to those produced by FARMTREE show that the new estimates are better, both for the stands for which the models were developed, and for an independent data set.

Individual tree diameter increment models based on distance-independent competition indices were also studied. Overall, the predictions for two-year diameter increment were not as good as for the previously studied areas of growth. This was especially noticeable when observing the results for the verification data set. These poorer results for diameter increment may be because of the less flexible methods used or perhaps partially due to the accumulation of previous prediction errors.

The methods and functions used are easy to apply, efficient, accurate and require minimal actual growth measurement information. They could be applied to other species in greater detail when more information becomes available and could be incorporated into FARMTREE or a similar package for use by owners and managers of small farm forests with the expectation of providing improved growth predictions.

Data

The complete set of *E. delegatensis* data is made up of 30 plots at four locations in Victoria, Australia. It was supplied by Victoria's Department of Natural Resources and Environment. At various times throughout this study, all or subsets of this information has been used, depending on the availability of details for a given plot. The unthinned plots are located in Broadford (north of Mount Disappointment), on Mount Macedon, west of Narbethong, and in the Powelltown area. Planted during the 1960's and 1970's, a broad range of planting densities are represented, ranging from around 200 to up to 7000 stems per hectare. Measurements have been made on the plots between the ages of 4 and 33 years but, due to damage by fires in 1982 and 1983, the maximum age for data that are used in this study is 25 years. The number of remeasurements of any one plot between these ages is 10.

A less complete set of data made up of a range of *Eucalyptus* species was also used, as was another *E. delegatensis* data set from Tasmania.

Basal area

FARMTREE

FARMTREE uses the Chapman-Richards function to project the diameter and height growth of trees based on age. Not only does it constrain maximum tree size, it also estimates the other parameters in a way different to the usual mathematical nonlinear methods.

In Loane's notation, the three-parameter Chapman-Richards function is:

$$Y = m (1 - e^{(b \cdot \text{age})})^c$$

where: Y = height or diameter at breast height (dbh);
m = maximum achievable height or dbhob;
age = age in years;
c is an early growth parameter,
set at 1.4 for height and 1.2 for diameter; and

$$b = \frac{\ln [1 - (Y_{pt}/m)^{(1/c)}]}{A_{pt}} m$$

where Y_{pt} is the height or dbhob in the year A_{pt} , preferably at mid-rotation.

Therefore, to determine height or diameter in FARMTREE, the maximum height or diameter must be estimated, along with a height or diameter measurement at a known age, preferably around mid-rotation.

If the user does not provide these, FARMTREE provides default data based on reference trees. Loane (1994) states that "the observed heights are taken from the most similar trees and sites for which records are available" and that when calculating diameters "the observed points should be mean diameters from an unthinned stand of known spacing". Even though adjustments are made to the results if the climate or spacing is different from the reference trees, one still has to question the accuracy of this broad method. To use more "on-site" observations should provide greater specificity.

A possible alternative

When choosing the most appropriate method one cannot simply choose the option that will provide the most accurate results as simplicity is also desired. The basal area model must try to strike a balance between minimal information to match what a landowner or consultant would realistically have and an acceptable level of accuracy to provide adequate predictions of tree growth.

Taking this into account, the Gompertz model using two early-age basal area measurements to estimate 'b' and 'c' while keeping 'a' constant at 50.29 was selected.

$$BA = 50.29.e^{[b.e^{(c \cdot \text{age})}]}$$

If only one early-age measurement is available, basal area of *E. delegatensis* should be estimated using:

$$BA = 50.29.e^{[-5.980.e^{(c \cdot \text{age})}]}$$

Mortality

FARMTREE

FARMTREE currently uses stocking as a predictive variable for mortality. It doesn't use a smooth function as in many of the other cases where stocking is used (e.g. Ek, 1974; Chikumbo *et al.*, 1996; Cao, 1997), instead it gives a percentage of trees that are not replaced per year for given stocking levels (Table A1). A stocking versus age curve for a stand initially planted at 2500 stems per hectare based on the FARMTREE values is shown in Figure A1.

Table A1. The procedure used to calculate mortality in FARMTREE.

Stocking	≥ 2000	≥ 1000	≥ 600	≥ 400	> 0
Mortality %/year	4	2.2	1.5	0.7	0.5

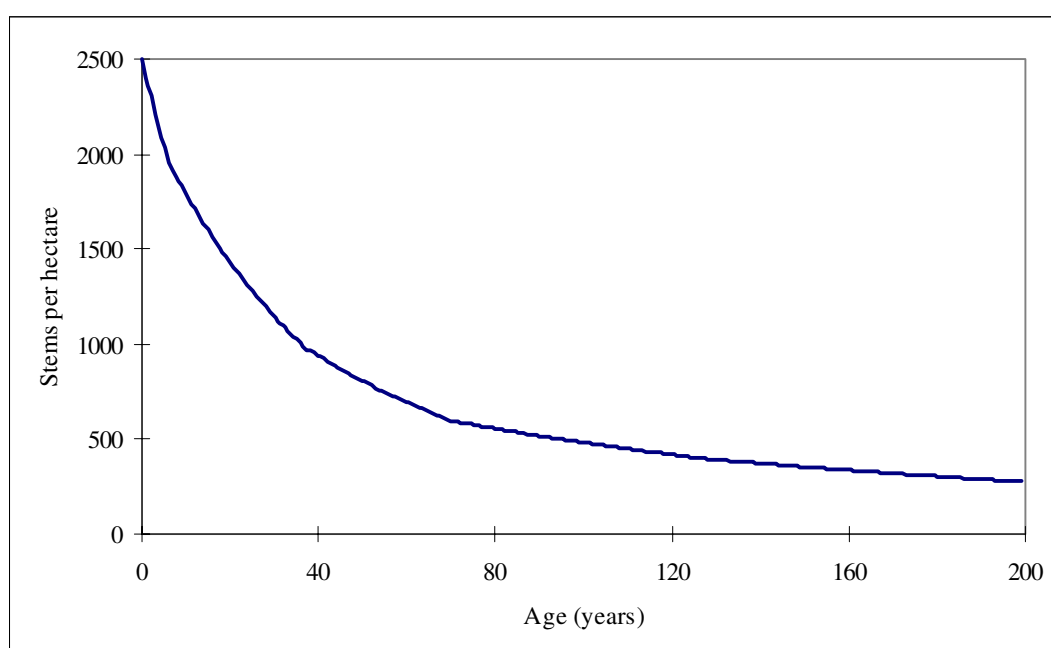


Figure A1. A representative stocking versus age curve for an Australian native species using FARMTREE's approach.

Vanclay (1995), Amateis *et al.* (1997), Incoll (pers. comm., 1997) and others have stated that mortality may be better predicted if other measures of competition such as basal area are included in the model. It has also been mentioned that site quality has an effect on mortality. These types of variables are unavailable though and Clutter *et al.* (1983) stated that "many analyses have failed to show any effect of site index on tree mortality", which may be due to a lack of suitable experimental data (Vanclay, 1994).

A possible alternative

A method for modelling mortality has been found that does not use density in its prediction. The selected model is based on the logistic function and measures the proportion of surviving trees based on basal area and age. If required, estimates of stand basal area can be used. The approach is more accurate than the one in FARMTREE that uses stem stocking as a guide to mortality.

The proportion of *E. delegatensis* trees surviving from age zero can be modelled as:

$$P = (1 + e^{(-4.39 - 0.00333 \cdot BA)})^{-age^{1.27}}$$

Diameter distributions

FARMTREE

FARMTREE generates diameter distributions for an unthinned stand by allocating the total number of stems present, based on its mortality function, into five classes, with a fixed proportion of the stems going into each class. Based on a pine agroforest (Loane, 1994), the five class midpoints are at 85, 90, 100, 105 and 125 percent of the mean diameter as estimated by FARMTREE, and the proportions of the stems that go into these classes are 25, 21, 16, 19 and 19 percent respectively. This discrete distribution is represented in Table A2 and Figure A2.

Table A2. FARMTREE distribution of tree diameters around the mean.

Diameter class	1	2	3	4	5
Midpoint of class in relation to mean	0.85	0.9	1	1.05	1.25
Proportion of stems in class	0.25	0.21	0.16	0.19	0.19

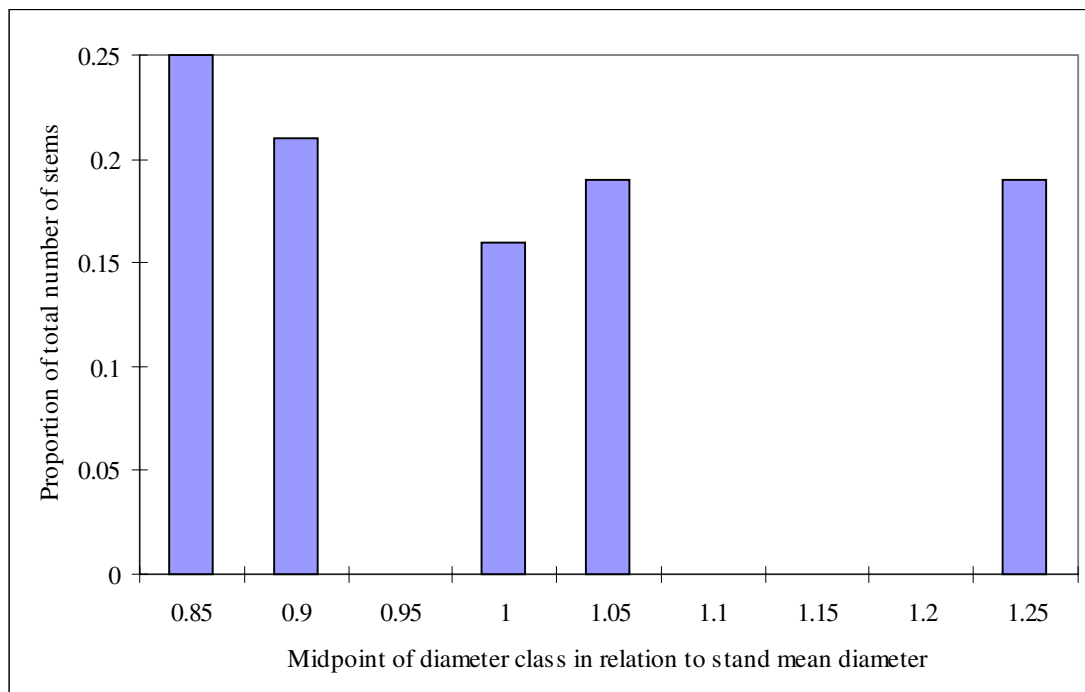


Figure A2. FARMTREE distribution of tree diameters around the mean.

The distribution is assumed to remain as above provided there is no artificial thinning, which is modelled as thinning from below or as a random thinning.

It is believed that more flexibility than this FARMTREE distribution is required as the current model is too simplistic and because distributions tend to change from positively skewed distributions in young stands to negatively skewed distributions as stands age.

A possible alternative

A parameter recovery method using percentiles as well as moments was chosen based on the data available and the model simplicity required. The methodology was obtained from Knowe (1992), Knowe and Stein (1995) and Knowe *et al.* (1992, 1994, 1997).

The procedure uses the Weibull distribution and is based on the 0th, 25th, 50th and 95th diameter percentiles. Percentiles are predicted as functions of quadratic mean diameter and age as shown below.

$$\ln(D_i) = \alpha_1 + \alpha_2 \ln(D_q) + \alpha_3/A + \varepsilon$$

where: D_i is a given diameter percentile (D_0 , D_{25} , D_{50} or D_{95});
 α_i are parameters to be estimated;
 D_q is the quadratic mean diameter;
 A is the plantation age; and
 ε is a normal random variable.

Once the percentile estimates have been obtained, they can be used to recover estimates of the Weibull function's parameters.

Assuming, as suggested in the references, that 'c' equals 3, the location parameter 'a' of the Weibull distribution is found using:

$$a = \frac{n^{0.3333} D_0 - D_{50}}{n^{0.3333} - 1}$$

where: D_0 = minimum diameter;
 D_{50} = median diameter; and
 n = sample size.

If the estimate of 'a' is negative it is set to zero.

The 'a' parameter is used along with the 25th (D_{25}) and 95th (D_{95}) percentiles to estimate the shape parameter 'c' where:

$$c = \frac{2.343088}{\ln(D_{95} - a) - \ln(D_{25} - a)}$$

The scale parameter, 'b', is then obtained by solving the second moment of the Weibull distribution for the positive square root, using the estimates of 'a', 'c', and D_q^2 . The 'b' parameter is estimated as:

$$b = -\frac{a\Gamma_1}{\Gamma_2} + \sqrt{\left(\frac{a}{\Gamma_2}\right)^2 (\Gamma_1^2 - \Gamma_2) + \frac{D_q^2}{\Gamma_2}}$$

where: $\Gamma_1 = \Gamma\left(1 + \frac{1}{c}\right)$
 $\Gamma_2 = \Gamma\left(1 + \frac{2}{c}\right)$ and

Γ is the gamma function.

The Weibull function using a percentile-based parameter recovery method appears to be a major improvement over the fixed diameter distribution currently incorporated in FARMTREE. The distribution modelling method is flexible and adequately represents distributions of eucalypt plantations.

Diameter increment

FARMTREE

In FARMTREE, the Chapman-Richards function is used to estimate the mean diameter of the stand as outlined earlier. Adjustments are then made to diameter increment according to competition and spacing (Loane, 1994). This is done by adjusting diameter increment relative to a crown competition factor (CCF). CCF measures the sum of the crown area of the trees per hectare expressed as a percentage of the ground area.

CCF is calculated in FARMTREE by estimating the crown area of open grown trees, which is a proxy for the zone of competition for each tree. It is the product of mean crown area and stocking per hectare. Crown area is determined from crown width, which in turn is estimated using a simple linear relationship with diameter based on data for *Pinus radiata*. For different values of CCF, relative diameter increments are determined.

Use of the CCF depends on having growth data for stands with a wide range of diameters and spacings. It also needs measurements of open grown trees to set CCF at 100 when each tree crown in a stand is equal in area to that of an open grown tree of the same diameter (Krajicek *et al.*, 1961). The validity of this model of the competitive process is not being tested, but it may be that other concepts of competition that rely on stand level distance-independent competition indices are more effective for modelling diameter increment.

A possible alternative

The distance-independent competition indices studied were:

- BA stand basal area per hectare;
- ST number of stems per hectare;
- BAL sum of basal area of trees larger than subject tree per hectare;
- STL number of stems larger than subject tree per hectare;
- DL sum of diameter of trees larger than subject tree per hectare;
- DR1 ratio of diameter of subject tree to mean diameter of stand;
- BAR ratio of basal area of subject tree to mean tree basal area of stand (Glover and Hool, 1979);
- DR2 ratio of sum of diameters of the stand per hectare to the dbh of the subject tree (Lorimer, 1983); and
- RD relative diameter (Nystrom and Kexi, 1997).

Trees larger than the subject tree are defined on the basis of diameter.

The function for DR2 and its relationship to DR1 is below.

$$DR2 = \frac{\sum dbh_{all}}{dbh_{subject\ tree}} = \frac{ST}{DR1}$$

Relative diameter (RD) is expressed as the ratio between dbh and basal area weighted mean diameter. It is calculated as:

$$\begin{aligned} RD &= \frac{\text{diameter}}{\text{BA weighted mean diameter}} \\ &= \frac{dbh_{subject\ tree}}{\sum dbh_{all} \cdot \frac{BA_{subject\ tree}}{\sum BA_{all}}} \end{aligned}$$

A number of competition indices in the literature were not examined. Reineke's stand density index, used as a competition index by West (1982) and Biging and Dobbertin (1995), is a combination of diameter and stocking. This index was not considered as its components have been included in other indices that may be able to be used together, and because it involves prior estimation of coefficients. Competitive status using the Lorenz curve and the Gini coefficient has also been used (Bi, 1989), but while it is a distance-independent competition index, it was not included in this study as it requires too much individual tree information for the simple methods desired and has complex parameterisation procedures. Percentiles of a distribution have not been examined as they have been rejected by Wykoff (1990) and Monserud and Sterba (1996) as they do not describe a tree's competitive status accurately and result in a counterintuitive response to thinning from below.

The research indicated that *E. delegatensis* and the other *Eucalyptus* species' two-year diameter increment could be modelled well using easy to measure distance-independent competition indices. Even though the spread of predictions was quite large and as diameter increment increased the reliability of the prediction decreased, the form of the model was still good with the predictions falling around the expected values. *E. delegatensis* two-year diameter increment can be adequately modelled using the equation below:

$$\begin{aligned} \text{two-year diameter increment} = & 2.276 + 0.110(\text{dbh}) - 0.0257(\text{BA}) \\ & - 0.0885(\text{age}) - 0.0223(\text{sqrtSTL}) \\ & + 159.3(\text{recipDR2}) \end{aligned}$$

where: sqrt = the square root; and
recip = the reciprocal.

Comparing *E. delegatensis* with the other species combined illustrated that the form of the models was very similar but that different coefficient estimates were needed.

8. References

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