

**Selection and Breeding of *Eucalyptus radiata* subsp. *radiata*  
to Improve the Economics of Essential Oil Production**

**Hugh A. K. Harris**

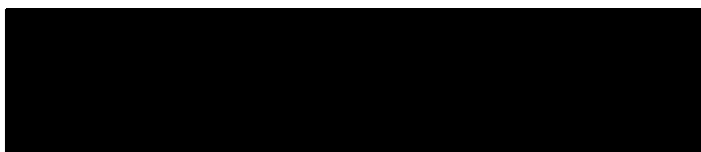
**B. Nat. Res (UNE)**

A thesis submitted for the degree of Master of Resource Science  
of the Faculty of Sciences

**March 2002**

I certify that the substance of this thesis has not already been submitted for any degree and is not currently being submitted for any other degree or qualification.

I certify that any help received in preparing this thesis and all sources used, have been acknowledged in this thesis.

A solid black rectangular box used to redact the signature of the author.

Signature

## Acknowledgements

I wish to thank my parents, Alan and Wendy for encouraging me in commencing this work, and continually supporting me through to finishing it.

Amanda - you have given me so much over the past few years. Hopefully I will now have a bit of time to give some back!

To my supervisors, Associate Professor Nick Reid and Dr John Doran, I am greatly indebted. Your knowledge and enthusiasm of the subject has been invaluable. Your ever-ready support and assistance when called on at short notice has been greatly appreciated. In particular to John, thank you for use of the trial at Brogo. Nick played a major role in carrying out a small Eucalyptus oil consultancy job with me; the proceeds of which were utilised to pay for the GC analyses for this project.

The CSIRO Australian Seed Centre generously provided funding to cover travel and accommodation costs when required to go to Canberra.

Kevin Johnson of Kylissa Estates provided access to the trial site, accommodation and other facilities during fieldwork at Brogo.

Shane Ruming provided much appreciated assistance in the collection of field data.

Dan Alter of the School of Agronomy and Soil Science carried out GC analysis.

Roger Arnold of the Australian Tree Seed Centre at CSIRO Forestry and Forest Products provided crucial assistance with sorting data, statistical analyses, interpretation of results, and editing.

Kron Aken of CSIRO Forestry and Forest Products compiled a map of the provenance and trial site locations

David Thompson of the Centre For Agricultural and Regional Economics provided technical assistance in the development of the economic model, as well as editing the economics chapter

Robyn Hean of NSW Agriculture also provided valuable input by editing the economics chapter

Memory of my brief meeting with Allan Coates often spurred me on.

## Table of Contents

Acknowledgements		i
List of Appendices		v
List of Tables		vi
List of Figures		viii
<b>Abstract</b>		<b>1</b>
<b>Chapter 1</b>	<b>Introduction and overview of commercial eucalyptus oil production</b>	<b>3</b>
1.1	A brief history of eucalyptus oil production in Australia	3
1.2	Current eucalyptus oil industry	4
1.2.1	Australian production	4
1.2.2	International production and markets	7
1.3	Commercial species and their use	9
1.3.1	Oil classification	9
1.3.2	Essential oil quality criteria	11
1.3.3	Medicinal oils	12
1.3.4	Industrial oils	14
1.3.5	Perfumery/flavouring oils	14
1.4	By-products from eucalyptus oil production	14
1.5	Oil gland morphology	15
1.6	Chemistry of eucalyptus oil	16
1.7	Sources of variation in tree growth and essential oil traits in <i>Eucalyptus</i> species	18
1.7.1	Variation in tree growth and essential oil traits between and within species due to genetic factors	18
1.7.2	Variation in tree growth and essential oil traits between and within species due to the type and age of leaf	20
1.7.3	Variation in tree growth and essential oil traits between and within species due to environmental factors	21
1.8	Heritability of tree growth and essential oil traits between and within species	23
1.9	Genetic and phenotypic correlation of tree growth and essential oil traits	26
1.10	Gain in growth and essential oil traits through selection and breeding	30
1.11	Breeding strategies for improving efficiencies in <i>Eucalyptus</i> oil production	31
1.12	<i>Eucalyptus radiata</i> as an essential oil producing species	35
1.12.1	General tree description, distribution and native growth habits of <i>E. radiata</i>	35
1.12.2	Botanical description of <i>E. radiata</i>	38
1.12.3	Taxonomy and chemical forms of <i>E. radiata</i>	40
1.12.4	Leaf oil concentration of <i>E. radiata</i> subsp. <i>radiata</i>	46
1.13	Technical aspects involved in <i>E. radiata</i> subsp. <i>radiata</i> plantation establishment and essential oil production	48
1.13.1	Plantation site selection	48
1.13.2	Ground preparation	48
1.13.3	Tree spacing	49

1.13.4	Irrigation requirement	50
1.13.5	Fertiliser requirements	51
1.13.6	Leaf harvesting	52
1.13.7	Oil distillation	53
1.13.8	Potential commercial <i>E. radiata</i> subsp. <i>radiata</i> plantation oil yield	55
1.14	Economic modelling of eucalypt plantations	56
1.15	Conclusions	62
<b>Chapter 2</b>	<b>Background to the study</b>	<b>63</b>
2.1	The need for the study	63
2.2	Aims	64
2.3	Objectives	64
<b>Chapter 3</b>	<b>Genetic parameters - variability, heritability, correlations and gain in growth and essential oil traits <i>E. radiata</i> subsp. <i>radiata</i></b>	<b>66</b>
3.1	Introduction	66
3.2	Materials and methods	67
3.2.1	Field trial site	67
3.2.2	Field sampling methodology	71
3.2.3	Laboratory methodology to determine leaf oil concentration and 1,8-cineole content	74
3.2.4	Statistical methodology to determine variation in tree growth and essential oil traits	75
3.2.5	Statistical methodology to estimate heritability of tree growth and essential oil traits	76
3.2.6	Statistical methodology to determine phenotypic and genetic correlation(s)	77
3.2.7	Statistical methodology to determine potential gain	78
3.3	Results	79
3.3.1	Variation in tree growth and essential oil traits	79
3.3.2	Heritability estimates for tree growth and essential oil traits	85
3.3.3	Phenotypic and genetic correlations of tree growth and essential oil traits	86
3.3.4	Potential gain in tree growth and essential oil traits	87
3.4	Discussion	89
3.4.1	Variation in tree growth and essential oil traits	89
3.4.2	Heritability estimates for tree growth and essential oil traits	91
3.4.3	Phenotypic and genetic correlations of tree growth and essential oil traits	93
3.4.4	Potential gain in tree growth and essential oil traits	95
<b>Chapter 4</b>	<b>Economic modelling of a commercial <i>E. radiata</i> subsp. <i>radiata</i> oil production enterprise</b>	<b>97</b>
4.1	Introduction	97
4.2	Materials and methods	98
4.2.1	The 'baseline' scenario	98
4.2.2	Sensitivity analysis	102
4.3	Results	104
4.4	Discussion	114

<b>Chapter 5.</b>	<b>Developing a breeding strategy for <i>E. radiata</i> subsp. <i>radiata</i> oil production</b>	<b>120</b>
5.1	Introduction	120
5.2	Factors influencing breeding strategy development	121
5.3	Proposed breeding strategy	123
5.4	Discussion	125
<b>Chapter 6</b>	<b>Conclusions</b>	<b>128</b>
<b>References</b>		<b>132</b>
<b>Appendices</b>		<b>148</b>

## List of Appendices

Appendix A - Typical chromatogram output from the gas chromatography analysis	148
Appendix B - Ranked comparison of tree growth and essential oil traits between sampling events at age 23 months and age 38 months of the Brogo <i>E. radiata</i> subsp. <i>radiata</i> provenance/progeny trial	149
Appendix C - Economic model interface	150
Appendix D - Schedule of plantation establishment costs	151

## List of Tables

Table 1.1 - Commercial eucalyptus oil species, grouped according to their end use classification	10
Table 1.2 - Major international standards (ISO) and Australian standards (AS) relating to eucalyptus oil production	12
Table 1.3 - Published estimates of narrow sense heritability ( $h^2$ ) from control-pollinated (C) and open-pollinated (O) progeny tests of six eucalypt species	25
Table 1.4 - Estimates of genetic correlations (above the diagonal) and phenotypic correlations (below the diagonal) for <i>Pinus radiata</i> in Australia	28
Table 1.5 - Estimates of genetic correlations (above the diagonal) and phenotypic correlations (below the diagonal) for 45 open-pollinated families of <i>E. globulus</i> in a progeny test at age 6 years	29
Table 1.6 - Geophysical features commonly associated with the mainland occurrence of <i>E. radiata</i>	37
Table 1.7 - Summary of Johnstone's (1984) commentary on the nomenclatural history of narrow-leaved peppermint	40
Table 1.8 - Chemical composition of Penfold and Morrison's four physiological varieties of <i>E. australiana</i> Baker and Smith (syn. <i>E. radiata</i> Sieb. ex DC)	44
Table 1.9 - The range in abundance in four key compounds in the oils of six chemical forms in a population of <i>E. radiata</i>	45
Table 1.10 - Typical <i>E. radiata</i> leaf oil concentration figures as determined by various authors	47
Table 1.11 - Break even production levels for an oil mallee venture on a typical Western Australian wheatbelt farm exploiting a eucalyptus oil market only	58
Table 1.12 - Break even production levels for an oil mallee venture on a typical Western Australian wheatbelt farm exploiting a market for both eucalyptus oil as well as a woody biomass residue for electricity production	59
Table 1.13 - Net financial return (\$ per litre of oil) for three different oil yields (presumably fresh wt) and three different tree planting densities	61
Table 3.1 - Origin of the 32 open-pollinated families of <i>Eucalyptus radiata</i> subsp. <i>radiata</i> in the trial at Brogo, NSW	69
Table 3.2 - Climatic details for <i>E. radiata</i> subsp. <i>radiata</i> provenances and trial site at Brogo, NSW, as determined by BIOCLIM	70



Table 3.3 - Mean growth and essential oil traits at 38 months of the four provenances in the <i>E. radiata</i> subsp. <i>radiata</i> provenance/progeny trial near Brogo, NSW	79
Table 3.4 – Family means for growth and essential oil traits at 38 months by family in the <i>E. radiata</i> subsp. <i>radiata</i> provenance/progeny trial near Brogo, NSW	80
Table 3.5 - Analyses of variance for survival (%), number of stems per tree, tree basal area (cm <sup>2</sup> ), leaf oil concentration (w/w% DW), and 1,8-cineole content (%) of provenances and families within provenances	85
Table 3.6 – Heritabilities and their standard errors for four traits in the <i>E. radiata</i> subsp. <i>radiata</i> provenance/progeny trial at Brogo, NSW, at age 38 months	86
Table 3.7 - Estimates of genetic correlations (above the diagonal) and phenotypic correlations (below the diagonal) for the <i>E. radiata</i> subsp. <i>radiata</i> provenance/progeny trial at Brogo, NSW, at age 38 months.	87
Table 3.8 - Predicted individual heritability and genetic gain over trial means for the four traits in the provenance/progeny trial of <i>E. radiata</i> subsp. <i>radiata</i> at Brogo, NSW, at age 38 months	88
Table 4.1. Production parameters used for modelling a farm-scale baseline <i>E. radiata</i> subsp. <i>radiata</i> plantation and essential oil production operation	101
Table 4.2 – Sensitivity of the NPV of the venture to discount rate	105
Table 4.3 – Relationship between oil production costs, plantation oil yield and oil sale price in achieving a 15 percent IRR	113

## List of Figures

Figure 1.1 - A selection of terpenes commonly found in the leaf oil of eucalypts, grouped according to their type and chemical structure	17
Figure 1.2 - Simplified diagram of the activity cycle for breeding and the hierarchy of four populations	34
Figure 1.3 - Diagrammatic representation of proposed breeding strategy for improving oil yields in <i>Melaleuca cajuputi</i> subsp. <i>cajuputi</i> in Indonesia.	35
Figure 1.4 - Natural distribution of <i>E. radiata</i> in Australia	37
Figure 1.5 - Botanical features of <i>E. radiata</i> subsp. <i>radiata</i>	39
Figure 1.6 - Distribution of <i>E. radiata</i> subsp. <i>radiata</i> (closed triangle) and subsp. <i>sejuncta</i> (open triangle), <i>E. robertsonii</i> subsp. <i>robertsonii</i> (open circle), and subsp. <i>hemisphaerica</i> (square) after Johnstone and Hill (1990)	43
Figure 1.7 - Sample output of annual net cashflow of an oil mallee plantation vs the existing agricultural enterprise using the Agriculture Western Australia Oil Mallee model	57
Figure 3.1 - Locations of <i>E. radiata</i> subsp. <i>radiata</i> (cineole variant) provenances (family numbers in brackets) and trial site at Brogo, NSW	68
Figure 3.2 - The <i>E. radiata</i> subsp. <i>radiata</i> provenance/progeny trial site at Brogo, NSW (trees aged 38 months)	69
Figure 3.3 - Randomised complete block design of the <i>E. radiata</i> subsp. <i>radiata</i> trial at Brogo, NSW, showing layout of replicates and families	71
Figure 3.4 - Measuring tree diameter of <i>E. radiata</i> subsp. <i>radiata</i> in the provenance/progeny trial at Brogo, NSW (tree age 38 months)	72
Figure 3.5 – The field laboratory established near the trial site to process the leaf samples collected from the <i>E. radiata</i> subsp. <i>radiata</i> provenance/progeny trial at Brogo, NSW	73
Figure 3.6 – Ranked family means for survival in the <i>E. radiata</i> subsp. <i>radiata</i> trial at Brogo, NSW, at age 38 months	81
Figure 3.7 – Ranked family means for the number of stems per tree in the <i>E. radiata</i> subsp. <i>radiata</i> trial at Brogo, NSW, at age 38 months	81
Figure 3.8 – Ranked family means for tree basal area (cm <sup>2</sup> ) in the <i>E. radiata</i> subsp. <i>radiata</i> trial at Brogo, NSW, at age 38 months	82
Figure 3.9 – Ranked family means for oil concentration (w/w% DW) in the <i>E. radiata</i> subsp. <i>radiata</i> trial at Brogo, NSW, at age 38 months	82

Figure 3.10 – Ranked family means for 1,8-cineole content (% of total oil) in the <i>E. radiata</i> subsp. <i>radiata</i> trial at Brogo, NSW, at age 38 months	83
Figure 4.1 - Cashflow of the baseline <i>E. radiata</i> subsp. <i>radiata</i> oil production venture	104
Figure 4.2 - Comparison of cashflow between the baseline venture and the same production scenario but with: all 15 ha of the plantation established in the first year; 5 ha established in each of the first three years; and 7.5 ha established in each of the first two years	106
Figure 4.3 - NPV and IRR of the venture considering three oil yield scenarios as determined by the level of improvement of plantation seedstock for high leaf oil concentration	107
Figure 4.4 - The effect on the net NPV of the venture by varying the farm-gate oil sale price while all other parameters of the baseline scenario are held constant	108
Figure 4.5 – Comparison of cashflow of the venture if farm-gate price received for oil was increased by 50% (i.e. \$34.50 kg <sup>-1</sup> ), and reduced by 50% (i.e. \$11.50), while all other parameters of the baseline scenario are held constant	109
Figure 4.6 - The effect on the NPV of the venture by varying the harvesting and distillation costs while all other parameters of the baseline scenario are held constant	110
Figure 4.7 - Comparison of cashflow of the venture if harvesting and distillation costs were increased by 50%, and if harvesting and distillation costs were reduced by 50% (and costs of mechanical harvesting plant are added), while all other parameters of the baseline scenario are held constant	111
Figure 4.8 - The effect on the NPV of the venture by concurrently reducing or increasing the harvesting and distillation costs and the oil sale price while all other parameters of the baseline scenario are held constant	112
Figure 5.1 – Breeding strategy for <i>E. radiata</i> subsp. <i>radiata</i> in southern New South Wales	125

*“Oil traits in eucalypts have been found to be under moderate to strong genetic control with substantial levels of genetic variation. This could facilitate the capture of useful gain from relatively simple, low input strategies to the present industry position of a static market and low prices”*

*(Doran, 2002).*