An Australian Government Initiative

Joint Venture Agroforestry Program

Rural Industries Research & Development Corporation

Forest & Wood Products Research & Development Corporation

Land & Water Australia

Scope for genetic improvement of natural durability in low rainfall eucalypts for vine trellis posts

by David Bush and Kevin McCarthy, CSIRO

January 2009

RIRDC Publication No 09/012
RIRDC Project No CSF-67A

ISBN 1 74151 818 0
ISSN 1440-6845

Scope for genetic improvement of natural durability in low rainfall eucalypts for vine trellis posts
Publication No. 09/012
Project No. CSF-67A

Researcher Contact Details

David Bush
CSIRO Plant Industry
PO Box E400
KINGSTON ACT 2600

Phone: 02 6281 8323
Fax: 02 6281 8312
Email: david.bush@csiro.au

Kevin McCarthy
CSIRO Materials Science and Engineering
Private Bag 10
CLAYTON VIC 3169

Phone: 03 9545 2336
Fax: 03 9545 2448
Email: kevin.mccarthy@csiro.au

In submitting this report, the researcher has agreed to RIRDC publishing this material in its edited form.

RIRDC Contact Details

Rural Industries Research and Development Corporation
Level 2, 15 National Circuit
BARTON ACT 2600

PO Box 4776
KINGSTON ACT 2604

Phone: 02 6271 4100
Fax: 02 6271 4199
Email: rirdc@rirdc.gov.au.
Web: http://www.rirdc.gov.au

Electronically published by RIRDC in January 2009

Foreword

This report examines the feasibility of genetically improving two key eucalypt species suited to Australia's low rainfall sheep-wheat belt for naturally durable vine trellis posts and similar products. The work is important because it simultaneously addresses the need to reduce the use of potentially harmful chemicals in Australia's food production systems, and identifies a potential product that can be grown on farms to provide environmental benefits and increase farm income diversity. The work also builds on other research carried out by JVAP on the genetic improvement of low rainfall species in partnership with the Australian Low Rainfall Tree Improvement Group, and on natural durability and other wood properties of low rainfall species with CSIRO.

The research has promisingly shown that one of the species assessed, *E. cladocalyx* (sugar gum), may be well-suited to the production of naturally durable posts, and is also amenable to genetic improvement. This finding can be integrated into existing genetic improvement programs for the species, and subject to further technical research, could lead to the development of an important product for Australian horticulture and agriculture.

This project was jointly funded by CSIRO and the Joint Venture Agroforestry Program (JVAP), which is supported by three R&D Corporations - Rural Industries Research and Development Corporation (RIRDC), Land & Water Australia (L&WA), and Forest and Wood Products Research and Development Corporation (FWPRDC). **The Murray-Darling Basin Commission (MDBC) also contributed to this project**. The R&D Corporations are funded principally by the Australian Government. **State and Australian Governments contribute funds to the MDBC**.

This report is an addition to RIRDC's diverse range of over 1800 research publications. It forms part of our Agroforestry and Farm Forestry R&D program, which aims to integrate sustainable and productive agroforestry within Australian farming systems. The JVAP, under this program, is managed by RIRDC. Most of our publications are available for viewing, downloading or purchasing online through our website:

- downloads at www.rirdc.gov.au/fullreports/index.html
- purchases at www.rirdc.gov.au/eshop

Peter O'Brien
Managing Director
Rural Industries Research and Development Corporation

Acknowledgments

The authors would like to thank Ian Nicholas for suggesting the concept of this study, and Roger Arnold for helpful suggestions during the development of the project. Bruce Sonogan and Philippa Noble assisted with access to and establishment of the sugar gum trial and Noel and Kim Passalaqua (Jayfields Nursery) provided same for the spotted gums. Randall Falkiner gave sage advice in the set-up of the extractives laboratory. Jenny Carr, Luke Bulkeley, Brioni Brammall, David Spencer, Paul Macdonell, Julie Davis and John Larmour provided valuable assistance in field sampling and laboratory analysis. Chris Harwood and Bruce Munday provided valuable review on drafts of the report.

Abbreviations

Abbreviation	**Expansion**
ALRTIG	Australian Low Rainfall Tree Improvement Group
A.S.L.	Above sea level
ATSC	Australian Tree Seed Centre
CCA	Copper chrome arsenate
CCC	*Corymbia citriodora* subsp. *citriodora*
CCV	*Corymbia citriodora* subsp. *variegata*
CEF	Commercial environmental forestry
CH	*Corymbia henryi*
CM	*Corymbia maculata*
DBHOB	Diameter at breast height over bark
DBHUB	Diameter at breast height under bark
FNSW	Forests NSW
MAR	Mean annual rainfall
MOE	Modulus of elasticity
MOR	Modulus of rupture
PEC	Pigment emulsified creosote
ROP	Region of provenance
s.e.	Standard error
s.e.d.	Standard error of difference
y.o.	Years old

Contents

Foreword ..... **iii**
Acknowledgments ..... **iv**
Abbreviations ..... **iv**
Executive Summary ..... **vii**
1. Introduction **1**
1.1. Research rationale 1
1.2. Use and demand for naturally durable and preservative-treated timbers in Australia 1
1.2.1. Post specifications 2
1.3. Natural durability 3
1.4. Potential plantation species for durable vine posts 4
1.4.1. *E. occidentalis* - swamp yate 4
1.4.2. *E. cladocalyx* - sugar gum 4
1.4.3. Spotted gums - *Corymbia* spp. 5
1.4.4. Other species 6
1.5. Determinants of genetic improvement 6
1.5.1. Natural durability traits 7
2. Materials and methods **9**
2.1. Investigative procedure 9
2.2. Genetic materials and trial locations 9
2.3. Analytical and sampling procedures 11
2.3.1. Coring 11
2.3.2. Heartwood-sapwood boundary definition and proportion 12
2.3.3. Basic density 12
2.3.4. Accelerated biodeterioration 12
2.3.5. Extractive weight determination 12
2.3.6. Statistical analysis 13
3. Results **15**
3.1. Pilot study 15
3.2. *E. cladocalyx* – sugar gum 16
3.2.1. Growth traits 16
3.2.2. Heartwood proportion 18
3.2.3. Basic density 19
3.2.4. Methanol heartwood extractives 19
3.2.5. Mass loss 20
3.2.6. Genetic correlations 21
3.3. Spotted gums - *Corymbia* spp. 22
3.3.1. Heartwood proportion 22
3.3.2. Basic density 23
3.3.3. Methanol heartwood extractives 26
3.3.4. Mass loss 26
3.3.5. Phenotypic correlations between traits 27
4. Discussion and implications **29**
5. References **33**

Tables

Table 1. Natural durability rating system with examples of heartwood durability for various softwoods and hardwoods as assigned by AS 5606-2005 3

Table 2. Examples of estimates of heritability and/or provenance variation for durability-related traits in various forest tree species........ 7

Table 3. Composition of the Benalla *E. cladocalyx* provenance-progeny trial 10
Table 4. Details of spotted gum provenances included in the study 11

Table 5. Mass loss of treated and untreated samples subjected to four fungi for 12 weeks. Standard errors of the mean are given in parentheses. 15

Table 6. Trait means, significance of effects (F probabilities) and genetic parameters for *E. cladocalyx* 17

Table 7. Genetic correlations (upper triangle) with standard errors (lower triangle) between pairs of traits in *E. cladocalyx* 22

Table 8a. Trait means and significance of effects (F probabilities) for spotted gum species and provenances at Yarralumla. 24

Table 8b. Trait means and significance of effects (F probabilities) for spotted gum species and provenances at Holbrook. 25

Table 9. Phenotypic (Pearson) correlations between pairs of traits for *Corymbia* spp. at Yarralumla. 28

Figures

Figure 1. DBHOB for whole of Benalla trial. 16

Figure 2. Provenance heartwood DBH as a percentage of DBHOB within region-of-provenance...... 18

Figure 3. Basic density of heartwood and sapwood for *E. cladocalyx* provenances. 19
Figure 4. *E. cladocalyx* heartwood methanol extractives (percentage of heartwood by weight) 20

Figure 5. Percentage mass loss of *E. cladocalyx* heartwood samples exposed to two brown and one white rot fungus. 21

Figure 6. *Corymbia* heartwood diameter and DBHOB at two sites 23

Figure 7. Provenance means for *Corymbia* spp. methanol heartwood extractives in spotted gums at Yarralumla 26

Figure 8. Accelerated biodeterioration (percent mass loss) of *Corymbia* spp. heartwood provenances 27

Executive Summary

What the report is about

This report examines the feasibility of genetically improving eucalypt species suited to Australia's low rainfall sheep-wheat belt for naturally durable wood production, particularly vine trellis posts. Traits relating to natural durability from trees of young-aged trials (8-12 years) of three eucalypt taxa, *Eucalyptus cladocalyx*, *E. occidentalis* and spotted gums (*Corymbia* spp.), were assessed. The research has shown that *E. cladocalyx* may be well-suited to production of naturally durable posts, and is also amenable to genetic improvement.

Re-establishment of deep-rooted woody vegetation in Australia's low rainfall sheep-wheat belt may afford a variety of environmental benefits including sequestration of carbon, remediation of dryland salinity and enhanced biodiversity. However, for the planting to be established at the scale required to make a significant impact, production of commercial products from the plantings may be an important driver. Amongst the most prospective species for this purpose are sugar gum (*E. cladocalyx*), swamp yate (*E. occidentalis*) and spotted gums (*Corymbia* spp.). Vineyard trellis posts might be produced within about 8-12 years from these species and/or be sourced from thinnings of a longer-term sawlog crop.

The Australian vineyard industry relies on wooden posts to support vine trellises. The majority of posts used at present are CCA-treated pine and are prone to breakage from mechanical harvesters. Untreated pine is insufficiently durable to last more than a few years in most soils, and much less than the 25 years in-ground that is required of a vineyard post. New vineyards and replacement of posts creates demand for approximately 5.5 million posts per year, costing the industry over $30 million. Naturally durable posts for other farming and horticultural enterprises (especially organic farming and horticulture) would also be desirable. Clearly there is a sizeable potential market, and a significant opportunity for entry of a new, environmentally sustainable product.

The research reported is a first step in developing a new and environmentally sound product from eucalypt plantations in Australia's low rainfall sheep-wheat belt. The finding that young-aged (8-year-old) *E. cladocalyx* has good scope for genetic improvement is complemented by the observed natural durability properties. However, further research is needed into the technical feasibility of posts (e.g. strength, splitting), possible removal of sapwood from posts, *in situ* testing, plantation silviculture for post production and economic viability.

Who is the report targeted at?

This report is targeted at researchers, extension workers and industries in the wine growing regions, as well as other horticulture, agriculture and commercial environmental forestry sectors. For the wine growing sector this research addresses the development of a new product that is essential to the industry, can be produced in an environmentally sustainable manner, is free from chemical preservatives, performs at least as well as the existing products and can be readily disposed of. There should be a significant potential market if they can be produced at a reasonable cost.

The commercial environmental forestry sector will find the report of interest because it discusses a medium-value product that can be grown within a short timeframe (around 10 years) on low rainfall sites. Such a product, if commercially viable, has the potential to significantly lift planting rates and generate concomitant environmental and economic benefits in the sheep-wheat belt.

Aims/objectives

The study set out to examine whether it might be possible to genetically improve the natural durability of two low rainfall eucalypt species with vineyard trellis posts as a potential target product. The aim was to assess pole-sized, very young eucalypt material (8-12 y.o.), the natural durability of which has not been studied previously. The study initially targeted *E. cladocalyx* and *E. occidentalis* that were considered good prospects for being sufficiently durable, based on information from older specimens. *E. occidentalis* failed to show promise in an initial pilot study, and so a third species group, the spotted gums (*Corymbia* spp.) was substituted as a likely prospect. This species was chosen because it is highly suited to sawn timber production, and the heartwood development trait critical to producing durable posts would also be beneficial for this purpose.

Methods used

Of the two species initially selected for study (*E. cladocalyx* and *E. occidentalis*), the durability properties including the durability of young aged (<25 y.o.) wood of *E. cladocalyx* has been researched more intensively than that of *E. occidentalis*. Accordingly, an initial pilot study focussing on the durability as measured by accelerated decay of a small sub-sample of trees was carried out. This study indicated that the durability of *E. occidentalis* was not sufficient to merit further study, so a third species complex, the spotted gums *(Corymbia* spp.), which also has excellent sawn timber properties was included.

The study then examined a suite of traits likely to be directly or indirectly related to natural durability within wood samples (cores taken at breast height) from three field trials (one of *E. cladocalyx* and two of *Corymbia* spp.). These included heartwood proportion, heartwood extractive amount, basic density of heartwood and sapwood, and accelerated decay of core segments exposed to three separate fungal cultures (one white rot and two brown rots) in soil jars. The accelerated decay technique allowed us to predict whether vine posts are likely to be sufficiently durable in-ground for the 25+ years required.

Statistical analysis of the *E. cladocalyx* trial allowed calculation of genetic parameters including heritability estimates for each trait (the amount of measured variation that can be passed on to subsequent generations) and trait correlations (whether selecting for one trait will impact positively, negatively or have little effect on others). The *Corymbia* study was focused at the species and provenance level, and tested whether there are differences between the species and provenances that could be used as a basis for selection in tree breeding, both for naturally durable posts and sawn timber.

Results/key findings

The study has shown that heartwood development (defined as heartwood diameter as a proportion of DBHOB) is quite strong in both *E. cladocalyx* and the *Corymbia* species studied at 8-10 years after planting. Since heartwood is the only part of wood that can be considered to be naturally durable, this is a fundamentally important trait. Significant genetic variation in heartwood proportion indicated that genetic improvement by species/provenance selection in the *Corymbia* and both provenance and family-within-provenance selection in *E. cladocalyx* should be possible. This trait would also be desirable for sawlog production.

The accelerated decay study showed genetic variation in both *E. cladocalyx* and *Corymbia* spp. for resistance to both brown and white rotting fungi. However the most important finding was that while the *E. cladocalyx* has good overall resistance (particularly the South Flinders Range provenances) to fungal deterioration, the *Corymbia* heartwood was attacked severely, particularly that of the *C. maculata* samples.

We also found significant genetic variation in basic density in both the *E. cladocalyx* and *Corymbia* spp. Density is usually strongly related to strength properties and sometimes durability. However, though significant, the range of density was quite low. Both species have dense wood even at young age (over 600 $kg.m^{-3}$) which means that post strength is very likely to be high, especially relative to *P. radiata*.

Correlations between the different wood traits studied were in many cases significant, though no undesirable correlations were identified. Extractive content was, in both taxa, negatively correlated with mass loss associated with decay caused by the three fungi, as was basic density in all but one case. The strength of the correlations varied from weak to strong.

Implications for stakeholders

The study has implications for two main groups: (1) those who are interested in developing commercial environmental plantations in Australia's sheep-wheat belt, and (2) the vineyard, horticulture and agriculture sectors who are interested in chemical-free alternatives to CCA and other preservative-treated posts.

This study has identified a potential product from a key low rainfall species (*E. cladocalyx*), that can be produced within a comparatively short time frame (probably 8-12 years on typical sites). This is an important development, because while this species is likely to produce high-quality sawlogs, a disincentive to investment is the long lead-time to final harvest (probably more than 25 years). A commercial product available from thinnings earlier in the rotation would greatly improve the economics of *E. cladocalyx* plantations. Production of pulpwood and/or other composites from thinnings is unlikely to be feasible given the high density of the wood, and high extractives content (as demonstrated here).

The move towards food production systems which are free from chemicals is an important driver for Australia's viticulture and farming sectors and desirable in export markets. Also, disposal of CCA-treated vine trellis posts is an increasing problem, especially with mechanical harvesting that has led to higher breakage rates. The potential for naturally durable posts as replacements and for new vineyards is therefore substantial. Naturally durable *E. cladocalyx* posts may be a solution to the marketing perception, disposal and strength problems that exist with CCA-treated *P. radiata*. Though other materials such as cypress pine and non-wood alternatives (steel, concrete) exist, plantation-grown wood that also accrues environmental benefits where it is grown may be a preferred alternative.

Recommendations

Determination of the feasibility and cost-effectiveness of *E. cladocalyx* vineyard post production requires answers to several further technical questions:

- Whether or not sapwood removal is necessary
- Strength determination
- Heartwood taper
- Pole performance with respect to driving and handling.

In situ testing of poles in a vineyard application would be necessary to fully answer some of these questions.

There is also an opportunity to investigate the natural resistance to biodeterioration of young aged heartwood of other emerging plantation species, particularly those of Class 1 durability suited to low rainfall environments. The natural durability properties of coppice regrowth of *E. cladocalyx* should be assessed, both for future management of plantations by this system, and because of the potential to utilise the extensive existing plantations on farms in western Victoria and elsewhere.

1. Introduction

1.1. Research rationale

This project assesses the scope for creation of genetically improved varieties of three putatively naturally-durable low rainfall eucalypts tailored to post production; particularly vineyard posts. Though commercially focussed, the overall drivers for this research are environmental: firstly, there is a need to develop commercial products to encourage wide-scale planting of deep-rooted woody vegetation capable of generating environmental goods in Australia's sheep-wheat belt, and secondly; there is a need to lessen the use of toxic materials in Australia's horticulture and agriculture industries.

Re-establishment of deep-rooted woody vegetation in Australia's low rainfall sheep-wheat belt may afford a variety of environmental benefits including sequestration of carbon, remediation of dryland salinity and enhanced biodiversity. However for the planting to be established at the scale required to make a significant impact, production of commercial products from the plantings may be an important driver (so-called 'commercial environmental forestry – CEF'). During the last decade, a large amount of work has been done by a number of research organisations to select and genetically improve a small suite of tree species suited to sawlog production in southern Australia's wheat-sheep belt. Amongst the most prospective are sugar gum (*Eucalyptus cladocalyx*), swamp yate (*E. occidentalis*) and spotted gums (*Corymbia* spp.) - see for example Harwood *et al.* (2001); Arnold *et al.* (2005); Bush (2008). Though they have moderately good growth rates for this region, sawlogs might still be expected to take 25 years or longer to reach harvestable size. Clearly a use for smaller sized logs, taken either as thinnings from a sawlog crop or harvested for a specific purpose, would be an incentive for establishment of plantings, especially as most of the sheep-wheat belt is privately owned farmland. Vineyard trellis posts potentially fall into this category, because the product might conceivably be produced within about 8-12 years and/or be sourced from thinnings of a longer-term sawlog crop.

The Australian vineyard industry relies on wooden posts to support vine trellises. The majority of posts used at present are CCA-treated pine: untreated pine is not sufficiently durable to last the 25 years in-ground that is required of a vineyard post. Softwoods are also weak cf. hardwoods; breakages are frequent and post replacement costly. The expansion of new vineyards and replacement of breakages creates a sizeable demand for posts, an estimated 5.5 million per year, costing $33 million (Cookson *et al.* 2002). At times, there is insufficient supply and alternative materials are being sought. A replacement product that has similar or better durability and strength would therefore have a ready market. Naturally durable posts for other farming and horticultural enterprises (especially organic farming) would also be desirable.

1.2. Use and demand for naturally durable and preservative-treated timbers in Australia

There are numerous *Eucalyptus* species that have long been known to have good in-ground durability, making them suitable for fence posts, poles and other structural applications involving contact with soil. Many Australian farms made use of local resources of eucalypt poles for their fencing requirements. In recent decades, posts made from softwoods treated with preservative chemicals have dominated the market. There are a number of factors favouring the use of treated softwoods over naturally durable eucalypts including:

- Ready supply of cheap, plantation-grown softwood timber sourced from thinnings of sawlog plantations
- High performance preservatives, most notably copper-chrome-arsenate (CCA) which extend the in-ground life of non-durable pine species such as *Pinus radiata* to 25+ years
- A move away from native forest logging – the only large source of naturally durable hardwood posts
- Clearance of suitable timber from farms
- Depletion and protection of local stands of naturally durable timbers in local farming environments

A large user of treated pine posts is Australia's wine growing industry. The area of vineyards has expanded significantly in the last two decades, and now covers 174 000 hectares (Wine Australia 2008a). The wine industry is very significant, and $3 000 000 000 of exports are produced each yea r (Wine Australia 2008b). Cookson *et al.* (2002) estimated that around 5.5 million posts per year are required by the industry, placing the market at that time in the order of $33 million per year.

However there are some issues with treated pine posts that might discourage their use in the grape growing and other horticultural industries:

- They have low strength per cross-sectional area cf. hardwood posts and up to 15% are broken or need replacing due to decay each year (Cookson *et al.* 2002).
- Broken CCA posts are difficult and expensive to dispose of due to their heavy metal content – they cannot be burnt as firewood, for example.
- There may be negative marketing connotations in using treated posts to grow food crops (same would apply to farm fence posts). 'Organic' food that has had the lowest possible exposure to man-made chemicals is becoming increasingly popular in both domestic and export markets.

In addition, non-wood fencing materials such as steel and concrete posts have been substituted for traditional, naturally durable posts. However these materials are not cheap, and require significant quantities of energy to produce. They may become relatively less economically viable to produce if energy costs increase and/or greenhouse gas emission issues become limiting in future.

1.2.1. Post specifications

Trellis posts are of two main sorts: end strainer posts and intermediate posts. Treated softwood intermediate trellis posts are usually 2700 mm long and of 75-100 mm diameter, while the strainer posts are 3000 mm long and usually at least 150 mm in diameter. With the advent of mechanical harvesting of grapes, posts are subject to increased stress, and softwood intermediate post failure is common. As *P. radiata* is a relatively low strength timber, hardwood intermediate posts could conceivably be of somewhat lower diameter than *P. radiata* (perhaps 60 mm) and still be of at least equivalent strength. A 100 kgm^{-3} increase in air dry density (12% moisture content) results in a circa 15-25% increase in modulus of rupture (MOR) based on regression of density and MOR data for a wide range of species given in Keating and Boltza, (1982). For example in a study of PEC (pigment emulsified creosote) treated hardwood posts Cookson *et al*., (2002) showed that 5-year old, 100 mm *E. globulus* posts that had been grown under effluent irrigation broke at around 500 kg of force, whereas PEC treated radiata broke at 400 kg. Usage of narrower posts would also confer an additional advantage in that each post creates a ‘shadow’ area that cannot be mechanically harvested, that increases with post diameter.

1.3. Natural durability

Natural durability is a property of wood that allows it to resist breakdown caused by various organisms, including fungi, termites and borers without treatments of preservative chemicals or coatings. The Australian Standard 5604-2005 for natural durability (Standards Australia 2005) assigns durability ratings for timbers in above-ground, in-ground and marine applications. For in-ground applications, separate ratings are assigned for resistance to termites and resistance to soil fungi. The fungal ratings for in-ground and above ground application are summarised in Table 1 with some examples. Numerous further examples are listed in the standard itself.

Table 1. Natural durability rating system with examples of heartwood durability for various softwoods and hardwoods as assigned by AS 5606-2005

Class	Durability above ground (years)	Durability in-ground	Examples
1	>40	>25	Ironbarks (e.g. *E. tricarpa*, *E. sideroxylon*), *E. cladocalyx*, grey gums (e.g. *E. punctata*)
2	15-40	15-25	Spotted gums (*Corymbia* spp.), Blackbutt (*E. pilularis*), River redgum (*E. camaldulensis*), *Callitris* spp. (native cypress pine)
3	7-15	5-15	Western red cedar (*Thuja plicata*), Sydney, Tas. blue gums (*E. saligna*, *E. globulus* respectively)
4	0-7	0-5	Ash (*E. delegetensis*, *E. regnans*). Douglas fir (*Pseudotsuga menziesii*), Dunn’s white gum (*E. dunnii*), *Pinus radiata* (radiata pine)

These ratings were first determined in the 1950s and were based upon laboratory trials, the experience of foresters and those writing the standard (Tamblyn 1966). Durability is based upon the resistance of the outer heartwood of mature timbers. The sapwood of all species is considered non-durable, and for many timbers the inner heartwood and pith is also of lower natural durability than the outer heartwood (Giordano, 1981; Windeisen *et al*., 2002; Gambetta *et al.*, 2004).

There is also a common perception that heartwood of younger trees, especially those that are faster grown, will be markedly less durable than ‘old-growth’ wood. However, CSIRO research has shown that younger aged plantation heartwood from Queensland (Johnson, Thornton *et al.* 1993) and southern Australian low rainfall species (McCarthy *et al.* in press) is not necessarily much less durable than old-growth material. The strongest reason that the perception exists is that younger trees, especially those that are rapidly growing and have a vigorous crown, will have a greater proportion of sapwood present, and this of course will be of low durability unless treated.

There are a number of determinants of wood’s natural ability to resist biodeterioration, i.e. physical and chemical attack by bacteria, fungi, insects, and marine animals that can cause severe degradation of the wood structure. Certain timbers are noted for their resistance to biodeterioration and are recommended for use in untreated in-ground applications. Conversely, others are known to be highly susceptible to biodeterioration. Despite this, there is usually significant diversity in resistance within species, so that the service life of timbers cut from different trees can be widely variable (Gambetta *et al.* 2004).

The factors responsible for the differences in durability are numerous and diverse. However the most important factor is the presence of extractives within the wood itself. These are formed as an axial core after the sapwood is transformed into heartwood, and it is therefore not surprising that it is only the heartwood of 'durable' species that are actually durable: sapwood is highly susceptible to biodeterioration. Heartwood can provide both static and dynamic defence against decay. Toxic polyphenolic extractives act as chemical barriers and tyloses act as physical barriers limiting access to the transpiration system. Tyloses are also actively produced as a response to sapwood wounding (Beckman 2000). Extractives can posses both fungicidal properties (though this is not always the case, even in highly durable heartwood) as well as being excellent free radical scavengers (antioxidants) (Schultz and Nicholas 2000).

1.4. Potential plantation species for durable vine posts

1.4.1. *E. occidentalis* - swamp yate

E. occidentalis is distributed in the southern part of Western Australia including the Stirling Ranges. The principal occurrence is on lower country, usually alluvial flats subject to flooding, where the soil is often clayey. It can thrive near salt lakes and some provenances are notably salt-tolerant (Boland *et al.* 1984; Marcar and Crawford 2004). The species is also highly tolerant of drought, and is well-suited to low rainfall sites receiving between 400-600 mm MAR.

The heartwood is pale, hard, and somewhat straight-grained. There is high tannin content in the bark (Boland *et al.* 1984). The wood has been used for posts and poles, and while it has been used in situations where heavy and strong wood is required, it is regarded as inferior to the related species, yate (*E. cornuta*), that is rated one of the hardest and strongest timbers in the world (Hall *et al.* 1992) There appears to be a potential for producing finer sawn products from swamp yate (Bird 2000).

Swamp yate was not included in the CSIRO in-ground field-test of Australian timbers. The revised CSIRO natural durability classifications and the Australian Standard list the closely related yate as durability class 2 (Standards Australia 2005).

Genetic improvement of swamp yate commenced in the 1980s with provenance trials, and a formal breeding program commenced in 1999 (Harwood 2001). The species has generally quite poor stem form, though some provenances are much better than others. Unlike the other eucalypts selected for this study, it is relatively easy to propagate by cuttings (Brammall and Harwood 2001), which makes clonal plantations of trees with good durability properties a possibility.

1.4.2. *E. cladocalyx* - sugar gum

Sugar gum is endemic to South Australia with naturally occurring populations in three areas (South Flinders Ranges, Eyre Peninsula and Kangaroo Island). This species is a prime candidate for planting in semiarid areas with about 400-600 mm annual rainfall falling predominantly in winter. *E. cladocalyx* tolerates low to moderate salinity and a wide variety of infertile soils including calcareous soils, but is intolerant of waterlogging (Marcar *et al.* 1995) and very light sandy soils.

It was commonly used for poles, posts, bridge piles, heavy and general construction and railway sleepers (Boas 1947) though its use in western Victoria, where it was a common plantation species from the 1880s onward, appears to have declined post-World War II (Andrew Lang, Smart Timbers, Lismore pers. comm.). The sapwood of sugar gum is pale and susceptible to lyctid borer attack (Standards Australia 2005). The heartwood is yellowish to brown, of fine uniform texture, grain commonly interlocked and the wood is hard, heavy and of moderate strength and highly durable (Boland *et al.* 1984).

Sugar gum was given a tentative durability rating of Class 2 in the 1950s (Tamblyn 1966). However, CSIRO field-testing has led to a reclassification of (mature) sugar gum to Class 1 (Thornton *et al.*, 1997; Standards Australia, 2005). Thornton *et al.* were able to show that the mean rating of the outer heartwood of sugar gum was amongst the most resistant of hardwood species with respect to decay and termites at the 21-year inspection. Further inspection by Johnson *et al.*, (1996) showed that after 25 years' exposure at the five Australian sites, sugar gum was in a group of the more durable species that had yet to become unserviceable at four of the five sites. Its performance appears to be similar to timbers of the highest durability such as red ironbark, tallowwood and grey ironbark.

Sugar gum has good potential as a low rainfall plantation species, with moderate growth rates and good form in the better provenances. Formal genetic improvement commenced in 1999 (Harwood and Bulman 2001). Rates of planting appear to have increased markedly during 2007 based on volumes of seed sold (Australian Tree Seed Centre unpublished data).

1.4.3. Spotted gums - *Corymbia* spp.

Spotted gums naturally occur in the coastal areas of New South Wales as far south as Bega and also extends northwards to Maryborough in Queensland. One native stand also occurs in far eastern Victoria, northwest of Orbost (Brooker *et al.* 1997). The group formerly consisted of four species: *Corymbia citriodora* (lemon scented gum), *C. variegata* (spotted gum), *C. henryi* (large leafed spotted gum) and *C. maculata* (spotted gum), with *C. henryi*, *C. maculata* and *C. variegata* all having been classified as *E. maculata* prior to identification of *Corymbia* as a separate genus (Hill and Johnson 1995). On the basis of isozyme studies (McDonald *et al.* 2000) and morphological evidence, *C. variegata* was relegated to sub-specific status as *C. citriodora* subsp. *variegata* by McDonald and Bean (2000). In this report the taxa names are abbreviated to CCV for *C. citriodora* subsp. *variegata*, CCC for *C. citriodora* subsp. *citriodora*, CM for *C. maculata* and CH for *C. henryi.*

Spotted gum (*C. maculata*) was selected as a key species by the Australian Low Rainfall Tree Improvement Group because of its widely demonstrated growth, form and sawn timber properties in many low rainfall farm forestry plantations in southern Australia (Harwood *et al.* 2001). Relative to the other ALRTIG key hardwood species, including *E. cladocalyx* and *E. occidentalis*, spotted gum has the advantage of producing trees of superior stem form, even in open grown situations or at low stocking densities. Its timber properties are excellent, and it is among the best Australian hardwoods in terms of sawn timber recovery. Its growth rates are very good on appropriate sites receiving greater than 500 mm annual rainfall, or where additional groundwater is available. However, it is the least hardy of the key low rainfall species, and is not suited to waterlogged, saline or very dry sites. Its use is therefore restricted to only the best sites at the upper end of rainfall in the sheep-wheat belt, but its excellent timber properties might also see it widely utilised for timber production in medium rainfall areas receiving between 600 and 800 mm MAR.

Spotted gum is used for heavy engineering construction, poles, piles, flooring and plywood (Bootle 1985). It has been one of the major pole timbers for Australia's power and telecommunications networks, in particular throughout Queensland (McCarthy and Greaves 1990). It is a favoured species for outdoor applications such as decking. The sapwood is pale and is very susceptible to lyctid attack. The heartwood is light to dark brown, the grain often interlocked and moderately coarse-textured with fiddle-back figure. The heartwood is hard, strong and has a reputation for good durability.

The Australian Standard 5604-2005 assigns spotted gum to durability class 2. Johnson *et al.* (1996) indicated that after 25 years' exposure in in-ground field trials, replicates of spotted gum heartwood specimens were only present at one of the five sites: Rowville. After 21 years exposure, at least 75% of replicates had become unserviceable at Brisbane due to decay, Innisfail due to termite attack, Pennant Hills due to decay and Walpeup due to termites. All replicates were still serviceable at Rowville (considered the least active of the sites). We are aware that 'Queensland spotted gum' (presumably CCV) has an anecdotal reputation for being more durable than its southern counterpart (which could be any of CM, CH or CCV). (Bolza 1978) mentions that the wood of some NSW south coast stock may be durability class 3 rather than 2, and that there is considerable variation from tree to tree and within tree (from outer heartwood to pith) within the spotted gums.

Genetic improvement programs for the spotted gums are being carried out by a number of organisations, including ALRTIG, FNSW and Queensland Department of Primary industries. The form of the species is generally very good. In areas of summer dominant rainfall, *Ramularia* shoot blight is frequently a problem, and CCV is most commonly planted, as some genetic material has resistance to the disease. In southern Australia, CM usually outperforms CCV with respect to survival and diameter growth (Bush *et al.* 2007).

1.4.4. Other species

Generally, tree species that are well-adapted to low rainfall environments tend to be at least moderately durable, and often highly durable. Other species that are currently of interest for commercial environmental forestry include *E. camaldulensis* and its hybrids, the red ironbarks (*E. tricarpa* and *E. sideroxylon*) and grey gums (e.g. *E. punctata*, *E. major*, *E. biturbinata* and *E. longirostrata*). Of these, *E. camaldulensis* is durability class 2 while the others are durability class 1 (Standards Australia 2005). These species would certainly be of interest for durable post production, and their suitability for the purpose can be assessed within the next five years once trials established by CSIRO and state organisations reach a sufficient age and size for assessment.

1.5. Determinants of genetic improvement

Genetic improvement of a species aims to systematically improve performance with respect to specific traits that are important to the target product. For genetic improvement of a trait to proceed, there must be both *variability* and *heritability*. If there is no observable variation in the trait (if for example the trees in a population all have the same diameter), then it will be impossible to select superior trees and make genetic gain for diameter growth. If there is variation, it will be possible to identify and select a subpopulation comprised of the largest trees from which to breed. Heritability refers to the passing on of genes from one generation to the next. If the diameter trait is heritable, the progeny of the selected subpopulation will inherit this property, to some extent, and thus will be genetically improved (i.e. have a larger mean diameter) compared with the original population. It is possible to carry out genetic improvement at the species/provenance level, or within provenances. Heritability estimates are usually measured on a scale of 0-1, corresponding to the proportion of observed variation that is passed on. It follows that the rate of genetic improvement is a function of heritability, variability and also intensity of selection. More information on this subject in the context of eucalypt domestication and breeding is available in Eldridge *et al.*, (1993).

1.5.1. Natural durability traits

To achieve a breeding objective of maximising production of naturally durable poles and posts, tree breeders might focus on maximising the yield of poles with sufficient heartwood diameter per hectare per year, and simultaneously maximising the durability of that heartwood and the strength of the pole or post. There are a number of selection traits that may contribute to achieving this objective:

1. Heartwood diameter, area or proportion
2. Resistance to decay by various types of fungus and other biological attack (e.g. fungal mass loss or longevity in-ground or in an accelerated decay facility)
3. Strength (e.g. modulus of elasticity - MOE, modulus of rupture - MOR)
4. Extractive content and composition
5. Lignin and/or cellulose content
6. Basic density

One or more of these traits have been examined in each of the various studies listed in Table 2. A large range of heritabilities (broad and narrow sense) from low to high have been estimated, though the majority of authors have concluded that it would be possible to make significant genetic gain through selection and breeding for these traits. Reviews of studies in softwood species have also indicated that the heartwood and sapwood properties are usually more heritable than growth traits (Paques 2001). There is little available published research that specifically addresses genetic improvement of natural durability traits in hardwood species.

Of the traits listed above, the first three relate directly to properties of the target product (i.e. naturally durable posts). The other three are more or less likely to be correlated to the first three, given that the constituents of wood confer resistance or susceptibility to decay.

Genetic variation of natural durability traits has not been well-studied in eucalypts, though it has long been recognised that genetic variation is an important source of observed variation (Rudman 1964). Extractives are an exception: they are a key trait for pulp production (impacting negatively on the pulping process). Heritability estimates therefore tend to have been from species that are well-suited to pulping and are low in extractives relative to ones that might be chosen for end-uses requiring naturally durable.

Provenance selection is an important way of making genetic gains, and should be exploited at the start of any breeding programme (Eldridge *et al.* 1993). Significant provenance effects for extractives content have been found in *E. globulus* (Washusen *et al.*, 2001; Miranda and Pereira, 2002) and for heartwood area in *E. grandis* (dos Santos *et al.*, 2004) (Langat and Kariuki, 2004), *E. obliqua* (Nicholls and Matheson, 1980) and *Tectona grandis* (teak) (Kjaer *et al.*, 1999) suggesting provenance selection could be used to improve some traits.

Correlation between traits is another important consideration in tree breeding. It may be reasonable to assume that since extractives are a component of the heartwood (up to 20% but typically less than 10% by weight in eucalypts), greater extractive yield might be positively correlated to higher density. It then follows that since decay resistance is likely to be positively correlated to higher extractive yield, it might also be correlated to higher density.

Table 2. Examples of estimates of heritability and/or provenance variation for durability-related traits in various forest tree species

Species	Trait	Heritability (narrow sense unless noted)	Note	Author
Eucalyptus	Extractives	0.37		(Poke *et al.* 2006)
globulus	Extractives	N/A	Significant between provenances	(Miranda and Pereira 2002), (Washusen *et al.* 2001)
E. grandis	HW area %	0.39		dos Santos *et al.*, (2004)
	HW area %	N/A	Significant between provenances	Langat and Kariuki, (2004)
E. obliqua	HW area %	N/A	Significant between provenances, but not families within	Nicholls and Matheson, (1980)
Larix spp	HW radius	0.75-0.92	Broad-sense	Paques, (2001)
	HW proportion	0.63-0.99		Paques, (2001)
	Mass loss	0.39	*Coniophora puteana*(broad-sense)	Venalainen *et al.*, (2001)
Picea glauca	Fungal growth rate	0.21	*Gloeophyllum*	Yu *et al.*,(2003)
		0.27	*trabeum*	
		0	*Trametes versicolor*	
			Fomitopsis pinicola	
Pinus banksiana	HW area %	0.23		Magnussen and Keith, (1990)
P. radiata	HW area prop.	0.2		Nicholls and Brown, (1974)
	HW area prop.	0.98		Nyakuengama *et al.*, (2000)
P .sylvestris	HW dbh	0.3-0.54		(Ericsson and Fries, 1999); (Fries and Ericsson, 1998)
	Mass loss	~0		Harju *et al.*, (2001)
	Mass loss	0.29	*C. puteana.* Mass loss positively correlated to density	Harju and Venalainen, (2002)
P. taeda	Mass loss	0.22	Broad sense. Trait-trait correlation = -0.64	Schmidtling and Amburgey, (1982)
	Basic density	0.64		
Tectona grandis	HW area %	n/a	Significant variation within and between provenances	Kjaer *et al.*, (1999)

Support for this comes from Schmidtling and Amburgey, (1982) who found that the decay susceptibility of *P. taeda* wood to a brown rot decay fungus *Gloeophyllum trabeum* is inversely related to its specific gravity. However in five other studies of softwoods identified in a literature review by Harju and Venalainen, (2002) (Southam & Ehrlich 1943, Rennerfelt 1947, 1956, Richards 1950, Suolahti, 1948), no relationship between density and decay resistance was identified. Moreover, Harju and Venalainen, (2002) identified an unfavourable positive genetic correlation between the heartwood density and mass loss in *P. sylvestris*, and surmised that increased heartwood density may have enhanced the availability of cellulose for the brown rot fungus (*C. puteana*) used in their study. Yu *et al.*, (2003) found a similar positive correlation between brown rot growth and basic density in *Picea glauca*.

2. Materials and methods

2.1. Investigative procedure

The study was conducted in two phases: an initial pilot study, followed by a more detailed study. The pilot study examined the heartwood properties of a small subset of samples of *E. cladocalyx* and *E. occidentalis* (the species nominated for study in the initial project design) to investigate whether or not the amount of heartwood in young-age (post-sized) trees was sufficient to be considered for a vineyard post, and also whether the resistance to decay was sufficient for the target product.

The results of the pilot study (see Section 3.1) indicated that while *E. cladocalyx* was a promising subject for further study, *E. occidentalis* lacked sufficient resistance to soil decay organisms. This finding, taken together with newly emerged results from a study on termite resistance that concluded as the pilot study commenced (McCarthy *et al.* In press) showed that *E. occidentalis* has the highest susceptibility to termite attack of a suite of low rainfall species tested, whereas young-age *E. cladocalyx* and spotted gum performed well. A decision was made to instead investigate wood properties associated with natural durability and heartwood variation in spotted gum (*Corymbia*) species. Though members of this group are listed as durability class 2, a study by McCarthy *et al.*, (in press) indicated promising results from young-aged (<25 y.o.) material. Spotted gum also produces excellent sawn timber, and hence heartwood properties are of general interest, even without natural durability properties – a further advantage over *E. occidentalis*. Though trials suitable for calculation of genetic parameters such as heritability were not available, it was thought useful to investigate whether there are significant differences between the main species of spotted gum planted in Australia. A spotted gum trial at Yarralumla, ACT was analysed first for all traits, and the results from this study were used to select traits to measure in a larger spotted gum trial at Holbrook, NSW. The traits measured at Holbrook were restricted to heartwood proportion and basic density only, since the accelerated decay results from Yarralumla were not promising.

2.2. Genetic materials and trial locations

2.2.1. Swamp yate – *E. occidentalis*

Data were collected from a small, random sample of trees from six separate families in a provenance-progeny trial situated at Shelford, Victoria. The trial was established in 1998 and its composition was eight replicates of 85 families from 17 natural provenances planted in five-tree plots. The trial was planted at 1235 stems per hectare. Growth data were collected prior to first thinning in August 2006. Disks were sampled from six trees at breast height for heartwood and accelerated decay testing. Wood disks were taken at the time of first thinning in August 2006. This trial was only used for the pilot study, since results (see section 3.1.) indicated unsatisfactory resistance to biodeterioration.

2.2.2. Sugar gum – *E. cladocalyx*

Data were collected in August 2006 from an *E. cladocalyx* progeny trial situated at Benalla, Victoria. The site was established in 1998 by CSIRO as a provenance-progeny trial. All families included were collected as representative random samples from wild populations with the exception of the Gilgandra planted stand. The trial incorporates 73 families from seven provenances (Table 3) that come from three regions of provenance as defined by McDonald *et al.*, (2003): South Flinders Ranges, Eyre Peninsula and Kangaroo Island. The Gilgandra entry is from a bulk collection of unknown origin. It is most likely that this seedlot is based on material taken originally from the South Flinders Ranges, as this material was the most widely dispersed from the 1870s onward. The Benalla trial was established as four replicates of five-tree plots in randomised complete blocks. An additional four replicates of randomised plots including a subset of families were also established. The trial was planted at 1235 stems per hectare. It had not been thinned at the time the core samples were taken in August 2006.

Table 3. Composition of the Benalla *E. cladocalyx* provenance-progeny trial

Regions of provenance and provenance	ATSC seedlot number	No families in trial	Families sampled	Samples taken
South Flinders Ranges				
6.7 km NE Wirrabara Forest	16013	11	6	26
Wilmington	19348	10	7	35
9 km S Wilmington PO	16089	10	10	48
Eyre Peninsula				
Marble Range	19349	10	5	21
6.1 km ESE Wanilla PO	16018	10	5	20
Kangaroo Island				
Flinders Chase National Park 1	16022	12	11	55
Flinders Chase National Park 2	19717	10	5	21
Planted stand				
Gilgandra	11834	1	1	4
Total	**8**	**74**	**49**	**226**

The diameter of all trees in the trial was measured in 2006, allowing assessment of growth performance. The trial had reached the canopy closure stage in circa 2003 and had not been thinned.

Families were selected for sampling on the basis of their diameter growth ranking, with larger-diameter families ranking highest. Trees were preferentially selected within families on the basis of potential suitability (sufficient diameter and straightness to a height of 3 m where possible) for a vineyard post at the time of sampling. As this trial was based entirely on unselected, wild material, it was not always possible to find enough trees with these characteristics, and so trees having sufficient diameter but not stem straightness were selected in some cases. This procedure was chosen over completely random sampling because it creates a future opportunity to harvest test poles whose performance can be related to the data reported here.

2.2.3. Spotted gum – *Corymbia* spp.

Spotted gum data were collected from two trial sites, one situated on the CSIRO Yarralumla campus in the ACT and another 20 km from Holbrook in NSW. The trials contain pedigreed trees from four of the spotted gum taxa, namely *C. maculata, C. henryi, C. citriodora* ssp. *variegata* and *C. citriodora* ssp. *citriodora*. These taxa are denoted CM, CH, CCV and CCC respectively. Table 4 shows numbers of trees sampled from each taxon at each site. The Yarralumla site was established in August 1997 and the Holbrook site in September 1996.

Table 4. Details of spotted gum provenances included in the study

Species and provenance	ATSC seedlot number	Latitude	Longitude	Altitude (m a.s.l.)	No. sampled Holbrook	No. sampled Yarralumla
Corymbia maculata						
Mottle Range, VIC	19382	3737	14813	280	12	2
Mumbula SF	19421	3638	14956	120	-	2
Kiola SF	19308	3535	15020	70	-	7
Nelligen, NSW	19481	3537	15004	200	16	-
Wingello S.F., NSW	19263	3444	15011	580	11	2
Curryall SF	19663	3204	14950	650	-	11
Yarrat SF Taree	19751	3149	15225	60	-	4
C. citriodora ssp. variegata						
Paddys Land SF	19564	3006	15210	1100	-	18
Richmond Range S.F., NSW	19469	2850	15244	350	27	7
45 k W of Dalby, QLD	17755	2713	15052	380	8	-
Woondum SF	19756	2617	15217	120	-	2
Barkula SF, QLD	19664	2616	15032	300	4	-
Mt Hutton	19690	2552	14816	650	-	9
Saddler Springs	19665	2506	14804	700	-	7
Monto	19694	2449	15056	475	-	5
C. citriodora ssp. citriodora						
20km W/NW Monto	19693	2448	15059	500	-	5
5km S Herberton	14851	1723	14523	1000	-	3
C. henryi						
S. of Grafton, NSW	19468	2909	1529	50	16	-
Ewingar S.F., NSW	16899	2901	15229	520	24	-
Braemer SF	19750	2902	15258	90	-	5
Total					**118**	**89**

The Holbrook site was initially established as five replicates of five-tree plots per family. It had been fully thinned at the time of sampling in November 2007, leaving one of the original five trees per family per block replicate. The Yarralumla site was a completely randomised design of single tree plots.

2.3. Analytical and sampling procedures

2.3.1. Coring

Two 12 mm diameter, bark-to-bark cores were removed from each tree at breast height using the CSIRO Trecor powered coring device. The two cores were aligned with less than 20 mm vertical displacement between centres. All cores were taken from the same (north-south) orientation, and the northern end was marked on each core along with the individual tree identity. The cores were wrapped in plastic film and kept cool in the field, and transferred to a laboratory cold room (3^0C) for short-term storage on return. In most cases the bark separated from the sapwood during coring; it was removed and discarded from those cores where it was still attached.

2.3.2. Heartwood-sapwood boundary definition and proportion

On return from the field, one core from each pair was stained along its length with dimethyl yellow. This stain is a pH indicator, and is an accepted method for sharply delineating the heartwood-sapwood boundary of eucalypts (Hillis 1987). The heartwood boundary was traced from the stained core to the unstained core. The core sapwood and heartwood lengths were measured using a vernier caliper, giving heartwood and sapwood proportions of total diameter at breast height under bark (DBHUB). An alternative measure used in some studies is the proportion of heartwood by area, a more relevant measure of the trait if sawn boards are the target product. We have chosen heartwood diameter because this can be directly referenced to post diameter. All stained cores were photographed for later reference. DBH over bark (DBHOB) was determined in the field using a diameter tape, and bark diameter and thickness was determined by subtracting DBHUB from DBHOB of the cored stem.

2.3.3. Basic density

The stained core was placed in cold water for 24 hours to achieve fibre saturation. The core was then partitioned into three sections, two sections of sapwood and the heartwood, and each section was labelled. The volume of each core section was then accurately determined by the water displacement method (TAPPI 1989). The core segments were then oven dried at 103^0C +/- 1^0C for 24 hours and weighed. Basic density for the sapwood and heartwood of each tree's core sample was then determined as the oven-dry weight divided by the volume for each segment.

2.3.4. Accelerated biodeterioration

Following basic density determination, the stained heartwood segments were prepared for accelerated decay testing. Prior to exposure to decay fungi, specimens were sterilized by gamma (γ) irradiation. Three fungi, two brown-rot (*Gloeophyllum abietinum [13851]* and *Fomitopsis lilacino-gilva [1109])* and one white-rot (*Perenniporia tephropora [7904]*) were used to evaluate the core specimens. In the pilot study, an additional brown rot, *Coniophora olivacea* was also included. Glass jars with a 250 mL capacity were filled with 136 g fresh (damp) Toolangi soil and moistened with 14 mL to 100% water holding capacity. One poplar sapwood veneer feeder strip (40 x 45 x 2 mm) which had been soaked overnight in 1% malt extract solution was placed on top of the soil in each jar. Metal lids were used to close the jars which were then sterilized by autoclaving and allowed to cool. Feeder strips were introduced into the jars and inoculated with actively growing mycelium of the test fungi and incubated at 25^oC. When the feeder strips were fully colonized by the fungi, two sterile test specimens were placed on top. A replicate set of jars was left uninoculated as a sterile control. Specimens were also placed into these jars to determine any mass loss or gain not attributable to fungal attack. All jars were incubated at 25^oC for 12 weeks. Test specimens were then removed from the jars and wiped of any adhering mycelium. The test specimens were then weighed to determine moisture content, and left to air dry for 12 days. Specimens were then dried in vacuum ovens at 40^oC and -95 kPa for five days, weighed, adjusted to accommodate any changes recorded in the sterile controls, and percentage mass losses determined.

2.3.5. Extractive weight determination

Methanol was selected as the most suitable solvent because it is now the most often used for *Eucalyptus* extractive determinations due to its relative safety compared with alternatives (Standards Australia 2003). The second, unstained set of cores was used in the determination of heartwood extractive content. The sapwood portions of the core were excised, and the heartwood portion ground to a 200 micron granule using coarse then fine Wiley mill screens.

Ground wood samples were then oven dried at 103^0C +/- 1^0C for 24 hours and placed in an air-tight desiccator until cool. Once cool, 2.000 +/- 0.100 g of wood granules from each sample was weighed into a cellulose extraction thimble. The sample was placed in a soxhlet apparatus charged with 180 mL of methanol and extracted for 6 hours. The methanol extract was rotary evaporated under reduced pressure until circa 5 mL of extract remained. It was transferred to a watch glass of known weight, and placed in an oven at 70^0C for 12 hours to fully evaporate the solvent. The watch glass was removed from the oven, allowed to cool in a desiccator and then weighed to determine the mass of extractive as a percentage of the heartwood mass.

2.3.6. Statistical analysis

Statistical analyses were carried out to determine means, significance of effects and variance parameters of the traits assessed. Genstat version 11 (VSN International, Hemel Hempstead, UK) was used for restricted maximum likelihood analysis of variance in each measured trait. The analyses were all based on general linear mixed models of the form:

[Equation 1] $$\mathbf{y} = \mathbf{Xb} + \mathbf{Zu} + \mathbf{e}$$

where **y** is the vector of observations on *n* traits, **b** and **u** are vectors of fixed and random effects respectively, **X** and **Z** are incidence matrices for fixed and random model terms and **e** is a vector of random residual terms. Variants of this model were applied as follows:

1. For estimation of significance of effects and effect means (all taxa)

The vector **b** (Equation 1) contained sub-vectors for fixed effects of replicate, region-of-provenance (in *E. cladocalyx*) or species (in spotted gum), provenance and family effects, and **u** contained sub-vectors for the random effects of plots and incomplete blocks in the equivalent DBH analysis of the whole trial in *E. cladocalyx*. The incomplete block and plot terms were dropped from analyses of traits where variance components were small or negative and with large standard errors. In practice this was virtually all of the wood property traits. Wald tests were performed for fixed effects with approximate F statistics and corresponding numbers of residual degrees of freedom using the method devised by Kenward and Roger, (1997) implemented in Genstat 11.

2. For estimation of variance components and functions of variance components in E. cladocalyx

ASReml version 2.0 (VSN International, Hemel Hempstead, UK) was used to determine genetic variance components and perform calculations using these components. This software calculates standard errors of variance component functions using a first-order Taylor series expansion to approximate the variance of a ratio of variances (Lynch and Walsh, 1998; Gilmour *et al.*, 2002). Univariate analyses estimated the heritability of each trait, and multivariate analyses estimated correlations between traits (Type-A correlations). Families were modelled as nested within provenances. Incomplete blocks and plots were modelled without covariance, while family effects and the error vector **e** were modelled with covariance to determine genetic correlations. Narrow-sense heritability (family within provenance) was estimated for each trait as:

[Equation 2]

$$\hat{h}^2 = \frac{2.5\sigma_f^2}{\sigma_f^2 + \sigma_e^2},$$

where σ_f^2 is the variance of half-sib families and σ_e^2 is the error variance and 2.5 represents a coefficient of relationship of 0.4 assuming an average outcrossing rate of 70%. For the DBH trait, the plot variance component was also added to the denominator of Equation 2. The Gilgandra seedlot was excluded from the heritability estimations and type A correlations.

As family level variance components were not estimated for the spotted gum material, phenotypic rather than genetic correlations were calculated. The product-moment (Pearson) correlations and two-tailed tests of the hypothesis that the correlations are different from 0 were implemented in Genstat 11 using the `FCORRELATION` procedure.

3. Results

3.1. Pilot study

A small sample (twelve disks from six trees) of *E. occidentalis* was examined. The objective was to ascertain whether or not very young-aged *E. occidentalis* (8 years old) material has enough heartwood, and whether the heartwood is suitably durable for in-ground uses such as vineyard posts. Some older (20 years), but not mature *E. cladocalyx* was also included. Prior indications from studies on somewhat older (9-25 years) *E. occidentalis* (McCarthy, Cookson *et al.* in press) were that its natural durability might be lower than *E. cladocalyx*, but possibly of suitable durability for the application considered in this study.

In *E. occidentalis*, heartwood was visually conspicuous from sapwood (unusually, heartwood is a paler colour in this species), whereas colour transition in *E. cladocalyx* was not well defined. The heartwood sapwood boundary in *E. cladocalyx* was determined using methyl yellow pH indicator dye (see Section 2.3.2). Heartwood diameter in the small samples was suitably broad (greater than 60 mm in each tree at 1.3 m above ground) to produce a vineyard post. Sample blocks were cut from the discs and they were placed under test for biodeterioration as described in section 2.3.4. Various controls consisting of treated and untreated *Pinus radiata* and sapwood samples, and two experimental preservative treatments (one waterborne and one solvent-borne) were also included. The preliminary tests indicated that *E. occidentalis* is probably not suitably durable for in-ground use as vineyard posts, with significant decay evident, especially for samples inoculated with the white rot fungus, which performed similarly to the untreated *P. radiata* sapwood controls. Mass loss of less than 5% in these tests is generally considered to be the acceptable “pass” threshold for preservative treatments and the swamp yate did not attain this standard with any of the fungi (see Table 5). The *E. cladocalyx* samples performed well in this study.

Table 5. Mass loss of treated and untreated samples subjected to four fungi for 12 weeks. Standard errors of the mean are given in parentheses.

Treatments	Mean Mass Loss* % (s.e.)			
	C. olivacea 1779 BR	*F. lilacino-gilva* 1109 BR	*G. abietinum* 13851 BR	*P. tephropora* 7904 WR
P. radiata + water	61.8 (2.1)	39.4 (2.1)	29.5 (0.7)	21.1 (1.1)
P. radiata + solvent	53.5 (7.8)	39.4 (1.8)	34.2 (1.4)	15.7 (0.8)
P. radiata + waterborne preservative	5.4 (2.6)	3.0 (0.9)	0.6 (0.2)	0.4 (0.1)
P. radiata solvent-borne preservative	0.7 (0.5)	31.7 (2.9)	4.6 (0.9)	1.9 (0.7)
E. cladocalyx (20 y.o.)	0.9 (0.1)	4.8 (0.5)	1.9 (0.3)	3.9 (0.7)
E. occidentalis (8 y.o.)	10.6 (2.3)	14.3 (3.1)	9.3 (1.6)	21.6 (4.7)

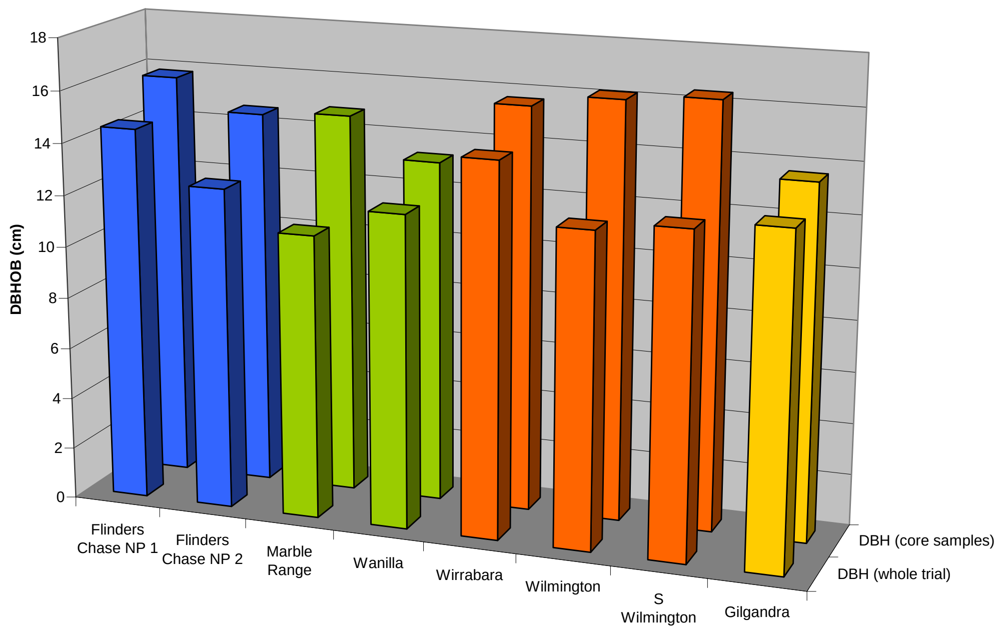
* Mean of six replicates per treatment

3.2. *E. cladocalyx* – sugar gum

3.2.1. Growth traits

There were significant differences for DBHOB (Fpr.<0.001) between ROPs (regions of provenance), provenances and families within provenances for the whole of trial population (n=1600) (see Table 6). Coefficients of additive and phenotypic variance of the trial population were low and high respectively, but the converse was true for the selected trees, reflecting the bias in the sampling strategy. The heritability estimate for the whole population was 0.26 (s.e. 0.08) but was also much higher for the cored subpopulation. The Flinders Chase and NE Wirrabara Forest provenances had particularly good diameter growth (see Figure 1). The mean DBH of dominant stems was 12 cm with a standard deviation of 3 cm.

Figure 1. DBHOB for whole of Benalla trial. [Eyre Pa = green; Kangaroo Is. = blue; S. Flinders Ra. = orange]. Standard errors of difference of provenance means are 0.81 and 0.70 cm for the core samples and whole of trial respectively.



Trees for the coring study were selected on the basis of their potential to make a vineyard post (see methods). This sample population (n=230) had a mean DBH of dominant stems of 15 cm with a standard deviation of 3 cm. There were significant differences (Fpr.<0.001) at the ROP and family levels for bark thickness; South Flinders trees had significantly thicker bark (gauged by standard errors of difference) than either Kangaroo Island or Eyre Peninsula (1.4 > 1.1 ≈ 0.9 cm radial thickness respectively) . There was no significant difference between heartwood and sapwood symmetry along the axis in the north-south direction in which the cores were taken.

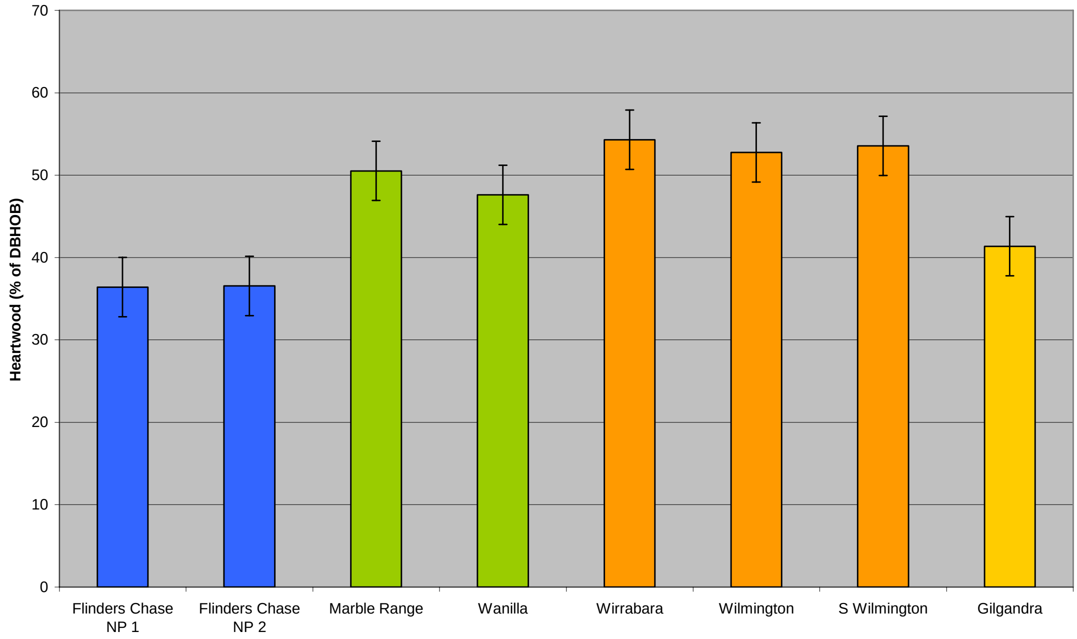
Table 6. Trait means, significance of effects (F probabilities) and genetic parameters for *E. cladocalyx*

Provenance	% heart mass loss *(F. lilacino-gilva)* [1109]	% heart mass loss *(P. teph.)* [7904]	% heart mass loss *(G. abietinum)* [13851]	DBHOB (core samples) cm	DBHOB (whole trial) cm	Bark thickness (cm)	Basic density heart (kgm^{-3})	Basic density sap (kgm^{-3})	Basic density wood (kgm^{-3})	Methanol extractives (% of heart weight)	Heart % of DBHUB	Heart % of DBHOB
South Flinders Ranges												
Gilgandra (planted)	6.0	2.4	1.8	13.7	12.8	2.5	688	674	683	15	51	41
S Wilmington	6.3	3.9	2.7	16.4	12.5	2.9	718	687	707	11	65	54
Wilmington	8.3	3.5	2.9	16.2	12.1	2.7	701	679	693	11	63	53
Wirrabara	9.7	4.8	3.9	15.7	14.4	2.5	716	680	702	12	64	54
Eyre Peninsula												
Marble Range	12.0	5.2	2.8	14.8	11.0	1.7	683	653	670	12	57	51
Wanilla	11.8	4.9	3.4	13.3	12.1	2.2	671	644	661	11	57	48
Kangaroo Island												
Flinders Chase NP 1	14.5	13.0	9.3	15.8	14.5	2.0	681	684	683	7	42	36
Flinders Chase NP 2	13.7	7.2	5.0	14.6	12.5	2.2	710	695	701	9	43	37
Grand mean	*11.9*	*6.13*	*2.4*	*13.2*	*12.8*	*2.5*	*673*	*639*	*661*	*12*	*62*	*51*
s.e.d	**2.9**	**2.4**	**1.8**	**0.81**	**0.70**	**0.37**	**13**	**13**	**12**	**0.72**	**3.9**	**3.6**
ROP	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Prov. within ROP	0.5	0.02	0.02	<0.001	<0.001	0.213	0.004	0.605	0.064	0.003	0.272	0.221
Family within prov.	0.092	<0.001	<0.001	<0.001	<0.001	<0.001	0.002	0.04	<0.001	0.057	0.007	<0.001
h^2 (s.e.)	0.13 (0.14)	0.52 (0.11)	0.58 (0.10)	0.59 (0.08)	0.26 (0.08)	0.43 (0.11)	0.41 (0.10)	0.23 (0.12)	0.39	0.25 (0.13)	0.30	0.38
CVp	0.75	1.15	1.28	0.18	0.29	0.49	0.06	0.06	0.05	0.23	0.28	0.29

3.2.2. Heartwood proportion

Heartwood diameter was expressed as a proportion of DBHOB and DBHUB for each tree. There were significant differences between ROPs and families (nested within provenances within ROPs), but not between families for both proportions (Table 6). Figure 2 shows that the South Flinders Ranges provenances have significantly more heartwood as a percentage of DBH than the Kangaroo Island material, and slightly more than the Eyre Peninsula provenances. Heritability (family with provenance) was estimated at 0.38 and 0.30 for heartwood percentage of DBHOB and DBHUB respectively, and the phenotypic coefficient of variation (CV_p) 28 and 29% respectively, indicating good prospects for the genetic improvement of this trait. Mean heartwood DBH for the sampled trees was 72 mm, with Kangaroo Island and South Flinders Ranges. ROPs having 58 and 82 mm respectively.

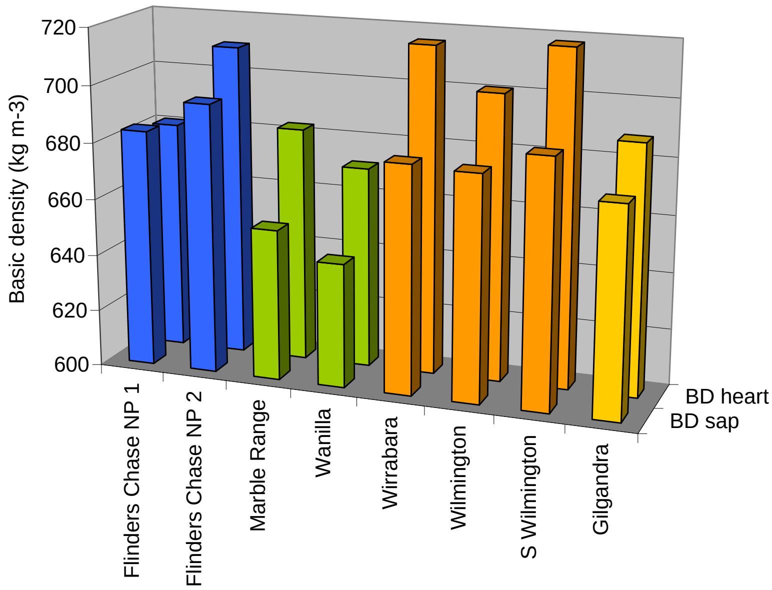
Figure 2. Provenance heartwood DBH as a percentage of DBHOB within region-of-provenance [Eyre Pa = green; Kangaroo Is. = blue; S. Flinders Ra. = orange]. Error bars show average standard errors of difference of provenance means.



3.2.3. Basic density

Significant differences between regions-of provenance exist for heartwood, sapwood and whole-of core basic density (F pr. <0.001), though the significance of the effect at the family level is higher for heartwood than sapwood basic density (see Figure 3). The Eyre Peninsula was markedly less dense than the Kangaroo Island and South Flinders Ranges material. Sapwood was less dense (640 kg m^{-3}) than heartwood (mean 670 kg m^{-3}) for all provenances with mean density 660 kg m^{-3}. Heartwood basic density was moderately heritable h^2 =0.41 (0.10) whereas sapwood BD was less so h^2= 0.23 (0.12). Phenotypic variation in this trait was low: CVp = 5%.

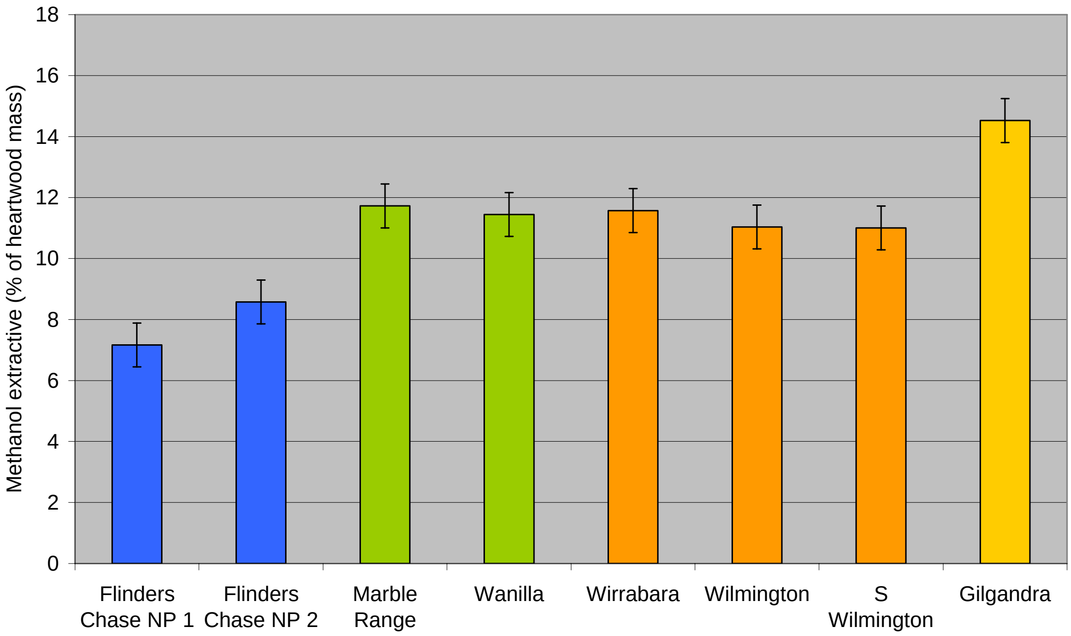
Figure 3. Basic density of heartwood and sapwood for *E. cladocalyx* provenances. Average standard errors of difference for both heartwood and sapwood means are 13 kg m^{-3}.



3.2.4. Methanol heartwood extractives

Mean methanol extractive content for the sample set was 12%, with strong region-of-provenance and provenance differences (F Pr.<0.003), and weakly significant family-within-provenance effects (F pr.=0.06). The South Flinders Ranges and Eyre Peninsula provenances had a much higher proportion of heartwood extractives than the Kangaroo Island provenances (see Figure 4). The overall extractive content is high compared with less-durable species such as *E. globulus*. Heritability is estimated at 0.25 and CVp is 0.23. The mean extractive content of the Gilgandra seedlot (a 4-tree sample) ranked marginally higher than any of the family samples, the nearest being a S. Wilmington family at 13.9%. All 11 of the Kangaroo Island families are ranked in the bottom 14 of 50 families, the lowest family mean extractive content being 6.3%.

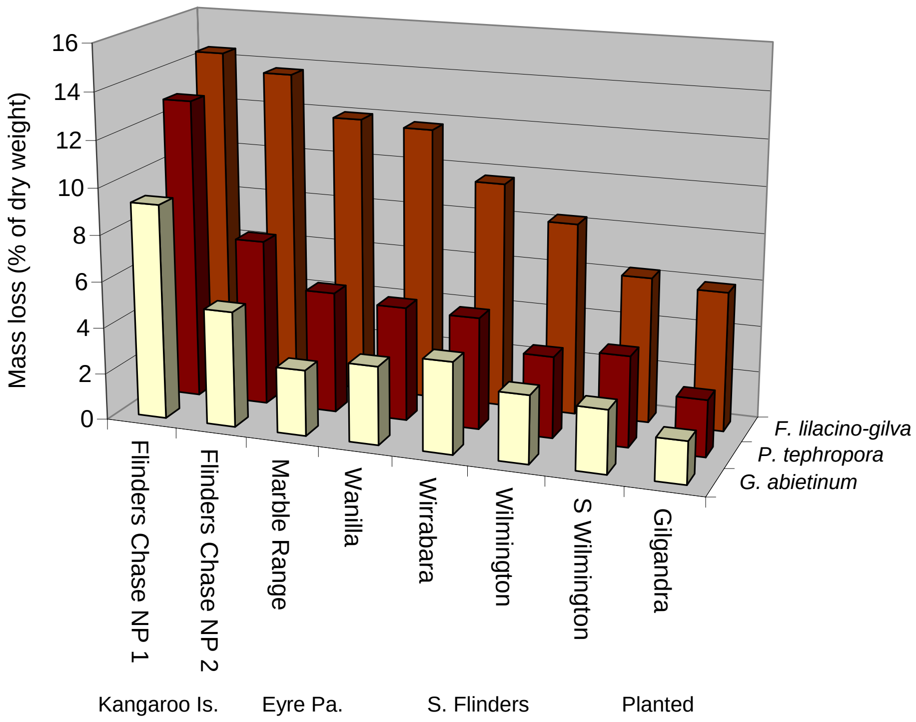
Figure 4. *E. cladocalyx* heartwood methanol extractives (percentage of heartwood by weight)



3.2.5. Mass loss

The mass loss results indicate differential responses of provenances to the three different fungi, though overall, mass loss was low to moderate, with better families from the South Flinders Ranges having less than 5% mass loss for all three fungi. The most aggressive fungus, *F. lilacino-gilva [1109]*, was a brown rot. The Kangaroo Island provenances (two from Flinders Chase) were the least decay resistant to the three fungi (see Fig. 5). Heritability estimates for *P. tephropora* and *G. abietinum* were high (0.52 and 0.58 respectively) while the estimate for *F. lilacino-gilva* was low with a high standard error 0.13 (0.14). While there is a large amount of variation within provenances for decay resistance to *F. lilacino-gilva* (appearing as a highly significant F probability at the ROP stratum in Table 6), there is little family-within-provenance variation.

Figure 5. Percentage mass loss of *E. cladocalyx* heartwood samples exposed to two brown and one white rot fungus. Average standard errors of difference are 2.9% 2.4% and 1.8% for *F. lilacino-gilva*, *P. tephropora* and *G. abietinum* respectively.



3.2.6. Genetic correlations

Genetic correlations (Table 7) between mass loss resulting from the three fungi were all positive, with *P. tephropora* [7904] (the white rot) very strongly correlated to the two brown rots. The correlation between 1109 and 13851 was not as strong, and with a high standard error. Correlations involving 1109 could not be determined in some cases, and had high associated standard errors in others. However, there was a very strong negative correlation between 1109 and DBHOB (larger trees are less susceptible to decay). Decay and heartwood extractive percentage were moderately strongly and negatively correlated to heartwood basic density for both of 13851 and 7904 (i.e. denser wood and wood with a higher extractive content were less susceptible to decay). Heartwood basic density was weakly negatively correlated with heartwood proportion, DBHOB and bark thickness.

Table 7. Genetic correlations (upper triangle) with standard errors (lower triangle) between pairs of traits in *E. cladocalyx*

	Decay 13851	Decay 7904	Decay 1109	Basic density of heartwood	Extractive	heartwood % of dbhub	heartwood % of dbhob	DBHOB
Decay7904	0.95							
Decay1109	0.33	1.04						
Basic density of heartwood	-0.67	-0.54	0.09					
Extractive	-0.61	-0.44	-0.14	0.20				
Heartwood % of DBHUB	0.08	-0.69	*	-0.19	-0.00			
Heartwood % of DBHOB	0.16	-0.46	*	-0.11	-0.01	0.98		
DBHOB	0.15	-0.40	-1.02	-0.16	-0.42	0.50	0.44	
Bark thickness	-0.20	-0.57	-0.21	-0.08	-0.19	-0.34	-0.54	0.39

Standard errors								
Decay7904	0.12							
Decay1109	0.44	0.28						
Basic density of heartwood	0.20	0.14	-0.46					
Extractive	0.27	0.28	0.55	0.31				
Heartwood % of DBHUB	0.35	0.22	*	0.33				
Heartwood % of DBHOB	0.32	0.24	*	0.29	0.36	0.02		
DBHOB	0.24	0.20	0.27	0.25	0.26	0.21	0.21	
Bark thickness	0.27	0.23	0.46	0.28	0.33	0.33	0.24	0.21

3.3. Spotted gums - *Corymbia* spp.

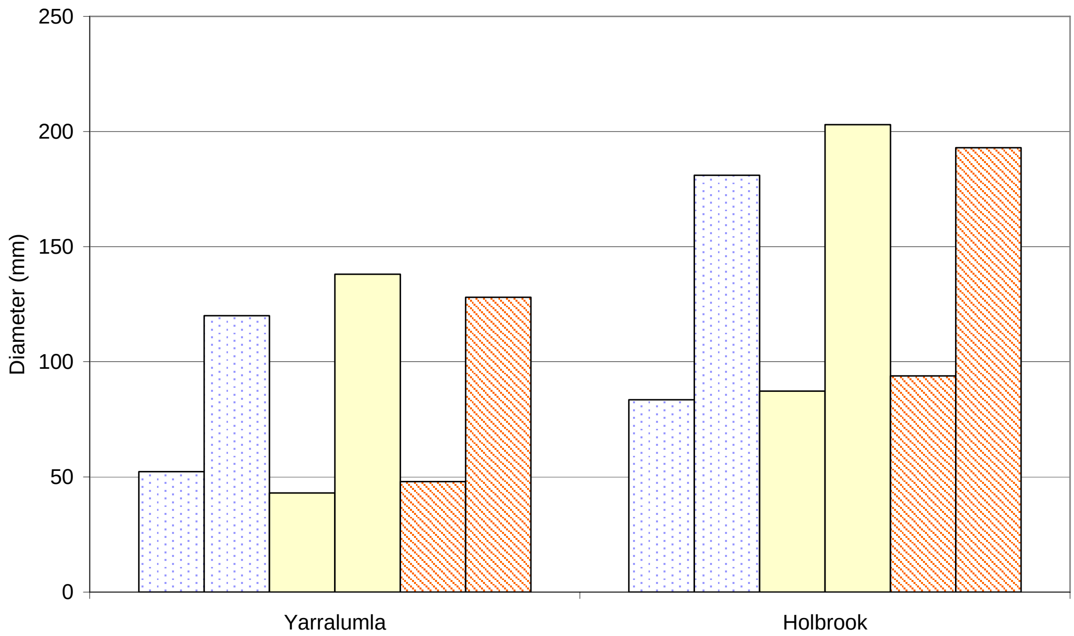
Results of analyses are given in Table 8a for Yarralumla and 8b for Holbrook. Note that due to the relatively higher number of samples of CC and CM cf. CH at Yarralumla, s.e.d.s between pairs of species level differ appreciably and are given separately in Table 8a (average s.e.d.s are given elsewhere in the report). Replication at the provenance level at the Yarralumla site is in many cases very low, contributing to high standard errors.

The results of the initial biodeterioration study on the Yarralumla site clearly showed that young aged wood of the spotted gums lack sufficient resistance to decay for the target product, so it was decided not to carry out further biodeterioration determinations on the Holbrook samples. However, the spotted gums are of interest for sawn timber production, so the heartwood proportion and basic density determinations proceeded, because these are also target traits for sawlogs.

3.3.1. Heartwood proportion

There were significant differences between species and provenances within species for DBHOB at Yarralumla, but there were no significant species or provenance differences, and no significant between-family differences, at Holbrook. There was also a significant difference between provenances for DBHUB at Yarralumla, but no differences at Holbrook. Mean DBHOB and DBHUB of sampled trees (respectively) was 12.8 and 10.8 cm at Yarralumla and 19.2 and 16.5 cm at Holbrook, reflecting the extra year's growth and probably higher site productivity at Holbrook. Mean heartwood proportion was 54% (s.e. 4%) at the Holbrook site and 39% (s.e. 12%) at Yarralumla. These proportions correspond to mean heartwood DBH of 88 mm at Jayfields and 47 mm at Yarralumla. The *Corymbia citriodora* species grouping (predominantly composed of CCV with a few CCC entries at Yarralumla and entirely CCV at Holbrook) had significantly more heartwood as a proportion of DBH than CM at both sites. Figure 6 shows that heartwood diameter at breast height is actually greater for CC than CM at both sites. There is a very weak phenotypic correlation between this pair of traits (Table 9).

Figure 6. *Corymbia* heartwood diameter and DBHOB at two sites**:** each pair of bars shows heartwood diameter at breast height and DBHOB respectively. CH=stipple; CM=solid; CC=diagonal stripe



3.3.2. Basic density

There were significant differences between provenances for both heartwood and sapwood and between species for sapwood basic density at Yarralumla (Table 7a). At Holbrook there were significant differences between species and provenances within species for both heartwood and sapwood basic density, and also for heartwood at the provenance level. The sapwood was consistently denser than the heartwood at both sites (basic density of 664 and 607 kg m^{-3} at Yarralumla and 683 and 661 kg m^{-3} at Holbrook). At the species level, CCC/V had significantly denser sapwood than CM at both sites, and this was also true for heartwood at Holbrook but not statistically significant at Yarralumla.

Table 8a. Trait means and significance of effects (F probabilities) for spotted gum species and provenances at Yarralumla. CC= *C. citriodora* subspp. *citriodora* and *variegata*, CM= *C. maculata*, CH= *C. henryi*.

Species	Provenance (listed north to south)	% heart mass loss *(F. lilacino-gilva)* 1109	% heart mass loss (*P. tephropora*) 7904	% heart mass loss (*G. abietinum*) 13851	Heart% of DBHUB	DBHOB (mm)	DBHUB (mm)	Basic density wood (kgm^{-3})	BD sap (kgm^{-3})	BD Heart (kgm^{-3})	Methanol extractives (% of heart weight)
CCC	Herberton	15.0	8.8	*	41%	105	91	733	741	697	10.1%
CCC	Monto CCC	*	*	*	39%	92	68	644	639	640	11.0%
CCV	Monto CCV	19.6	5.2	13.45	46%	136	107	680	708	647	16.9%
CCV	Saddler Springs	22.4	5.9	1.8	38%	123	98	676	697	642	15.7%
CCV	Mt Hutton	17.6	15.4	4.3	41%	113	99	675	739	620	11.0%
CCV	Woondum SF	27.7	5.5	*	41%	113	96	641	654	607	12.9%
CCV	Richmond Range SF	18.2	7.8	7.84	52%	151	119	657	722	593	12.5%
CH	Braemer SF	21.1	10.9	14.52	49%	123	101	614	655	574	10.3%
CCV	Paddys Land SF	19.4	19.0	8.26	45%	137	117	628	672	577	10.6%
CM	Yarrat SF Taree	21.4	45.1	1.14	40%	154	119	649	685	624	8.5%
CM	Curryall SF	12.3	9.0	1.58	36%	136	109	627	642	623	13.3%
CM	Wingello SF	31.8	4.2	39.09	31%	119	96	586	591	560	6.0%
CM	Kiola SF	30.2	25.5	23.55	25%	160	126	622	605	648	8.7%
CM	Mumbula SF	38.3	*	*	16%	144	113	607	542	526	10.5%
CM	Mottle Range	49.3	15.5	42.49	*	120	*	562	*	530	5.7%
Trial mean		**24.59**	**13.66**	**14.37**	**39%**	**128**	**104**	**640**	**664**	**607**	**10.9%**
Av. s.e.d. between provenances		*8.541*	*10.33*	*9.539*	***12%***	***1.48***	***13***	*34*	***33***	***43***	***3.1%***
Species											
CC		19.75	13.63	7.49	43%	12.8	108.3	666	696	618	12.4%
CH		21.12	10.91	14.52	51%	12.0	101.4	609	650	576	10.0%
CM		23.87	18.69	15.13	31%	14.3	116.2	616	627	604	10.5%
s.e.d. CH		*4.98*	*6.30*	*6.91*	*8%*	*1.2*	*10.1*	*23*	*27*	*29*	*2.2%*
s.e.d. CM-CC		*3.26*	*4.50*	*4.91*	*4%*	*0.6*	*5.5*	*12*	*15*	*16*	*1.1%*
F prob. (prov. within sp.)		0.033	0.014	0.009	0.838	0.002	0.016	<0.001	0.014	0.015	0.025
F prob. (species)		0.672	0.326	0.118	0.009	0.018	0.23	0.024	<0.001	0.307	0.105

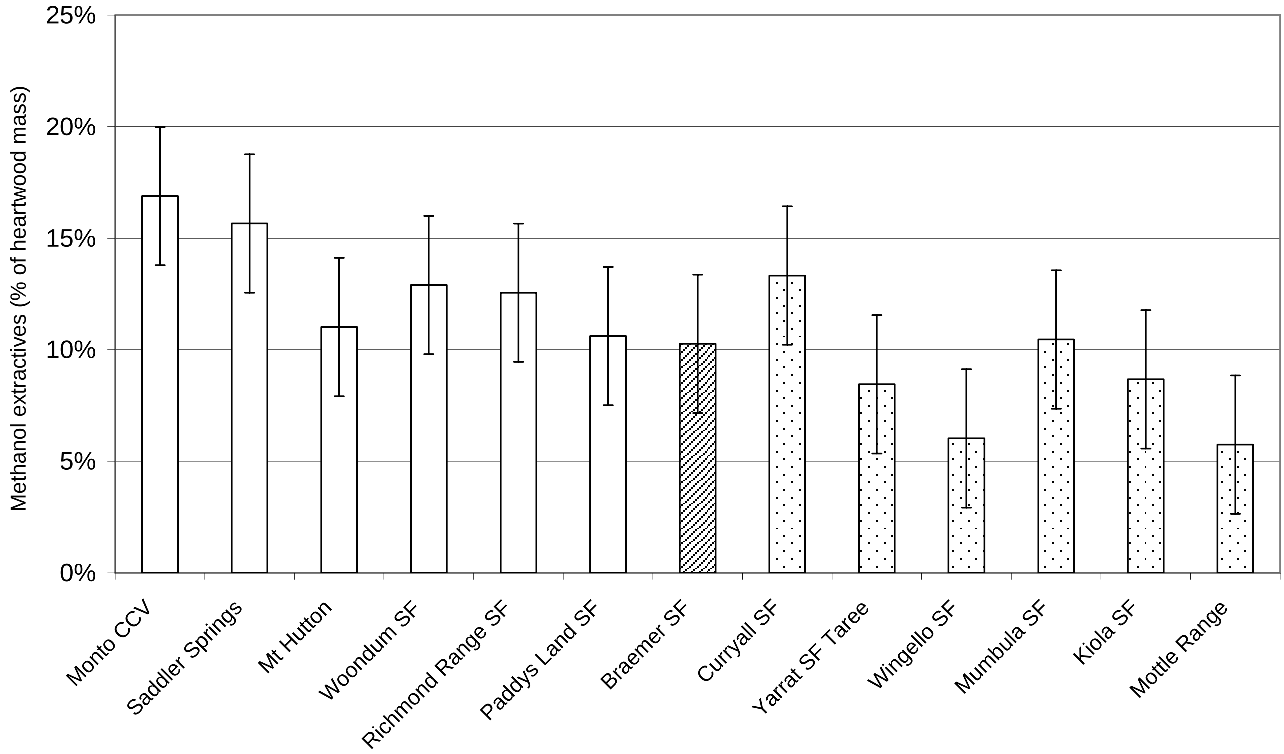
Table 8b. Trait means and significance of effects (F probabilities) for spotted gum species and provenances at Holbrook. CCV= *C. citriodora* subsp. *variegata*, CM= *C. maculata*, CH= *C. henryi*

Species	Provenance	Heart% of DBHUB	DBHOB (mm)	DBHUB (mm)	Basic density wood (kgm^{-3})	BD sap (kgm^{-3})	BD Heart(kgm^{-3})
CH	Myrtle Ck	54%	175	144	691	712	665
CH	Ewingar	55%	187	158	679	693	667
CCV	Richmond Range SF	55%	195	168	693	710	666
CCV	W Dalby	57%	188	165	680	670	692
CCV	Barkula	62%	200	167	730	756	716
CM	Nelligen	49%	201	173	636	637	635
CM	Wingello	48%	203	178	647	652	656
CM	Mottle Range	53%	200	171	612	631	593
Trial mean		**54%**	**192**	**165**	**671**	**683**	**661**
Av. s.e.d. between provenances		*4%*	*11.6*	*11.7*	*13*	*25*	*26*
Species							
CCV	CCV	56%	194.3	167.21	694	706	680
CH	CH	55%	182.9	152.68	684	701	666
CM	CM	50%	201.2	173.45	631	640	627
Av s.e.d. between species		*2%*	*6.3*	*6.33*	*13*	*14*	*14*
Fprob.(species)		0.02	0.02	0.01	<0.001	<0.001	0.00
Fprob.(prov.within sp.)		0.59	0.75	0.69	0.16	0.23	0.07
Fprob.(family within prov.)		0.022	0.914	0.749	0.486	0.804	0.034

3.3.3. Methanol heartwood extractives

Methanol heartwood extractives as a proportion of heartwood mass were assessed for the Yarralumla dataset. There were significant differences between provenances within species (F Pr.= 0.025) but not between species, and the trial mean was 10.9% (Table 8a). Four of the six *C. maculata* provenances had relatively low extractive proportions (below 10%) (Figure 7).

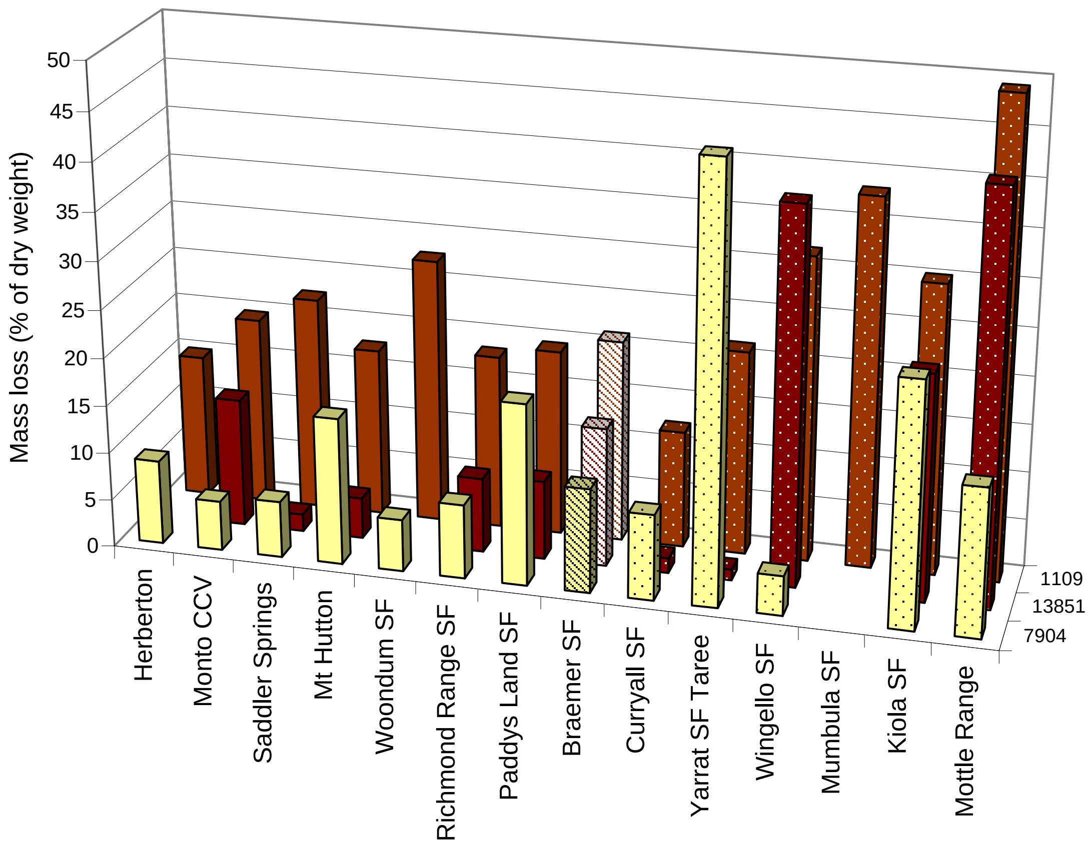
Figure 7. Provenance means for *Corymbia* spp. methanol heartwood extractives in spotted gums at Yarralumla (error bars indicate average standard error of difference). Solid bars= CCC/V; diagonal lines=CH; stipple=CM



3.3.4. Mass loss

There were significant differences between provenances for all three of the fungi (Table 8b, Figure 8). Importantly, all fungi caused significant mass loss (25%, 14% and 14% respectively for 1109, 7904 and 13851). The 1109 (*F. lilacino-gilva*) brown rot consistently caused very significant decay with only one sample in the experiment having less than 5% decay, and only five less than 10%. Mass losses in the *P. radiata* heartwood controls were 76, 92 and 77% for the three fungi respectively, the white rot being characteristically aggressive on this softwood species. Though there were no significant differences at the species level, the most aggressively decayed provenances by all three of the fungi were of *C. maculata*. Had the biodeterioration results indicated better overall resistance to decay in *Corymbia*, a logical follow-on would have been to also submit the Holbrook cores to a similar set of tests.

Figure 8. Accelerated biodeterioration (percent mass loss) of *Corymbia* spp. heartwood provenances exposed to one white rot [7904] and two brown rot [13851, 1109] fungi. Solid bars= CCC/V; diagonal stripes=CH; stipple=CM



3.3.5. Phenotypic correlations between traits

The mass loss traits are all positively correlated with each other, the two brown rots (1109 and 13851) strongly and significantly (Table 9). Mass loss for each of the fungi is negatively correlated to the basic density measures (i.e. decay decreases as density increases), moderately strongly and significantly for some combinations of fungus and heart/sapwood. Extractive percentage of heartwood mass was positively and significantly correlated with heartwood basic density, as might be expected because it is a component of heartwood matter contributing to the overall density. Extractives are negatively correlated with each of the decay fungi (i.e. higher extractive content leads to less decay), moderately strongly and significantly in the case of 13851. The heartwood proportion of overall DBHUB was weakly and mostly negatively correlated with each of the other traits, with the exception of mass loss in 1109, where the correlation was moderate, negative and significant. This means that the heartwood of trees with proportionately more heartwood is less susceptible to decay by 1109. The three basic density measures were strongly and significantly correlated.

Table 9. Phenotypic (Pearson) correlations between pairs of traits for *Corymbia* spp. at Yarralumla. Correlations in bold type face are statistically significant (P<0.03)

	Extractive % of heartwood	Heart mass loss %			Basic density		
		(F. lilacino-gilva) 1109	(*G. abietinum*) 13851	(*P. tephropora*) 7904	Heart	Sap	Whole
% heart mass loss *(F. lilacino-gilva)* 1109	-0.30						
% heart mass loss (*G. abietinum*) 13851	**-0.56**	**0.79**					
% heart mass loss (*P. tephropora*) 7904	-0.22	0.26	0.18				
Basic density heart	**0.49**	-0.27	**-0.43**	**-0.48**			
Basic density sap	0.36	**-0.56**	**-0.64**	-0.18	**0.63**		
Basic density whole	**0.51**	**-0.42**	**-0.58**	-0.33	**0.92**	**0.87**	
Heart %_of dbhob	-0.15	**-0.53**	-0.26	-0.01	-0.26	0.28	-0.08

4. Discussion and implications

The study has examined a variety of traits related to natural durability and heartwood properties in young aged (pole sized) samples of two species. It is usual to test wood from only a few trees per species, often ignoring the possibility of significant genetic variation, in making assessments of natural durability (for example in determining the ratings for the Australian Standard). By contrast, 223 trees of *E. cladocalyx* and 207 of the *Corymbia* spp. were sampled here. This study therefore contributes significant extra information on the durability and wood characteristics of the species under test, and considerably improves our understanding of the heartwood characteristics of very young eucalypt wood. The importance of the findings and implications are discussed below:

4.1. Heartwood development

The results of growth and heartwood proportion analyses for both *E. cladocalyx* and *Corymbia* taxa indicate that significant heartwood is present by around 8-10 years of age on the low rainfall sites studied. At Benalla (*E. cladocalyx*) and Holbrook (*Corymbia*) there was sufficient heartwood (72 and 88 mm respectively) at breast height to indicate that a round post of 75 mm large-end heartwood diameter could probably be produced within 8-10 years. Heartwood development was much greater in these low rainfall (and non-irrigated) trials than reported for seven year-old *E. camaldulensis* in irrigated trials at Mildura, where heartwood was only circa 20-30 mm within a 100 mm diameter pole (Cookson *et al.* 2002). Moreover, heartwood proportion is a moderately heritable trait in *E. cladocalyx* and there is significant scope for provenance level selection in both the *E. cladocalyx* and the *Corymbia* spp. tested here.

In *E. cladocalyx* the South Flinders Range ROP has significantly more heartwood on average, while in the spotted gums, the *C. citriodora* subspp. are superior in this trait to *C. maculata*. This is an interesting finding for the spotted gums, because while the CM group is often found to have superior diameter growth to CCV in southern Australia (e.g. Bush *et al.*, 2007), the development of heartwood and actual heartwood diameter at breast height appears to be inferior in CM, which has negative implications for sawlog development. Whether this trend continues or is indeed significant in older logs (where sapwood will progressively become a smaller component of wood volume) should be monitored. Further studies on heartwood taper would also be a logical follow-up to this study, to estimate likely heartwood proportions at small and large end diameters of a bottom-log post of approximately 2400 mm length.

As sapwood is generally proportional to the size of crown it has to support, it usually forms a large proportion of the overall wood of young, actively-growing trees. It is possible that the trees sampled in these studies have an unusually high proportion of heartwood (62% of DBHUB at Benalla, 39% at Yarralumla and 54% at Holbrook) due to their relatively low growth rates, and in the case of the Yarralumla and Benalla sites, small crowns. The high proportion of heartwood at Benalla (*E. cladocalyx*) may have been positively influenced by the fact that the stand had not been thinned when canopy closure occurred at circa four years, leading to high, narrow and small crowns. Indeed it was well overdue for thinning if the usual sawlog silvicultural strategy of maintaining rapid diameter growth had been the objective. The effects of silviculture (for example timing of thinning) on heartwood development would be a necessary further step in developing a dedicated plantation regime for heartwood-rich post production.

4.2. Resistance to biodeterioration

Of the three taxa examined only one, *E. cladocalyx* has shown satisfactory resistance to decay from both brown and white rots. There is also wide scope for genetic improvement, both by provenance and family-within-provenance selection within this species. The other two taxa, *E. occidentalis* and *Corymbia*, showed so much less resistance to decay as to probably not warrant further investigation as vineyard posts at this young age. A study on termite resistance that concluded as the pilot study commenced showed that *E. occidentalis* has the highest susceptibility to termite attack of a suite of low rainfall species tested, whereas young-age *E. cladocalyx* and spotted gum performed well (McCarthy *et al.* in press).

Despite the poor overall performance of the *Corymbia* spp. with respect to resistance to decay in this very young aged material, the study has demonstrated that there is significant genetic variation in this trait. The findings support the assertion by Bolza, (1978) that south coast NSW wood is of lower durability (class 3) than northern *E. maculata* (which includes CCV) in that the CM provenances generally showed poorer resistance to biodeterioration than the CCV.

An interesting finding was the extremely strong negative genetic correlation between DBHOB and decay caused by the 1109 fungus in *E. cladocalyx*, and moderately strong correlation for 7904. Bearing in mind that genetic parameter estimates for 1109 were generally of poor precision, this phenomenon might be explained by very aggressive attack of this fungus on core samples of low diameter. It is well known that the pith region of the heartwood is less resistant to decay than the outer heartwood (e.g. Hillis 1987). In preparing samples for decay testing from the 12 mm cores, outer heartwood was taken preferentially, but in small sized trees, increasing proportions of inner heartwood were necessarily included. This may have contributed to the more rapid decay of the Kangaroo Island material, as it tended to have a smaller heartwood core, though extractive content within that core is also likely to have a bearing on decay rates.

4.3. Extractive content

Genetic variation in heartwood extractive content (proportion of heartwood mass) was evident in both the *E. cladocalyx* and *Corymbia* studies. In *E. cladocalyx*, the Kangaroo Island material had markedly less extractives (circa 8% on average) than the Eyre Peninsula and South Flinders provenances (around 11-12%). The Gilgandra seedlot (of unknown genetic origin) had a very high extractive proportion (14%), placing it amongst the top ranking entries at the family level within the South Flinders ROP. This suggests that the origin of this seedlot is probably the South Flinders Ranges, as is commonly the case with planted stands of this species. In the *Corymbia* study, the CM provenances tended to have less heartwood extractives than the CC, with a large amount of variation (three-fold at the provenance level).

It is often stated that resistance to biodeterioration is as a direct result of extractive content (e.g. Standards Australia, 2005). This is supported by the moderately strong (and negative) genetic correlations between extractive content and biodeterioration from 13851 and 7904 (brown and white rots respectively) in *E. cladocalyx* and the moderate and negative phenotypic correlation with 13851 in the spotted gums. In the *Corymbia*, Mottle Range is notable in having the lowest extractive content and the highest levels of decay, whilst the best performing CM provenance, Curryall, has the highest extractive content within the species.

4.4. Basic density

Genetic variation in basic density was found for both *E. cladocalyx* and the *Corymbia* spp. In *E. cladocalyx*, the heartwood was found to be denser than the sapwood, and the Kangaroo Island and South Flinders Ranges ROPs were significantly denser than the Eyre Peninsula. This finding is probably not of great practical importance in itself, since the Eyre Peninsula is not suitable for post production due to its relatively low growth rates and poor form (Harwood and Bulman 2001). The magnitude of the difference is only circa 20-30 kgm^{-3} with a grand mean of 660 kgm^{-3}, making all of the young aged wood quite dense: the Kangaroo Island material would still be too dense for pulp production for example. As density is usually strongly correlated with strength, the prospects for making posts that are of narrower diameter than the typical *P. radiata* treated posts are good.

The wood of the *Corymbia* species was also dense, 640 and 670 kgm^{-3} at Yarralumla and Holbrook respectively, making it of similar density to the *E. cladocalyx*. In contrast to *E. cladocalyx*, the sapwood at breast height was significantly denser than the heartwood at both sites, despite the high extractive content of the heartwood. This phenomenon is usually due to low density wood near the pith (Chauhan *et al.*2006) and is not uncommon in hardwoods.

Basic density of heartwood was moderately genetically correlated with both mass loss (negatively) and extractive content (positively) in *E. cladocalyx* for fungi 13851 and 7904, suggesting that genetic gains might well be made for decay resistance and higher extractive content by selecting for trees with high basic density. This is an encouraging finding, because it is much cheaper to assess basic density than extractive content or decay. Similarly in *Corymbia* species, basic density was moderately phenotypically correlated to extractive proportion and negatively and low-moderately correlated to decay.

4.5. Implications

The study has made a preliminary assessment of the scope for genetically improving natural durability traits in three eucalypt taxa. The study has shown that one of the three species, *E. cladocalyx* has natural durability properties at a young age (8 years) that might make it suitable for production of naturally durable posts for in-ground use. Indications are that young aged (pole-sized) material of spotted gum and *E. occidentalis* would not have sufficient resistance to fungal attack to warrant development for this application. In the case of *E. occidentalis*, low resistance to termite attack will also be limiting (McCarthy *et al.* In press).

The study has demonstrated that there is significant genetic variation in natural durability traits, and favourable correlations between traits for both *E. cladocalyx* and the spotted gums. In the case of *E. cladocalyx*, the heritability of resistance to fungal attack would appear to be high, at least for two of the fungi we assessed, and there is also significant scope for improving this trait by provenance or ROP selection. Likewise, there is strong variation in extractive content and heartwood proportion in this species.

A very encouraging finding is that the South Flinders Ranges provenances and families within this ROP tend to have the highest heartwood proportion, the strongest resistance to decay and higher extractive content than the Kangaroo Island provenance material tested. This has important implications for the existing breeding program implemented by ALRTIG (Harwood and Bulman 2001) for this species. This program has a mixture of South Flinders Ranges, Kangaroo Island and planted stand materials derived originally from the South Flinders. If naturally durable and/or increased heartwood production is a priority, it would be advantageous to screen the populations for some of the traits studied here, or as a lower cost alternative, reduce the proportion of Kangaroo Island-origin individuals in the breeding population.

Though the study found that very young aged *Corymbia* is not likely to be sufficiently durable for in-ground post use in vineyard applications, potentially important variation in heartwood properties were identified. The finding that heartwood development in CCV is greater than CM, whereas DBHOB growth is the converse, may impact on the choice of species for sawlog production, especially if small sawlogs are under consideration. Heartwood is considered to be generally superior to sapwood in eucalypt sawn timber, because it is less susceptible to checking and other defects, and not susceptible to *Lyctus* borer – to which spotted gum sapwood is particularly susceptible. There are existing trials in southern Australia that are approaching the size and age where small sawlogs could be produced that would be suitable for carrying out the required research.

Production of pulpwood and composite products from low rainfall species is not an objective of the ALRTIG breeding program, due to the likelihood that even young-aged material grown on low rainfall sites would be outside the preferred range (400-600 kg.m^{-3} see Downes *et al.*, 1997). This study has confirmed this, and also that extractives content in both *Corymbia* and *E. cladocalyx* are much higher than desirable for pulpwood (which requires a very low or nil extractives content for pulp fibre production).

4.7. Further research

The finding that *E. cladocalyx* may be suitable for production of untreated posts warrants follow-up research. Though this study has shown promising resistance to decay in the laboratory, and good prospects for genetic improvement, there are a number of technical questions and problems that need to be addressed to further develop the opportunity. These include:

- Strength determination of *E. cladocalyx* posts and determination of whether smaller-diameter posts (relative to the ~100 mm treated *P. radiata* standard) could be used
- Assessment of longitudinal heartwood development in pole sized plantation-grown material, including coppice from the western Victorian windbreak plantation resource
- *In situ* testing of posts in a vineyard application
- Assessment of whether there is a need to peel or otherwise remove the sapwood from the whole length or the in-ground portion of untreated posts
- Development or adaptation of existing machinery (such as that used to remove sapwood from power transmission poles) to peel or otherwise remove sapwood from small posts
- Assessment of handling, driving and end-splitting of *E. cladocalyx* posts
- Development of silviculture to maximise heartwood development

These research questions would need to precede economic feasibility determinations.

A further opportunity for *E. cladocalyx* might be the harvest of coppice regrowth poles from new and existing plantations. There are extensive farm windbreak plantings in western Victoria and South Australia. Assessment of heartwood proportion and natural durability of coppice regrowth poles using the techniques described would be a relatively straightforward exercise with considerable benefits should the coppice poles prove to have good natural durability properties.

Other plantation species that are suitably durable could also be investigated. Mature wood of many of the low rainfall species are class 1 durable, and amongst these the *E. argophloia*, ironbarks (*E. tricarpa* and *E. sideroxylon*) and grey gums (e.g. *E. punctata*) are currently in the early stages of domestication and would be suitable targets for this application. Also, some species suited to higher rainfall situations such as *E. bosistoana* and *E. quadrangulata* might have potential for naturally durable wood production in New Zealand (I. Nicholas pers comm.) and perhaps coastal areas of Australia.

5. References

Arnold RA, Bush DJ, Stackpole D (2005) Genetic variation and tree improvement. In 'New Forests for Wood and Environmental Services in the Murray-Darling Basin'. (Eds EKS Nambiar and IS Ferguson) pp. 25-49. (CSIRO Publishing: Melbourne)

Beckman, C.H., 2000. Phenolic-storing cells: keys to programmed cell death and periderm formation in wilt disease resistance and in general defence responses in plants? Physiological and Molecular Plant Pathology, 57(3): 101-110.

Bird, P.R., 2000. Farm forestry in southern Australia: a focus on clearwood production of specialty timbers. The State of Victoria, Department of Natural Resources and Environment, Melbourne, 265 pp.

Boas, I.H., 1947. The Commercial Timbers of Australia, their properties and uses. CSIRO Australia.

Boland, D.J. *et al.*, 1984. Forest Trees of Australia. Nelson-CSIRO, Canberra.

Bolza, E., 1978. The mechanical properties and characteristics of the timber of spotted gum (*Eucalyptus maculata* Hook.) in relation to origin and maturity, The University of Melbourne, 208 pp.

Bootle, K.R., 1985. Wood in Australia: Types, properties and uses. McGraw-Hill Book Company Australia Pty Ltd.

Brammall, B. and Harwood, C.E., 2001. Vegetative propagation by rooted cuttings of *Eucalyptus* species from temperate low-rainfall environments, IUFRO conference: Developing the Eucalypt of the Future. IUFRO, Valdivia, Chile.

Brooker, M.I.H., Connors, J.R., Slee, A.V. and Kemp, L., 1997. EUCLID: Eucalypts of south-eastern Australia, (CD-ROM identification key). CSIRO Australia.

Bush DJ, Severino D, Jackson T, Collins S, Driscoll J, Stackpole D, Ho A, Tepper C, Brammall B 2007 Genetic gain trials of eucalypts for low rainfall sites. In 'ANZIF Conference'. (ANZIF: Coffs Harbour)

Bush DJ 2008 *Genetic Improvement for High-Value Eucalypt Timber*. In '*Plantation Eucalypts for High-Value Timber: enhancing investment through research and development*'. (Eds *AG Brown* and *CL Beadle*) pp. 139-155. (Joint Venture Agroforestry Program: *Canberra*)

Chauhan S, Donnelly R, Huang C-L, Nakada R, Yafang Y, Walker J 2006 Wood quality: in context. In 'Primary Wood Processing'. (Eds M Spear and J Walker) pp. 127-142. (Springer: Netherlands)

Cookson, L., McCarthy, K., Scown, D. and Mollah, M., 2002. Vineyard posts from eucalypts grown on effluent water. RIRDC Publication No 02/014. Rural Industries Research and Development Corporation, Canberra, 33 pp.

dos Santos, P.E.T., Geraldi, I.O. and Garcia, J.N., 2004. Estimates of genetic parameters of wood traits for sawn timber production in *Eucalyptus grandis*. Genetics and Molecular Biology, 27(4): 567-573.

Downes, G.M. *et al.*, 1997. Sampling plantation eucalypts for wood and fibre properties. CSIRO Publishing, Melbourne, 132 pp.

Eldridge, K., Davidson, J., Harwood, C. and van Wyk, G., 1993. Eucalypt domestication and breeding. Oxford University Press, Oxford, 288 pp.

Ericsson, T. and Fries, A., 1999. High heritability for heartwood in north Swedish Scots pine. Theoretical and Applied Genetics, 98(5): 732-735.

Fries, A. and Ericsson, T., 1998. Genetic parameters in diallel-crossed Scots pine favor heartwood formation breeding objectives. Canadian Journal of Forest Research, 28(6): 937-941.

Gambetta, A., Susco, D. and Zanuttini, R., 2004. Determination of the natural durability of larch wood (*Larix decidua* Mill.) from the Western Italian Alps. Holzforschung, 58(6): 678-681.

Gilmour, A.R., Gogel, B.J., Cullis, B.R., Welham, S.J. and Thompson, R., 2002. ASReml User Guide Release 1.0. VSN International Ltd, Hemel Hempstead, HP1 1ES, UK.

Giordano, G., 1981. Tecnologia del legno Vol. 1, 126 UTET, Turin, Italy.

Hall, N. *et al.*, 1992. The use of trees and shrubs in the dry country of Australia. Australian Government Publishing Service, Canberra, 558 pp.

Harju, A.M. and Venalainen, M., 2002. Genetic parameters regarding the resistance of *Pinus sylvestris* heartwood to decay caused by *Coniophora puteana*. Scandinavian Journal of Forest Research, 17(3): 199-205.

Harju, A.M., Venalainen, M., Beuker, E., Velling, P. and Viitanen, H., 2001. Genetic variation in the decay resistance of Scots pine wood against brown rot fungus. Canadian Journal of Forest Research, 31(7): 1244-1249.

Harwood, C., 2001. Genetic improvement strategy for *Eucalyptus occidentalis* in southern Australia

Australian Low Rainfall Tree Improvement Group: Compendium of Hardwood Breeding Strategies. Rural Industries Research and Development Corporation, Canberra, pp. 67-87.

Harwood C, Bulman P, Bush D, Stackpole D, Mazanec R (2001) 'Australian Low Rainfall Tree Improvement Group: Compendium of Hardwood Breeding Strategies.' (Rural Industries Research and Development Corporation: Canberra)

Harwood, C. and Bulman, P., 2001. Genetic improvement strategy for *Eucalyptus cladocalyx* in southern Australia, Australian Low Rainfall Tree Improvement Group: Compendium of Hardwood Breeding Strategies. Rural Industries Research and Development Corporation, Canberra, pp. 45-66.

Hill, K.D. and Johnson, L.A.S. (1995) Systematic studies in the eucalypts. 7. A revision of the bloodwoods, genus *Corymbia* (Myrtaceae). *Telopea* 6(2-3) : 185-504.

Hillis, W.E., 1987. Heartwood and tree exudates. Springer series in wood science. Springer-Verlag, Berlin, 268 pp.

Johnson, G.C., Thornton, J.D. and N.-K., N., 1993. An accelerated field simulator study of the natural durability of heartwood from mature and regrowth trees (Topic 2/21), 24th Forest Products Research Conference, Melbourne, pp. 9.

Johnson, G.C., Thornton, J.D. and N.-K., N., 1996. An in-ground natural durability field test of Australian timbers and exotic reference species. XI. Results after more than 25 years' exposure. Material u. Organismen, 30 (3): 219-230.

Keating, W.G. and Boltza, K., 1982. Characteristics, properties and uses of timbers: Vol 1 South-east Asia, Northern Aust and Pacific. CSIRO Melbourne.

Kenward, M.G. and Roger, J.H.T., 1997. The precision of fixed effects estimates from restricted maximum likelihood. Biometrics 53: 983-997.

Kjaer, E.D., Kajornsrichon, S. and Lauridsen, E.B., 1999. Heartwood, calcium and silica content in five provenances of teak (*Tectona grandis* L.). Silvae Genetica, 48(1): 1-3.

Langat, D.K. and Kariuki, J.G., 2004. Variations in heartwood proportion and basic density between provenances of Eucalyptus grandis in Kenya. Journal of Tropical Forest Science, 16(2): 179-186.

Lynch, M. and Walsh, B., 1998. Genetics and Analysis of Quantitative Traits. Sinauer Associates, Inc., Sunderland, Massachusetts, USA.

Magnussen, S. and Keith, C.T., 1990. Genetic improvement of volume and wood properties of jack pine: selection strategies. For.Chron.(66): 281-286.

McCarthy, K., Cookson, L. and Scown, D., In press. Natural durability of six eucalypt species from farm forestry and low rainfall areas. Rural Industries Research and Development Corporation, Canberra, 74 pp.

McCarthy, K. and Greaves, H., 1990. Decay detection and remedial treatments in wooden poles, (Topic 1/5), 23rd Forest Products Research Conference, pp. 16

McCarthy, K., Cookson, L., Mollah, M., Norton, J. and Hann, J. 2005, The suitability of plantation thinnings as vineyard posts. FWPA Project No. PN02.3900 185 pp.

McDonald, M.W. and Bean, A.R., 2000. A new combination in *Corymbia* 'section Politaria': *C. citriodora* subsp. *variegata* (Myrtaceae). Austrobaileya 5: 735-736.

McDonald, M.W., Butcher, P.A. and Bell, J.C., 2000. Genetic variation in the spotted gum group. Australian Systematic Botany, 13: 491-507.

McDonald, M.W., Rawlings, M., Butcher, P.A. and Bell, J.C., 2003. Regional divergence and inbreeding in *Eucalyptus cladocalyx* (Myrtaceae). Australian Journal of Botany, 51(4): 393-403.

Marcar N, Crawford D, Leppert P, Jovanovic T, Floyd R, Farrow R (2004) 'Trees for saline landscapes.' (RIRDC: Canberra)

Miranda, I. and Pereira, H., 2002. Variation of pulpwood quality with provenances and site in *Eucalyptus globulus*. Annals of Forest Science, 59 283-291.
Nicholls, J.W.P. and Brown, A.G., 1974. The Inheritance of Heartwood Formation in *Pinus radiata* D. Don. Silvae Genetica, 23(5): 138-141.
Nicholls, J.W.P. and Matheson, A.C., 1980. Variation in wood characteristics in thinnings from a field trial of *Eucalyptus obliqua*. Australian Forest Research, 10: 239-247.
Nyakuengama, J.G., Matheson, A.C., Spencer, D.J., Evans, R. and Vinden, P., 2000. Genetics of heartwood formation and moisture status in *Pinus radiata*. Appita Journal, 53(1): 30-35.
Paques, L.E., 2001. Genetic control of heartwood content in larch. Silvae Genetica, 50(2): 69-75.
Poke, F.S., Potts, B.M., Vaillancourt, R.E. and Raymond, C.A., 2006. Genetic parameters for lignin, extractives and decay in *Eucalyptus globulus*. Annals of Forest Science, 63(8): 813-821.
Rudman, P., 1964. Durability in the genus *Eucalyptus*. Australian Forestry, 28(4): 242-257.
Schmidtling, R.C. and Amburgey, T.L., 1982. Genetic variation in decay susceptibility and its relationship to growth and specific gravity in loblolly pine. Holzforschung, 36(3): 159-161.
Schultz, T.P. and Nicholas, D.D., 2000. Naturally durable heartwood: evidence for a proposed dual defensive function of the extractives. Phytochemistry, 54(1): 47-52.
Standards Australia, 2003. Methods of test for pulp and paper: Method 012s - organic solvent extractives in wood, pulp and paper, Standards Australia, Homebush, NSW.
Standards Australia, 2005. Timber-Natural durability ratings. AS 5604-2005, Standards Australia, Homebush, New South Wales.
Tamblyn, N., 1966. Natural durability ratings, CSIRO Forest Products Newsletter, pp. 1.
TAPPI (1989) Basic density and moisture content of pulpwood. Technical Association of the Pulp and Paper Industries (TAPPI), South Norcross, Georgia
Thornton, J.D., Johnson, G.C. and Nguyen, N.-K., 1997. Revised CSIRO natural durability classification: in-ground durability rating for mature outer heartwood, CSIRO Forestry and Forest Products, Melbourne.
Venalainen, M. *et al.*, 2001. Genetic variation in the decay resistance of Siberian larch (*Larix sibirica* Ledeb.) wood. Holzforschung, 55(1): 1-6.
Washusen, R., Ades, P., Evans, R., Ilic, J. and Vinden, P., 2001. Relationships between density, shrinkage, extractives content and microfibril angle in tension wood from three provenances of 10-year-old Eucalyptus globulus Labill. Holzforschung 55 176-182.
Windeisen, E., Wegener, G., Lesnino, G. and Schumacher, F., 2002. Investigation of the correlation between extractives content and natural durability in 20 cultivated larch trees. Holz Roh-Werkst, 60(373-374).
Wine Australia, 2008a. Winefacts: areas of vines and grape production by variety - 2006-07, Australian Wine and Brandy Corporation.
Wine Australia, 2008b. Winefacts: Australian Wine Sector At A Glance, 2007, Australian Wine and Brandy Corporation.
Yu, Q., Yang, D.Q., Zhang, S.Y., Beaulieu, J. and Duchesne, I., 2003. Genetic variation in decay resistance and its correlation to wood density and growth in white spruce. Canadian Journal of Forest Research, 33(11): 2177-2183.