Across-rotation factors affecting genetic improvement of *Eucalyptus globulus* in Australia

by

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Declarations

This thesis contains no material which has been accepted for a degree or diploma by the University or any other institution, except by way of background information and duly acknowledged in the thesis, and to the best of my knowledge and belief no material previously published or written by another person except where due acknowledgement is made in the text of the thesis. This thesis is not to be made available for loan or copying for two years following the date this statement was signed. Following that time the thesis may be made available for loan and limited copying in accordance with the *Copyright Act 1968.*

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Abstract

In forest tree improvement, ensuring that a breeding objective (BO) is well defined yet broad enough to cope with changes over time, is problematic. Two of the major changes to occur in the *Eucalyptus globulus* pulpwood plantation industry that may impact on tree improvement that were investigated in this study are coppice management of 2nd rotation crops and international demands for improved sustainability (e.g. the trade in environmental services such as carbon sequestration).

Coppice can provide a cheap alternative to replanting in the 2nd rotation. Regeneration following felling of a 9 year old progeny trial revealed significant genetic diversity in coppicing traits both within and between subraces. After 14 months, 67% of trees coppiced but subrace means varied from 43 to 73%. Heritabilities for coppice success (0.07) and subsequent growth (0.16-0.17) were low but statistically significant. The ability of a tree to coppice was genetically correlated with tree size prior to felling ($r_g = 0.61$), and with nursery-grown seedling traits such as the number of nodes with lignotubers ($r_g = 0.66$) and seedling stem diameter at the cotyledonary node ($r_g = 0.91$). These seedling traits were poorly correlated with later age growth and with each other. The results suggest coppicing is influenced by three independent factors - lignotuber development, enlargement of the seedling stem at the cotyledonary node and vigorous growth.

A discounted cash-flow model was developed to compare the profitability of coppice and seedling crops in 2nd rotation *E. globulus* pulpwood plantations. A

gain of 20% in dry matter production over the original seedling crop from 2nd rotation seedlings (through genetic improvement and provenance selection) would result in equivalent net present value (NPV) for 2nd rotation seedling and coppice crops. Incremental NPV was strongly affected by the level of genetic gain available (the genetic quality of 1st rotation stock relative to the available genetically improved stock), and the productivity of coppice relative to the first rotation crop.

The integration of environmental services (in the form of carbon seuquestration) into production system models to define economic BOs for the genetic improvement of pulpwood plantations was investigated. Carbon dioxide equivalent accumulation in biomass in the Australian *E. globulus* plantation estate between 2004 and 2012 was estimated at ~146 t CO_2e ha^{-1}, of which 62 t CO_2e ha^{-1} were tradable in 2012 and a further 30 t CO_2e ha^{-1} were tradable in 2016. Where revenues for carbon sequestration were dependant upon biomass in a plantation, it was possible to determine whether economic BOs were sensitive to the revenue from carbon sequestration. The correlated response of BOs with and without carbon revenues (ΔcG_{H_1}) was 0.93. Where economic BOs were based on maximizing NPV by increasing biomass production, the consideration of carbon provided no significant gain in NPV.

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Format of thesis chapters

Chapters 3 and 4 of this thesis have been written in the format of published scientific journal articles. Chapter 5 was presented as a conference paper and has been rewritten to provide a level of detail appropriate to a thesis. Acknowledgements and lists of references have been combined into single versions for the whole document. Figures, tables and equations have also been renumbered. Due to the diverse nature of this research, Abstracts, introductions, and conclusions are presented in each experimental chapter, with a general discussion highlighting the key findings and implications.

Publications and other output during candidature

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Whittock SP, Apiolaza LA, Kelly CM, Potts BM. 2003. Genetic control of coppice and lignotuber development in *Eucalyptus globulus*. *Australian Journal of Botany* **51**: 57-67.

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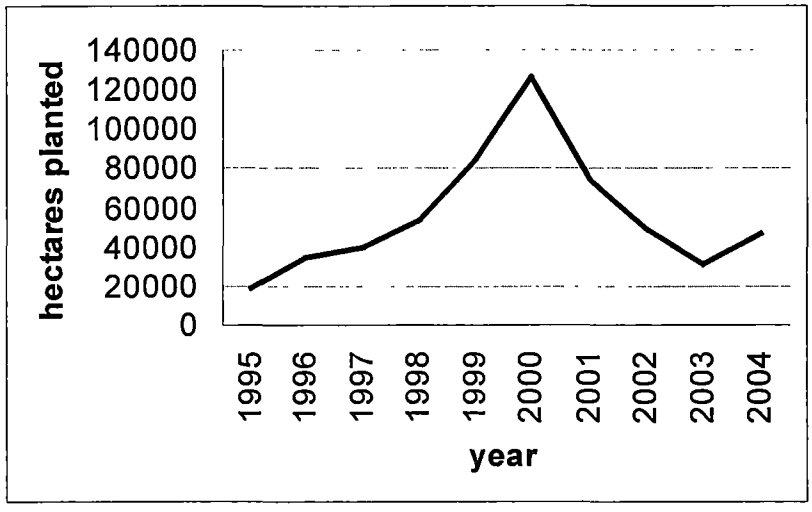
Chapter 1: Introduction to *Eucalyptus globulus* pulpwood plantations

Declining production of traditional products from natural forests, increasing institutional awareness of environmental issues such as climate change (Montreal Process Liaison Office 2000; FAO 2005; Reid *et al.* 2005), and market forces such as potential investments in carbon sequestration (Lecocq 2004) have resulted in a rapid increase in the rate of plantation establishment (Carle 2001). Some regions, such as Asia, almost doubled their plantation area between 1995 and 2000 (Dudley *et al.* 1999). The global plantation estate expanded from 124 million ha in 1995, to 140 million hectares in 1998 (Evans 1998; Dudley *et al.* 1999), and to 187 million hectares of plantation with 62% (115 million hectares) in Asia in the year 2000 (Carle 2001). Commercial timber production is becoming concentrated on a smaller land area in intensively managed plantation forests. In the year 2000, plantations made up 5% of the global forest area and supplied about 35% of the global roundwood requirements (Carle 2001). It was estimated that by the year 2050 commercial scale timber production will be concentrated in one quarter or less of the global forest area (Dudley *et al.* 1999). It has been argued that intensification of forest management in plantations will provide more opportunities for flexibility in the management of natural forests, making them less important for commercial wood production (Byron and Sayer 1998).

No sector of world forestry has expanded faster than the industrial use of eucalypts (Turnbull 1999). The high demand for pulp and paper products in the latter part of the 20th century has driven the rapid development of eucalypts for

industrial forestry. It is well recognised that *Eucalyptus globulus* is the premier forestry species for the pulp and paper industry in temperate areas (Cotterill *et al.* 1999; Grattapaglia 2003; Villena 2003). The fast growth rate, broad adaptability, and the physical and chemical properties of the wood of *E. globulus* have resulted in its extensive use in plantations in temperate areas, for the production of eucalypt kraft pulp (Villena 2003). At the end of 1995, it was estimated that about 1.7 million ha of *E. globulus* plantation had been established worldwide (Tibbits *et al.* 1997). Varmola and Del Lungo (2003) stated that *E. globulus* was the eighth most planted forest tree species in the world in 2003 despite the area planted (390,470 ha) being underestimated. It is likely that the global area currently planted to *E. globulus* is in excess of 2.5 million ha (Potts *et al.* 2004b). In Australia, the area of hardwood plantations has trebled since 1995 (National Forest Inventory 2004b), with *E. globulus* accounting for ~60% of the hardwood plantation estate (equivalent to 349,796 ha, calculated from Australia's National Forest Inventory 2004a).

Figure 1. New areas of hardwood plantation established each year in Australia between 1995 and 2004. From Australia's National Plantation Inventory (2000; 2002; 2003; 2004b; 2005).



The total plantation estate in Australia stood at 1.67 million hectares in 2004. Hardwood species made up 41% of this figure. The rate of new hardwood plantings slowed from around 126,211 ha in the year 2000, to 31,379 ha in 2003 (Figure 1 and National Forest Inventory 2004b). Most *E. globulus* plantations are for the production of pulpwood and will be harvested on rotations of 10-15 years. Therefore the plantation area of harvestable age will steadily increase until 2010, in line with the increase in plantings up to 2000 (see Figure 1). In this situation, priorities are changing from the basic requirements of land acquisition, to the development of a sustainable industry in later rotations. The development of a sustainable plantation forestry industry is, in part, based on identification of the requirements for genetic improvement and the application of appropriate methods to achieve improvement goals. The importance of many tree products and services to people, the diversity and richness of forest genetic resources, the brief history of informed domestication of most taxa, and the gains made by established breeding programs suggest that genetic improvement has a significant role to play in the future of intensive forestry (Kanowski 1996).

Step one in Ponzoni's (1986) process of breeding objective definition is the description of the production system. There is a need to develop better production functions to evaluate the economic effects of changes to forestry (Abel *et al.* 2003), and achieve alternative goals using genetic improvement. The genetic gains and associated financial returns delivered by breeding activities depend partly on the value of products and services of improved populations (Burley and Kanowski 2005). The development of methods for lifecycle assessment of wood products (Pingoud and Lehtilä 2002; Berg and Karjalainen 2003; Dias *et al.* 2004) and ecological footprinting (e.g. Monfreda *et al.* 2004; Copley 2005) offer the

possibility of valuing social, ecological and economic concerns in forest management and tree improvement.

There are many potential issues when considering the future development of breeding objectives in *E. globulus*, some of the major ones being: integrating fibre properties affecting paper quality into breeding objectives, potential solid wood products; plantation nutrient and water use; biodiversity; pests and diseases; planting in marginal environments; clonal forestry; social issues; alternative silviculture such as coppice systems: and finally new sources of income such as revenue from carbon sequestration and other ecosystem services. For many of the issues highlighted above the impact on the production system will extend beyond a single rotation. This thesis explores some across rotation problems relevant to the future genetic improvement of *E. globulus* in Australia, namely:

- quantitative genetic variation in the ability of *E. globulus* to coppice (Chapter 3)
- the economics of coppice crops versus improved seedling crops (Chapter 4)
- the impact of potential revenues from carbon sequestration on breeding objectives for *E. globulus* pulpwood plantations (Chapter 5).

These issues are introduced briefly in the literature review (Chapter 2) and in depth in the respective chapters. Other issues are discussed in terms of genetic improvement only in the literature review.

Chapter 2: A review of the literature on alternative breeding goals for *Eucalyptus globulus*

2.1 Breeding objectives for *Eucalyptus globulus*

Early industrial eucalypt plantings provided fuel-wood, mine timbers and railway cross-ties (Doughty 2000). The recent expansion of industrial forestry based on eucalypts has been driven by demand for short fibre pulp for the pulp and paper industry (Potts 2004), with *E. globulus* the species of choice for pulp and paper production (Cotterill *et al.* 1999; Grattapaglia 2003; Villena 2003). There has been considerable effort expended on the genetic improvement of *E. globulus* for pulpwood plantations in Australia (Volker and Orme 1988; Borralho *et al.* 1993; Jarvis *et al.* 1995; Greaves *et al.* 1997b; Borralho and Dutkowski 1998; Harbard *et al.* 1999; Kerr *et al.* 2001). In Australia genetic improvement of *E. globulus* is wholly intra-specific.

Rigorous definition of the breeding objective is necessary to optimise selection in a breeding program (Apiolaza and Garrick 2001), yet breeding objectives must be broad enough to cope with changes over time (Namkoong *et al.* 1988). Ponzoni (1986) outlined 4 essential stages in the development of economic breeding objectives: (1) the specification of the production system; (2) identification of sources of income and costs; (3) identification of the biological traits influencing income and costs; and (4) determination of the economic value or weight of each trait in the objective. Following this process a selection index can be constructed

in the form of an objective (H), defined as a linear combination of additive genetic values (a_i), weighted by their respective economic importance (w_i),

$$H = w_1a_1+w_2a_2+....+w_na_n \qquad [1]$$

or, using matrix notation,

$$H=\mathbf{w'a}. \qquad [2]$$

The central problem of objective definition then becomes the estimation of the economic weights in $\mathbf{w}$. The traits in H must have an economic impact in the system under study (Apiolaza and Greaves 2001). Tree improvement is generally focused on the end-product of forestry (Muhs 1995), the value of which depends on yield, quality, uniformity or the shortening of rotation length. Most traits in the objective will be expressed at harvest age. In spite of this, the assessment of progeny trials is normally carried out at early age to reduce generation interval, or because most traits are too difficult or expensive to assess directly at harvest age. Hence, other characters known as selection criteria are assessed. Selection criteria are genetically correlated with the objective traits and are feasible to include in the routine evaluation of progeny tests. There is a clear distinction between objective traits and selection criteria, with objective traits having a direct influence on the models measuring profit and included in the breeding objective, while selection criteria are the characteristics assessed on trees which are then used to predict the genetic values for the objective traits (Apiolaza and Greaves 2001).

The production system associated with intensive forestry using *E. globulus* was described by Borralho *et al.* (1993) who derived economic breeding objectives for the production of kraft pulp from plantation grown *E. globulus*. The economic

importance of each trait was calculated for five different pulp and forest industry scenarios with widely different cost structures, and selection indices integrating various combinations of volume growth, wood density, and pulp yield being compared. Consistently, across the range of breeding objectives and cost structures studied, selection indices integrating volume, wood density and pulp yield gave the most accurate selection and maximised genetic gain in breeding objectives, with substantial implications for company profitability. Further work incorporating variable capital and operating costs and more detailed pulp mill relationships, considering standing volume, basic density, pulp yield and stem form showed that basic density and standing volume were the most important traits, providing the greatest savings in the total cost of producing kraft pulp (Greaves *et al.* 1997b). Combined selection using basic density and volume provided 95% of the gains possible from an index involving all traits considered, and stem form had minimal effect on the cost of producing pulp.

The particular aims of breeding depend upon the purpose for which the trees are to be used. In the case of a competitive industry, the overall goal of breeding is to increase profit. Decisions about which traits are included in the breeding objective should be based on purely economic grounds (Borralho *et al.* 1993). The breeding objectives developed by Borralho *et al.* (1993) and Greaves *et al.* (1997b) were based on the production kraft pulp. However, breeding objectives determined by short-term market forces often lead to unwanted side effects (Olesen *et al.* 2000). International demands for improved sustainability (e.g. Millenium Ecosystem Assessment, Reid *et al.* 2005) have caused animal breeders to recognise the potential role of genetic improvement in the sustainable development of agriculture (Sarmiento *et al.* 1998; Brenøe and Donner 1999).

Similarly, changes in forestry and the socio-economic environment in recent years have seen other objectives explicitly considered and pursued (Kanowski 1996). The problems that sustainability presents for tree breeders are most readily identified and most pressing within large industrial plantations (Kanowski 1996). Some of the issues considered in recent years have been adaptedness and adaptability, environmental stress factors such as pollution and climate change, the recultivation of degraded areas (Muhs 1995), the impact of genetically modified organisms (Zamir 2001), and alternative forest products (Greaves *et al.* 2004a).

The diversity of the native gene pool of *E. globulus* has allowed the establishment of successful programs of species improvement both in Australia and overseas (Potts *et al.* 2004b; Burley and Kanowski 2005). Quantifiable genetic variation has been identified for traits of interest to breeders such as growth (Infante and Prado 1989; Volker *et al.* 1990; Infante and Prado 1991; Ipinza *et al.* 1994; Araujo *et al.* 1996; Dutkowski and Potts 1999; Sanhueza *et al.* 2002; Zang *et al.* 2003), stem form (Ipinza *et al.* 1994) and branch size (Volker *et al.* 1990), survival (Chambers *et al.* 1996; Sanhueza *et al.* 2002), flowering season, and precocity (Chambers *et al.* 1997), fecundity (McGowen *et al.* 2004) phase change from juvenile foliage (Ipinza *et al.* 1994; Jordan *et al.* 1999), wood properties (MacDonald *et al.* 1997; Schimleck *et al.* 1999; Muneri and Raymond 2000; Miranda *et al.* 2001b; Miranda *et al.* 2001c; Miranda *et al.* 2001a; Miranda and Pereira 2001; Miranda and Pereira 2002), rooting ability (Ipinza and Gutierrez 1992; Cañas *et al.* 2004), reproductive output (Ipinza *et al.* 1994), drought resistance (Toro *et al.* 1998; Dutkowski and Potts 1999), susceptibility to mammalian herbivores (O'Reilly-Wapstra *et al.* 2002), resistance to *Phoracantha*

semipunctata (Soria and Borralho 1997), *Myllorhinus* spp. (shoot-feeding weevils, Jones and Potts 2000), *Mnesampela privata* (autumn gum moth, Jones *et al.* 2002), *Chrysophtharta agricola* (southern eucalypt leaf beetle, Rapley *et al.* 2004), *Gonipterus scutellatus* (eucalypt weevil, Basurco and Toval 2004) and *Mycosphaerella sp.* (Potts *et al.* 2004a). The use of techniques such as near infrared reflectance (NIR) analysis is providing access to many more wood properties traits (Muneri and Raymond 2000; Muneri and Raymond 2001; Raymond and Muneri 2001; Raymond *et al.* 2001a; 2001b; Schimleck *et al.* 2004). However, the long-term nature of tree improvement in temperate forestry, and the complexity of sustainability mean that expectations of tree improvement should be carefully considered (Kanowski 1996).

2.1.1 Paper production

Wood density, pulp yield, and volume per hectare have been identified as the key biological traits influencing the economics of pulpwood production and economic breeding objectives have been developed reflecting this (Borralho *et al.* 1993; Greaves *et al.* 1997b). Extending such work beyond pulp to paper production is the logical next step for tree improvement in *E. globulus* (Potts 2004). Breeding for improved wood, pulp, and paper properties can have a collective impact on harvesting, transport, and downstream processing costs, that is greater than the impact of increased growth on overall costs (Whiteman *et al.* 1996). The paper qualities influenced by wood or fibre properties are specific energy consumption in pulp and paper manufacturing, tear and tensile strength, brightness, and opacity (Chambers and Borralho 1999). Key wood properties influencing pulp and paper production are basic density, pulp yield, cellulose content and fibre length (Raymond and Apiolaza 2004). Achieving greater gains in wood, for paper

production requires improved definition of the breeding objective and the development of rapid, cheap, and effective assessment techniques for wood properties (Whiteman *et al.* 1996).

Realized gains in growth traits range from 10 to 40% per generation despite these traits being under relatively weak genetic control ($h^2 \approx 0.2$). Wood quality traits are generally under stronger genetic control ($h^2 \approx 0.4$-0.8), however, these traits generally have lower coefficients of variation (Whiteman *et al.* 1996). Assessment of wood quality traits has in the past been destructive, difficult and expensive and single point samples usually do not correlate well with whole tree values. (Whiteman *et al.* 1996; Raymond and Apiolaza 2004). However, the medium to high heritability of wood properties does allow subsampling to be used in wood property assessment (Raymond and Apiolaza 2004). Indirect assessment methods such as near infrared reflectance (NIR) analysis (Muneri and Raymond 2001; Raymond and Muneri 2001; Raymond *et al.* 2001b) or fourier transform raman spectroscopy (Ona *et al.* 1997) allows an increased number of samples to be processed. Such analysis requires a wood core sample to be taken from a tree using a motorised corer (Downes *et al.* 1998), the core is then ground to produce wood meal, which is then measured in a spectrophotometer. Analysis requires the development of a calibration that relates the spectra of a large number of samples to their known chemical constitution. The calibration can then be used to predict the composition of further samples based on their spectrum (Raymond and Apiolaza 2004). Such assessment techniques are dependant on a good correlation between the properties of the core and whole tree values.

Using NIR analysis, core samples were found to be reliable predictors of whole-tree density, explaining between 84 and 89% of the variation between trees in *E.*

globulus and *E. nitens* respectively. Core orientation was not important and density was not related to tree size. Six whole-tree samples or eight core samples are required for estimating the mean density of a stand at a specific site to an accuracy of plus or minus 20 kg m^{-3} with a 95% confidence interval (Raymond and Muneri 2001). Core samples are reliable predictors of whole-tree fibre length with cores from the recommended sampling heights explaining 87% and 71% of variation for *E. globulus* and *E. nitens* respectively. The single core sample could only account for 54% and 45% of the variation in whole-tree fibre coarseness *E. globulus* and *E. nitens* respectively (Muneri and Raymond 2001). Core samples were found to be good predictors of whole-tree pulp yield for *E. globulus*, explaining more than 50% of variation in whole-tree pulp yield (Raymond *et al.* 2001b).

A clear understanding of the genetic correlations between selection traits and breeding objective traits is required to assess the relative value of a unit change in each trait on costs and profit, and develop appropriate economic breeding objectives. Careful consideration must be given to the development of the breeding objective to avoid mistakes, such as targeting increased specific gravity as a trait to improve due to its ease of measurement and impact on pulp yield, lumber strength, and lumber stiffness. Increased specific gravity however, lowers many paper strength and stiffness properties (Via *et al.* 2004).

In *Pinus radiata* inclusion of a pulp mill in the production system model changed the relative economic weights of volume and wood density in a two-trait breeding objective (Apiolaza and Garrick 2001). However, the genetic correlations between two-trait breeding objectives optimised for 3 different silvicultural regimes were above 0.9, indicating that a single breeding objective could be

adopted with little loss of genetic gain relative to selecting for a particular silvicultural regime (Apiolaza and Garrick 2001). Chambers and Borralho (1999) examined the effect of wood properties such as tracheid length, wood density wood brightness and fibre coarseness, on the total cost of producing thermomechanical pulp from *Pinus radiata*. Tracheid length and wood brightness were found to have almost as much influence as wood density on the cost of producing thermomechanical pulp. The breeding objective developed for the minimisation of the cost of production of kraft pulp from *E. globulus* had roughly equivalent economic weights for volume and density, while the economic weight for pulp was around half those for volume and density (Greaves *et al.* 1997b). The relative economic weights for wood properties such as cellulose content and fibre length are not understood in terms of the production of paper using the Australian *E. globulus* plantation resource.

2.1.2 Solid and composite wood products

Australia, has in the past, relied heavily on eucalypt timber for solid hardwood products. With declining production from native forests, an increase in the use of lower density regrowth and plantation stock is projected (Chafe *et al.* 1992; Byron and Sayer 1998; Greaves *et al.* 2004b). In order to use plantation grown eucalypts for solid wood products, the problems of knots and drying degrade must be addressed. Knots, checking (Kube and Raymond 2001), and tension wood (Washusen and Evans 2001) reduce quantity and quality of sawn wood from young plantation grown eucalypts. Checking is caused by collapse, collapse being abnormal shrinkage encountered during drying which causes significant timber degrade (Chafe *et al.* 1992). Tension wood is reaction wood in hardwoods that can lead to drying problems in solid wood during processing.

There are two potential approaches to overcoming the problems associated with the utilisation of plantation grown *E. globulus* for solid wood products (Chafe *et al.* 1992). The first is to understand the parameters responsible for the development of knots, checking and tension wood, their derivation with respect to the biology of the tree, and the likely effect of a variety of environmental influences and treatments for optimal product conversion. For example, it is likely that knots can be managed silviculturally through pruning and thinning regimes (Neilsen and Pinkard 2000). The second approach requires selection to produce individuals that have no predisposition to collapse. Significant genetic variation for wood property traits such as basic density, cellulose content, lignin content, fibre length, and transverse and longitudinal shrinkage (Raymond 2000) and spring in green quarter sawn boards (Greaves *et al.* 2004b) suggests that exploitation of genetic variation in shrinkage and collapse behaviour will have commercial value in the improvement of the recovery of veneer, stability of back-sawn boards, and the value of appearance grade sawn products through a relationship with internal and surface checking (Greaves *et al.* 2004b). This suggests a role for breeding in overcoming the problems associated with utilising plantation eucalypts for solid wood products.

Breeding objectives have been developed for both kraft and mechanical pulping of eucalypts, but the relevant issues for solid wood production are more complex and definition of clear breeding objectives difficult (Raymond 2000). Breeding objectives and potential improvements in profitability have not been well defined for solid wood products from plantation grown timber (Kube and Raymond 2001). There is a decent understanding of the economic drivers for both solid and composite products. Recovery (green and dry), grade, drying cost and sawing

productivity affect the economics of solid timber production, while recovery, grade, drying degrade, glue usage and energy consumption are the major economic drivers for in the production of composite wood products (Raymond and Apiolaza 2004). The key wood properties for solid wood products are basic density and gradient, microfibril angle, shrinkage and collapse, tension wood, knot size, incidence of decay, spiral grain and end splitting. In the case of composite products the key wood properties are basic density, lignin content, extractives content and cellulose content (Raymond and Apiolaza 2004). There are two major problems encountered when considering breeding for solid wood products. The first is the need for a well defined model of the production system, including products, cost structures and markets, and the second is the lack of suitable rapid, representative, and non-destructive sampling techniques for the assessment of the many desirable wood properties (Raymond 2000; Kube and Raymond 2001).

While plantation grown *E. globulus* is being processed into solid and composite wood products overseas (e.g. Spain, Alvite *et al.* 2002), the industrial infrastructure to utilise plantation timber for sawn wood products is currently under development in Australia. It is difficult to obtain the economic weights of different traits affecting the quality of sawn products without a clear understanding of the production system. Further adding to the difficulty of defining the production system is the fact that the market for sawn timber from *E. globulus* plantations is yet to be established, so market signals to growers are weak (Kube and Raymond 2002). Many potential products can be produced from the same trees, including veneer, sawn timber, poles, structural and appearance products, some of which require different wood properties, and all of which

require different cost functions (Raymond 2000). Despite this, extensive research is underway into overcoming the silvicultural (Waugh 2004; Nolan *et al.* 2005), economic (Greaves 2003; Greaves *et al.* 2004a), genetic (Greaves *et al.* 2004b), and wood property assessment problems.

2.1.3 Nutrients

A vertically integrated forest industry allowed the affect of plant genotype on nutrient export from the plantation site and the impact of plant genotype nutritional behaviour on the pulp/bleaching technologies to be investigated (Foelkel and de Assis 1995). It was demonstrated that different species and clones growing on different sites have different performances in relation to the amount of wood produced relative to the amount of individual nutrients such as nitrogen harvested. A better understanding of the scale of the impact that changing genotypes will have, both in plantations and in the pulp and paper production system would be required to establish the economic value of breeding as tool to address these issues. This highlights further the need to have better models of the production system. Production system models integrating timber production and processing allow more refined silvicultural management, but also would allow geneticists to make informed decisions as to the likely value of genetic improvement to an enterprise.

Another consideration associated with tree nutrients is their effect on other organisms and ecosystem processes. For example, studies in natural ecosystems have shown that condensed tannin inputs from foliage (under strong genetic control) explained about 55-65% of the variation in soil net nitrogen mineralisation (Schweitzer *et al.* 2004) and whole tree gas and water exchange

(Fischer *et al.* 2004). Foliar condensed tannins provide a mechanism whereby genes affect key processes in a riparian cottonwood (*Populus angustifolia, Populus fremontii,* their hybrids and backcrosses) ecosystem (Schweitzer *et al.* 2004). Plant genetic diversity is thought to be necessary for the maintenance of dependant animal communities (Wimp *et al.* 2004) and it has also been demonstrated that plant genetics affects arthropod community richness and composition in a eucalypt population (Dungey *et al.* 2000). Therefore it is likely that the genetics of a dominant plant species can affect ecosystem processes (Whitham *et al.* 2003; Schweitzer *et al.* 2004).

2.1.4 Gene flow

Plants dispersing by seed and becoming weeds have been a major problem in the management of natural ecosystems. Wildlings, which are seedlings established from plantation derived seed, have become a problem for the silviculture of *Pinus radiata* in Australia (Lindenmayer and McCarthy 2001). Typically in a eucalypt pulpwood plantation, some flowering may occur around the time of canopy closure, with a substantial reduction in flowering intensity when trees are subject to intense competition (Potts *et al.* 2003). However, flower bud abundance is often site dependant, so the risk of seed mediated dispersal from plantations will vary. In the case of *E. globulus*, the age to first flowering can be affected by environmental and genetic factors. There is a large amount of genetic variation for age to first flowering under normal plantation conditions (Potts *et al.* 2003). Within populations the onset to first flowering is genetically independent of the transition to adult foliage (Jordan *et al.* 1999), and growth and wood basic density (Chambers *et al.* 1997) meaning that delayed flowering may be selected without compromising economic traits (Potts *et al.* 2003).

Pollen mediated gene flow from *E. nitens* plantations has been demonstrated in Tasmania (Barbour *et al.* 2002). Verified F_1 hybrids between exotic plantation *E. nitens* and native *E. ovata* have been found established in the wild (Barbour *et al.* 2003). The probability of successful hybridisation generally decreases with taxonomic distance between species (Potts *et al.* 2003). Such pollen-mediated gene flow has become known as genetic pollution, or exotic geneflow in order to distinguish it from hybridisation and introgression that occur naturally. Pollen-mediated gene flow will be a problem for *E. globulus* in industrial plantations if reproductively mature plantations abut stands of native species with taxonomic affinities to *E. globulus*. This may occur in the case of natural *E. globulus* in Tasmania and southern Victoria, and species such as *E. camaldulensis* in areas such as western Victoria where plantations have been established on land previously cleared for agriculture.

Eucalypts, especially *E. globulus*, are an internationally utilised genetic resource. Therefore Australia has an international obligation for the long-term conservation of this genetic resource (Potts *et al.* 2003). Strategies to manage the gene pools of major plantation species and to minimise the impacts of genetic pollution are among the Commonwealth's indicators for sustainable forestry in Australia (Commonwealth of Australia 1998). There is currently no economic pressure to incorporate traits reducing reproductive output from plantation species in the breeding strategy. However, a framework for the assessment of the risk of genetic pollution from plantations has been developed (Potts *et al.* 2003; Barbour 2004). Such a framework could potentially be incorporated into certification schemes. In that situation, it may be possible to show an economic impact of the use of selection as a tool to reduce reproductive output from plantations.

2.1.5 Clonal propagation

The utility of clonal propagation in forestry and tree improvement has long been recognised (Larsen 1956; Libby and Ahuja 1993). Increased genetic gains through clonal deployment of superior genets or families is well recognised in eucalypts (Ruaud *et al.* 1999; Griffin 2001). Industrial scale clonal propagation of eucalypts for planting is widespread in the tropics and subtropics. Select clones are used extensively in Brazil, Congo, Morocco and South Africa. Cuttings can be obtained relatively easily from seedling or basal coppice material of many eucalypts, but the ability of cuttings to produce roots rapidly declines with tree age (Potts 2004). Temperate species such as *E. globulus*, *E. nitens*, and *E. regnans* have a reputation for being difficult to root (Ruaud *et al.* 1999; Potts 2004). Recent advances in technology for industrial scale clonal propagation of eucalypts have occurred with the development of intensive micro- and minicutting systems in Brazil. In both systems, field clonal hedges are replaced by intensively managed minihedges grown indoors using hydroponic systems (de Assis 2001). This reduces costs and makes the propagation cycle less dependant on weather conditions (Potts 2004).

Deployment programs based on clonal forestry or on specific combining ability of crosses exploit both additive and non-additive genetic effects, whereas strategies based on open-pollinated (OP) seed orchards concentrate on the utilisation of additive effects only (Costa e Silva *et al.* 2004). The use of clonal propagation would have the greatest benefits in a situation where non-additive genetic effects were large. In the cases of diameter and pilodyn (an indirect measure of wood density) in *E. globulus*, additive, dominance and epistatic effects were found to account for 10%, 0-4% and 0.4%, and 11-17%, 0% and 5% of the phenotypic

variance respectively (Costa e Silva *et al.* 2004), so non-additive effects appear small relative to additive genetic effects in the case of the important economic traits. This suggests that attempts to exploit non-additive variance may not add substantial extra genetic gain for the production population derived from the genetic material studied by Costa e Silva (2004), when compared to options capturing additive effects only.

When calculating genetic parameters for *E. globulus* OP material the coefficient of relatedness should be adjusted to account for self fertilisation (Potts *et al.* 1995; Dutkowski *et al.* 2001). Despite this, breeding values from OP material do not account for inbreeding depression, non-random mating and variable levels of outcrossing. Therefore additive and non-additive genetic effects are confounded in genetic parameter estimates based on OP progeny (Potts *et al.* 2004b). When comparing genetic parameters and parental breeding values from OP families and those obtained using pollen of the same 26 base parents in a factorial mating design (control pollinated - CP) it was found that for growth traits: (i) variation within OP families is high compared to CP (Hodge *et al.* 1996; Volker 2002); (ii) OP heritabilities are inflated even after adjustment (Hodge *et al.* 1996; Volker 2002); (iii) breeding values estimated from OP and CP progeny are poorly correlated (Hodge *et al.* 1996; Volker 2002) and; (iv) estimated levels of genotype x site interactions are less for OP progeny than CP (Hodge *et al.* 1996; Volker 2002), suggesting that OP estimates of additive by environment interactions are downwardly biased (Potts *et al.* 2004b). High within race or subrace genetic correlations for growth across many sites may reflect stable differences in inbreeding depression among OP families rather than consistent expression of additive genetic effects. However, growth is strongly affected by inbreeding

depression and other traits, such as frost tolerance, *Mycosphaerella* resistance, leaf morphology, pilodyn penetration (an indirect measure of wood density), phase change, and the onset of flowering show good correlations between breeding values calculated from OP and CP progeny (Potts *et al.* 2004b).

If even moderate genotype x environment interactions exist, a breeder may be able to utilise that variance to make additional genetic gains through some level of regionalisation (Hodge 1996). Potts *et al.* (2004b) found that for most traits measured, expression was relatively stable within races across 5 Tasmanian sites, and family by site interactions accounted for only 1% of variance in the case of both average pilodyn penetration at five years and diameter at age 4, compared to family effects accounting for 13% and 5% respectively. Virtually all main effects and interaction components were statistically significant, and with the exception of the race x site interaction components for diameter, the interaction variance components were small compared to the site stable components of genetic variance. This suggests that race x environment interactions may be more significant than genotype within race or subrace x environment interactions. Without a clear understanding of the magnitude or nature of genotype x environment interactions in *E. globulus* it is not possible to predict marginal gains from regionalisation.

Even in the absence of non-additive effects and genotype x environment interactions, clonal selection in a cloned breeding population may lead to genetic gains per year exceeding those of other plant production methods through a reduction in the time needed to deploy selected material (Hodge 1996; Araújo *et al.* 2004). Additionally, using clonal replicates in progeny tests can improve the accuracy of selection for additive genetic merit (Costa e Silva *et al.* 2004). The

potential genetic gains from clonal forestry can be evaluated using software such as GSIM (Dutkowski 2004). Evaluation systems integrating genetics with the production system economics of clonal forestry are yet to be developed, so it is difficult to assess the economic potential of clonal forestry in Australia at this time.

Where clones of *E. globulus* have been deployed, it has been following extensive screening for rooting ability, meaning that many selections were discarded because of failure to reach economically viable levels of rooting (Wilson 1992). Such screening drastically reduces the number of genotypes available for deployment, and the potential gain in traits of direct economic significance (MacRae and Cotterill 1997). An alternative is to select for propagation characteristics (such as rooting ability) in the breeding population to improve the cloning potential of the whole population (Ruaud *et al.* 1999). For a clone to be commercially viable at least 70% of cuttings must strike roots successfully (Wilson 1992). Without screening for rooting ability, the reported average rooting success of *E. globulus* varies between 4.3% and 40% (De Little and Ravenwood 1991; Ipinza and Gutierrez 1992; Borralho and Wilson 1994; England and Borralho 1995; Lemos *et al.* 1997; Ruaud *et al.* 1999).

Reported heritabilities for rooting ability range from 0.41 (Borralho and Wilson 1994) to 0.54 (Lemos *et al.* 1997), and there is evidence suggesting that non additive genetic effects (Lemos *et al.* 1997; Ruaud *et al.* 1999) and genotype by environment effects (Borralho and Wilson 1994) are small in the case of this trait. Selection for improved rooting ability should therefore be successful based on the parental breeding values for rooting ability (Borralho and Wilson 1994; Lemos *et al.* 1997; Ruaud *et al.* 1999). If adequate gains from clonal deployment are

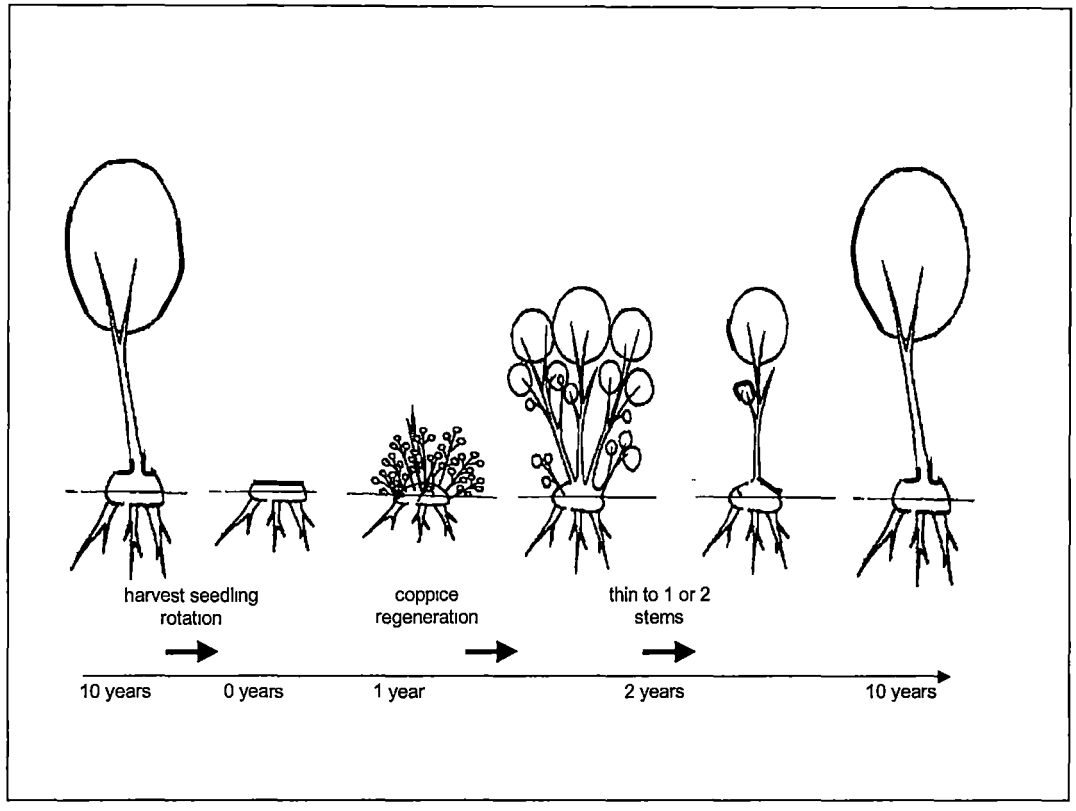
demonstrated, successful commercial vegetative propagation of *E. globulus* could be linked to breeding to improve rooting as described by Araújo *et al.* (2004).

2.1.6 Coppice

When felled near the ground most broad-leaved species regenerate from dormant buds on the side of the stool near ground level, or from dormant buds situated in the cambial layer around the periphery of the cut surface (Sennerby-Forsse *et al.* 1992). The regenerative powers of eucalypts have led to their utilisation in coppice systems for the production of cut foliage in floriculture (Wirthensohn and Sedgley 1998), logs for fuelwood, biomass for energy production and as pulpwood (Doughty 2000). In particular, *E. globulus* has been managed as a coppice crop in India (Matthews 1992), Portugal (Turnbull and Pryor 1984; de Almeida and Riekerk 1990) and Chile (Turnbull and Pryor 1984; Prado *et al.* 1990; Alarcón 1993). In India, *E. globulus* has been coppiced four times on a 10-15 year cutting cycle (Doughty 2000), but pulp production plantations tend to be coppiced only two or three times on rotations of 8-12 years (Eldridge *et al.* 1993).

Coppice crops derive considerable benefit from an established root system and initial biomass production exceeds that of seedlings (Blake 1980; Crombie 1997). In unthinned coppice the yield from the first coppice crop often exceeds that from the maiden crop (Hillis and Brown 1978). Decline in yield of later coppice rotations appears to be due to cumulative stump mortality rather than a loss of vigour in the surviving stumps (Matthews 1992). Using coppice to produce pulpwood requires thinning to one or two stems within the first two years of the coppice rotation (see Figure 2).

Figure 2. An example of the coppice system as applied in an *E. globulus* pulpwood plantation.



The development of successful programs of genetic improvement in *E. globulus*, and the probable increases in profitability over time supplied through genetic improvement mean that growers must give consideration to replanting rather than coppicing, especially on high quality sites where there is a high probability of successful establishment of a seedling crop. As coppicing allows the same genotype to continue in the production system over at least two rotations, the production system must be analysed across at least two rotations in order to assess the relative merits of coppice versus improved seedlings. An economic comparison of coppice and seedling crops across two rotations is presented in Chapter 4. An investigation of the genetic variation in coppice production, the level of genetic control, and the genetic relationship between coppice production and biological traits such as lignotuber development is presented in Chapter 3. The use of coppice systems impacts on the genetic improvement by slowing the

deployment of improved genotypes and causing a decrease in the level of realised gain per unit time. Therefore extensive use of the coppice system will have a long-term multi-rotation impact on the deployment of genetic gains in *E. globulus*.

2.1.7 Trade of ecosystem services

Industrial tree plantations have been recognised as supporting economic development and environmental enhancement through the protection of natural vegetation and biodiversity (Burley 1996; Dudley *et al.* 1999). However, serious questions remain concerning the social, economic, ecological, and environmental sustainability of industrial plantation forestry (Evans 1998; Dudley *et al.* 1999; Evans 1999; Namkoong 2000; Reid *et al.* 2005). The foundation of sustainable forest management is the integration of social and ecological concerns and knowledge (Lautenschlager 2000). In theory, sustainable forest management recognises that: forest resources should be maintained and enhanced for the health and vitality of forest ecosystems as well as for global carbon balance; forests should be tended for the biological diversity of forest ecosystems and to advance the socio-economic functions and conditions of forests; and wood and non-wood production forests should be encouraged (Montreal Process Liaison Office 2000; Gregersen and Contreras 2001).

In the past, forest management was considered in the context of sustainability of timber supplies. Concerns over the sustainability of ecosystems have now come to dominate forest policy discussions, decisions relating to forest planning, and evaluation of strategic alternatives (Ducey and Larson 1999). Management of

forests for sustained yield timber production has been replaced by the broader concept of sustainable forest management.

Achieving sustainable development requires the coordination of objectives with biological (environmental), economic (productive) and social (institutional) goals (Burley 2001). In many cases economists feel that market based instruments are the most efficient method for the integration of these goals. According to Dijkstra (1999) market based instruments were first proposed to combat pollution through emissions charges (Pigou 1920) and tradeable emission permits (Dales 1968). Market based instruments are currently being implemented, undergoing trials or used. Trading of emission permits began in the USA in the 1970s, but the first large scale consciously designed tradeable emission permit scheme was the Sulphur Allowance Trading program introduced in 1990 for the sulphur dioxide (SO_2) emissions of electricity utilities. Sulphur dioxide emissions were targeted because of their contribution to acid rain in North America (Dijkstra 1999). Emissions charges were introduced by the Dutch in 1970 to raise revenue for collective water purification. In 1991 Sweden introduced a system of emission charges for oxides of nitrogen (NO_x) and sulphur (Dijkstra 1999). Examples of market based instruments from Australia are the schemes trading in ecosystem services such as maintenance of water quality (e.g. The Hunter River Salinity Scheme: Murtough *et al.* 2002), control of groundwater recharge that causes salinity (Binning and Feilman 2000) and the protection of biodiversity (Binning and Feilman 2000; Murtough *et al.* 2002).

The Montreal protocol states that forest resources should be managed to maintain total carbon balance (Montreal Process Liaison Office 2000). The Australian forestry standard (Australian Forestry Standard Steering Committee 2003) follows

the form of the Montreal protocol where carbon is concerned. The Kyoto protocol allows carbon emissions to be offset by biomass in plantation forests established post 1990 on previously unforested land (Watson *et al.* 2000). One possible way for this to happen is through afforestation or reforestation of land cleared of forest before 1990. While there are several definitional and procedural problems associated with using plantations for carbon offsets or carbon trading, it seems likely that some sort of carbon economy will be in operation in the next decade (Lecocq 2004). Much of the Australian *E. globulus* plantation estate is likely to be eligible for consideration as a carbon offset, as it has been established on cleared agricultural land. The total potential carbon storage capacity of forests is low compared to the amount of carbon that needs to be locked away. Therefore, the price paid for carbon stored in planted forests can not be high, and it is unlikely that it will be economically viable to grow trees purely on the basis of carbon revenues. Estate based models of plantation growth, coupled with carbon sequestration exist (e.g. Dury *et al.* 2002), but the impact of genetic improvement on carbon revenues and the impact of carbon revenues on economic breeding objectives has not been investigated. The correlation between breeding objectives including an economic weight for carbon sequestration and a basic pulpwood objective were investigated in Chapter 5.

2.2 Conclusions

Two of the major steps in the development of an economic breeding objective for a genetic improvement program are the description of the production system, and the identification of all sources of income and costs. Economic breeding objectives have been described for the genetic improvement of *E. globulus* pulpwood plantations. Since the publication of these economic breeding

objectives, growers have begun to utilise the regenerative ability of *E. globulus* to produce a coppice crop from stumps harvested at the end of the first rotation. The use of coppice alters the silvicultural cycle and therefore impacts on the production system, and the incomes and costs associated with growing *E. globulus* in plantation. Increasing awareness of the value of sustainable forest ecosystems to maintaining environmental quality has been recognised in international agreements such as the Montreal and Kyoto protocols. At the same time trading schemes for environmental services have been pioneered. Such schemes have been used to combat industrial pollution (in the form of acid rain, effluent discharge and particulate emissions), manage water use, combat rising water tables and salinity, and it is hoped that the Kyoto Protocol will provide a mechanism to promote the sequestration of atmospheric carbon dioxide in terrestrial ecosystems, thereby helping to reduce the contribution of anthropogenic carbon dioxide to climate change and global warming. Such schemes represent an opportunity for plantation growers to add to their revenue streams by selling the value of the environmental services provided by growing trees at a particular site. Forest growers will benefit particularly in the case of schemes designed to combat rising water tables and salinity in certain areas, and schemes allowing the value of forest based carbon dioxide sequestration to be traded.

The environmental requirements of *E. globulus* preclude it as a species from being used to combat rising water tables in areas with soil salinity problems, but the wide extent and recent expansion of *E. globulus* plantations into land previously cleared for agriculture means that it will be possible to trade on the basis of carbon sequestered in the plantations. The trading of environmental services will add costs and incomes to the production system used to define the economic breeding objectives. The long generation interval in tree breeding means that

contemporary breeders can afford to plan and develop multiple-generation tree breeding systems. In order to do this, strategies must be devised to deal with future uncertainties. The development of techniques to assess across rotation impacts is one approach.

Chapter 3: Genetic control of coppice and lignotuber development

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3.1 Abstract

The economics of short-rotation pulpwood plantations of *Eucalyptus globulus* as a coppice crop, are influenced by stump survival and subsequent coppice growth rates. This study revealed significant genetic diversity in coppicing traits both within and between subraces, following felling in a progeny trial after 9 years of growth. Sixty seven percent of trees coppiced after 14 months, but subraces varied from 43 to 73%. Heritabilities for coppice success (0.07) and subsequent growth (0.16-0.17) were low but statistically significant. Strong genetic correlation between presence/absence of coppice, the number of stems coppicing from the stump and modal coppice height, indicate selection is possible using the binary trait. The ability of a tree to coppice was genetically correlated with tree growth prior to felling ($r_g = 0.61$), and with nursery-grown seedling traits, where large genetic differences were observed in the development of lignotubers. Coppicing was genetically correlated with the number of nodes with lignotubers ($r_g = 0.66$) and seedling stem diameter at the cotyledonary node ($r_g = 0.91$). These traits were uncorrelated with later age growth and with each other. The results suggest that coppicing is influenced by three independent mechanisms - lignotuber development, enlargement of the seedling stem at the cotyledonary node and vigorous growth - which enhance ability to survive catastrophic damage, and indicate that both lignotuber and coppice development can be altered by both natural and artificial selection.

3.2 Introduction

When felled near the ground, many hardwood trees regenerate through coppice shoots that sprout from the stump (Blake 1983). Eucalypts are no exception (Hillis and Brown 1978; Florence 1996), although the epicormic bud-producing structures are somewhat unique to the genus (Burrows 2002). Eucalypt plantations are often managed for coppice production, be it to produce cut foliage in floriculture (Wirthensohn and Sedgley 1998), logs for fuelwood, or pulpwood (Doughty 2000). While most plantations of the major pulpwood species *E. globulus* are managed by replanting following harvesting, there are references to *E. globulus* being managed as a coppice crop in India (Matthews 1992), Portugal (Turnbull and Pryor 1984; de Almeida and Riekerk 1990) , and Chile (Turnbull and Pryor 1984; Prado *et al.* 1990; Alarcón 1993). In India, *E. globulus* has been coppiced four times on a 10-15-year cutting cycle (Doughty 2000), but pulp production plantations tend to be coppiced only 2 or 3 times on rotations of 8 to 12 years, before replanting (Eldridge *et al.* 1993). Coppice regrowth derives considerable benefit from an established root system. Biomass production is initially greater than seedlings (Blake 1980; Crombie 1997) and yield from the first coppice crop often exceeds that from the maiden crop (Hillis and Brown 1978). However, yield on a per hectare basis is usually reduced, particularly in later rotations due to cumulative mortality of stumps rather than loss of vigour in living stumps (Matthews 1992).

Manipulation of coppicing requires knowledge of the genetic control and interrelationship amongst traits directly or indirectly affecting coppice production. One such trait, amenable to early selection, is lignotuber development.

Lignotubers are woody swellings found in the axils of the cotyledons (Boland *et al.* 1985) on seedlings which become buried as they develop, providing trees with a bank of meristematic tissue protected from lethal fire temperatures by an overlying mantle of soil (Noble 2001). These organs have long been believed to enhance regeneration by coppice, and along with bark enhance survival of catastrophic events such as fire, drought, frost, and browsing of seedlings in eucalypts (Kirkpatrick 1975; Jacobs 1979; Blake 1983; Noble 1984; Webley *et al.* 1986). Large genetically-based differences in lignotuber development have been reported between (Burgess and Bell 1983; Noble 2001) and within (Ladiges and Ashton 1974; Kirkpatrick 1975; Jacobs 1979; Potts and Reid 1985) other eucalypt species. Intra-specific variation in coppice production has also been reported for several species including *E. camaldulensis* (Grunwald and Karschon 1974), *E. grandis* (Reddy and Rockwood 1989) and *E. saligna* (Bowersox *et al.* 1990). However, few studies have examined the genetic relationship between lignotuber development and coppice production.

The study presented in this chapter aimed to determine the genetic control of coppicing and lignotuber development in *E. globulus* (*sensu* Brooker 2000) and their genetic interrelationship. The patterns of natural genetic variation in these traits in families sampled throughout the geographic range of the species were examined and the first estimates of their heritability in *E. globulus* provided. The genetic correlations amongst these regenerative traits and other economically important traits such as later age growth and wood density (McDonald *et al.* 1997; Dutkowski and Potts 1999) are also reported.

3.3 Materials and methods

3.3.1 Genetic material

The genetic control of coppicing was investigated using a common environment field trial at Massy Greene in northern Tasmania (41° 05'S, 145° 54'E), while a glasshouse trial with families in common with the Massy Greene trial provided a comparison between coppice production and seedling lignotuber development. Both trials were established from a range wide collection of open pollinated seed of *E. globulus* and intergrade populations, undertaken by the CSIRO Australian Tree Seed Centre in 1987 and 1988 (Gardiner and Crawford 1987; 1988). Genetic material within the Massy Greene trial in northern Tasmania represented a subset of the material used in previous studies of the genetic variation in *E. globulus* (McDonald *et al.* 1997; Dutkowski and Potts 1999; Jordan *et al.* 1999; 2000). The *E. globulus* population was arranged in 23 subraces (modified from Dutkowski and Potts 1999) reflecting the geographic origins of parent trees (Table 1). As with previous studies (e.g. Dutkowski and Potts 1999), samples from Wilson's Promontory Lighthouse were excluded from the analysis due to atypical shrub-like growth.

3.3.2 Coppice trial

The Massy Greene *E. globulus* base population trial was established by North Forest Products (now Gunns Ltd) in 1989. The trial consisted of five replicates in a resolvable incomplete block design (further details of the trial design are given in Jordan *et al.* 1994). The trial was converted to a seed orchard in November 1998, but cut stumps of culled trees were allowed to coppice. Of the nearly 6000

trees in the original trial, 3594 living trees were felled and available for assessment of coppice production. Measurement of coppice production was undertaken 15 months after felling. A low percentage of stumps covered with slash from felling were excluded leaving 3562 stumps for analysis (Table 2).

Table 1. Details of the subrace classification (modified from Dutkowski and Potts 1999) used in this study. The number of families per subrace in the Massy Greene trial (MG), the number of families for which data on coppice production was available (coppice), the number families with lignotuber information (lig), and the total number of families providing data used in the study (total).

Subrace location	Number of Families			
	M G	coppice	lig	total
Far Western Otways	6	5		6
Western Otways	120	92		120
Cape Patton	18	17		18
Eastern Otways	23	17	8	24
Strzelecki Ranges	58	43	8	58
Strzelecki Foothills	8	7		8
Gippsland Coastal Plain	13	10		13
Gippsland Foothills	3	3		3
Flinders Island	61	48		61
Southern Furneaux	50	39	1	50
St Helens	11	9	7	11
North-eastern Tasmania	19	15	15	25
Inland north-eastern Tasmania	20	17	7	20
Dromedary	4	3		4
South-eastern Tasmania	61	51		61
Southern Tasmania	27	19	20	32
Tasman Peninsula	5	3		5
Recherche Bay	4	3	6	9
Port Davey	6	2		6
Western Tasmania	29	27	7	29
King Island	32	29	8	32
Total	578	459	87	595

Table 2. Traits measured, the transformation used, overall means and their units. References refer to previously published studies in which the results of analyses included data for that trait from the Massy Greene trial; '*n*' is the number of measurements for each trait; and 'Mean' is the back-transformed whole trial mean for each trait.

Trait	Description and transformation	*n*	Mean
Field trial (Massy Greene)			
P/A	Presence (1) or absence (0) of coppice	3562	0.67
cheight (cm)	$(\text{cheight})^{0.85}$ Modal height of leaders coppicing from stump. Stumps not producing coppice were treated as missing values.	2443	85.6
cstems	$(\text{cstems})^{0.32}$ Number of major stems coppicing from the stump, counted at the base of stems. Stumps not producing coppice were treated as missing values.	2442	15.5
pilo (mm)	Pilodyn penetration at five years. One tree per plot in two replicates, the average of two measurements per tree. See MacDonald *et al.* 1997.	1392	13.2
dbh (cm)	Diameter at 1.3 m over bark at 8 years	4693	19.8
bark (mm)	$(\text{bark})^{0.71}$ Bark thickness, the average of two measurements. Only in four replicates. See Dutkowski and Potts 1999.	4409	7.7
Glasshouse			
noligno	The number of nodes with lignotubers at 1 year	374	0.8
ligwidth (mm)	Width across lignotubers at the cotyledonary node after 1 year	528	8.4
stemdiam (mm)	Stem diameter at the cotyledonary node after 1	528	6.8
rligno	(ligwidth- stemdiam)/stemdiam	528	0.2

Three measurements of coppice production were taken from each stump 15 months after the trees were felled: presence or absence (P/A) of coppice shoots; modal height of the coppice shoots (cheight); and the number of coppice shoots produced per stump (cstems). Other traits previously assessed at Massy Greene were incorporated into this study for cross correlation and comparison of relative levels of heritability. The additional traits included were diameter at breast height over bark prior to felling (dbh; 8 years); Pilodyn penetration at 5 years (pilo) (McDonald *et al.* 1997) and relative bark thickness at 4 years (bark) (Dutkowski

and Potts 1999) (see Table 2). Pilodyn penetration is an indirect measure of wood density, with increased pilodyn penetration indicating decreased wood density (Greaves *et al.* 1996; Raymond and MacDonald 1998). For modal coppice height, the number of coppice stems and bark thickness, the regression of log(standard deviation) on log(mean) indicated that power transformations were required to standardise the variances (Box and Cox 1964). The transformations are shown in Table 2.

3.3.3 Lignotuber trial

Sixty-six families were common to both the Massy Greene and glasshouse trials, allowing estimation of genetic correlations between seedling lignotuber formation and coppice production. The glasshouse trial contained 550 plants in all, from 87 open-pollinated families with 1 to 16 plants per family (Kelly 1997). The trial comprised 19 randomised blocks with between 4 and 81 families present in any block, and between 1 and 3 non-contiguous plants per family occurring in a block. The genetic material in the glasshouse trial was selected from 10 subraces with families representing the extremes of genetic variation in bark thickness within *E. globulus* (Dutkowski and Potts 1999). After 12 months, the number of nodes with lignotubers was counted (noligno), and width across lignotubers including the stem (ligwidth) and stem diameter at the cotyledonary node, perpendicular to the lignotubers (stemdiam) were measured. In order to account for growth, the size of lignotubers relative to stem diameter (rligno) was calculated following Ladiges and Ashton (1974):

$$rligno = \frac{(ligwidth - stemdiam)}{stemdiam} \qquad [3].$$

3.3.4 Statistical procedures

ASReml (Gilmour 1997; 2002) was used to conduct mixed model analyses of the trial data. Residual maximum likelihood estimates of variances, covariances and correlations uniquely attributable to genetic and design effects in the trials were obtained.

3.3.5 General linear mixed model

An individual tree model with subrace and replicate as fixed effects was used. The univariate model was defined as

$$\mathbf{y} = \mathbf{X}\beta + \mathbf{Z}_1\mathbf{c} + \mathbf{Z}_2\mathbf{a} + \mathbf{e} \qquad [4]$$

where **y** is the vector of *n* observations for the dependent variable; **ß** is the vector of fixed effects including subrace and the replicate term (in the respective trials); **c** is the vector of random incomplete block effects (only for the Massy Greene Trial); **a** is the vector of random additive genetic effects and **e** is the vector of random residuals. **X**, $\mathbf{Z}_1$ and $\mathbf{Z}_2$ are incidence matrices relating observations to factors in the model. The variance for each component is defined as

$$\text{Var}[c]=\mathbf{C}=\mathbf{I}\sigma_c^2 \qquad [5]$$

$$\text{Var}[a]=\mathbf{G}=\mathbf{A}\sigma_a^2 \qquad [6]$$

$$\text{Var}[e]=\mathbf{R}=\mathbf{I}\sigma_e^2 \qquad [7]$$

where **A** is the numerator relationship matrix for the additive genetic effects and, **C**, **G** and **R** represent incomplete block, additive and residual covariance matrices between the observations respectively.

The expected values and variances of the model are as follows.

$$E\begin{bmatrix}\mathbf{y}\\ \mathbf{c}\\ \mathbf{a}\\ \mathbf{e}\end{bmatrix}=\begin{bmatrix}\mathbf{Xb}\\ \mathbf{0}\\ \mathbf{0}\\ \mathbf{0}\end{bmatrix}, \qquad [8]$$

$$\mathrm{Var}\begin{bmatrix}\mathbf{y}\\ \mathbf{c}\\ \mathbf{a}\\ \mathbf{e}\end{bmatrix}=\begin{bmatrix}\mathbf{V} & \mathbf{ZC} & \mathbf{ZG} & \mathbf{R}\\ \mathbf{CZ'} & \mathbf{C} & \mathbf{0} & \mathbf{0}\\ \mathbf{GZ'} & \mathbf{0} & \mathbf{G} & \mathbf{0}\\ \mathbf{R} & \mathbf{0} & \mathbf{0} & \mathbf{R}\end{bmatrix}. \qquad [9]$$

The phenotypic covariance matrix is

$$\mathbf{V}=\mathbf{Z}_1\mathbf{C}\mathbf{Z}_1'+\mathbf{Z}_2\mathbf{G}\mathbf{Z}_2'+\mathbf{R}. \qquad [10]$$

In bivariate analyses **y**, **c**, **a**, and **e** consist of vectors containing observations for two traits so that

$$\mathbf{y}=(\mathbf{y}_1',\mathbf{y}_2'), \qquad [11]$$

$$\mathbf{c}=(\mathbf{c}_1',\mathbf{c}_2'), \qquad [12]$$

$$\mathbf{a}=(\mathbf{a}_1',\mathbf{a}_2'), \qquad [13]$$

$$\mathbf{e}=(\mathbf{e}_1',\mathbf{e}_2'), \qquad [14]$$

$$\mathbf{X}=\mathbf{X}_1\oplus\mathbf{X}_2, \qquad [15]$$

$$\mathbf{Z}_1=\mathbf{Z}_{1_1}\oplus\mathbf{Z}_{1_2}, \qquad [16]$$

$$\mathbf{Z}_2=\mathbf{Z}_{2_1}\oplus\mathbf{Z}_{2_2}, \qquad [17]$$

$$\mathbf{C}=\mathbf{I}_c\otimes\mathbf{C}_o, \qquad [18]$$

$$\mathbf{R} = \mathbf{I}_N \otimes \mathbf{R}_0 \text{ and} \qquad [19]$$

$$\mathbf{G} = \mathbf{A} \otimes \mathbf{G}_0 . \qquad [20]$$

The variance-covariance matrices for the incomplete block, additive genetic effects and residuals are represented by $\mathbf{C_0}$, $\mathbf{G_0}$ and $\mathbf{R_0}$ respectively:

$$\mathbf{C}_0 = \begin{bmatrix} \sigma^2_{c_1} & \sigma_{c_{12}} \\ \sigma_{c_{12}} & \sigma^2_{c_2} \end{bmatrix}, \qquad [21]$$

$$\mathbf{G}_0 = \begin{bmatrix} \sigma^2_{a_1} & \sigma_{a_{12}} \\ \sigma_{a_{12}} & \sigma^2_{e_2} \end{bmatrix} \text{ and} \qquad [22]$$

$$\mathbf{R}_0 = \begin{bmatrix} \sigma^2_{e_1} & \sigma_{e_{12}} \\ \sigma_{e_{12}} & \sigma^2_{e_2} \end{bmatrix} \qquad [23]$$

OPAINV (Dutkowski *et al.* 2001), a Fortran program for use with ASReml, was employed to form the inverse of the relationship matrix accounting for 30% selfing in open pollinated progeny (Griffin and Cotterill 1988).

Narrow sense heritabilities were calculated in ASReml as

$$h^2 = \frac{\sigma^2_a}{\sigma^2_a + \sigma^2_e} . \qquad [24]$$

The genetic correlation between an all-or-none trait and another normally distributed can be estimated without transformation so long as the incidence level of the all-or-none trait exceeds ten percent (Olausson and Rönningen 1975). Thus, pairwise genetic correlations between the presence of coppice and other traits were calculated directly, as for quantitative traits. However, heritability of

coppicing (based on presence/absence data) was estimated using the general linear model with a probit link function. The significance of the heritability estimates and genetic correlations were tested using a t-test.

Least squares means for each subrace were estimated from the PREDICT statement in ASReml. Pilodyn penetration and bark thickness were not sampled in all replicates of the Massy Greene trial. In the case of cross-classified data with information absent in some cells, least squares means are not estimable from the PREDICT statement (Gilmour *et al.* 2002). Therefore, subrace least squares means for these variables were estimated ignoring the effect of replicate. Pairwise (Pearson's) correlations between subrace least squares means were estimated using PROC CORR in SAS Version 8 (SAS Institute 1999).

3.4 Results and discussion

3.4.1 Variation between subraces

Normally *E. globulus* coppices vigorously (Jacobs 1979; Turnbull and Pryor 1984; Matthews 1992; Wirthensohn and Sedgley 1998), but only 67% of the trees in the Massy Greene trial produced coppice. Such low rates of coppicing contrast with coppicing trials conducted in Chile where the success rate of coppicing in *E. globulus* was found to be around 93%, fourteen months after felling (Prado *et al.* 1990; Alarcón 1993). This could be due to factors such as differences in genetic material or season of felling. The starch content of *E. obliqua* lignotubers shows significant seasonal variation (Cremer 1973). Coppice reproduction in eucalypts is reported to be maximal when trees are felled in late winter or spring and minimal when felled in summer (Blake 1983; Wirthensohn and Sedgley 1998).

The Massy Greene trial was felled in November (late spring in Tasmania), and it is possible that the timing of felling was suboptimal for *E. globulus*.

There was significant variation between subraces in the presence of coppice and the number of stems produced but not for coppice height (Table 3, Figure 3a, b). The proportion of stumps coppicing ranged from 43% (Strzelecki Foothills) to 73% (Recherche Bay) at the subrace level (Table 4). The least squares means for coppice height at 14 months after felling, ranged from 63 cm (Foothills) to 94 cm; however Foothills and Dromedary were the only subraces with least squares mean for coppice height of less than 80 cm. Despite significant genetic correlations between the three measures of coppicing within subraces (r_g = 0.39-0.63; Table 5), the patterns of geographic variation at the subrace level were statistically independent (0.27-0.42: NS). There does not appear to be any geographic trend in the variation in coppice production based on presence/absence data, with the exception of a west/east clinal trend across the Otway Ranges (39°S, 144°E, Figure3a). The trend follows a rainfall gradient (Dutkowski and Potts 1999), and parallels local clines in increasing bark thickness (Dutkowski and Potts 1999) and drought tolerance (Dutkowski 1995). Subraces from south-east Victoria, including those from the Strzelecki Ranges produce fewer stems when coppicing than do subraces from the Furneaux group of islands and the Tasman Peninsula (Figure 3b).

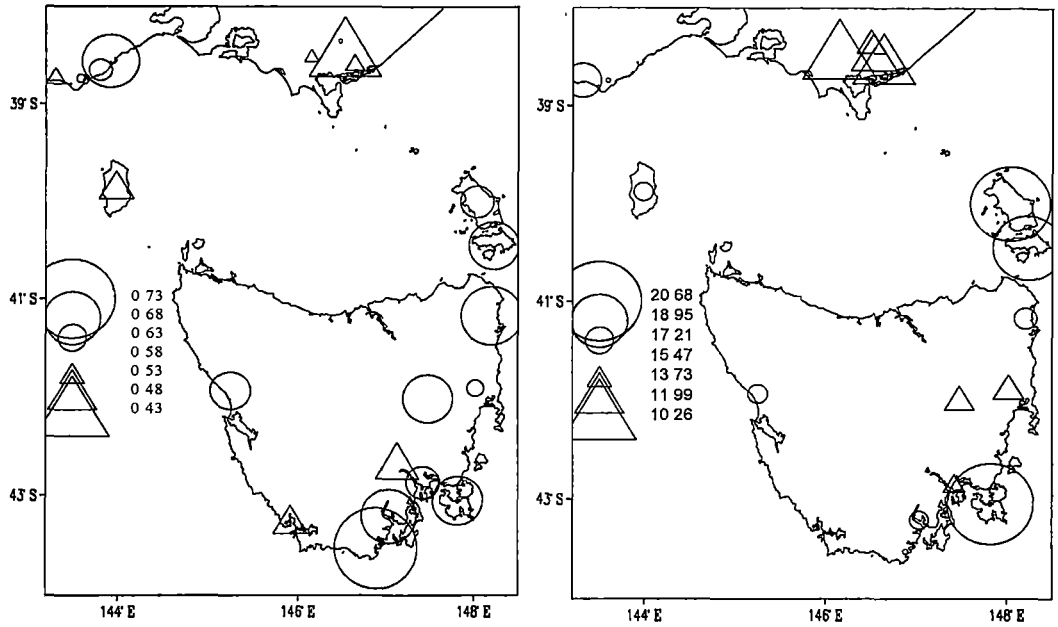
Table 3. Variance components and narrow sense heritabilities. For subrace the denominator *df* was taken to be equivalent to the residual *df* in all cases. Incomplete block is shown as iblock. The F values for fixed effects rep (replicate) and subrace are shown as F rep and F subrace, and their significance as Pr>F in each case. The number of subraces was used as the denominator *df* in the case of replicate. The values for the variance components are based on the transformed variable. Replicate in the Massy Greene Trial is not equivalent to replicate in the glasshouse trial. P/A is presence or absence of coppice; cheight is modal height of coppice leaders (cm); cstems is number of stems coppicing from the stump; pilo is Pilodyn penetration (5 years; mm); dbh is diameter at breast height (8 years; cm); bark is relative bark thickness (4 years); noligno is the number of nodes with lignotubers (1 year); stemdiam is diameter of the stem at the cotyledonary node (1 year; mm); ligwidth is the width across lignotubers at the cotyledonary node (1 year; mm); rligno is the lignotuber width relative to stem width as defined by Ladiges and Ashton (1974).

					Fixed effects							
		Variance components			Replicate		Between subraces		Within subraces			
	Trait	iblock	additive	error	F rep	Pr>F	F subrace	Pr>F	h^2	SE(h^2)	t	Pr>T
Field Trial	P/A (probit)	0.06	0.07	1.00	23.33	***	2.03	**	0.07	0.03	2.36	*
	cheight	5.91	29.69	151.08	12.37	***	1.36	NS	0.16	0.05	3.58	***
	cstems	0.01	0.04	0.20	49.24	***	5.14	***	0.17	0 04	3.79	***
	pilo	0.04	0.89	1.70	2.16	NS	9.56	***	0.34	0.09	3 97	***
	dbh	0.16	8.06	16.97	3.42	**	7.88	***	0.32	0.04	8.84	***
	bark	0.05	0.09	0.27	6.66	**	12.17	***	0.25	0.03	7.19	***
Glasshouse	noligno		0.11	0.23	1.39	NS	4.93	***	0.31	0.11	2.67	**
	stemdiam		0.54	0.64	5.30	**	1.44	NS	0.46	0.13	3.30	**
	ligwidth		1.48	1.97	4.62	**	4.23	***	0.43	0.13	3.10	**
	rligno		0.02	0.02	1.62	*	9.78	***	0.51	0.14	3.38	***

$P < 0.05$; ** $P < 0.01$; *** $P < 0.001$.

Table 4. Least squares means (standard errors) by subrace for all traits. Means for cheight, cstems, and bark have been back transformed. P/A is presence or absence of coppice; cheight is modal height of coppice leaders; cstems is number of stems coppicing from the stump; pilo is Pilodyn penetration (5 years); dbh is diameter at breast height (8 years); height is tree height (4 years); bark is relative bark thickness (4 years); noligno is the number of nodes with lignotubers (1 year); stemdiam is diameter of the stem at the cotyledonary node (1 year); ligwidth is the width across lignotubers at the cotyledonary node(1 year); rligno is the lignotuber width relative to stem width as defined by Ladiges and Ashton (1974).

	Field Trial (Massy Greene)						Glasshouse			
Subrace	**P/A (probit)**	**cstems**	**cheight**	**Dbh (cm)**	**Pilo (mm)**	**bark**	**noligno**	**ligwidth (mm)**	**stemdiam (mm)**	**rligno**
Far Western Otways	0.55 (0 08)	17.70 (2 57)	94 05 (7 34)	18.60 (1 03)	15 16 (0.51)	7 54 (0.31)				
Western Otways	0 58 (0.02)	15 76 (0.54)	88 42 (1 69)	22.02 (0 23)	13.88 (0.11)	8 21 (0 09)				
Cape Patton	0 62 (0.05)	15 58 (1.30)	80.31 (4.02)	21.46 (0 59)	13.91 (0.27)	8 57 (0 19)				
Eastern Otways	0 68 (0 04)	15 35 (1 10)	86 15 (3 48)	20 45 (0.52)	13.32 (0.29)	8 75 (0 17)	1.33 (0 12)	10.44 (0.43)	6.84 (0.26)	0.53 (0.05)
Strzelecki Ranges	0 58 (0 03)	13 45 (0 75)	91 22 (2 64)	20 99 (0 33)	12.16 (0 16)	8 26 (0 12)	1.00 (0 10)	8 75 (0 37)	6.95 (0.22)	0 27 (0.04)
Strzelecki Foothills	0.43 (0 08)	12.25 (1 97)	86 93 (7 29)	21 98 (0 90)	12 65 (0 42)	8.19 (0 28)				
Gippsland Coastal Plain	0.54 (0.06)	11 09 (1.38)	87 44 (5.48)	21.36 (0.77)	13.86 (0 38)	7 47 (0.22)				
Gippsland Foothills	0.55 (0.11)	10 26 (2.36)	63 71 (9.36)	20.36 (1 48)	12 59 (0.72)	7.40 (0.43)				
Flinders Island	0.64 (0.03)	20 32 (0 87)	88.01 (2.29)	20 24 (0 33)	12 95 (0.17)	7 68 (0.12)				
Southern Furneaux	0.67 (0.03)	19 68 (0 91)	86 55 (2.44)	19.67 (0 35)	12 72 (0 18)	7 54 (0 12)	0 67 (0 31)	7 75 (1 07)	6.92 (0.64)	0 12 (0.12)
St. Helens	0 69 (0 06)	16 84 (1 63)	87 57 (4 87)	19 07 (0 77)	13.83 (0 40)	8 66 (0 24)	0 78 (0.15)	8 46 (0 51)	6 44 (0.30)	0 31 (0.06)
North-eastern Tasmania	0 61 (0 05)	13.35 (1 14)	86 96 (3 97)	17 57 (0 59)	12.04 (0.31)	7 80 (0 18)	0 73 (0.09)	7 98 (0 31)	6.72 (0.19)	0 19 (0.03)
Inland North-eastern Tasmania	0 67 (0 04)	13.40 (1 08)	90.36 (3.79)	18 73 (0 57)	13.44 (0.29)	8.34 (0 18)	1 14 (0.11)	9.30 (0 39)	6.52 (0.23)	0.42 (0.04)
Dromedary	0 49 (0.10)	15 14 (2.83)	72.71 (8.81)	17.01 (1 26)	12 25 (0.71)	7.11 (0 37)				
South-eastern Tasmania	0.64 (0.03)	13.96 (0 64)	88 71 (2 19)	19.19 (0 32)	13.11 (0.17)	7.89 (0.11)				
Southern Tasmania	0.68 (0.04)	16.62 (1.11)	91 73 (3 37)	20 97 (0.48)	13.07 (0.23)	7.36 (0.15)	0.75 (0.07)	8 18 (0.25)	6 94 (0 15)	0.18 (0 03)
Tasman Peninsula	0 67 (0 09)	20.68 (2.86)	90 55 (7 42)	19 26 (1.14)	13.19 (0.55)	7.00 (0.33)				
Recherche Bay	0.73 (0.08)	15.78 (2.39)	84.72 (7 39)	19 20 (1.23)	12.10 (0.63)	7 46 (0.38)	0.45 (0 14)	6.76 (0.49)	6.25 (0.29)	0.08 (0.05)
Port Davey	0 51 (0 09)	15.21 (2.66)	88.88 (8.49)	16.86 (1.24)	13.33 (0.67)	6 20 (0 32)				
Western Tasmania	0 65 (0 03)	16.68 (0.98)	81.88 (2.90)	19.11 (0.46)	13.50 (0 26)	6 98 (0 15)	0.57 (0.13)	7.70 (0.46)	7 09 (0.27)	0.10 (0.05)
King Island	0.51 (0.04)	16.65 (1.09)	80.35 (3.23)	22.02 (0 45)	14.51 (0.19)	7 30 (0 14)	0.64 (0.10)	8.21 (0.38)	7.16 (0.23)	0.15 (0 04)



(a) Presence/absence of coppice (b) Number of stem

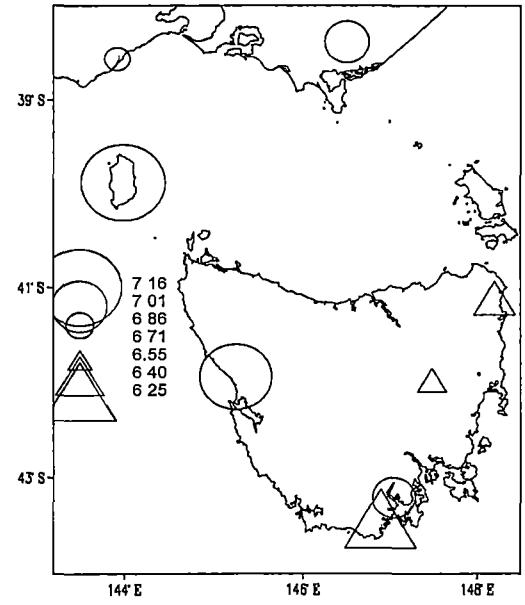
Figure 3. Geographic variation in (a) the presence/absence of coppicing and (b) the number of stems coppicing from the stump. Circles represent higher rates of coppice reproduction and more stems, triangles represent lower rates of coppice reproduction and fewer stems in *a* and *b* respectively. The marker scale is centred on the range mid-point of the subrace least squares means values.

Significant variation occurred between subraces in the glasshouse trial for number of lignotubers, lignotuber width and the relative size of lignotubers, but not seedling stem width (see Table 3). The number of nodes with lignotubers on a seedling ranged from zero to three over the period of the study (1 year). Lignotubers developed in every subrace studied, however, in the case of the Recherche Bay subrace, a mean of only 0.45 nodes had lignotubers per tree (Table 4), and only 33% of trees produced lignotubers (data not shown). The least squares means for relative lignotuber size ranged from 0.08 (Recherche Bay) to 0.53 (Eastern Otways) (Table 4 and Figure 4c). There was strong genetic correlation between the three measures of lignotuber size both within (0.64-0.84) and between (0.95-0.97) subraces (Table 5). The most extensive lignotuber development could be found in the Eastern Otways subrace, with a mean of 1.33 nodes with lignotubers per tree and 92% of trees producing lignotubers. Western

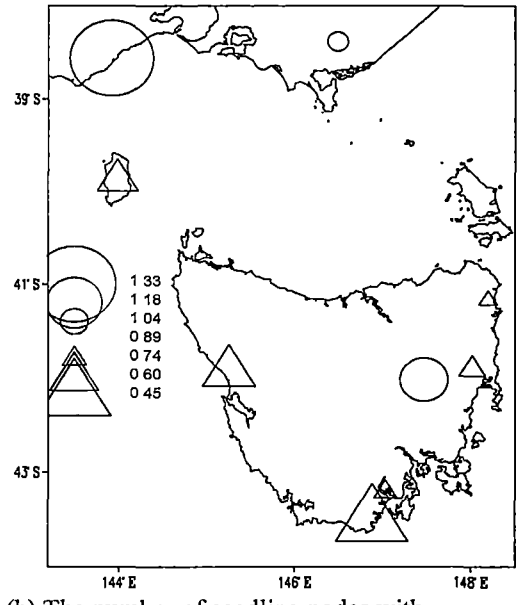
(Western Tasmania, King Island) and far south-east (Recherche, Southern Tasmania) Tasmanian subraces produced fewer lignotubers (Figure 4b). These subraces exist in wetter environments and have thinner bark (Kelly 1997; Dutkowski and Potts 1999). The latter trend is reflected in the significant correlation between lignotuber traits and relative bark thickness at the subrace level (Table 5). This result is consistent with previous reports of eucalypt species or populations from drier environments having greater lignotuber development (Gill 1997). There is limited correlation between lignotuber traits and relative bark thickness within subraces (0.13 – 0.46, Table 5), indicating that parallel selection may be acting on these traits.

Table 5. Pairwise genetic (lower) and subrace (Pearson's) correlations (upper) for all traits. Genetic correlations with presence/absence (P/A) data were calculated without transformation to the probit scale. Statistically significant ($P < 0.05$) correlations are shown in bold. Correlations involving traits from the glasshouse trial are based on only 10 subraces, correlations between traits measured at the Massy Greene trial are based on 21 subraces. P/A is presence or absence of coppice; cheight is modal height of coppice leaders (cm); cstems is number of stems coppicing from the stump; pilo is Pilodyn penetration (5 years; mm); dbh is diameter at breast height (8 years; cm); bark is relative bark thickness (4 years); noligno is the number of nodes with lignotubers (1 year); stemdiam is diameter of the stem at the cotyledonary node (1 year; mm); ligwidth is the width across lignotubers at the cotyledonary node (1 year; mm); rligno is the lignotuber width relative to stem width as defined by Ladiges and Ashton (1974).

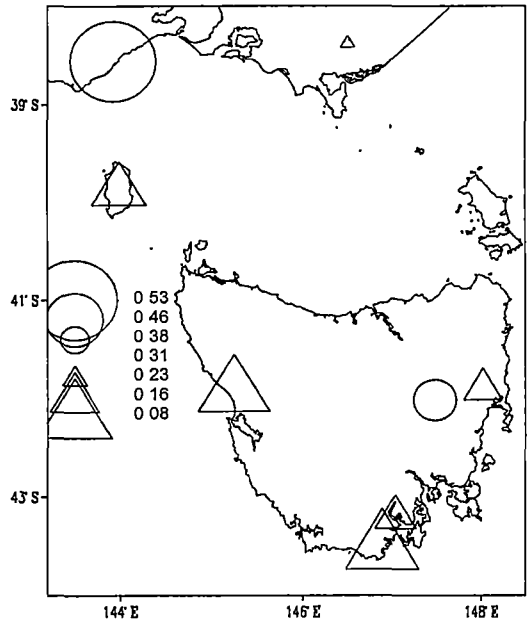
	Field Trial (Massy Greene)						Glasshouse			
	P/A	cheight	cstems	dbh	pilo	bark	noligno	ligwidth	stemdiam	rligno
P/A		0.27	0.42	-0.11	-0.11	0.25	0	-0.08	**-0.69**	0.15
cheight	**0.42**		0.36	0	0.24	0.16	0.48	0.31	-0.26	0.40
cstems	**0.63**	**0.39**		-0.13	0.23	-0.17	-0.47	-0.35	0.24	-0.44
dbh	**0.61**	0.12	**0.26**		0.24	**0.43**	0.12	0.21	0.57	0.01
pilo	0.07	-0.04	-0.16	0.13		0.06	0.10	0.31	0.33	0.20
bark	**0.33**	0.14	0.08	**0.57**	**0.25**		**0.79**	**0.75**	-0.41	**0.88**
noligno	**0.66**	0.10	0.19	-0.34	**0.63**	0.13		**0.97**	0.03	**0.95**
ligwidth	**0.89**	0.53	0.17	0.21	0.12	**0.46**	**0.77**		0.16	**0.95**
stemdiam	**0.91**	0.49	-0.27	0.18	0.16	0.34	0.22	**0.64**		-0.18
rligno	0.33	0.06	0 27	0.07	0.12	0.26	**0.84**	**0.66**	-0.15	



(a) Seedling stem diameter.



(b) The number of seedling nodes with lignotubers.



(c) The relative size of lignotubers as defined by Ladiges and Ashton (1974).

Figure 4. Geographic variation in (a) seedling stem diameter at the cotyledonary node, (b) the number of seedling nodes with lignotubers, and (c) the relative size of lignotubers as defined by Ladiges and Ashton (1974). Circles represent larger stem diameters, the presence of lignotubers at more nodes, and larger lignotubers relative to stem size, while triangles represent smaller stem diameters, fewer nodes with lignotubers and smaller lignotubers relative to stem size in a, b and c respectively. Plotted excluding the single family from the Southern Furneaux subrace. The marker scale is centred on the range mid-point of the subrace least squares means values.

3.4.2 Variation within subraces

Significant genetic variation was found within subraces for all coppice and lignotuber traits investigated (Table 3). The heritability of coppice characteristics was reported to range from 0.45 to 0.71 in a population of *E. grandis* (Reddy and Rockwood 1989). In the case of this population of *E. globulus* the heritability of coppicing traits was the lowest of all traits measured. Heritabilities ranged from 0.07 for the presence of coppice, to 0.16 and 0.17 respectively for modal coppice height and the number of coppice stems (Table 3). In contrast, lignotuber traits showed moderate heritability ranging from 0.31 to 0.51, with relative lignotuber size the most heritable trait measured (Table 3). Other traits assessed in the field trial also exhibited moderate levels of heritability ($h^2 = 0.21$ to 0.34) and the heritability of variation in seedling stem diameter was the second highest ($h^2 = 0.46$) (Table 3). Despite extensive reports of heritability for growth and wood property traits (Lopez *et al.* 2002), these are the first estimates of heritability for coppice and lignotuber traits in the species.

Within subraces, the presence of coppice regeneration was positively genetically correlated with all traits measured in the Massy Greene trial, except for pilodyn penetration. No significant relationship was found between pilodyn penetration and coppice production, indicating that coppicing is genetically independent of wood density. However, fewer measurements of pilodyn penetration than of the presence/absence of coppice (see table 2) could have resulted in the lack of detection of a significant relationship. Presence of coppice was significantly genetically correlated with tree size prior to felling (dbh v. P/A $r_g = 0.61$; Table 5). However, there was little association of subsequent coppice growth with tree size

prior to felling (dbh v. cstems $r_g = 0.26$; dbh v. cheight $r_g = 0.12$; Table 5). This is consistent with previous reports that plant vigor prior to damage is a primary determinant of successful vegetative regeneration (Hillis and Brown 1978; Blake 1983; Noble 1984). However, the present study indicates that plant vigor was only one of three mechanisms independently operating to determine the success of coppicing in *E. globulus*. Coppicing success is also strongly genetically correlated with seedling stem diameter (P/A v. stemdiam $r_g = 0.91$) and less strongly correlated with the number of nodes with lignotubers (P/A v. noligno $r_g = 0.66$). These two seedling traits were genetically independent of each other ($r_g = 0.22$: NS) and genetically independent of diameter at 8 years of age ($r_g = 0.18$: NS and $r_g = 0.21$: NS respectively). The genetic correlation between the presence of coppice and relative lignotuber size was not significant, and while there was a significant correlation between the presence of coppice and lignotuber width (P/A v. ligwidth $r_g = 0.89$; Table 5), this was solely due to co-variation with seedling stem diameter. For example, the partial genetic correlation between the presence of coppice and lignotuber width was only 0.37 when seedling stem diameter was included as a covariate, and was not significantly different from zero. Similarly, the partial genetic correlation between relative bark thickness and the presence of coppice (bark v. P/A $r_g = 0.33$) was not significant when dbh was included as a covariate (data not shown).

Lignotuber development has previously been suggested to enhance coppice production (Jacobs 1979; Webley *et al.* 1986; Bowersox *et al.* 1990; Noble 2001). The present study found the presence of coppice, and not subsequent coppice growth, to be correlated with lignotuber development in *E. globulus*. Bark thickness has no effect on coppice success at age 9, nor does wood density (as

measured by Pilodyn penetration; Table 5). Noble (2001) showed that lignotubers have an abundance of meristematic tissue available to differentiate into vegetative buds when the stem is damaged. The present study suggests that the probability of later age coppicing in *E. globulus* is not affected by the relative size of this organ, but the number of seedling nodes producing the organ. However, the strongest determinant of coppice success appears to be not the lignotuber *per se*, but the size of the seedling stem at the cotyledonary node.

It is clear from other observations that lignotubers *per se* are not essential for successful coppicing and the two closely related species *E. grandis* and *E. saligna* are a case in point (Gill 1997). *Eucalyptus grandis* tends not to have lignotubers while most *E. saligna* seedlings develop lignotubers (Burgess and Bell 1983), yet coppicing of both species is believed to be equivalent (Eldridge *et al.* 1993; Gill 1997). Broad swelling of the basal portion of the stem of seedlings rather than discrete lignotuberous organs occur in some eucalypts (e.g. *E. pilularis*) and this is also believed to enhance vegetative regeneration (Boland *et al.* 1985). While most of the internal wood is lignified, peripheral vascular tissues in lignotubers are known to function as sinks for carbohydrates and water (Noble 2001). It is possible that swollen stem bases in seedlings also act as carbohydrate sinks, thus providing nutrients for improved coppice production. Alternatively, the presence of a swollen seedling stem base or many lignotubers in *E. globulus* may reflect an increased density of epicormic meristem strands (as described by Burrows 2002) available to produce regenerative buds. In any case, the work presented in this chapter shows that these mechanisms are genetically independent, can co-occur in the same species (and potentially even the same individual) and may represent primary storage and bud proliferation functions.

3.5 Conclusions

Significant genetic variation between and within subraces in their ability to reproduce by coppice and produce lignotubers was found in a field and a glasshouse trial, indicating both traits are amenable to artificial and natural selection. Further, seedling stem diameter and the number of seedling nodes with lignotubers appear to be indicators of the ability of a tree to produce coppice and may provide useful selection traits to alter the success of coppice regeneration, although environmental and seasonal factors may affect the behaviour of *E. globulus* coppice. This quantitative genetic approach has argued for three independent genetically based mechanisms impacting on coppice success. The success of coppice production in *E. globulus* is dependent upon tree vigour prior to felling, the number nodes with lignotubers in seedlings and finally the diameter of the stem at the cotyledonary node of seedlings.

Chapter 4: Comparing returns from coppice and genetically improved seedling crops

Published as: SP Whittock, BL Greaves and LA Apiolaza 2004. A cash flow model to compare coppice and genetically improved seedling options for *Eucalyptus globulus* pulpwood plantations. *Forest Ecology and Management*, **191**: 267-274.

4.1 Abstract

Coppice can provide a cheap alternative to replanting in the second rotation in *Eucalyptus globulus* Labill. plantations. However, replanting with genetically improved stock may provide a more profitable alternative. A discounted cash-flow model was used to compare the profitability of coppice and seedling crops in second rotation *E. globulus* pulpwood plantations, using incremental net present value (NPV). Using the model presented in this paper as a framework it is possible to say that a gain of 20% over the original seedling crop in dry matter production from second rotation seedlings through genetic improvement and provenance selection would result in equivalent NPV for second rotation seedling and coppice crops. Sensitivity analysis showed that incremental NPV is strongly affected by the level of genetic gain available (and therefore the genetic quality of the first rotation stock relative to the available genetically improved stock), and the productivity of coppice relative to the first rotation crop. Any reduction in the basic density of coppice reduces the level of genetic gain required to make replanting with improved seedlings economically justifiable.

4.2 Introduction

Eucalyptus globulus is one of the major hardwood species in temperate plantation forestry (Potts *et al.* 2004b). Considerable effort has been expended on the domestication and genetic improvement of this species (Volker and Orme 1988; Borralho *et al.* 1993; Greaves *et al.* 1997b; Borralho and Dutkowski 1998; Dutkowski and Potts 1999; Harbard *et al.* 1999; Kerr *et al.* 2001). Genetic improvement in the form of provenance selection and breeding promises gains in productivity. Estimates of such gain in *E. globulus* range from 7 to 17% for volume (Volker *et al.* 1990), 20 to 47% for dry matter (Borralho *et al.* 1992) and up to 18% saving in total pulp costs (Greaves *et al.* 1997a). Gains will be maximised where first rotation (1R) stock is based on seed collected from unselected natural stands.

Eucalyptus globulus regenerates readily through stump coppice following the removal of the stem and crown at harvesting (Blake 1983; Opie *et al.* 1984). This ability to coppice and the fact that second rotation establishment costs are avoided have lead many plantation managers to assume that the second rotation (2R) may be managed as a coppice crop. While a coppice crop may be optimal in some situations, potential increases in plantation productivity through genetic improvement may argue in favour of replanting in the second rotation.

Previous economic models of eucalypt coppice have dealt with the optimum number of shoots to retain (Agnihotri and Arya 1994) or the number of coppice rotations and rotation length for optimum economics in a plantation (Nobre and Rodriguez 2001), or charcoal production system (Platais and Betters 1989). No

direct comparison has been made between seedling and coppice crops in *E. globulus* pulpwood plantations for coppice stands thinned to one stem per stump. Such comparisons are complicated by the need to use the same genetic material for the establishment of first and second rotation crops. In the current study, a cash flow model is developed to allow an assessment of the level of genetic gain required to produce a second rotation seedling crop that exceeds the value of a second rotation coppice crop.

4.3 Methods

4.3.1 Model Description

The model was developed in Microsoft Excel®, based on cost structures for managing *E. globulus* plantations from seedlings in the first rotation, and from seedlings or coppice in the second rotation (Tables 6 and 7). All costs are in Australian dollars. Costs and the timing of costs differ between seedling and coppice crops. The model allows changes in productivity due to coppicing or genetic improvement to be investigated in terms of net present value (NPV), incremental NPV (Irvin 1978) was used to compare the two mutually exclusive options (Dasgupta and Pearce 1972). A positive incremental NPV indicated that the NPV of coppice exceeded the NPV of seedlings in the second rotation, whilst a negative incremental NPV indicated that the NPV of a seedling crop exceeded the NPV of a coppice crop in the second rotation.

Two series of two 10 year rotations, representing a seedling crop established on an open paddock followed by either a seedling crop, or a coppice crop (Table 6) were considered. A lag time of 1 year between clearfall and replanting seedlings built

into the model (Table 6) meant that the lifespan of the two crop types (coppice or seedlings) differed by one year at the end of two rotations. Small differences in project lifespan should not impact significantly on the performance of financial models (Brigham and Houston 2002). This was checked by converting the NPV of coppice and seedling crops to an equivalent annuity (Zerbe and Dively 1994). The equivalent annuities system did not alter the interpretation of the results, and the results presented remain in the form of NPV or incremental NPV.

Table 6. The system used to calculate the incremental NPV of seedling and coppice crops. *Est* indicates a cost associated with seedling establishment, *man* indicates a cost associated with coppice management, *H* indicates an income at harvest, *fallow* is the lag period of 1 year between harvest of the first rotation and establishment of second rotation seedlings, PV is present value and NPV net present value. Numbers in the 'cost' and 'income' columns refer to the year in the rotation that the cost or income occurs.

		Coppice			Seedling	
Year		**Cost**	**Income**		**Cost**	**Income**
0	Rotation 1 unimproved seedling	*Est1*	*1*	Rotation 1 unimproved seedling	*Est1*	*1*
1		*Est2*	*2*		*Est2*	*2*
2		*Est3*	*3*		*Est3*	*3*
3		*4*	*4*		*4*	*4*
4		*5*	*5*		*5*	*5*
5		*6*	*6*		*6*	*6*
6		*7*	*7*		*7*	*7*
7		*8*	*8*		*8*	*8*
8		*9*	*9*		*9*	*9*
9		*10*	*H10*		*10*	*H10*
10	Rotation 2 coppice	*Man1*	*1*		*fallow*	*0*
11		*Man2*	*2*	Rotation 2 improved seedling	*Est1*	*1*
12		*Man3*	*3*		*Est2*	*2*
13		*4*	*4*		*Est3*	*3*
14		*5*	*5*		*4*	*4*
15		*6*	*6*		*5*	*5*
16		*7*	*7*		*6*	*6*
17		*8*	*8*		*7*	*7*
18		*9*	*9*		*8*	*8*
19		*10*	*H10*		*9*	*9*
20					*10*	*H10*
		PV_{costs}	PV_{income}		PV_{costs}	PV_{income}
			NPV			NPV

Table 7. Illustrative costs for the management and establishment of *E. globulus* plantations.

	Cost Per Hectare ($AU/ha)		
	1st Rotation	2nd Rotation	
Activity	**Paddock**	**Seedling**	**Coppice**
Administration	$240.00	$10.00	$10.00
Preparation	$1018.00	$1468.00	$5.00
1st. Year	$206.00	$176.00	$21.50
2nd year	$256.00	$256.00	$696.00
3rd year	$58.00	$58 00	$241.00
annual costs	$213.00	$213.00	$213.00

The net present value (NPV) of systems was calculated as

$$NPV = I_{PV} - C_{PV} \qquad [25]$$

Where, I_{PV} is the present value of all incomes and C_{PV} the present value of all costs. All costs and incomes were discounted to the time of plantation establishment (year 0). Present value was calculated using the standard formula:

$$P = V\left(1 + \frac{d}{100}\right)^{q_V} \qquad [26]$$

Where P is the present value of a cost or income, q_V is the time (year) in which V occurs, and d is the annual discount rate in percentage points. A discount rate of 7% was used in a study of fibre production from *E. globulus* in Australia (Selkirk and Spencer 1999), and was adopted as the base rate in this study. "Present" is the time of plantation establishment (year 0).

It was assumed the enterprise was selling timber as a standing crop. Income was calculated based on the value for an oven-dried tonne of wood delivered (I_O). This was converted to a value per green tonne delivered using the basic density of the crop, and then transport and harvest costs were removed to give the stumpage price. This system allowed changes in basic density due to genetic improvement or coppice to affect the value of the standing crop at harvest.

Basic density was calculated separately for each series (seedling or coppice) in each rotation. The basic density of the first rotation crop (D) was altered by the gain in basic density from genetic improvement in percentage points ($DGAIN$) in second rotation seedling crops, and reduced by a small percentage (u) in a coppice crop. The base value (first rotation mean basic density) assumed was 530 kg m^{-3} (see Macfarlane and Adams 1998; Schimleck *et al.* 1999; and Miranda and Pereira 2001 for estimates of E. globulus basic density). Ferrari (1993) reported that the basic density of *E. globulus* coppice was up to 8% lower than the basic density of the original stem on the same stumps. A decrease in basic density was also reported in *E. camaldulensis* coppice (Sesbou and Nepveu 1991).

The gross value per green tonne delivered was calculated as I_{G1}, I_{G2s}, and I_{G2c}, in first rotation, second rotation seedling and second rotation coppice crops respectively. The green specific gravity (S) was assumed to equal one tonne per cubic metre (Albertsen *et al.* 2000).

$$I_{G1} = \frac{I_O \times D}{S} \qquad [27]$$

$$I_{G2s} = \frac{I_O \times D\left(1 + \frac{DGAIN}{100}\right)}{S} \quad [28]$$

$$I_{G2c} = \frac{I_O \times D\left(\frac{1-r}{100}\right)}{S} \quad [29]$$

The stumpage (net income per green tonne for the grower, I) was calculated by removing the harvest cost per green tonne (h) from the gross income per green tonne. The harvest cost ($17 per green tonne) given by Albertson *et al.* (2000) was used as the base value in this case. The number of stumps with multiple stems and form problems such as hooking towards the base of the stem will increase the cost of extraction and transport of a coppice crop. A penalty (f) was applied to reflect potential difficulties associated with the harvest of coppice material.

$$I = I_G - h(1 + f) \quad [30]$$

Yield in metric tonnes (Y) for the first rotation was calculated as:

$$Y = MAI \times q_R \quad [31]$$

MAI was the mean annual increment (merchantable volume) calculated as cubic metres per hectare per year, and q_R is the rotation length in years. The base value applied for MAI was 20 m^3 ha^{-1} yr^{-1}. Yield of a second rotation coppice crop (Y_c) was calculated as:

$$Y_c = MAI \times \left(1 + \frac{CPROD}{100}\right) \times q_{R_c} \quad [32]$$

Where q_{R_c} was the rotation length (years) for a coppice crop, and *CPROD* describes the change in coppice productivity relative to the original seedling crop. Loss of stumps is a common cause of reduced MAI in coppice crops (Matthews 1992). However, there was insufficient information available on the effect of stump mortality on end of rotation yield to include it directly as a variable. The yield of coppice was considered only relative to the first rotation crop. The yield from a seedling crop in the second rotation (Y_s) was calculated as:

$$Y_s = MAI \times \left(1 + \frac{VGAIN}{100}\right) \times \left(q_{R_s} - 1\right) \qquad [33]$$

where q_{R_s} was the rotation length for a seedling crop, including the fallow period of one year between harvesting and replanting, and *VGAIN* is the gain in volume production in second rotation seedlings. Genetic gain (*GGAIN*) in this case refers solely to increases in dry matter production directly attributable to provenance selection and breeding. *GGAIN* was made up of changes in volume production and gains in basic density (*DGAIN*) so that:

$$VGAIN = x \times GGAIN \qquad [34]$$

and

$$DGAIN = (1 - x) \times GGAIN \qquad [35]$$

where X was the proportion of genetic gain contributing to an increase in volume. The remainder of genetic gain contributes to increasing basic density.

All abbreviations used above are listed and described in Table 8.

Table 8. A list of abbreviations used to describe of the model, and their meanings.

Abbreviation	Description
NPV	Net Present Value
I_{PV}	Present value of incomes
C_{PV}	Present value of costs
P	Present value
V	Any cost or income
d	Discount rate
q	Time in years (q_V the time a cost or income occurs, q_0 the time of plantation establishment, q_R rotation length, q_{R_s} the rotation length for seedlings, and q_{R_c} the rotation length for coppice).
I_G	Income per green metric tonne delivered (I_{G1} 1R, I_{G2s} 2R seedling, I_{G2c} 2R coppice)
I_O	Income per oven dried metric tonne delivered
D	Basic density (metric tonnes per cubic metre)
DGAIN	Percentage genetic gain affecting basic density
u	Percentage reduction in basic density in coppice relative to maiden crop
S	Green specific gravity
I_s	Stumpage per green tonne
h	Harvest and transport cost per green tonne
f	A percentage of the harvest and transport cost, a penalty incurred when harvesting coppice
Y	Yield (green tonnes.hectare^{-1})(Y_c yield from coppice, and Y_s the yield from seedlings
MAI	Mean annual increment (green tonnes.hectare^{-1}.year^{-1})
CPROD	The percentage change in productivity of coppice in relation to first rotation yield
GGAIN	The percentage genetic gain in seedlings over the previous crop
VGAIN	The genetic gain in volume production
x	The proportion of genetic gain contributing to increased volume production

4.3.2 Sensitivity analysis

The sensitivity of the model to variation in input variables was examined using Crystal Ball® 2000.2 (Decisioneering Inc. 2002) to fit probability distributions to variables and run Monte Carlo simulations. The base values in the model (Table 9) reflect realistic estimates derived from the literature and discussions with *E. globulus* plantation growers in Australia.

Table 9. Base values for model parameters, used in all cases where alternative values are not specifically stated. Coppice productivity (*CPROD*) is relative to the first rotation crop.

Assumption	Units	Base value	Range	Reference
Discount rate (*d*)	%	7.0	5.6-8.4	(Selkirk and Spencer 1999)
Basic density (*D*)	tonnes m^{-3}	0.53	0.42-0 64	
Reduction in basic density (*r*)	%	0	0-20	(Ferrari 1993)
Harvest costs (*h*)	\$ $tonne^{-1}$	17	13.6-20.4	(Albertsen *et al.* 2000)
Coppice harvest penalty (*f*)	%	10	0-20	
MAI (*MAI*)	m^3 ha^{-1} $year^{-1}$	20	16-24	
Coppice productivity (*CPROD*)	%	100	80-120	
Genetic gain (*GGAIN*)	%	20	0-40	
Density·volume (*X*)	proportion	0.2	0-1	
\$/oven dried tonne delivered (*O*)	\$ OD $tonne^{-1}$	115	92-138	(WRI 2002)

Sensitivity analyses looked at the impact changes in model variables had on the NPV of first and second rotation crops, and the incremental NPV of coppice and seedling crops in the second rotation. Sensitivity to changes in a particular variable was calculated as a rank correlation over 10000 iterations. All variables, with the exception of the cost penalty at harvest (*f*) associated with a coppice crop and the proportion of density increases in genetic gain, were allowed to vary according to a triangular distribution with maximum and minimum values ±20% of the base value. The coppice harvest and transport penalty was fitted with a triangular distribution ranging from 0-20% with the likeliest value 10%. The proportion of density gain to volume gain in genetic gain was allowed to vary from 0 (all gain is in volume) to 1 (all gain is in density) with a uniform distribution.

4.4 Results and Discussion

If the productivity of a coppice crop were equivalent to the first rotation seedling crop, then genetic gain of between 20% and 25% (dry matter production) would be required for a seedling crop to have a NPV equivalent to a coppice crop (Incremental NPV is zero) (Figure 5). This is due to the reduced establishment and management costs for a coppice crop. Changes in the productivity of coppice have a large effect on the choice of crop system in the second rotation. A coppice crop producing 90% of the dry matter of the original seedling crop will be outperformed by a new seedling crop with genetic gain of 15% (Figure 5). Such levels of genetic gain through provenance selection and breeding are probably achievable in *E. globulus* (Borralho *et al.* 1992), as many first rotation plantations were established with open pollinated native forest seed.

At a discount rate of 7%, varying coppice productivity from 70% to 130% relative to the original seedling crop resulted in a range of incremental NPV of approximately $5000 per hectare (Figure 5). The range of incremental NPV resulting from variation in the productivity of coppice is more contracted at a discount rate of 12% (< $2500/ha, Figure 6). The influence of changes in productivity due to the performance of coppice or genetic improvement are minimised at high discount rates (Figure 6). Genetic gain of approximately 35% would be required before a seedling regime was favoured at a discount rate of 12%, when coppice productivity was equivalent to that of the first rotation crop (Figure 6).

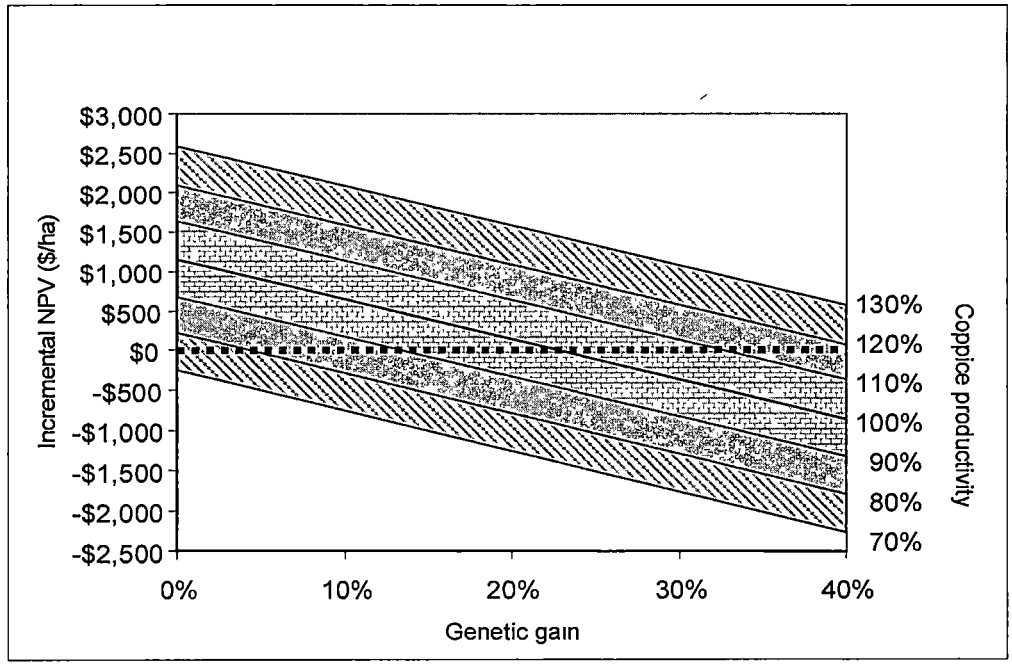


Figure 5. Incremental NPV plotted against genetic gain (measured as percentage increase in dry matter production) showing the effect of increasing coppice productivity at the model base values. An incremental NPV of zero (broken line) indicates no difference in value between coppice and seedling crops in the second rotation. Incremental NPV's above zero indicate the value of coppice exceeding the value of seedlings, and incremental NPV's below zero indicate the value of seedlings exceeding the value of coppice. If the productivity of coppice crops is between 90 and 110% of the original seedling crop, then seedlings will start to become economically viable when genetic gain of 15 to 35% is available.

Early growth of coppice is assisted by the established root system (Blake 1983). The rapid growth of eucalypt coppice has led several authors (Carter 1974; Jacobs 1979; Matthews 1992; Sims *et al.* 1999; Underdown and Bush 2002) to suggest that coppice crops will produce up to 125% of the volume of the original seedling crop. Other authors (Skolmen 1981; Prado *et al.* 1990; Alarcón 1993 and Chapter 3 of this thesis) have reported levels of stump mortality following harvest that would significantly reduce the productivity of a coppiced *E. globulus* plantation. Large differences in the ability of eucalypt species to regenerate through coppice (Blake 1983; Sims *et al.* 1999; Little and Gardner 2003) mean that yield

information from other species may not apply in the case of *E. globulus*. In the absence of direct measurements, the broad range of coppice productivity covered in Figure 5 and Figure 6 realistically represents the possible range of *E. globulus* coppice productivity.

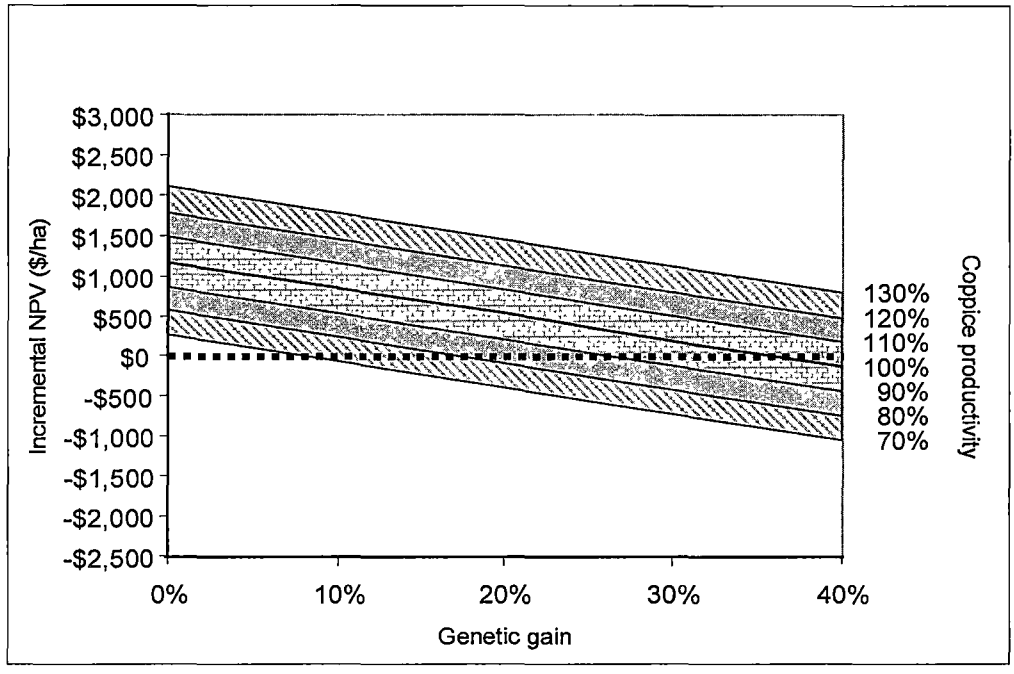


Figure 6. Incremental NPV plotted against genetic gain (measured as percentage increase in dry matter production) showing the effect of increasing coppice productivity at high discount rates (12%). An incremental NPV of zero (broken line) indicates no difference in value between coppice and seedling crops in the second rotation. Incremental NPV's above zero indicate the value of coppice exceeding the value of seedlings, and incremental NPV's below zero indicate the value of seedlings exceeding the value of coppice. The reduction in cost of management combined with similar yields in a coppice crop when compared to a seedling crop mean that an increased discount rate drives the economics of plantation production towards using coppice in the second rotation.

Sensitivity analysis showed that changes in basic density (*D*), MAI and the price paid for an oven-dried tonne of chip (*O*) are the major factors affecting the NPV of first and second rotation crops (Table 10). Genetic gain (*GGAIN*) and coppice productivity (*CPROD*) have rank correlations of a similar magnitude in second

rotation seedling and coppice crops respectively (0.41 and 0.33) (Table 10), and a reduction in the basic density of a coppice crop (u) has a strong negative effect on its NPV (-0.48) (Table 10). The main variables driving changes in incremental NPV (the difference in value between coppice and seedling crops) are reduction in basic density (r), genetic gain (*GGAIN*) and coppice productivity (*CPROD*) (-0.63, -0.52, and 0.44 respectively) (Table 10). This demonstrates that while the level of genetic improvement is an important consideration when choosing between coppice and seedlings in the second rotation, it will be very important to understand the factors affecting the productivity of a coppice crop.

Table 10. Rank correlations for first rotation NPV (1R), second rotation seedling crop NPV (2R seedling), second rotation coppice crop NPV (2R coppice) and incremental NPV (iNPV). 'Basic density' refers to the basic density of the first rotation crop, 'Reduction in basic density' is the reduction in basic density of the wood in a coppice crop, 'Harvest costs' include the cost of harvesting and transporting roundwood, 'Penalty' is the cost penalty incurred when harvesting and processing a coppice crop, 'MAI' is mean annual increment (m^3 ha^{-1} $year^{-1}$), 'Coppice productivity' is the productivity of coppice relative to the first rotation seedling crop, 'Genetic gain' refers to the increase in dry matter production from the first rotation crop to the second rotation seedling crop due to genetic improvement, 'Density:volume' is the ratio of density gain to volume gain in genetic gain, '$/oven dried tonne delivered' is the price paid for an oven dried metric tonne of wood delivered, and 'Discount rate' is the annual discount rate applied.

Assumption	1R	2R seedling	2R coppice	iNPV
Basic density (*D*)	0.58	0.52	0.46	-0.09
Reduction in basic density (*u*)	-	-	-0.48	-0.63
Harvest costs (*h*)	-0.16	-0.13	-0.15	-0.01
Coppice harvest penalty (*f*)	-	-	-0.07	-0.10
MAI (*MAI*)	0.42	0 39	0.32	-0.09
Coppice productivity (*CPROD*)	-	-	0.33	0.44
Genetic gain (*GGAIN*)	-	0.41	-	-0.52
Density:volume (*x*)	-	0.08	-	-0.12
$/oven dried tonne delivered (I_O)	0.59	0.53	0.47	-0.09
Discount rate (*d*)	-0.21	-0.21	-0.16	0.07

The practice of varying underlying assumptions by ±20% for a sensitivity analysis does not take into account the likely variability of the underlying variables (Belli *et al.* 1998). The basic density of eucalypt coppice material has been found to be lower than that of the first rotation material (5%, Sesbou and Nepveu 1991; 8%, Ferrari 1993). However, the coppice material assessed was younger than the original stem material when tested (Sesbou and Nepveu 1991), or as in the case of Ferrari (1993), the coppice growth had not been thinned. The sensitivity analysis conducted in this case may exaggerate the effect of a change in the basic density of coppice relative to the basic density of the initial seedling crop.

Coppice foliage in eucalypts typically shows higher stomatal conductance (Crombie 1997; dos Reis and Reis 1997), and higher stomatal number (Blake 1980). *Eucalyptus globulus* coppice foliage has a higher moisture content and increased carbon:nitrogen ratio when compared to seedling foliage (Steinbauer *et al.* 1998). Physiological changes in coppice foliage appear to leave it more susceptible to *Mycosphaerella sp.* in *E. marginata* (Abbott *et al.* 1999) and insect damage in *E. globulus* (Steinbauer *et al.* 1998), than seedling material. Replanting and turnover of genotypes may help to manage the risk of damage or loss due to pests and diseases. Coppice offers a plantation grower an opportunity to achieve a return for less investment. However, the risks associated with coppiced *E. globulus* plantations are likely to change over time. Where the NPV of coppice and seedling crops in the second rotation is equivalent, the grower should make their decision based on the crop that will incur less risk for the same NPV.

4.5 Concluding remarks

The use of a discounted cash flow model has identified situations where both seedling and coppice crops would be preferable in the second rotation. The current understanding of the productivity of coppice crops in *E. globulus* pulpwood plantations is inadequate to allow firm conclusions. However, the use of low quality genetic material to establish the first rotation will increase the relative level of genetic gain available in seedlings at the start of the second rotation, and make replanting more attractive. If it is assumed that a coppice crop will produce yields roughly equivalent to the first rotation crop, then a grower should start to consider replanting with genetically improved stock if the increase in dry matter yield would exceed 15% over the already established plantation.

Chapter 5: Carbon Revenues and economic breeding objectives

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5.1 Abstract

This chapter investigated the integration of carbon revenues into production system models used to define economic breeding objectives for the genetic improvement of *Eucalyptus globulus* pulpwood plantations. A model estimated that carbon dioxide equivalent (CO_2e) accumulation in biomass in the Australian *Eucalyptus globulus* plantation estate established between 2004 and 2012 was in the order of ~146 t CO_2e ha^{-1}, of which 62 t CO_2e ha^{-1} were tradable in 2012 and a further 30 t CO_2e ha^{-1} were tradable in 2016. By considering a system where revenues for carbon sequestration were directly dependent upon biomass production in a plantation, it was possible to determine whether economic breeding objectives for the genetic improvement of *E. globulus* were sensitive to the revenue from carbon sequestration. The correlated response of breeding objectives with and without carbon (ΔcG_{H_1}) never fell below 0.86 in sensitivity analysis, and the mean was 0.93. As such, where economic breeding objectives for the genetic improvement of *Eucalyptus globulus* for pulpwood plantations are based on maximizing NPV by increasing biomass production, the consideration of carbon in economic breeding objectives will provide no significant gains in NPV.

5.2 Introduction

Definition of an economic breeding objective is accomplished by (1): specifying the production system, then (2): identifying sources of income and costs, (3): indentifying biological traits that influence income and costs, and (4): determination of the economic value or weight of each trait in the objective (Ponzoni 1986). Economic breeding objectives for the production of kraft pulp from plantation grown eucalypts have been defined previously (Borralho *et al.* 1993; Greaves *et al.* 1997b). Both authors identified the same three biological traits (clearfall volume, wood basic density and kraft pulp yield) as having the greatest economic value. The recent advent of carbon dioxide (CO_2) trading schemes adds a source of income separate to the production of pulpwood to the plantation system. Such schemes allow a grower to trade any permanent increase in the carbon density per hectare on their estate. While most of the carbon in a forest is held below ground (Malhi *et al.* 1999), it has been shown that in a plantation system most of the change in carbon density per hectare is associated with changes in perennial woody biomass (Madeira *et al.* 2002). Therefore, changes in the productivity of a plantation will affect the amount of revenue that might be obtained for carbon sequestration in that plantation.

There has been considerable effort expended on the genetic improvement of *E. globulus* for pulpwood plantations (Volker and Orme 1988; Borralho *et al.* 1993; Greaves *et al.* 1997b; Borralho and Dutkowski 1998; Harbard *et al.* 1999; Kerr *et al.* 2001), and it is expected that the use of improved genotypes will increase harvested volume and total dry matter production (Pallett and Sale 2004). Increasing harvested volume and dry matter production through genetic

improvement is likely to result in an increase in the amount of woody biomass per unit area of plantation, and therefore increase the amount of carbon stored per hectare in a plantation (Jayawickrama 2001).

The most widely publicised carbon-trading scheme is that outlined in the Kyoto Protocol. This provides a mechanism for the trade of 90% of any increase in carbon density per hectare during a commitment period in forests established on land not forested prior to 1990 (Watson *et al.* 2000). The first commitment period is set down for the period 2008-2012 and further contiguous commitment periods are envisaged for the years following 2012 (Watson *et al.* 2000). To date, the published models used to describe *E. globulus* pulpwood plantation production systems in economic breeding objectives only consider costs and incomes within a single rotation. Long-term carbon sequestration in biomass and therefore carbon revenues, will be the result of multiple sites of different ages within an estate (Brand *et al.* 2000; Dean *et al.* 2004). Therefore, in order to assess the impact of carbon revenues on the economic breeding objectives for *E. globulus* pulpwood plantations, the production system must be scaled up to include multiple sites at different stages within their rotations.

The work presented in the current chapter investigates the impact of carbon revenues from the first two commitment periods (2008 –2012 and 2012 – 2016) as outlined in Watson *et al.* (2000), on the economic weights for clearfall volume and wood basic density, and the correlated response with breeding objectives excluding carbon revenues. Income was calculated based on the sale of woodchips for export from Australia, and carbon revenues were directly proportional to biomass accumulation in the plantation estate. As such, carbon revenues calculated in this study are extremely sensitive to biomass production,

and the sensitivity of the economic breeding objective to carbon revenues will probably be higher than would be expected in reality. Therefore, if the carbon revenues in the scenario presented here do not have a large impact on the correlated response of the economic breeding objectives including and excluding carbon revenues, then the real effect of carbon revenues will be negligible.

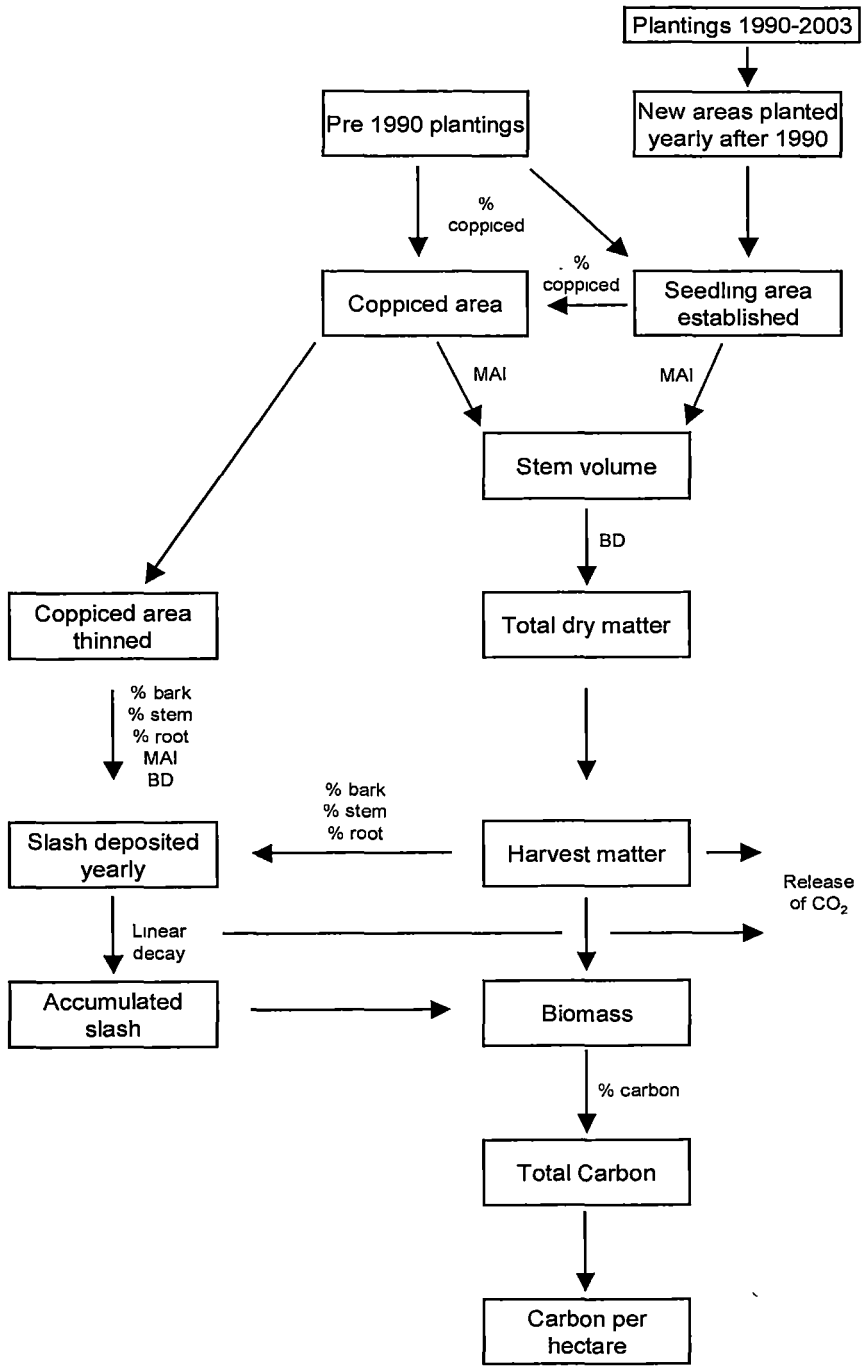
5.3 Materials and methods

5.3.1 Modelling the area planted, tree growth and silviculture

Planting figures from Australia's National Plantation Inventory (NPI, 2003 - see Figure 1) were used to establish planting rates for the estate. The rate of establishment of new *E. globulus* plantation areas between 2004 and 2016 was extrapolated from the NPI data, assuming that *E. globulus* made up 60% by area of all hardwood planting (National Forest Inventory 2004a). A negative curvilinear function was fitted to the planting figures for 2000-2003 to and extrapolated to give estimates of the establishment of new area of *E. globulus* between 2004 and 2016. Growth was defined by clearfall merchantable volume at the end of a ten-year rotation. Whole tree growth was proportional to merchantable volume increment. Allocation of biomass between different tree components (roots, stem, branches, leaves, bark) followed that described by Madeira *et al.* (2002) for 6 year old *E. globulus* trees. Allocation was assumed to remain unchanged over time. A 1-year fallow period was assumed between the harvest and replanting of a site. Estimates of the estate area occupied by plantations established between 2004 and 2016, total CO_2 equivalent (CO_2e) sequestration and CO_2e sequestration per hectare were obtained. When coppice was used to produce the second rotation crop, the new stems began to grow

immediately following harvest of the first rotation crop. It was assumed that there was no stump mortality and that the initial growth was the same as in the first rotation crop. Thinning of the coppice from between 10 and 20 stems per stump (Table 4), to one or two stems per stump at the age of 2 years was assumed to remove ~60% (Table 11) of the living above ground biomass at that site. The remaining stems then grew at a rate that resulted in the same harvest volume as was obtained in the original seedling rotation. The root biomass of a coppiced tree was maintained unchanged from the end of the seedling rotation, throughout the coppice rotation after which the stumps and roots decayed. Biomass in harvest residue (harvested logs were assumed to be debarked on site), thinned material, stumps and roots, was assumed to decay linearly over a 7-year period (Watson *et al.* 2000). A schematic representation of the system used to calculate the biomass accumulation in the *E. globulus* estate is shown in Figure 7.

Figure 7. A schematic representation of the model used to calculate biomass accumulation in the Australian *E. globulus* plantation estate.



5.3.2 The production system

The production system modelled the export of *E. globulus* wood chips from Australia. The system used was adapted from the ChipEx model (Greg Dutkowski, pers. com.), which was similar to that described in Chapter 4, but incorporated more details of the transport and processing of roundwood. The production system was designed to calculate the NPV per hectare of growing *E. globulus* to produce wood chips for export on a ten-year rotation, on the basis of the whole estate modelled, where:

$$NPV = I - C, \qquad [36]$$

$$I = \frac{R}{\left(1 + \frac{d}{100}\right)^q}, \qquad [37]$$

where

$$R = Sold \times p \qquad [38]$$

and

$$Sold = (1 - L_c) \times VOL_{lo} \times BD \qquad [39]$$

and

$$VOL_{lo} = VOL_{cf}(1 - L_a)(1 - L_h). \qquad [40]$$

The present value of costs discounted to the start of the rotation was:

$$C = {}^{PV}C_L + {}^{PV}C_M + {}^{PV}C_H + C_E, \qquad [41]$$

where

$${}^{PV}C_L = \frac{C_L\left(1-\left(1+\frac{d}{100}\right)\right)^{-q}}{\frac{d}{100}}, \qquad [42]$$

$${}^{PV}C_M = \frac{C_M\left(1-\left(1+\frac{d}{100}\right)\right)^{-q}}{\frac{d}{100}}, \qquad [43]$$

$${}^{PV}C_H = \frac{\left(C_{th}+Mill+C_H\right)}{\left(1+\frac{d}{100}\right)^{q}}, \qquad [44]$$

$$C_{th} = Load \times C_{tw}, \qquad [45]$$

$$Load = VOL_{lo} \times S \times \left(1-b_h\right), \qquad [46]$$

$$Mill = C_c \times VOL_{lo} \times S, \qquad [47]$$

$$C_H = VOL_{cf} \times C_v, \qquad [48]$$

and

$$C_{tw} = F + \left(C_d \times Haul\right). \qquad [49]$$

All symbols used are defined in Table 12.

Unlike the production systems described in Borralho *et al.* (1993) and Greaves *et al.* (1997b) conversion of woodchips to pulp was not considered. Costs for growing, harvesting, transport and chipping were included. Growing costs were proportional to the area planted, harvest costs proportional to clearfall volume and transport costs proportional to transport distance and harvest volume. Harvest and chipping losses were accounted for. Revenue was earned for an oven dry metric ton of wood chips for export. All costs and revenues were discounted to the present (2004). The production system was used to define economic breeding objectives both including, and excluding carbon revenues. The overall aim of the breeding objectives was to maximize the net present value (NPV) per hectare of growing *E. globulus* in plantation. The NPV of plantings between 2004 and 2012 (to the end of the first commitment period) was calculated over the period 2004 to 2021 so that the revenue from sold timber from all the plantings in the period 2004 – 2012 were considered. In the case of the second commitment period (2012-2016) NPV was calculated over the period 2004 – 2025. All costs and incomes were discounted to the present (2004). All costs and prices are presented in Australian dollars.

Table 11. Assumptions, base values, and minima and maxima for model variables in the sensitivity analysis of the estate based production system.

Assumption	Units	Base	Min	Max
E. globulus	% *E. globulus*	60	48	72
Area 2002	area planted 2002	51,026	39,344	59,016
Area 2003	area planted 2003	32,601	28,241	34,517
Bark allocation	% bark in total biomass	8	6	10
Stem allocation	% stem in total biomass	56	45	67
Root allocation	% root in total biomass	21	17	25
Carbon in biomass	% carbon in total biomass	46	37	55
Coppice	% coppice	0	0	40
Coppice biomass thinned	% thinned	60	48	72
Clearfell volume	$m^3\ ha^{-1}$	250	200	300
Clearfell basic density	$t\ m^{-3}$	0.54	0.43	0.64
Specific gravity	$t\ m^{-3}$	1.03	0.82	1.24
Bark	% havested	13	10	16
Area loss	%	3	2	4
Harvest loss	%	2	2	2
Chipping loss	%	5	4	6
Lease cost	$\$\ ha^{-1}\ a^{-1}$	300.00	240.00	360.00
Establishment cost	$\$\ ha^{-1}$	1,000.00	800.00	1,200.00
Maintenance cost	$\$\ ha^{-1}\ yr^{-1}$	80.00	64.00	96.00
Harvest cost	$\$\ m^{-3}$	11.00	8 80	13.20
Transport flagfall	$\$\ t^{-1}$	4 00	3.20	4.80
Transport distance cost	$\$\ t^{-1}\ km^{-1}$	0 10	0.08	0.12
Haul distance	km	75.00	60.00	90.00
Chipping and loading costs	$\$\ t^{-1}$	27 00	21.60	32.40
Selling price	$\$\ t^{-1}$	168.00	134.40	201.60
Annual discount rate	$\%\ yr^{-1}$	10	8	12
Carbon price	$\$\ t^{-1}\ CO_2e$	8.00	6.40	9.60
σ_a volume	m^3	38.00	30.40	45.60
σ_a density	$t\ m^{-3}$	0.02	0.02	0.02
$r_{vol\ den}$		-0.10	-0.12	-0.08

Table 12. Assumptions in the production system, abbreviations used to represent them and their units.

Description	Abbreviation	Units
Assumptions		
Clearfall standing underbark volume	VOL_{cf}	$m^3\ ha^{-1}$
Clearfall basic density	*BD*	OD $t\ m^{-3}$
Selling price	*p*	\$ OD t^{-1}
Specific gravity	*S*	
Bark (fraction of total weight)	b_h	proportion
Area loss (fraction of plantation area)	L_a	proportion
Harvest loss (fraction of harvest volume)	L_h	proportion
Rotation age	*q*	years
Discount rate (annual, compounding)	*d*	%
Haul distance	Haul	km
Lease cost	C_L	\$ $ha^{-1}\ q^{-1}$
Establishment costs	C_E	\$ ha^{-1}
Maintenance costs	C_M	\$ $ha^{-1}\ q^{-1}$
Harvest cost per hectare	C_H	\$ ha^{-1}
Transport flagfall per green ton loaded	*F*	\$ t^{-1}
Transport distance cost	C_d	\$ $t^{-1}\ km^{-1}$
Chipping loss (fraction of chipped volume)	L_c	proportion
Chipping and loading cost per green ton	C_c	\$ t^{-1}
Calculations		
Underbark volume after harvest and area losses	VOL_{lo}	$m^3\ ha^{-1}$
Harvested green weight of logs with bark	*Load*	$t\ ha^{-1}$
Sold chips	*Sold*	OD $t\ ha^{-1}$
Harvest cost per unit volume	C_v	\$ m^{-3}
Transport cost per green ton	C_{th}	\$ t^{-1}
Per hectare transport cost	C_{tw}	\$ ha^{-1}
Per hectare processing cost	*Mill*	\$ ha^{-1}
Revenue from sale of chips (undiscounted)	*R*	\$ ha^{-1}
Costs (discounted to establishment)		
Discounted lease costs	$^{PV}C_L$	\$ ha^{-1}
Discounted maintenance costs	$^{PV}C_M$	\$ ha^{-1}
Discounted harvest and processing costs	$^{PV}C_H$	\$ ha^{-1}
NPV Income	*I*	\$ ha^{-1}
NPV costs	*C*	\$ ha^{-1}
Net present value per hectare	*NPV*	\$ ha^{-1}

5.3.3 Carbon revenues

Under the system outlined in the Kyoto Protocol the tradable unit of CO_2 is the biomass equivalent of one metric ton of CO_2 (1 ton CO_2e). Carbon was assumed to make up 46% of oven dry tree biomass (Pate and Arthur 2000). Every ton of biomass carbon is equivalent to 3.67 tons CO_2 (Watson *et al.* 2000). Ninety percent of carbon sequestered in each commitment period (2008 – 2012 and 2012 – 2016) in forests established on land not forested prior to 1990 is eligible to be traded. A base price of \$8.00 t^{-1} CO_2e was calculated by converting the prices in US dollars for Kyoto pre-compliant CO_2 sequestration given in Lecocq (2004) to Australian dollars. Much of the Australian *E. globulus* plantation estate has been established on ex-pasture sites (Mendham *et al.* 2003), with the major expansion of the estate occurring after 1990 (National Forest Inventory 2003). Therefore, the model considers all new areas planted after 2004 eligible to sequester carbon. In keeping with the default approach of the Intergovernmental Panel on Climate Change in the first commitment period, carbon in wood products was not considered (Watson *et al.* 2000), and all carbon in biomass sold was lost to the system immediately upon harvest.

5.3.4 Correlated response

Where two traits have a non-zero genetic correlation, selection on one trait will lead to a genetic change in the other (Searle 1961; Weller 1994). Similarly, where traits in different economic breeding objectives have non-zero genetic correlations, selection on one objective will lead to a genetic change in the other. For two breeding objectives the correlated response in objective one (H_1) when selection is based on an index derived to maximize response on breeding objective

two (H_2) is calculated as the regression of H_1 on H_2 (e.g. Apiolaza and Garrick 2001):

$$\Delta cG_{H_1} = b_{H_1H_2}\Delta G_{H_2} \quad [50]$$

$$= \frac{\mathrm{Cov}(H_1, H_2)}{\mathrm{Var}(H_2)}\Delta G_{H_2} \quad [51]$$

$$= v'\boldsymbol{G}w(w'\boldsymbol{G}w)^{-1}\Delta G_{H_2} \quad [52]$$

where $\boldsymbol{v}$ and $\boldsymbol{w}$ are the vectors of economic weights for H_1 and H_2 respectively, $\boldsymbol{G}$ is the additive covariance matrix for objective traits and ΔG_{H_1} is the direct response for breeding objective H_1. The first breeding objective (H_1) contained two traits: harvest volume and basic density. The second breeding objective (H_2) included the same two traits, but the revenues for carbon sequestration in the plantation estate altered the economic weights for volume and basic density.

5.3.5 Sensitivity analysis

Sensitivity analysis consisted of Monte Carlo simulation of 100,000 iterations varying the plantation estate parameters by ±20% (with a uniform distribution) using Crystal Ball® (Decisioneering Inc. 2000). Minima and maxima for model variables in the sensitivity analysis are shown in Table 11. The ranges of forecasts between the 5th and 95th percentiles (covering the central 90% of all forecasts) are reported in Table 13. Sensitivities of key forecasts to variation in model variables were calculated as a percentage of total variance in forecast values contributed by each assumption, and are reported in Table 14.

5.4 Results and Discussion

5.4.1 Estate and carbon revenue

It was estimated that biomass accumulation in forests established between 2004 and 2016 was equivalent to 45 t C ha^{-1} (data not shown). Long-term CO_2e sequestration in the biomass component of the Australian *E. globulus* plantation estate established between 2004 and 2016 (34,507 hectares) assuming no change in productivity over time was 146 t CO_2e ha^{-1} (Table 13). The addition of carbon revenues produced a change in NPV (ΔNPV) per hectare of $216 ha^{-1} (Table 13) in the first commitment period, and $287 ha^{-1} (Table 13) when the carbon revenues of the first and second commitment periods were combined.

Table 13. Forecast means and values for the 5th and 95th percentiles (the central 90% of all forecasts fall within the range shown) following sensitivity analysis. Values are for new areas planted between 2004 and 2016.

Forecast	Units	Mean	5%	95%
Estate				
Seedling area	ha	3,148.64	1,502.55	6,239.78
Coppice area	ha	596.02	60.65	1,452.02
Biomass total	Mt	3.68	1.63	7.29
CO_2e ha^{-1} long term	t CO_2e ha^{-1}	146.05	90.69	218.32
CO_2e ha^{-1} 2012	t CO_2e ha^{-1}	62.35	37.95	94.47
CO_2e ha^{-1} 2016	t CO_2e ha^{-1}	29.70	16.18	48.02
CO_2 revenue				
(H_2 - H_1) 2012 ΔNPV	M$	7.87	3.06	16.18
(H_2 - H_1) 2012 ΔNPV ha^{-1}	$ ha^{-1}	215.76	121.25	346.01
(H_2 - H_1) 2016 ΔNPV	M$	10.74	3.87	23.34
(H_2 - H_1) 2016 ΔNPV ha^{-1}	$ ha^{-1}	287.08	157.18	467.66
Economic weights				
H_1 2012 Volume	$ m^{-3}	14.20	5.15	25.66
H_1 2012 Basic density	$ kg^{-1} m^{-3}	14.93	9.51	21.79
H_2 2012 Volume	$ m^{-3}	15.06	5.87	26.67
H_2 2012 Basic density	$ kg^{-1} m^{-3}	15.33	9.84	22.28
H_1 2016 Volume	$ m^{-3}	17.59	6.28	32.26
H_1 2016 Basic density	$ kg^{-1} m^{-3}	18.50	11.45	27.61
H_2 2016 Volume	$ m^{-3}	18.74	7.24	33.63
H_2 2016 Basic density	$ kg^{-1} m^{-3}	19.03	11.89	28.23
Correlated response				
ΔcG_{H_1} 2012		0.93	0.87	0.97
ΔcG_{H_1} 2016		0.93	0.86	0.97

The economic weights for volume and basic density excluding carbon revenues in the first commitment period were \$14.20 m^{-3} ha^{-1} and \$14.93 kg^{-1} m^{-3} respectively (Table 13), and the ratio of the economic weight per unit volume for volume and the economic weight per unit basic density was 0.95. Inclusion of first commitment period carbon revenues altered the economic weights for volume and basic density to \$15.06 m^{-3} ha^{-1} and \$15.33 kg^{-1} m^{-3} respectively (Table 13), with a greater emphasis on volume (the ratio of the economic weight per unit volume for volume and the economic weight per unit basic density was 0.98). When the second commitment period is considered the economic weights without carbon were \$17.59 m^{-3} ha^{-1} and \$18.50 kg^{-1} m^{-3} for volume and basic density respectively (Table 13) without carbon revenues, and \$18.74 m^{-3} ha^{-1} and \$19.03 kg^{-1} m^{-3} including carbon revenues (Table 13), but the ratios between the weights for volume and basic density did not differ from the first commitment period.

Coppice crops in the second rotation are likely to change the dynamics of woody biomass in an *E. globulus* plantation. In a coppice crop the stumps are allowed to resprout following the first rotation harvest, and the rootstock is retained as living biomass. In *E. globulus*, up to 20 stems are produced by each stump (see Table 4), and thinning to one or two stems per stump after the first 2 years of growth is required to produce an economically viable pulpwood crop. Such thinning removes a large percentage of the above ground biomass from each plant, resulting in a large build up of decaying biomass in the plantation. Therefore the dynamics of carbon storage will differ between seedling and coppice crops in an *E. globulus* plantation. However, while coppicing was included as a variable in this study, its effect on carbon sequestration in plantations was small over the

period considered (2004 – 2025). Longer timescales would have to be studied to fully assess the impact of coppicing on carbon accumulation in the plantation estate.

In sensitivity analysis 97% of the total variation in the amount of CO_2 accumulated per hectare in the estate (CO_2e ha^{-1} 2012, Table 14) was contributed by changes in the biomass allocated to the stem, basic density, clearfall volume and the percentage of carbon in biomass (46%, 17%, 17%, and 17% respectively, Table 14). Sensitivity analysis also found that variation (97%, Table 14) in the difference in NPV in 2012 between scenarios with and without carbon revenues ($(H_2 - H_1)$ 2012 ΔNPV ha^{-1}, Table 14) was also driven by changes in the biomass allocated to the stem, basic density, clearfall volume and the percentage of carbon in biomass (35%, 13%, 13% and 13% respectively, Table 14) with changes in the price per unit CO_2e and the annual discount rate applied (13% and 10% respectively, Table 14) contributing significant percentages of the variation. Increasing the biomass allocation to the stem resulted in a reduction in the amount of CO_2e sequestered per hectare because the stem is the portion of the tree harvested and in this case, all carbon in harvested biomass is assumed released immediately upon harvest. However, it is unlikely that biomass allocation to the stem of the tree in plantations will vary to the extent (±20%) applied in the sensitivity analysis. Therefore increasing volume production and clearfall basic density in plantations will increase the amount of CO_2e sequestered in plantations and also increase the value of a crop in a situation where CO_2 sequestered in plantations can be traded.

5.4.2 Correlated response

The changes in the economic weights of the traits harvest volume and basic density because of carbon revenue in either commitment period (2012 or 2016) result in the correlated response of H_1 to selection based on H_2 (ΔcG_{H_1}) being 0.93. In sensitivity analysis 40% (Table 14) of the variation in the correlated response of breeding objectives was due to variation in the price obtained for wood chips. Increasing the price obtained for woodchips increased the correlated response by decreasing the relative value of carbon revenues. Increasing the price obtained per unit CO_2e sequestered had a small negative impact on the correlated response of breeding objectives, contributing 6% of variation in sensitivity analysis (Table 14). As the correlated response of H_1 to selection based on H_2 is so high, it is unlikely that some of the assumptions in the model (i.e. no age dependant change to within tree biomass allocation) will affect the overall conclusions. This is supported by the results of the sensitivity analysis for the NPV of each breeding objective in the first commitment period (2008-2012). In each breeding objective (excluding and including CO_2 revenue), changes in the unit price of woodchips for export, and the basic density at clearfall both contributed over 69% of the variation, with the remainder being made up by changes the same set of variables in each objective (NPV H_1 2012 and NPV H_2 2012, Table 14). It is important to note that changes in the unit price of CO_2e contributed less than 1% of the variation in NPV of H_2 in 2012.

Table 14. The sensitivity results for key output variables presented as a percentage of total variation, based on 100,000 iterations varying input variables by ± 20% with an even distribution. All variables contributing greater than 1% of variation are shown. At least 95% of all variation for each forecast is shown.

		Forecasts				
Assumptions		**CO_2e ha^{-1} 2012**	**(H_2 - H_1) 2012 ΔNPV ha^{-1}**	**ΔcG_{H_1} 2012**	***NPV H_1* 2012**	***NPV H_2* 2012**
Area 2002	area planted 2002			1	3	3
Area 2003	area planted 2003				-1	-1
Stem allocation	% stem in total biomass	-46	-35	16		
Carbon in biomass	% carbon in total biomass	17	13	-6		
Coppice	% coppice	2	2			
Clearfelvolume	m^3 ha^{-1}	17	13		6	7
Clearfell basic density	t m^{-3}	17	13	13	35	35
Specific gravity	t m^{-3}			11	10	9
Lease cost	\$ ha^{-1} a^{-1}				-3	-3
Establishment cost	\$ ha^{-1}				-2	-2
Chipping and loading costs	\$ t^{-1}			-4	-3	-3
Selling price	\$ t^{-1}			40	35	34
Annual discount rate	% yr^{-1}		-10		-1	-1
Carbon price	\$ t^{-1} CO_2e		13	-6		

5.5 Conclusions

Tree breeding is a long-term enterprise and the impact of decisions made today will not be seen for at least 20 years (Greaves *et al.* 1997b). It would be redundant to consider tree improvement in terms of carbon sequestration if the only period in which carbon could be traded was between 2008 and 2012. However, if in the future the carbon density on a site is increased above the site average of 2008-2012, then that carbon could potentially be traded. In order that the carbon "stored" to 2012 is maintained in the longer term, further contiguous commitment periods following 2008-2012 must be envisaged. It is possible that in subsequent commitment periods carbon sequestered in forest products will be included in the calculations of the amount of carbon tradable in forest sector (Pingoud and Lehtilä 2002). This should increase the NPV of alternative objectives, because models of carbon sequestration incorporating processing of wood and wood products have already shown positive carbon balances (Côté *et al.* 2002). Therefore, even though the initial Kyoto commitment period is too soon and too short for tree improvement to address directly, it is possible that future tree improvement in the direction of increasing carbon sequestration per hectare in *E. globulus* plantations could have an effect on carbon revenues. In this study the correlated response to selection of an economic breeding objective without carbon when selection is based on an economic breeding objective including carbon sequestration was found to be very high (between 0.86 and 0.97) in a system designed to maximise carbon revenues relative to biomass production. Therefore, inclusion of carbon revenues in economic breeding objectives for *E. globulus* appears unnecessary.

Chapter 6: General Discussion

6.1 *Eucalyptus globulus* coppice

Prior to 1995 there were less than 80,000 hectares of hardwood plantation in Australia. A large part of the Australian *E. globulus* plantation estate was established between 1990 and the year 2000 (Figure 1) with most of the expansion in Victoria, South Australia and Western Australia. The establishment of new areas of hardwood plantations peaked in the year 2000 at 126,211 ha (National Forest Inventory 2004b). There were 715,531 ha of hardwood plantations in Australia in 2004 (National Forest Inventory 2005), 61%, or 441,946 ha of this was *E. globulus* (National Forest Inventory 2004a).

Most early plantings were based on seed collected from natural stands. As domestication of the species continued the seed was increasingly taken from targeted trees of specific provenances, resulting in a level of improvement in the productivity of plantations. Provenance selection, breeding and improved silviculture have provided significant improvements in volume production, wood density and wood quality in plantation eucalypts (Pallett and Sale 2004). Most of the estate was established with the aim of producing pulpwood on 10-15 year rotations (Turnbull 1999). Large areas of this estate are now becoming available for harvest, and subsequent re-establishment of the second rotation. Experience in Australia and overseas has demonstrated the potential for managing *E. globulus* as a coppice crop in pulpwood plantations (Goes *et al.* 1967; Carter 1974; Jacobs 1979; Skolmen 1981; Prado *et al.* 1990; Matthews 1992; Sennerby-Forsse *et al.* 1992; Alarcón 1993; Doughty 2000).

Some species of eucalypt (*E. regnans*, *E. gigantea* and *E. fraxinoides*: Jacobs 1955) do not produce coppice. *Eucalyptus nitens* and *E. astringens* rarely produce coppice (Jacobs 1955). Non-coppicing eucalypts do not have lignotubers, but there are non-lignotuberous species that produce coppice. Non-lignotuberous species are often sensitive to fire, but *E. fastigata* and *E. grandis* throw out new shoots from the bases of saplings which have stockings of thick bark at the base, even after severe fires. Broad swelling of the basal portion of the stems of seedlings rather than discrete lignotuberous organs occur in some eucalypts such as *E. pilularis* (Boland *et al.* 1985) and *E. globulus* (Chapter 3) and this is strongly correlated with the ability to produce coppice (Table 5). Eucalypts appear to be one of the more fire resistant genera of woody plants, and the survival of fire depends largely on the fate of the regenerative buds. Most eucalypt species produce bole or crown epicormic shoots after fire, while low levels of epicormic growth are recorded in non-eucalypt woodlands following fire (Burrows 2002).

The regenerative buds of eucalypts are formed from epicormic meristem strands that differ in their anatomy from those of other angiosperm species (Burrows 2002). In most angiosperms and gymnosperms, epicormic buds or meristems are usually located close to the surface where they can be easily damaged, while the epicormic meristems in eucalypts develop in the inner bark or even the outer secondary xylem (Burrows 2002). Meristematic tissue also forms in lignotubers (Noble 2001), where it is protected by bark and, or soil (Burrows 2002). There are more epicormic meristem strands at the bases of trunks of trees which have lignotubers than at the bases of trees which do not have them (Jacobs 1955).

Significant genetic diversity was found for coppicing traits within and between subraces, following felling of an *E. globulus* progeny trial after 9 years of growth

in the Massy Greene field trial. At the subrace level the proportion of stumps coppicing ranged from 43% (Strzelecki Foothills) to 73% (Recherche Bay, see Table 4). Within subraces heritabilities for coppice success (0.07) and subsequent growth (0.16-0.17) were low but statistically significant. Strong genetic correlation between presence/absence of coppice, the number of stems coppicing from the stump and modal coppice height, indicate selection is possible using the binary trait. The ability of a tree to coppice was genetically correlated with tree growth prior to felling ($r_g = 0.61$), and with nursery-grown seedling traits, where large genetic differences were observed in the development of lignotubers.

With the exception of a west-east clinal trend across the Otway ranges (39°S, 144°E, Figure 3a) in south-western Victoria, there appears to be little evidence for the provenances from drier environments showing better regeneration by coppice on this specific trial site. However, strong genetic correlations were found between the ability to regenerate through coppice and the extent of lignotuber development in seedlings (see Table 5). Coppicing was genetically correlated with the number of nodes with lignotubers ($r_g = 0.66$) and seedling stem diameter at the cotyledonary node ($r_g = 0.91$). These traits were uncorrelated with later age growth and with each other. In the case of lignotuber development, subraces from wetter environments produced fewer lignotubers and had thinner bark. This result is consistent with previous reports of eucalypt species or populations from drier environments having greater lignotuber development (Gill 1997).

The results presented in Chapter 3 suggest that coppicing is influenced by three independent mechanisms - lignotuber development, enlargement of the seedling stem at the cotyledonary node and vigorous growth - which enhance ability to survive catastrophic damage, and indicate that both lignotuber and coppice

development can be altered by both natural and artificial selection. In terms of economic traits, there was a positive genetic correlation between the presence of coppice and tree growth prior to felling, and no significant genetic correlation was found between the presence of coppice and pilodyn penetration (an indirect measure of wood basic density). It should be noted that a subsequent unpublished (Ass. Prof. B Potts, *pers. com*). study genetic parameters for *E. globulus* coppice on a different site has shown different responses of subraces to coppicing and, as at Massy Greene there was a significant within trial environmental variation in coppice success, indicating a strong influence of environmental factors on the success of regeneration of *E. globulus* through coppice.

Australian plantation growers face a choice between replanting a site with genetically improved stock, or managing regeneration from the stumps as a coppice crop. A number of factors influence the economic performance of a coppice crop in the second rotation. Stump survival can be adversely affected by environmental stress (such as heat, frost and drought - Blake 1983), and is dependant to some extent on the season of felling (Cremer 1973; Blake 1983; Ritson and Pettit 1991). Normally *E. globulus* coppices vigorously (Jacobs 1979; Turnbull and Pryor 1984; Matthews 1992; Wirthensohn and Sedgley 1998), but in the Massey Greene trial studied in Chapter 3 only 67% of the trees produced coppice in the 14 months following felling but subraces varied from 43 to 73% (Table 4). Such low rates of coppicing contrast with the results of trials conducted in Chile, where the success rate of coppicing in *E. globulus* was found to be about 93% 14 months after felling (Prado *et al.* 1990; Alarcón 1993).

Variation in the production of coppice between provenances has been found in other eucalypt species such as *E. camaldulensis* (Grunwald and Karschon 1974;

Sesbou and Nepveu 1991), *E. grandis* (Reddy and Rockwood 1989), and *E. nitens* (Little *et al.* 2002). The potential significance of the differences between subraces is highlighted by the contrasting ability to produce coppice in the three subraces of commercial importance. Subraces from the southern Furneaux Islands and eastern Otway Ranges both produced coppice at relatively high rates, while the lowest subrace mean was observed in the subrace from the Strzelecki Ranges (see Table 4 and Figure 3a). The genetic origin of the first rotation planting stock may affect the successful regeneration of a second rotation coppice crop. The work in Chapter 3 was largely based on data from a single trial, and coppice growth was assessed after only fifteen months, so it is difficult to generate conclusions about which provenances and genotypes coppice best generally, or produce the best end of rotation yields, but it is clear that genetic differences do exist.

A site that is difficult to work on, or expensive to recultivate or establish seedlings on may be more profitably managed as a coppice crop, although a site that is difficult to recultivate may also cause difficulties when thinning the coppice. There is evidence that trees growing vigorously prior to felling are more likely to produce coppice (Blake 1983), and it is possible that on marginal sites where growth rates are low, coppice production will not be maximal. As such, it has been argued that a coppice crop is best suited to high quality sites where the maiden crop performed particularly well, and more marginal sites would be better replanted with genetically improved seedlings (Underdown and Bush 2002). Conversely, a high quality site may be better suited to replanting with seedlings of high genetic quality to maximise realised gain, as the establishment of seedlings on a good site carries less risk of losses.

Where the first rotation was established using unselected OP seed collected from natural stands, the relative benefits of replanting seed orchard derived stock will be greater, making replanting more attractive. It has been suggested that the first coppice crop following felling of the maiden crop will exceed the productivity of the maiden crop by between 20% (Goes *et al.* 1967; Carter 1974) and 25% (Matthews 1992). Such levels of increased productivity are probably possible where the coppice is not thinned and the rotation very short (e.g. Dyson 1974; Kaumi 1983; Sims *et al.* 1999) as early development of coppice is rapid due to the established root system (Carter 1974; Blake 1980). The fact that Garcia and Ruiz (2003) were unable to integrate data from both first rotation and unthinned coppice stands in a growth model for *E. globulus* in Galicia, northern Spain, indicates that the growth differs between unthinned coppice, and seedling crops. In the case of coppice thinned to produce pulpwood on longer (10 – 15 years) rotations, yield tends to decrease relative to the maiden crop due to stump mortality (Myburgh 1967; Carter 1974) or nutrient export from the site (de Miranda *et al.* 1998).

Wood density increases from pith to bark, and from the base of the stem to the top (Nolan *et al.* 2005). A tree grows by depositing a new layer of wood, under the bark, on the outside of the previous year's deposited wood. The wood that is deposited in a year's growth is different from the wood deposited in the previous year's growth, up a point (usually 20 to 40 years old), after which time the deposited wood is relatively consistent year-to-year. Whole tree basic density increases with tree height in *E. globulus* (Raymond and MacDonald 1998), and as a tree ages. Decreased basic density relative to the seedling crop has been reported in wood from coppice, however the coppice material tested was either

younger than the seedling material (i.e. Sesbou and Nepveu 1991) or the coppice had not been thinned (i.e. Ferrari 1993). A valid comparison of the basic density of thinned coppice and seedling material at the same age has not been conducted.

Production of a commercially viable coppice crop from *E. globulus* requires that coppice regrowth be thinned from up to 20 stems (Table 4) down to one or two stems per stump (Matthews 1992). How such a drastic removal of biomass affects the end of coppice rotation productivity is not well understood. In Chapter 4 it was shown that if the productivity of a coppice crop is similar to that of the original seedling crop, the productivity of a second rotation seedling crop would have to increase by ~15% through provenance selection and breeding for it to be competitive with the cheaper option of managing the site as a coppice crop. Estimates of such genetic gain in *E. globulus* range from 7 to 17% for volume (Volker *et al.* 1990), 20–47% for dry matter (Borralho *et al.* 1992) and up to 18% saving in total pulp costs (Greaves *et al.* 1997a). However, when compiling and presenting the model used in Chapter 4, it became apparent that the relative productivities of seedling and coppice crops are poorly understood in the context of Australian *E. globulus* pulpwood plantations, and this is a clear area for future research.

A grower must consider the risks involved in establishing the second rotation seedling crop, and coppice crops with pre-established root systems may be an option where the risks associated with replanting are too high. Some risk factors that may be relevant include the differential impact of browsing and susceptibility to pathogens between coppice and seedlings. By replanting a grower turns over genotypes in a plantation, and this may restrict pathogen build up. Further, replanting may allow a period of water recharge on a site as root systems of the

new trees explore the soil profile, whereas coppice utilises the established root systems that have already fully explored the soil profile. On more marginal sites there may not be adequate soil water recharge to support a coppice crop throughout a second rotation. Our understanding of such later rotational issues will improve as eucalypt plantation forestry matures in Australia.

With declining production from native forests, an increase in the use plantation stock for solid and composite wood products is projected (Chafe *et al.* 1992; Greaves *et al.* 2004b; Nolan *et al.* 2005). It is likely that the development of solid or composite wood products from plantation grown *E. globulus* will require the use of intense thinning regimes (Raymond 2000; Shield 2004; Waugh 2004; Nolan *et al.* 2005), and the control of coppice regeneration would be required. However, the use of herbicide to control coppice regrowth in thinned forests is known to kill or detrimentally affect retained trees in both conifer (Eis 1972) and hardwood forests (Willoughby 1999), through root grafting. The problem (known as "flashback") has been noted in Australia in *E. dunnii* trials (C. E. Harwood, pers com.), and when conducting pre-commercial thinning of stands of *Corymbia citriodora* subsp. *variegata*, *E. cloeziana* and *E. grandis* (Dickinson and Huth 2003).

Root grafting is the functional union of two or more roots subsequent to their formation (Graham and Bormann 1966). Grafts are commonly established between roots of the same tree or between roots of neighbouring trees of the same species (Keeley 1988; Külla and Lõhmus 1999), and root grafts are known to transmit natural pathogens between individuals (Schultz 1972; Epstein 1978). Root grafts also allow the transfer of phloem (Stone 1974), water (Stone and Stone 1975), and consequently soluble herbicides between individuals. The

stumps of girdled or felled trees can be maintained alive through root grafts (Liphschitz *et al.* 1987; Ferreira *et al.* 1999), sometimes causing stagnation of growth in the retained trees (Eis 1972; Dosen and Iyer 1979; Liphschitz *et al.* 1987). In *E. obliqua* forest in Tasmania it is thought that root grafting may play a role in inter-tree competition determining the small-scale spatial pattern of dominant trees (West 1984). Spacing within plantations is an important determinate for the occurrence of root grafting (Schultz 1972; Stone 1974; Stone and Stone 1975; Thomson 1979; Fakirov 1986; Külla and Lõhmus 1999). Cultivation practices and stand age can also affect the occurrence of root grafting, with grafts always found to occur within rows and most grafts being established at between 10 and 20 years of age in a study of *Picea abies* (Norway Spruce, Külla and Lõhmus 1999).

In a pulpwood plantation the ability of *E. globulus* to regenerate through coppice is a bonus where a coppice crop is desired, but may cause problems when a grower wishes to replant a site. Properly managed use of herbicide can be very cost effective at controlling the regeneration of stumps at rotation (Hamilton and McHenry 1982), however, pressure to minimise the use of herbicides has led to investigation of the mechanical removal of stumps at rotation. Mechanical options for stump removal are expensive and therefore, in such a situation there may be enough of an economic incentive to use selection to lower the ability of plantation stock to regenerate through coppice. A reduction in the ability to regenerate through coppice in the plantation might be achieved through the planting of certain provenances, or selection in seedlings to exploit the strong genetic correlation between seedling stem diameter at the cotyledonary node and coppice production at later age ($r_g = 0.91$, Table 5).

6.2 Genetic improvement and carbon sequestration

The financial returns delivered through genetic gains made in a breeding program are partially dependant upon the value of products and services provided by improved populations (Burley and Kanowski 2005). Intensively managed plantations must be highly productive, economically efficient, supply an increasing range of products and maintain a high standard of sustainability. The guiding principles for achieving these goals are set out in documents such as the Australian Government's 2020 vision for forestry (Commonwealth of Australia 1997), the Montreal Protocol (Montreal Process Liaison Office 2000), and the Australian Forestry Standard (Australian Forestry Standard Steering Committee 2003). The importance of sustainable management of forest industries was highlighted in the Millenium Ecosystem Assessment (Reid *et al.* 2005). While economists continue to favour the use of market based instruments over policy mechanisms for the management of environmental issues (Hockenstein *et al.* 1997; Stavins 1998; Stavins 2004; Goldemberg 2005; Stavins and Richards 2005), it is likely that markets for ecosystem services will expand. The establishment of markets for ecosystem services will provide a mechanism by which the environmental impacts of, or services provided by plantations may influence plantation economics.

Some schemes trading in ecosystem services may add to the revenue streams of plantation growers. Climate change, related to anthropogenic increases in the concentration of atmospheric CO_2 and other greenhouse gasses is a significant global issue (Watson *et al.* 2000). The global community has attempted to limit the increase in the atmospheric concentration of greenhouse gasses though the Framework Convention on Climate Change and its subsidiary agreement, the

Kyoto Protocol (Stavins 2004). The aim of the Kyoto Protocol is to reduce greenhouse gas emissions to 95% of the 1990 level within the commitment period of 2008-2012. The flexibility mechanisms built into the Kyoto Protocol allow for emissions trading as a means to achieve the goal of reducing CO_2 emissions from anthropogenic activities (Goldemberg 2005). Article 3 of the Kyoto Protocol to the United Nations Framework Convention on Climate Change makes provision to take afforestation, reforestation, deforestation, and land use change activities into account when calculating carbon emissions (Watson *et al.* 2000). Two forms of carbon may be traded: (i) greenhouse gas emission allowances, where allowances are allocated under existing or upcoming cap-and-trade regimes, and (ii) project-based emission reduction transactions, where a buyer purchases emission reductions from a project which reduces greenhouse gases emissions compared with what would have happened otherwise (Lecocq 2004). Plantation forestry operations could take advantage of trade in the latter. A synthesis of several studies estimated the cost of forest based carbon sequestration to be within the range of US$7.50 to US$22.50 per metric tonne of CO_2 sequestered (Stavins and Richards 2005).

If the Australian Government were to ratify the Kyoto Protocol, much of the Australian *E. globulus* plantation estate established on land previously cleared for agriculture would qualify to sequester CO_2 (Watson *et al.* 2000). Even without the numerical requirements for the Kyoto Protocol of a minimum of 55 nations representing 55% of industrialised worlds 1990 CO_2 emissions being met in November 2004, and despite criticisms that the effect of the Kyoto Protocol on climate change will be trivial to non-existent (Stavins 2004), a considerable trade in non-Kyoto compliant carbon had already been established in 2004 (Lecocq

2004). In 2003, the biomass carbon equivalent of one tonne of CO_2 traded for between US$5, and US$12 $t^{-1}CO_2e$ (Lecocq 2004).

The contribution of genetic improvement to increasing the ability of plantations to sequester CO_2 depends on the ability of tree improvement to increase biomass production (including the extent of deployment of genetically improved stock), and the nature of genetic improvement. The net sequestration in a plantation will be the sum of changes in the stocks of carbon held in pools in the soil and the above- and below-ground biomass. While the soil carbon pool is usually larger than that of the living biomass (Malhi *et al.* 1999; Brand *et al.* 2000), carbon storage in a plantation system is largely associated with accumulation in woody biomass (above- and below-ground biomass, including litter) production (Madeira *et al.* 2002). Therefore the increase in carbon in *Eucalyptus globulus* plantations is proportional to biomass production (Madeira *et al.* 2002). Where process based models or allometric equations are used to calculate biomass in *E. globulus* plantations there will be significant differences between stands in the amount of carbon held (Brand *et al.* 2000).

It has been demonstrated that selection for improved volume production would increase the amount of CO_2 sequestered in planted pine forests in New Zealand (Jayawickrama 2001). Genetic improvement in the form of provenance selection and breeding can increase the productivity of *Eucalyptus* plantations (Pallett and Sale 2004). Borralho *et al.* (1992) estimated gain in dry matter production attributable to tree improvement activities in *E. globulus* to range from 20 to 47% in Portugal. Increased harvest biomass will increase standing plantation biomass, but the precise relationship between harvest and total plantation biomass is not clear. Genotype, survival, tree age, irrigation and nutrient status all affect biomass

(and therefore carbon) partitioning (see Beets and Whitehead 1996; Bernardo *et al.* 1998; Misra *et al.* 1998; Reed and Tomé 1998; Pate and Arthur 2000). Silvicultural practices such as coppicing will alter biomass and carbon accumulation in plantations, and delay deployment of genetic gain into plantations. In a coppice crop managed for pulpwood production most of the root biomass is maintained across two rotations, and there is likely to be a build up of biomass in litter due to harvesting of the first rotation and intense thinning of the coppice. Increasing the percentage of the harvested estate coppiced had a small positive impact on the total carbon accumulation (2% of total variation, Table 14) in the *E. globulus* plantation estate in the sensitivity analysis presented in Chapter 5. A longer timespan would have to be investigated to obtain an insight on the general effect of extensive use of coppice crops on the carbon storage capacity of *E. globulus* plantations.

Consideration of a system where revenues for carbon sequestration were directly dependant upon biomass production in a plantation, allowed assessment of the impact of any potential revenue from carbon sequestration on economic breeding objectives for the genetic improvement of *E. globulus* (Chapter 5). The revenue calculated for carbon sequestration in Chapter 5 did not take into account emissions from the use of fossil fuels or soil disturbance in forestry operations, or the implementation costs of a carbon sequestration program. Implementation costs can be significant, including, for example, marketing the program, establishing the conditions for payments, negotiating contracts, processing claims for subsidies, assessing tax liabilities, and monitoring the compliance and performance of landowners with respect to carbon sequestration practices or quantities (Stavins and Richards 2005).

The correlated response of breeding objectives with and without revenues from plantation based carbon sequestration was 0.93 (Table 13). Where economic breeding objectives are based on maximizing NPV by increasing biomass production, the inclusion of carbon revenues in economic breeding objectives will provide no significant gains in NPV. Changes in vegetation biomass alone do not provide a complete indicator of net influence of forest sector activities. While carbon stocks in forest products appear to be small relative to forest biomass and soil pools, they can offset a significant proportion of carbon emissions from the forestry sector (Apps *et al.* 1999) and should be considered when calculating the net carbon balance of forestry activities (Apps *et al.* 1999; Côté *et al.* 2002). Carbon in forest products will not be considered under the terms of the Kyoto Protocol in the first commitment period (2008-2012, Watson *et al.* 2000). A further commitment period is envisaged following 2012 (Goldemberg 2005), and it is possible that carbon in forest products will be considered in sequestration models at that time (Watson *et al.* 2000; Pingoud and Lehtilä 2002). Breeding for either solid wood products or an economic breeding objective for the production of paper (as suggested by Whiteman *et al.* 1996; Potts 2004; and Burley and Kanowski 2005) may emphasise wood quality or fibre characteristics, potentially moving the focus away from biomass production in tree improvement. Incorporation of forest products in models of carbon sequestration, and widening economic breeding objectives to include solid wood, or pulp and paper quality may change the influence revenues from carbon sequestration have on breeding objectives.

6.3 In Summary

This thesis reports some initial estimates of the success of regeneration, and the genetic control of coppicing in *E. globulus* in Australia (Chapter 3). The subraces of commercial interest appear to differ widely in their ability to regenerate through coppice, and therefore there may be noticeable differences between plantations in the success of coppice crops depending on the genetic origin of the planting stock. The heritability of coppice production within subraces was low but significant, and a highly significant genetic correlation with seedling stem diameter in a multi-trial analysis suggests a mechanism by which selection may alter coppicing ability at the population level. However, there are currently no economic incentives to use selection to alter the potential of pulpwood plantation stock. In using the coppice system a grower forgoes available genetic gain and incurs the costs involved with managing a coppice crop. The cash-flow analysis presented in Chapter 4 suggested that an increase in biomass production of ~15% through provenance selection and breeding would make a second rotation seedling crop economically competitive with a coppice crop. This assessment required modelling the costs and incomes of the plantation production system across two rotations.

In order to consider the impact of potential revenue from plantation based carbon sequestration the production system model was extended to cover 35 years from 1990 to 2025, revenues from the trade of CO_2 sequestered in planted forests (as defined under the Kyoto Protocol) were integrated (Chapter 5). Using this model, it was suggested that revenues from the trade of sequestered CO_2 would have no significant impact on the economic weights for harvest volume and basic density in a breeding objective designed to maximise dry matter production from

plantations. However, inclusion in the model of processing to pulp and paper, and carbon stored in forest products might give a different result.

The long timescales involved in tree improvement mean that breeding programs must be flexible and able to respond to possible future shifts in plantation use (Namkoong 1998; Greaves *et al.* 2004a; Burley and Kanowski 2005). Most of the Australian *E. globulus* plantation estate is likely to be utilised for pulpwood. However, it is possible to produce other timber products from plantation grown *E. globulus*. Changes in the availability or marketability of native forest timber may mean that timber products other than pulpwood are sourced from plantations. Just as the expected products from plantation forests may change, so may the broader expectations of plantation forests. However, the role of plantations in providing ecosystem services (such as carbon sequestration), appears unlikely to impact on the goals of tree improvement while the cash value of those ecosystem services is small compared to wood revenues, and spread across rotations. The work presented in this thesis is an attempt to assess the potential impact of some of these broader issues in terms of the genetic material in the ground and economic impacts relating to the genetic improvement of *E. globulus* as a plantation species.

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Appendices

Conference posters presented

Whittock SP, Apiolaza LA, Potts BM. 2001. Breeding for sustainability in *Eucalyptus globulus*. Proceedings of IUFRO Symposium: "Developing the Eucalypt of the Future". 10-15 September, Valdivia, Chile.

University of Tasmania

Breeding for sustainability in *Eucalyptus globulus*

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A SPIRT funded PhD project with the Southern Tree Breeding Association

1 Current breeding objectives aim to optimise the economics of growing *E. globulus* for pulp and paper production

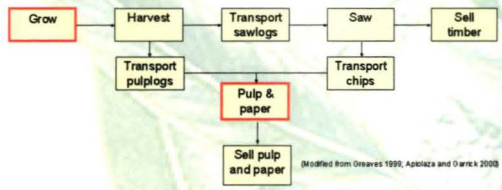

Fig. 1 The industrial system
The aspects of the system that are most heavily influenced by genetic variation are growth and the production of pulp and paper. These components of the system are also the most easily targeted when considering the possibilities for breeding for sustainability.

2 What is sustainability ?

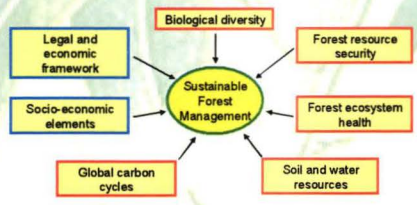

Fig. 2 Summary of the criteria for SFM produced in the Montréal Process.

Sustainability is about providing future generations with an environment that has the same or greater potential than the one in which we exist. The Montreal Process produced seven criteria for sustainable forest management (SFM). Breeding can contribute to the criteria highlighted in red: the conservation of biological diversity; the maintenance of forest resource security, maintenance and enhancement of forest ecosystem health, the conservation of soil and water resources and maybe the maintenance of the contribution of forests global carbon cycles.

3 Breeding can impact on sustainability by

- **manipulating genetic diversity**
  - within plantations
  - conservation of the native gene pool
- **reducing the risk of genetic pollution**
  - reduce reproductive potential of plantation stock
- **reducing the need for pesticides**
  - through minimising susceptibility to pests and diseases
- **reducing environmental impacts from the pulp process**
  - manipulating the chemical composition of wood
- **reducing site degradation**
  - minimise erosion at rotation
  - minimise nutrient demands on the site

Breeding can contribute to sustainability in areas where genetics affects both the industrial system and the environment.

Quantitative genetics and economic analysis can provide insights into the trade off between short-term gain and long-term sustainability

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University of Tasmania

When to replant: genetics and economics of coppicing *Eucalyptus globulus*

CRC-SPF

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Part of a SPIRT funded PhD project with the Southern Tree Breeding Association

1. At what level of genetic gain are improved seedlings economically preferable to coppice?

Growers of *E. globulus* pulpwood can proceed with the second rotation on a site either by replanting seedlings, or by coppicing the established trees. Managing coppice has lower costs than replanting. But genetic gain in seedlings can compensate for the additional cost of replanting.

2. A spreadsheet model was used to investigate the financial costs and benefits (Net Present Value) associated with coppice and seedling crops in the second rotation.

Eucalyptus globulus seedlings

Eucalyptus globulus stump coppice

Seedlings ~ $1000/hectare

- Site preparation
- Stump control
- Seedlings
- Planting
- Weed control

Approximate cost of management

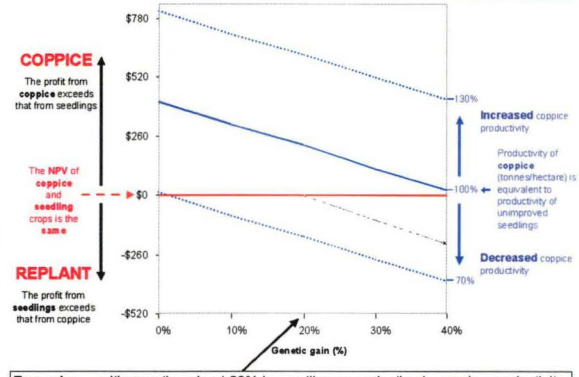
Coppice ~ $600/hectare

- Pruning / thinning

Assumptions:

- Base values: MAI (25m³/ha.yr), rotation length (10 years), basic density (440kg/m³), and stumpage ($23/tonne) are the same in both coppice and seedling crops.
- Genetic gain comprises improvements in volume production and basic density at a ratio of approximately 5:1 respectively.

Note: The model allows other scenarios to be investigated. The results presented here are specific to the assumptions given, and should not be taken out of context.



Example: with genetic gain at 20% in seedlings, a reduction in coppice productivity of ~17% (relative to unimproved seedlings) is necessary before improved seedlings will be more profitable the coppice

3. Increasing the level of genetic gain decreases the difference in NPV between seedlings and coppice in the second rotation.

Coppice when:

- coppice productivity is equal to or greater than an unimproved seedling crop (blue line in figure)
- low levels of genetic gain

Replant when:

- high stump mortality
- high levels of genetic gain

Other Considerations:

- risks and limitations of each system
- site environment
- end use of the crop.

*The authors would like to acknowledge the co-operation of **WA Plantation Resources (WAPRes)**, especially **Simon Hunter**, in the development of this project.*

Whittock SP, Apiolaza LA, Greaves BL. 2003. An economic assessment of genetic gain and coppice productivity in second rotation plantations. XIX International Congress of Genetics. Melbourne, Victoria. 6-11 July 2003.

University of Tasmania

AN ECONOMIC ASSESSMENT OF GENETIC GAIN AND COPPICE PRODUCTIVITY IN SECOND ROTATION PLANTATIONS

Co-operative Research Centre for Sustainable Production Forestry

Simon Whittock, Bruce Greaves and Luis Apiolaza

School of Plant Science and CRC for Sustainable Production Forestry
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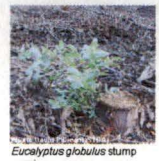
1. What level of genetic gain is required in seedlings to compensate for the additional expense of replanting?

- There are two choices for the re-establishment of *E. globulus* plantations in the second rotation
- Coppice management is less expensive than re-establishing seedlings on a site.
- Genetic gain will increase the value of a second rotation seedling crop.

2. The Model

- The values of coppice and seedling crops were compared using Net Present Value (NPV)
- Variables: mean annual increment (20m³/ha.yr), rotation length (10 years), basic density (530kg/m³), and price ($115/Tonne delivered), Discount rate (7%).
- Changes in basic density and volume production contribute to genetic gain, which is an increase in dry matter production from rotation 1 to rotation 2 due to provenance selection and breeding.

3. The result



Eucalyptus globulus stump coppice

Eucalyptus globulus seedlings

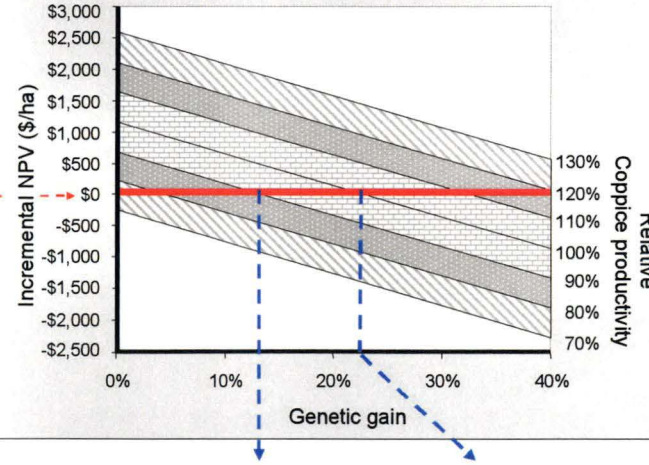
COPPICE

The value of **coppice** exceeds that of seedlings

The **value** of **coppice** and **seedling** crops is the **same**

The value of **seedlings** exceeds that of coppice

REPLANT



4. Summary

High productivity, high available genetic gain, and high stump mortality will favour replanting, but controlling stump coppice is vital for successfully replanting a site.

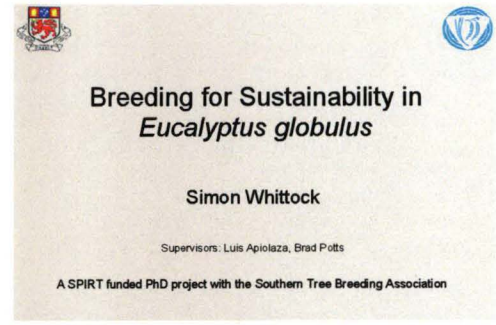
Genetic gain above **~13%** will favour seedlings where coppice productivity is equivalent to 90% of the original seedling crop.

Genetic gain above **~22%** will favour seedlings where a coppice crop produces yield equivalent to the original seedling crop.

This work was supported by SPIRT grant with the Southern Tree Breeding Association (STBA) and the Australian Research Council.

Oral presentations

Whittock SP, Apiolaza LA, Potts BM. 2001. Breeding for sustainability in *Eucalyptus globulus*. Introductory Ph.D. Seminar. School of Plant Science, Hobart, Tasmania. 17 August 2001.



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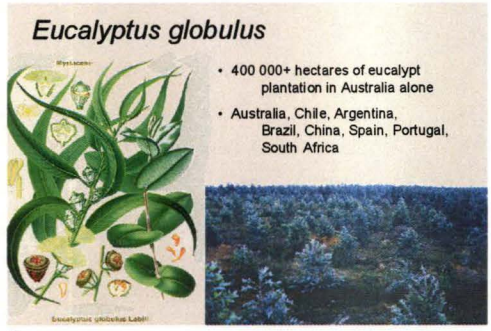

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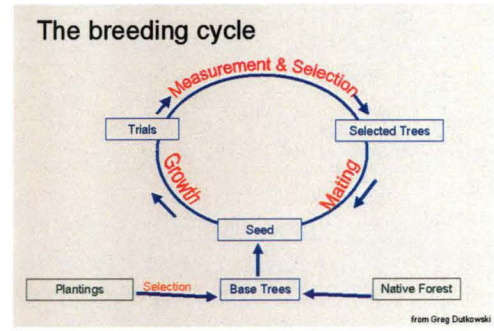

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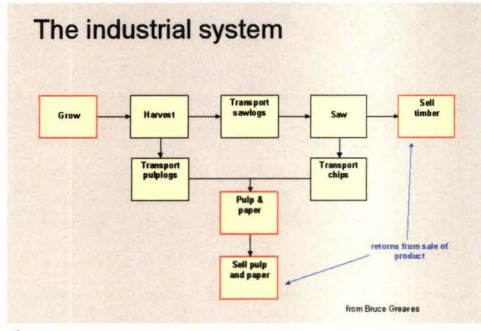

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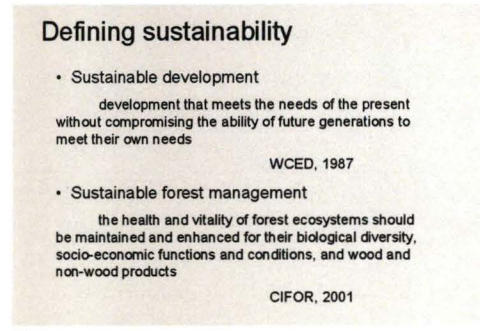

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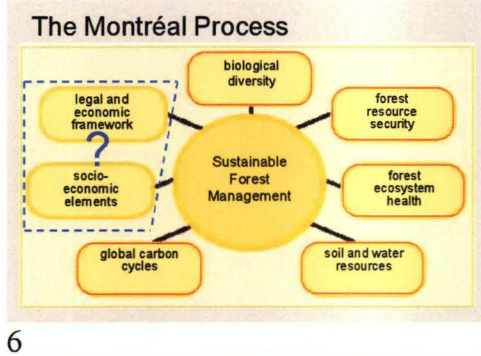

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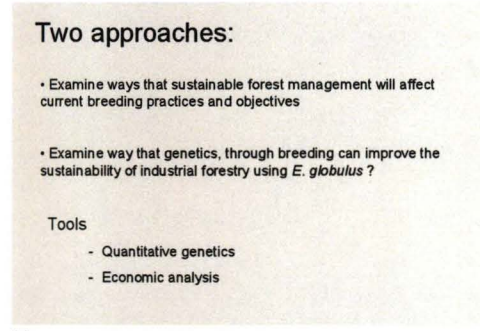

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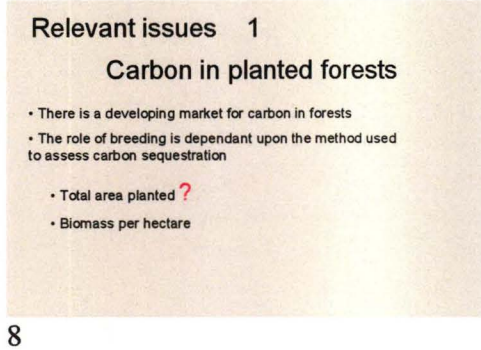

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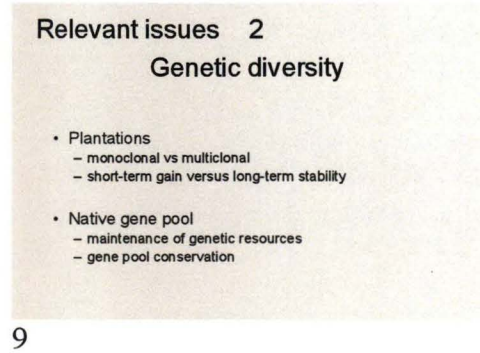
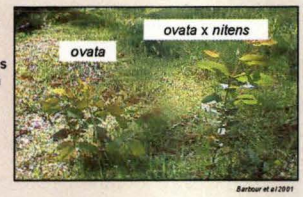


9

Relevant issues 3
Genetic pollution

- Eucalypt species known to hybridise naturally
- Plantations may serve as a source of exotic pollen
- Wildlings



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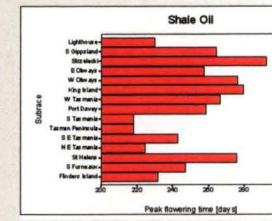
Relevant issues 3
Genetic pollution

- Flowering time
- Flowering precocity
- Flower abundance

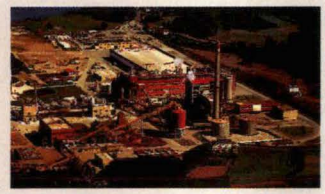


Luis Apiolaza

11

Relevant issues 4
Industrial pollution

- Plantations:
  - chemicals
- Processing:
  - emissions, chemicals, energy

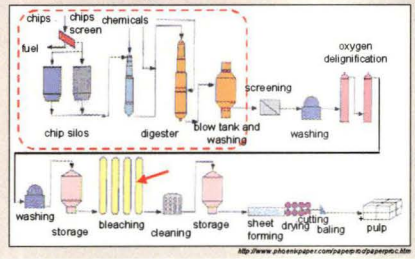


12

Breeding for pest and disease resistance

13

Relevant issues: Industrial pollution
Pulp production



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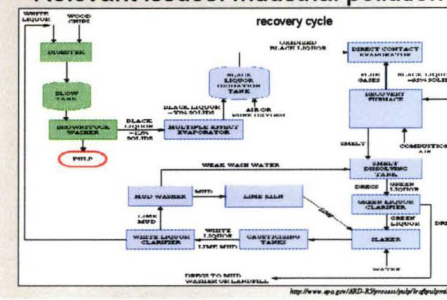
Relevant issues: Industrial pollution



15

Relevant issues 5
site degradation

- Soil disturbance
- Nutrient export
- Erosion

16

Coppicing

- Economic analysis
- Genetic parameters
- Gunns Massy Greene Trial
  - -Established 1989
  - -CSIRO seed collection
  - -500+ families
  - -Felled 1998 (9 yr old)

Traits
- coppice (p/a)
- coppice height
- coppice stems
- dbh 8yrs
- tree height 4yrs

17

Coppicing

- Variation between populations

	F	Pr>F
coppice (p/a)	2.4	**
mean coppice height	1.2	NS
coppice stems	5.7	***

- Variation within populations (heritability)

	h^2	t	Pr>T
coppice (p/a)	0.05	2.26	*
mean coppice height	0.16	3.77	***
coppice stems	0.17	3.84	***
dbh (8yrs)	0.33	8.98	***
tree height (4yrs)	0.34	9.83	***

18

Summary

- Breeding can contribute to sustainability in areas where genetics affects both the industrial system and the environment
  - Carbon
  - Genetic diversity
  - Genetic pollution
  - Industrial pollution
  - Plantation site degradation
- Trade off between short term productivity and sustainability

19

Whittock SP, Greaves BL, Apiolaza LA. 2003. 2nd rotation: seedlings and genetic gain, or coppice? Presentation for Great Southern Plantations. Albany, Western Australia 21 January 2003.

2nd Rotation:

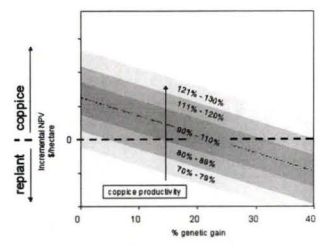
Seedlings and genetic gain, or coppice?

Simon Whittock, Bruce Greaves and Luis Apiolaza

With help from Simon Hunter (WAPRes) and David Pilbeam (STBA)

1

The output



2

System

1st Rotation - unimproved seedlings

2nd Rotation - improved seedlings after a fallow period (up to 1 year), or

- thinned coppice crop.

Comparison made after 2 rotations.

Incremental NPV

NPV(Coppice) – NPV(Seeding)

NPV = PV(Income) – PV(Costs)

Discount rate

3

First Rotation Income (Stumpage calculation)

$/ODT delivered

Basic Density

Harvest and transport

Yield (m^3/hectare)

MAI (m^3/hectare/year)

4

Second Rotation Income (Stumpage calculation)

Seedlings	Coppice
$/ODT delivered	$/ODT delivered
Basic Density + gain	Basic Density – decrease
Harvest and transport	Harvest and transport + Penalty
Yield (m^3/hectare)	Yield (m^3/hectare) ± coppice productivity
MAI (m^3/hectare/year) + gain	MAI (m^3/hectare/year)

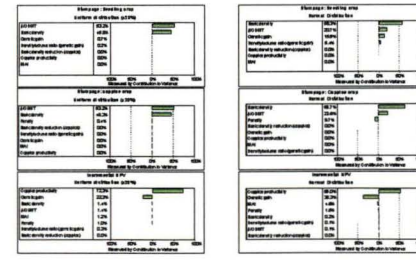
5

Costs ($/ha)

Seedlings		Coppice	
Administration		Administration	
Preparation		Preparation	
Establishment		1st year	
1st year	Pest and weed control	2nd year	Thinning
2nd year		3rd year	
3rd year		annual	
annual			
~$1000/ha		~$500/ha	

6

Sensitivity Analysis



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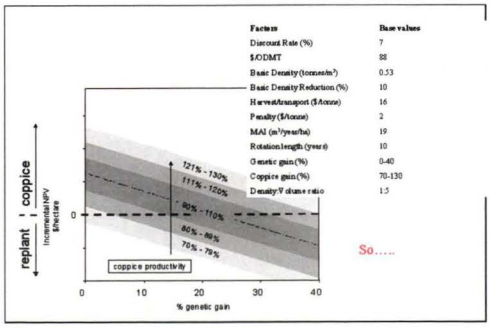


Factors	Base values
Discount Rate (%)	7
$/ODMT	88
Basic Density (tonnes/m^3)	0.53
Basic Density Reduction (%)	10
Harvest/transport ($/tonne)	16
Penalty ($/tonne)	2
MAI (m^3/year/ha)	19
Rotation length (years)	10
Genetic gain (%)	0-40
Coppice gain (%)	70-130
Density/Volume ratio	1:5

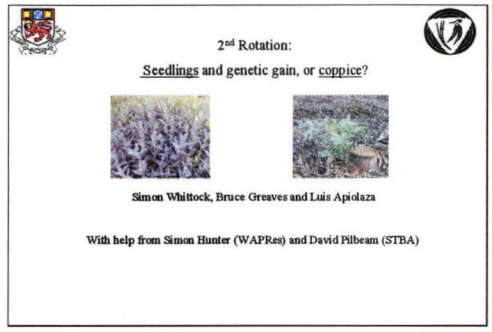
So…..

8

Know your site

Whittock SP, Greaves BL, Apiolaza LA. 2003. 2nd rotation: seedlings and genetic gain, or coppice? Presentation for W.A. Plantation Resources. Manjimup, Western Australia, 23 January 2003

Whittock SP, Greaves BL, Apiolaza LA. 2003. 2nd rotation: seedlings and genetic gain, or coppice? Southern Tree Breeding Association Technical Advisory Committee Meeting. Arthur Rylah Institute, Heidelberg, Victoria. 13-15 May 2003.



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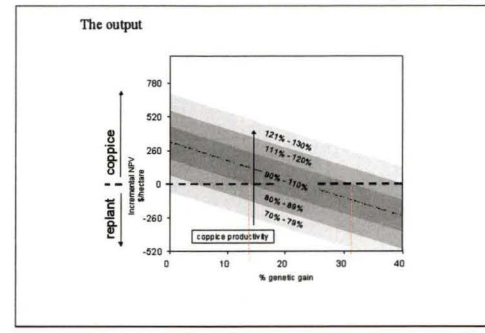

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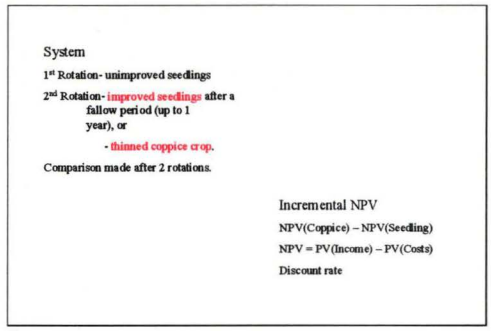

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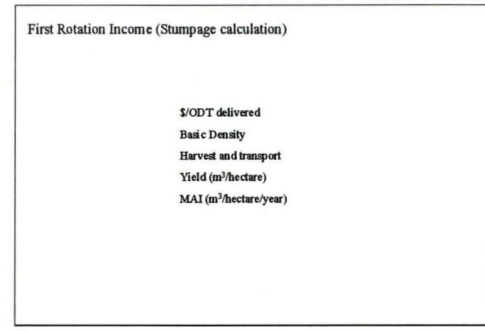

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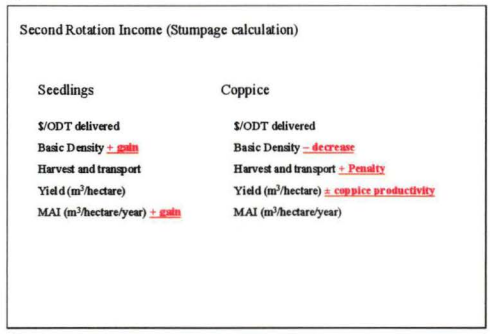

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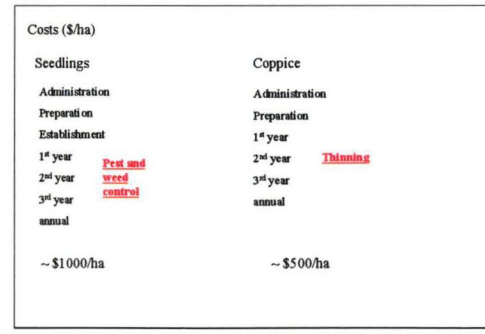

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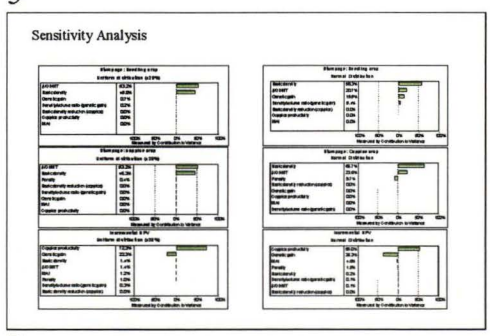

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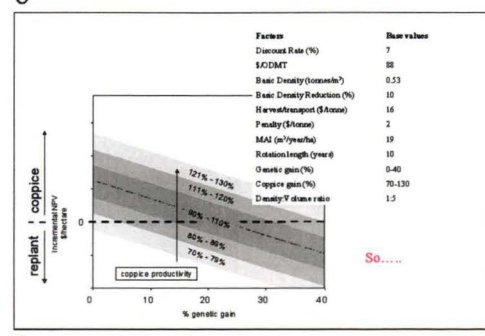


8

Whittock SP, Greaves BL, Dutkowski GW, Hunter S, Apiolaza LA. 2004. The incremental value of dry matter gains as influenced by propagule cost. Presentation at workshop *Benchmarking clonal propagation for the blue gum plantation industry.* Mt Gambier, South Australia. 8-12 March 2004.

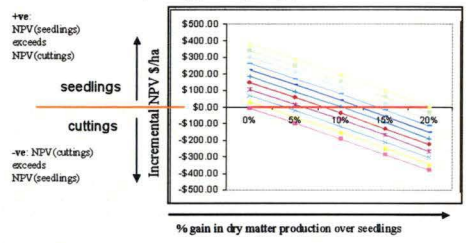
The incremental value of dry matter gains as influenced by propagule cost

Simon Whittock, Bruce Greaves, Greg Dutkowski *School of Plant Science and University of Tasmania*
Simon Hunter, *WA Plantation Resources*
Luis Apiolaza, *Forestry Tasmania*

1

Incremental Net Present Value

$iNPV/ha = $/ha(seedlings) - $/ha(cuttings)



2

Incremental Net Present Value

Two Systems: Dry matter production

1

- 10 year seedling rotation
- MAI 25m³/ha/yr
- Basic density 530kg/m³
- $0.30/seedling ready to plant

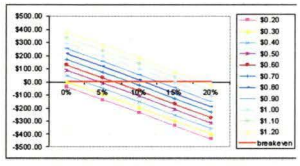
2

- 10 year rotation
- Increase in dry matter production from 0 – 20% over system 1
- Costs from $0.20 to $1.20 per propagule ready to plant

3

Incremental Net Present Value

$iNPV/ha = $NPV/ha(seedlings) - $NPV/ha(cuttings)



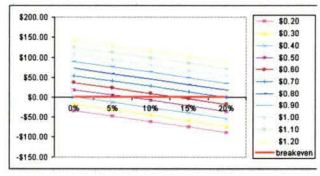
Seedlings $0.30 each
MAI 25m³/ha/yr
Basic Density 530kg/m³
Discount Rate 8%
Chip Price $94/ODMT
Harvest $16/green tonne
Rotation length 10 years
900 Stems/ha

Propagule costs can increase by Approximately $0.04 for every 1% increase in dry matter production.

4

Incremental Net Present Value

$iNPV/ha = $NPV/ha(seedlings) - $NPV/ha(cuttings)



Seedlings $0.40 each
MAI 25m³/ha/yr
Basic Density 530kg/m³
Discount Rate 8%
Chip Price $94/ODMT
Harvest $16/green tonne
Rotation length 10 years
1100 Stems/ha

5

Whittock SP, Apiolaza LA, Greaves BL, Dutkowski GW and Potts BM. 2004. Coppice, Carbon and Cash: second rotation *Eucalyptus globulus* pulpwood plantations. Final PhD seminar. School of Plant Science, University of Tasmania, Hobart, Tasmania. 17 September 2004.

Coppice, Carbon and Cash:

second rotation *Eucalyptus globulus* pulp-wood plantations

Simon Whittock

Supervisors:

Luis Apiolaza, Bruce Greaves, Greg Dutkowski and Brad Potts

1

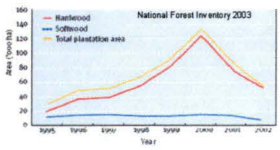
Eucalyptus globulus estate in Australia

- 21% of the total plantation estate
- ~350 000 ha in 2004
- Harvested on 10 year rotations for pulp-wood production

2

Most of the estate established since 1990

- Approaching harvest age
- Genetic improvement means that better stock is available for planting
- How to proceed in the second rotation?



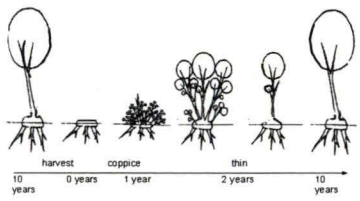
3

What are the issues?

- Clonal forestry
- Solid wood products
- Plantation water use
- Pests and diseases
- Social issues
- Marginal environments
- Biodiversity
- New sources of income: carbon sequestration
- Alternative silviculture: coppicing

4

The coppice system in pulp-wood plantations



5

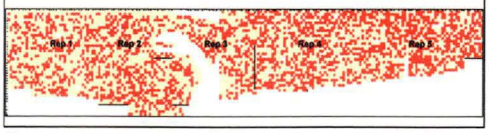
Research into coppicing

- Is there genetic variation in the production of coppice?
- Is coppicing predictable?
- Are there any relationships between coppicing and economic traits?
- Should you replant a second rotation site or use a coppice crop?

6

Massey Greene Field Trial

- NFP (now Gunns Ltd) 1989
- 21 subraces / 600 families / ~6000 trees
- Resolvable incomplete block design, 5 reps, 21 incomplete blocks with 2 trees per plot
- Measurement of selection traits
- Thinned to create a seed orchard at 8 years
- Coppice measured 14 months after felling



7

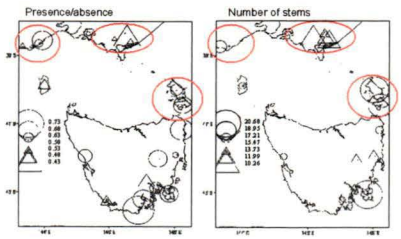
There is genetic variation

Mixed model analysis: replicate
subrace
incomplete block
family

	n	Environmental variation F rep	Prob	Between subraces F subrace	Prob	Within subraces h^2	t	Prob
Presence of coppice	3582	23.33	***	2.03	**	0.07	2.36	*
Height of coppice	2443	12.37	***	1.36	NS	0.16	3.58	***
Number of stems	2442	49.24	***	5.14	***	0.17	3.79	***

8

Subrace variation in coppice production



9

Coppicing is linked to lignotuber development

- Starch reserves
- Dormant meristems
- Develop in seedlings

10

Can coppicing be predicted?

- Field experiment: correlation with traits prior to felling (8 years)
  - Diameter
  - Bark thickness
- Pedigree links to a glasshouse trial
- Glasshouse:
  - Lignotuber development
  - Seedling growth

11

Genetic variation in seedling traits

Glasshouse trial established by Corinna Kelly
550 plants, 10 subraces, 87 families
19 randomised blocks
66 families in common

	n	Environmental variation F rep	Prob	Between subraces F subrace	Prob	Within subraces h^2	t	Prob
• Number of nodes with lignotubers	374	1.39	NS	4.83	***	0.31	2.67	**
• Stem diameter at the cotyledonary node	528	5.30	**	1.44	NS	0.46	3.30	**
• Lignotuber width	528	4.62	**	4.23	***	0.43	3.10	**
• Relative lignotuber size	528	1.62	*	9.78	***	0.51	3.38	***

12

Independent mechanisms operating in the production of coppice

Genetic correlations

		coppice presence/absence	
Field	diameter	0.61	***
	bark	0.33	**
Glasshouse	# lignotubers	0.66	*
	lignotuber width	0.89	**
	stem diameter	0.91	**

1. Vigour prior to felling
2. Number of seedling nodes with lignotubers
3. Stem diameter at the cotyledonary node of seedlings

Number of seedling nodes with lignotubers and the seedling stem diameter at the cotyledonary node are uncorrelated with **later age growth** and with **each other**.

13

Is coppicing related to economic traits?

- Volume growth: diameter
- Basic density: pilodyn penetration

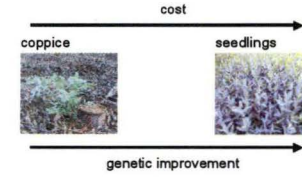
Genetic correlations

		coppice presence/absence
Field	diameter	0.61
	pilodyn	0.07

- Positive relationship between coppice and growth
- No relationship with basic density

14

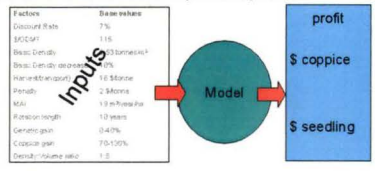
Is coppicing more profitable than replanting?



15

Cash-flow modelling:

- Account for all costs and incomes in production system



Sensitivity Analysis
- Likely range of answers
- Which assumptions are important

16

Cost: coppice is cheaper

Seedlings	Coppice
Administration	Administration
Site preparation	Site preparation
Establishment	1st year
1st year — Pest and weed control	2nd year — Thinning
2nd year	3rd year
3rd year	annual
annual	
~ $1000/ha	~ $500/ha

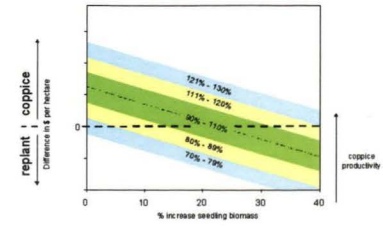
17

Income: wood chips for export

Seedlings		Coppice	
Basic Density	+ gain	Basic Density	– decrease
Harvest and transport		Harvest and transport	+ Penalty
Yield (cubic metres /hectare)	+ gain	Yield (cubic metres /hectare)	coppice productivity
$ per ton of wood chips		$ per ton of wood chips	

18

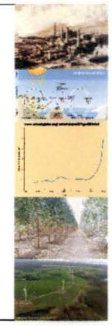
Biomass from new seedling crops must increase by 15%



19

Carbon credits

- Accounting based on the Kyoto system
- Carbon sequestered between 2008-2012
- Aforestation/Reforestation on land cleared before 1990
- 10% buffer (only 90% of carbon sequestered in eligible forests can be sold)



20

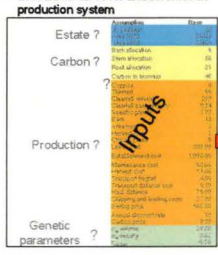
Will carbon revenues affect economic breeding objectives for *Eucalyptus globulus* plantations?

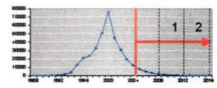
- How much CO_2 will be available for trade?
- What will the trade of CO_2 be worth?
- What is the correlation between breeding objectives ± carbon revenue?

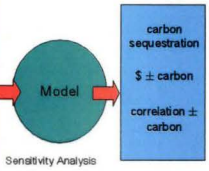
21

Cash-flow modelling:

- account for all costs and incomes in production system



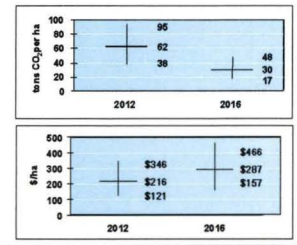




Sensitivity Analysis
- Likely range of answers
- Which assumptions are important

22

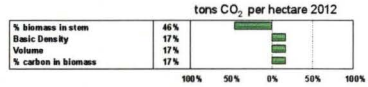
How much CO_2 can be traded, and what is its value?



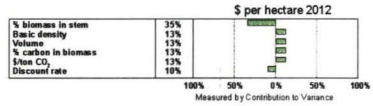
23

Which assumptions are important?

tons CO_2 per hectare 2012



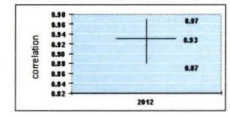
$ per hectare 2012

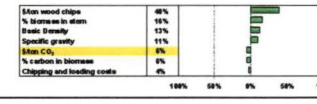


Measured by Contribution to Variance

24

What is the correlation between a traditional breeding objective and one including carbon revenues?

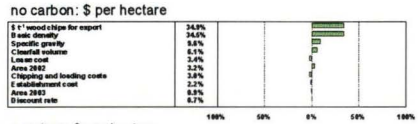




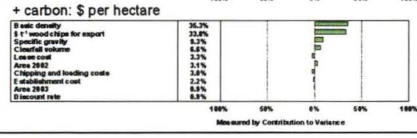
25

Why is the correlation so high?

no carbon: $ per hectare



+ carbon: $ per hectare



Measured by Contribution to Variance

26

Carbon revenue does not affect breeding objectives

- 62 t CO_2 ha^{-1}
- \$216 ha^{-1}
- correlation between breeding objectives is 0.93

27

Overall conclusions

- Genetic variation in coppicing
- Production model allowing comparison used and highlights gaps in knowledge
- $ carbon: limited impact on breeding but could impact on plantation profitability in marginal areas
- Will it have any impact globally?

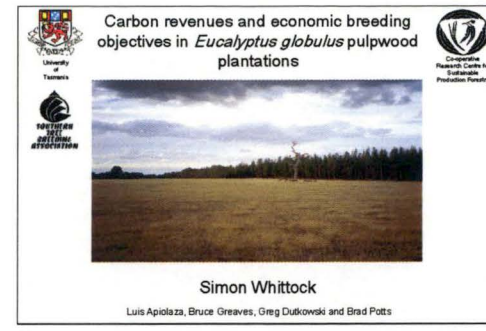
28

Acknowledgements

- STBA: Tony McRae
  David Pilbeam
  Peter Cunningham
- WAPRes: Simon Hunter
- Martin Lavery
- Corinna Kelly
- Paul Tilyard

29

Whittock SP, Apiolaza LA, Dutkowski GW, Greaves BL, Potts BM. 2004. Carbon revenues and economic breeding objectives in *Eucalyptus globulus* pulpwood plantations. *In* Proceedings of the IUFRO conference "*Eucalyptus* in a changing world", Aveiro, Portugal. Eds NMG Borralho, JS Pereira, C Marques, J Coutinho, M Madeira and M Tomé. RAIZ, Instituto Investigação da Floresta e Papel, Portugal. 11-15 October, 2004. p 146-150.



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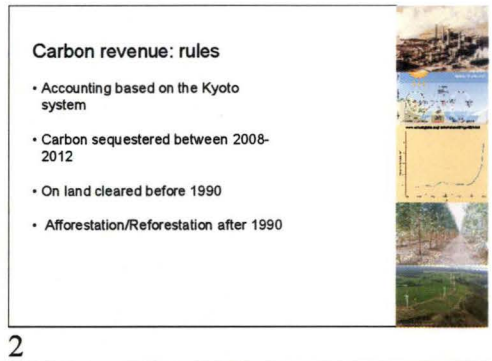

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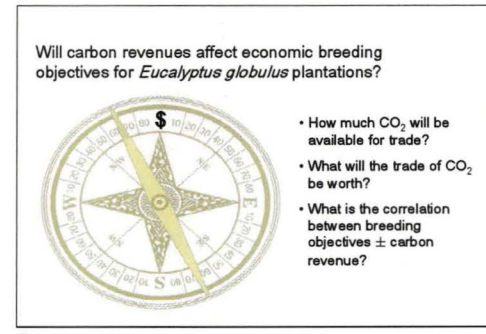

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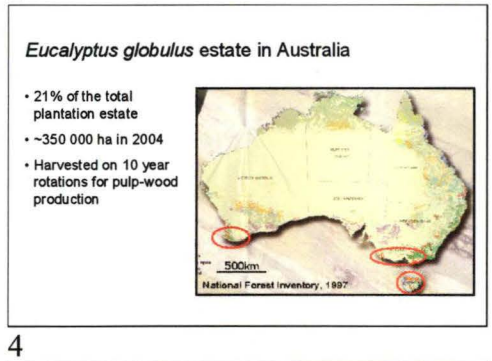

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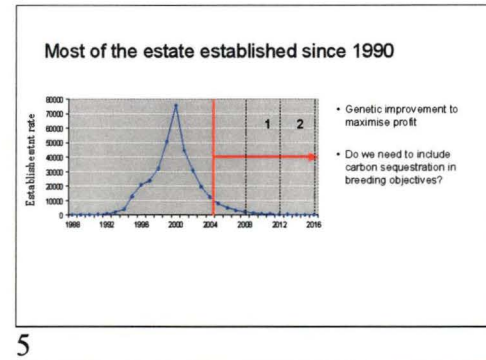

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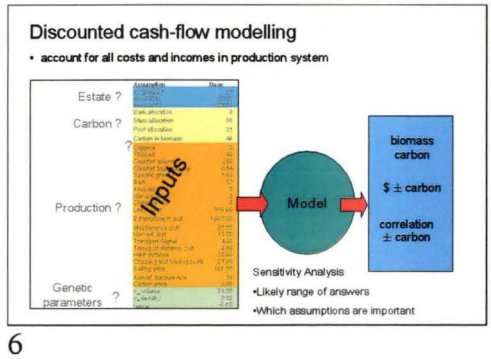

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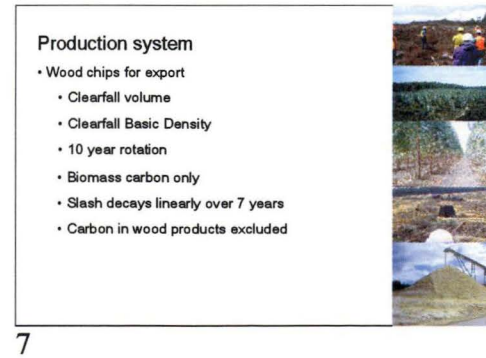
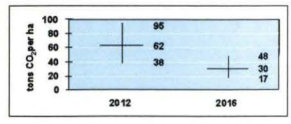


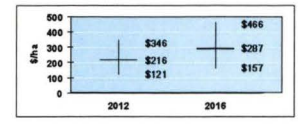
7

62 tons CO_2/ha tradable in 2012



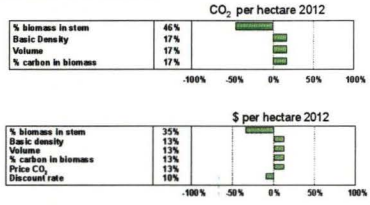
8

$216/ha from trade of carbon in 2012



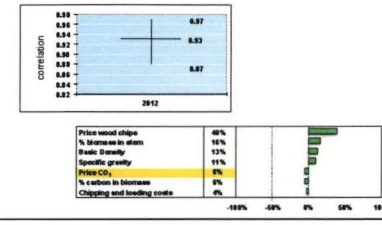
9

Important assumptions: contribution to variance



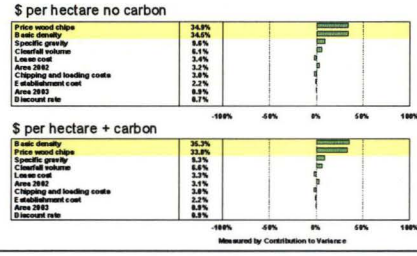
10

What is the correlation between breeding objectives?



11

Why is the correlation so high?



12

Carbon revenue does not affect breeding objectives

- 62 t CO_2 ha^{-1}
- \$216 ha^{-1}
- correlation between breeding objectives is 0.93
- \$ carbon: limited impact on breeding but could impact on plantation profitability in marginal areas
- Will carbon sequestration in terrestrial ecosystems have any impact on atmospheric CO_2?

13

Acknowledgements

- STBA: Tony McRae
  David Pilbeam
  Peter Cunningham

14

Whittock SP, Apiolaza LA, Greaves BL, Dutkowski GW, Potts BM. 2004. Coppice, Carbon and Cash: second rotation *Eucalyptus globulus* pulpwood plantations. Presentation to STBA *E. globulus* Breeding Strategy Review. Albany, Western Australia. 22-24 February 2005.

Coppice, Carbon and Cash:
second rotation *Eucalyptus globulus* pulp-wood plantations

Simon Whittock

Luis Apiolaza, Bruce Greaves, Greg Dutkowski and Brad Potts

1

What are the issues?

- Clonal forestry
- Solid wood products
- Plantation water use
- Pests and diseases
- Social issues
- Marginal environments
- Biodiversity
- New sources of income: carbon sequestration
- Alternative silviculture: coppicing

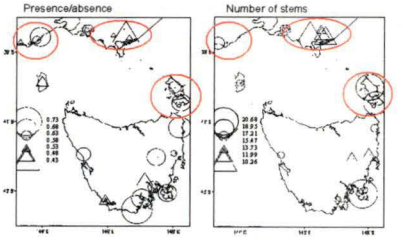
2

Research into coppicing

- Is there genetic variation in the production of coppice?
- Is coppicing predictable?
- Are there any relationships between coppicing and economic traits?
- Should you replant a second rotation site or use a coppice crop?

3

Subrace variation in coppice production



4

Is coppicing related to economic traits?

- Volume growth: diameter
- Basic density: pilodyn penetration

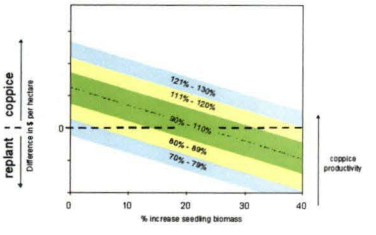
Genetic correlations — coppice presence/absence

Field	diameter	0.61
	pilodyn	0.07

- Positive relationship between coppice and growth
- No relationship with basic density

5

Biomass from new seedling crops must increase by 15%



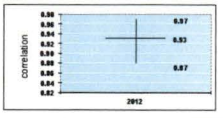
6

Will carbon revenues affect economic breeding objectives for *Eucalyptus globulus* plantations?

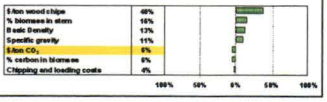
- How much CO_2 will be available for trade?
- What will the trade of CO_2 be worth?
- What is the correlation between breeding objectives ± carbon revenue?

7

What is the correlation between a traditional breeding objective and one including carbon revenues?



62t ha^{-1} CO_2 worth $216 ha^{-1}



8

Overall conclusions relevant to the improvement of *E. globulus*

- Genetic variation in coppicing – only one site, knowledge is increasing
- Production model – decision making
- $ carbon: limited impact on breeding but could impact on plantation profitability in marginal areas
- Including environmental credits in breeding objectives will be difficult unless the breeding enables access to new environments

9

Conference papers

Whittock SP, Apiolaza LA, Dutkowski GW, Greaves BL, Potts BM. 2004. Carbon revenues and economic breeding objectives in *Eucalyptus globulus* pulpwood plantations. *In* Proceedings of the IUFRO conference "*Eucalyptus* in a changing world", Aveiro, Portugal. Eds NMG Borralho, JS Pereira, C Marques, J Coutinho, M Madeira and M Tomé. RAIZ, Instituto Investigação da Floresta e Papel, Portugal. 11-15 October, 2004. p 146-150.

CARBON REVENUES AND ECONOMIC BREEDING OBJECTIVES IN *EUCALYPTUS GLOBULUS* PULPWOOD PLANTATIONS

Simon P. Whittock[1], Luis A. Apiolaza[2], Gregory W. Dutkowski[1], Bruce L. Greaves[1], and Bradley M. Potts[1]

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[2] Forestry Tasmania, GPO Box 207, Hobart, Tasmania 7001, Australia

ABSTRACT

This paper investigates the integration of carbon revenues into production system models used to define economic breeding objectives for the genetic improvement of *Eucalyptus globulus* pulp-wood plantations. A model was used to estimate that carbon dioxide equivalent accumulation in biomass in the Australian *Eucalyptus globulus* plantation estate established between 2004 and 2012 was in the order of ~146 t CO_2e ha^{-1}, of which 62 t CO_2e ha^{-1} were tradable in 2012 and a further 30 t CO_2e ha^{-1} were tradable in 2016. By considering a system where revenues for carbon sequestration are directly dependant upon biomass production in a plantation, it was possible to determine whether economic breeding objectives for the genetic improvement of *E. globulus* will be sensitive to the revenue from carbon sequestration. The correlated response of breeding objectives with and without carbon (ΔcG_{H_1}) never fell below 0.86 in sensitivity analysis, and the mean was 0.93. As such, where economic breeding objectives for the genetic improvement of *Eucalyptus globulus* for pulpwood plantations are based on maximizing NPV by increasing biomass production, the consideration of carbon in economic breeding objectives will provide no significant gains in NPV.

INTRODUCTION

Definition of an economic breeding objective is accomplished by (1): specifying the production system, then (2): identifying sources of income and costs, (3): indentifying biological traits that influence income and costs, and (4): determination of the economic value or weight of each trait in the objective (Ponzoni 1986). Economic breeding objectives for the production of pulpwood or kraft pulp from plantation grown *E. globulus* have been defined previously (Borralho *et al.* 1993; Greaves *et al.* 1997). Both authors identified the same three biological traits (clearfall volume, wood basic density and kraft pulp yield) as having the greatest economic value. The recent advent of carbon dioxide (CO_2) trading schemes adds a source of income separate to the production of pulpwood to the plantation system. Such schemes allow a grower to trade any permanent increase in the carbon density per hectare on their estate.

While most of the carbon in a forest is held below ground (Malhi *et al.* 1999), it has been shown that in a plantation system most of the change in carbon density per hectare is associated with changes in perennial woody biomass (Madeira *et al.* 2002). Therefore changes in the productivity of plantations will affect the amount of revenue achievable for carbon sequestration in that plantation.

There has been considerable effort expended on the genetic improvement of *E. globulus* for pulp-wood plantations (Volker and Orme 1988; Borralho *et al.* 1993; Greaves *et al.* 1997; Borralho and Dutkowski 1998; Harbard *et al.* 1999; Kerr *et al.* 2001), and it is expected that the use of improved genotypes will increase harvested volume and dry matter production. Increasing harvested volume and dry matter production through genetic improvement is likely to result in an increase in the amount of woody biomass per unit area of plantation, and therefore increase the amount of carbon held per hectare in a plantation (Jayawickrama 2001).

The most widely publicised carbon-trading scheme is that outlined in the Kyoto Protocol. This provides a mechanism for the trade of 90% of any increase in carbon density per hectare during a commitment period in forests established on land not forested prior to 1990 (Watson *et al.* 2000). The first commitment period is set down for the period 2008 and 2012 and further contiguous commitment periods are envisaged for the period following 2012 (ie. 2012 – 2016). To date, the published models used to describe *E. globulus* pulpwood plantation production systems in economic breeding objectives only consider costs and incomes within a single rotation. Long-term carbon sequestration in biomass and therefore carbon revenues, will be the result of multiple sites of different ages within an estate (Dean *et al.* 2004). Therefore, in order to assess the impact of carbon revenues on the economic breeding objectives for *E. globulus* pulpwood plantations, the breeding objective must be scaled up to include multiple sites at different stages within their rotations.

The current paper investigates the impact of carbon revenues from the first two commitment periods (2008 –2012 and 2012 – 2016) on the economic weights for clearfall volume and wood basic density, and the correlated response of breeding objectives including and excluding carbon revenues. Income was calculated based on the sale of woodchips for export from Australia, and carbon revenues were directly proportional to biomass accumulation in the plantation estate As such, carbon revenues calculated in this study are extremely sensitive to biomass production, and therefore, the sensitivity of the economic breeding objective to carbon revenues will probably be higher than would be expected in reality Therefore, if the carbon revenues in the scenario presented here do not have a large impact on the correlated response of the economic breeding objectives including and excluding carbon revenues, then the real effect of carbon revenues will be negligible

MATERIALS AND METHODS

Area planted, tree growth and silviculture. Planting figures from Australia's National Plantation Inventory (2003) were used to establish planting rates for the estate The rate of establishment of new *E. globulus* plantation areas between 2004 and 2016 was extrapolated from the NPI data, assuming that *E. globulus* made up 60% by area of all hardwood planting (National Forest Inventory 2004). A quadratic growth curve was assumed, as defined by clearfall merchantable volume at the end of a ten-year rotation. Whole tree growth was proportional to merchantable volume increment. Allocation of biomass between different tree components (roots, stem, branches, leaves, bark) followed that described by Madeira *et al.* (2002) for 6 year old *E. globulus* trees Allocation was assumed to remain unchanged over time. A 1-year fallow period was assumed between harvests and replanting of a site Estimates of the estate area occupied by plantations established between 2004 and 2016, total CO_2 equivalent (CO_2e) sequestration and CO_2e sequestration per hectare were obtained When coppice was used to produce the second rotation crop, the new stems began to grow immediately following harvest of the first rotation crop It was assumed that there was no stump mortality and that the initial growth was the same as in the first rotation crop Thinning of the coppice from between 10 and 20 stems per stump, to one or two stems per stump at the age of 2 years was assumed to remove ~60% (Table 1) of the living above ground biomass at that site. The remaining stems then grew at a rate that resulted in the same harvest volume as was obtained in the seedling rotation. The root biomass of a coppiced tree was maintained unchanged from the end of the seedling rotation, throughout the coppice rotation after which the stumps and roots decayed Biomass in harvest residue (harvested logs were assumed to be debarked on site), thinned material, stumps and roots, was assumed to decay linearly over a 7-year period (Watson *et al* 2000).

The production system. The production system modeled the export of *E. globulus* wood chips from Australia. The system used was similar to that described by Whittock *et al* (2004), but described only a single seedling derived rotation, and incorporated more detail of the transport and processing of roundwood Unlike the production systems described in Borralho *et al* (1993) and Greaves *et al.* (1997) conversion of woodchips to pulp was not considered. Costs for growing, harvesting, transport and chipping were included. Growing costs were proportional to the area planted, harvest costs proportional to clearfall volume and transport costs proportional to transport distance and harvest volume Harvest and chipping losses were accounted for. Revenue was earned for an oven dry metric ton of wood chips for export All costs and revenues were discounted to the present. The production system was used to define economic breeding objectives including and excluding carbon revenues The overall aim of the breeding objectives was to maximize the net present value (NPV) per hectare of growing *E globulus* in plantation The NPV of plantings between 2004 and 2012 (to the end of the first commitment period) was calculated over the period 2004 to 2021 so that the revenue from sold timber from all the plantings in the period 2004 – 2012 were considered. In the case of the second commitment period (2012-2016) NPV was calculated over the period 2004 – 2025 All costs and incomes were discounted to the present (2004). All costs and prices are presented in Australian dollars

Carbon revenues. Under the system outlined in the Kyoto Protocol the tradable unit of carbon is one metric ton of CO_2e Carbon was assumed to make up 46% of oven dry tree biomass (Pate and Arthur 2000) Every ton of biomass carbon is equivalent to 3 67 tons CO_2 (Watson *et al* 2000) Ninety percent of carbon sequestered in each commitment period (2008 – 2012 and 2012 – 2016) in forests established on land not forested prior to 1990 is eligible to be traded A base price of \$8 00 t^{-1} CO_2e was calculated by converting the prices in US dollars for Kyoto pre-compliant CO_2 sequestration given in Lecocq (2004) to Australian dollars Much of the Australian *E. globulus* plantation estate has been established on ex-pasture sites (Mendham *et al.* 2003), with the major expansion of the estate occurring after 1990 (National Forest Inventory 2003) Therefore, all new areas planted after 2004 were considered eligible to sequester carbon In keeping with the default IPCC approach, carbon in wood products was not considered, and all carbon in biomass sold was lost to the system immediately upon harvest (Watson *et al* 2000)

Table 1. Model base values, and minima and maxima for model variables in the sensitivity analysis of the estate model based production system

Assumption	Units	Base	Min	Max
E. globulus	% *E globulus*	60	48	72
Area 2002	area planted 2002	51026	39344	59016
Area 2003	area planted 2003	32601	28241	34517
Bark allocation	% bark in total biomass	8	6	10
Stem allocation	% stem in total biomass	56	45	67
Root allocation	% root in total biomass	21	17	25
Carbon in biomass	% carbon in total biomass	46	37	55
Coppice	% coppice	0	0	40
Thinned	% thinned	60	48	72
Clearfell volume	m^3 ha^{-1}	250	200	300
Clearfell basic density	t m^{-3}	0 54	0.43	0 64
Specific gravity	t m^{-3}	1 03	0.82	1 24
Bark	% havested	13	10	16
Area loss	%	3	2	4
Harvest loss	%	2	2	2
Chipping loss	%	5	4	6
Lease cost	\$ ha^{-1} a^{-1}	300.00	240 00	360 00
Establishment cost	\$ ha^{-1}	1,000 00	800.00	1200.00
Maintenance cost	\$ ha^{-1} yr^{-1}	80 00	64 00	96 00
Harvest cost	\$ m^{-3}	11 00	8.80	13.20
Transport flagfall	\$ t^{-1}	4 00	3.20	4 80
Transport distance cost	\$ t^{-1} km^{-1}	0.10	0 08	0 12
Haul distance	km	75 00	60 00	90.00
Chipping and loading costs	\$ t^{-1}	27.00	21.60	32 40
Selling price	\$ t^{-1}	168 00	134 40	201 60
Annual discount rate	% yr^{-1}	10	8	12
Carbon price	\$ t^{-1} CO_2e	8.00	6 40	9 60
σ_a volume	m^3	38 00	30 40	45 60
σ_a density	t m^{-3}	0 02	0 02	0.02
$r_{vol\ den}$		-0.10	-0 12	-0 08

Correlated response. Where two traits have a non-zero genetic correlation, selection on one trait will lead to a genetic change in the other (Weller 1994) Similarly, where traits in different economic breeding objectives have non-zero genetic correlations, selection on one objective will lead to a genetic change in the other For two breeding objectives the correlated response in objective 1 (H_1) when selection is based on an index derived to maximize response on breeding objective 2 (H_2) is calculated as the regression of H_1 on H_2 (eg Apiolaza and Garrick 2001)

$$\Delta cG_{H_1} = b_{H_1H_2}\Delta G_{H_2}$$
$$= \frac{\mathrm{Cov}(H_1,H_2)}{\mathrm{Var}(H_2)}\Delta G_{H_2}$$
$$= \boldsymbol{v}_1'\boldsymbol{G}\boldsymbol{w}\left(\boldsymbol{w}'\boldsymbol{G}\boldsymbol{w}\right)^{-1}\Delta G_{H_2}$$

where $\boldsymbol{v}_1$ and $\boldsymbol{w}$ are the vectors of economic weights for H_1 and H_2 respectively, $\boldsymbol{G}$ is the additive covariance matrix for objective traits and ΔG_{H_1} is the direct response for breeding objective H_1 The first breeding objective (H_1) contained two traits: harvest volume and basic density The second breeding objective (H_2) included the same two traits, but the revenues for carbon sequestration in the plantation estate altered the economic weights for volume and basic density

Sensitivity analysis. Sensitivity analysis consisted of Monte Carlo simulation of 100000 iterations varying the plantation estate parameters by ±20% (with an even distribution) using Crystal Ball® (Decisioneering). Minima and maxima for model variables in the sensitivity analysis are shown in Table 1. The ranges of forecasts between the 5th and 95th percentiles (the central 90% of all forecasts) are reported in Table 2 Sensitivities of forecasts to variation in model variables were calculated as a percentage of total variance in forecast values contributed by each assumption, but are not reported here.

RESULTS AND DISCUSSION

Estate and carbon revenue. It was estimated that biomass accumulation in forests established between 2004 and 2016 was equivalent to 45 t C ha^{-1} (Table 2) Long-term CO_2e sequestration in the biomass component of the Australian *E globulus* plantation estate established between 2004 and 2016 (34507 hectares) assuming no change in productivity over time was 146 t CO_2e ha^{-1} (Table 2) The addition of carbon revenues produced a change in NPV (ΔNPV) per hectare of \$216 ha^{-1} (Table 2) in the first commitment period, and \$287 ha^{-1} (Table 2) when the carbon revenues of the first and second commitment periods were combined.

The economic weights for volume and basic density excluding carbon revenues in the first commitment period were \$14 20 m^{-3} and \$14 93 kg^{-1} m^{-3} respectively, and the ratio of the economic weight per unit volume for volume and the economic weight per unit basic density was 0 95 Inclusion of first commitment period carbon revenues altered the economic weights for volume and basic density to \$15.06 m^{-3} and \$15.33 kg^{-1} m^{-3} respectively, with a greater emphasis on volume (the ratio of the economic weight per unit volume for volume and the economic weight per unit basic density was 0.98). When the second commitment period is considered the economic weights without carbon were \$17.59 m^{-3} and \$18 50 kg^{-1} m^{-3} for volume and basic density respectively without carbon revenues, and \$18.74 m^{-3} and \$19.03 kg^{-1} m^{-3} including carbon revenues, but the ratios between the weights for volume and basic density did not differ from the first commitment period

Table 2. Forecast means and values for the 5th and 95th percentiles (the central 90% of all forecasts fall within the range shown) following sensitivity analysis. Values are for new areas planted between 2004 and 2016

FORECAST	Units	Mean	5%	95%
ESTATE				
Seedling area	ha	3148 64	1502 55	6239.78
Coppice area	ha	596 02	60 65	1452 02
Biomass total	Mt	3.68	1.63	7.29
CO_2e ha^{-1} long term	t CO_2e ha^{-1}	146.05	90 69	218 32
CO_2e ha^{-1} 2012	t CO_2e ha^{-1}	62.35	37.95	94 47
CO_2e ha^{-1} 2016	t CO_2e ha^{-1}	29 70	16 18	48 02
CO_2 revenue				
CO_2 revenue 2012	M\$	\$7.87	\$3.06	\$16.18
CO_2 revenue 2016	M\$	\$2 88	\$0 79	\$7.24
(H_2 - H_1) 2012 ΔNPV	M\$	7.87	3.06	16 18
(H_2 - H_1) 2012 ΔNPV ha^{-1}	\$ ha^{-1}	215 76	121 25	346 01
(H_2 - H_1) 2016 ΔNPV	M\$	10 74	3.87	23.34
(H_2 - H_1) 2016 ΔNPV ha^{-1}	\$ ha^{-1}	287.08	157.18	467.66
ECONOMIC WEIGHTS				
H_1 2012 Volume	\$ m^{-3}	14.20	5.15	25 66
H_1 2012 Basic density	\$ kg^{-1} m^{-3}	14 93	9 51	21 79
H_2 2012 Volume	\$ m^{-3}	15.06	5 87	26 67
H_2 2012 Basic density	\$ kg^{-1} m^{-3}	15 33	9 84	22 28
H_1 2016 Volume	\$ m^{-3}	17.59	6.28	32.26
H_1 2016 Basic density	\$ kg^{-1} m^{-3}	18.50	11.45	27 61
H_2 2016 Volume	\$ m^{-3}	18 74	7.24	33 63
H_2 2016 Basic density	\$ kg^{-1} m^{-3}	19 03	11 89	28 23
CORRELATED RESPONSE				
ΔcG_{H_1} 2012		0 93	0 87	0 97
ΔcG_{H_1} 2016		0.93	0.86	0.97

Coppice crops in the second rotation are likely to change the dynamics of woody biomass in an *E. globulus* plantation In a coppice crop the stumps are allowed to resprout following the first rotation harvest, and the rootstock is retained as living biomass. In *E. globulus*, up to 20 stems are produced by each stump (Whittock *et al.* 2003), and thinning to one or two stems per stump after the first 2 years of growth is required to produce an economically viable pulpwood crop Such thinning removes a large percentage of the above ground biomass from each plant,

resulting in a large build up of decaying biomass in the plantation. Therefore the dynamics of carbon storage will differ between seedling and coppice crops in an *E. globulus* plantation However, while coppicing was considered as a variable in this study, plantation dynamics over a longer period of time than that considered here (2004 – 2025) would have to be studied to fully assess the impact of coppicing on carbon accumulation in the plantation estate

Correlated response. The changes in the economic weights of the traits harvest volume and basic density because of carbon revenue in either commitment period (2012 or 2016) result in the correlated response of H_1 to selection based on H_2 (ΔcG_{H_1}) being 0 93 As the correlated response of H_1 to selection based on H_2 is so high, it is unlikely that some of the assumptions in the model (i e. no age dependant change to within tree biomass allocation) will affect the overall conclusions

CONCLUSIONS

Tree breeding is a long-term enterprise and the impact of decisions made today will not be seen for at least 20 years (Greaves *et al.* 1997). It would be redundant to consider tree improvement in terms of carbon sequestration if the only period in which carbon could be traded was between 2008 and 2012 However, if in the future the carbon density on a site is increased above the level of 2008-2012, then that carbon could potentially be traded In order that the carbon sequestered to 2012 is maintained in the longer term, further contiguous commitment periods following 2008-2012 must be envisaged. It is possible that in subsequent commitment periods carbon sequestered in forest products will be included in the calculations of the amount of carbon tradable in forest sector (Pingoud and Lehtila 2002) This should increase the NPV of alternative objectives, because models of carbon sequestration incorporating processing of wood and wood products have already shown positive carbon balances (Apps *et al* 1999, Côté *et al.* 2002). Therefore, even though the initial Kyoto commitment period is too soon and too short for tree improvement to address directly, it is possible

that future tree improvement in the direction of increasing carbon sequestration per hectare in *E. globulus* plantations could have an effect on carbon revenues. However, as the correlated response to selection of an economic breeding objective without carbon when selection is based on an economic breeding objective including carbon sequestration is so high (between 0.86 and 0.97) in a system designed to be maximise carbon revenues relative to biomass production, inclusion of carbon revenues in economic breeding objectives for *Eucalyptus globulus* is unnecessary

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Genetic control of coppice and lignotuber development in *Eucalyptus globulus*

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Abstract. The economics of short-rotation pulpwood plantations of *Eucalyptus globulus* as a coppice crop are influenced by stump survival and subsequent coppice growth rates. This study revealed significant genetic diversity in coppicing traits, both within and between subraces, following felling in a progeny trial after 9 years of growth. A total of 67% of trees coppiced after 14 months, but subraces varied from 43 to 73%. Heritabilities for coppice success (0.07) and subsequent growth (0.16–0.17) were low but statistically significant. Strong genetic correlation between presence/absence of coppice, the number of stems coppicing from the stump and modal coppice height, indicate that selection is possible by using the binary trait. The ability of a tree to coppice was genetically correlated with tree growth prior to felling (r_g = 0.61) and with nursery-grown seedling traits, where large genetic differences were observed in the development of lignotubers. Coppicing was genetically correlated with the number of nodes with lignotubers (r_g = 0.66) and seedling stem diameter at the cotyledonary node (r_g = 0.91). These traits were uncorrelated with later age growth and with each other. The results suggest that coppicing is influenced by three independent mechanisms—lignotuber development, enlargement of the seedling stem at the cotyledonary node and vigorous growth—which enhance ability to survive catastrophic damage, and indicate that both lignotuber and coppice development can be altered by both natural and artificial selection

Introduction

When felled near the ground, many hardwood trees regenerate through coppice shoots that sprout from the stump (Blake 1983). Eucalypts are no exception (Hillis and Brown 1978), although the epicormic bud-producing structures appear unique to the genus (Burrows 2002). Eucalypt plantations are often managed for coppice production, be it to produce cut foliage in floriculture (Wirthensohn and Sedgley 1998), logs for fuelwood, or pulpwood (Doughty 2000) While most plantations of the major pulpwood species *Eucalyptus globulus* are managed by replanting following harvesting, there are references to *E. globulus* being managed as a coppice crop in India (Matthews 1992), Portugal (Turnbull and Pryor 1984; Almeida *et al* 1990) and Chile (Turnbull and Pryor 1984; Prado *et al.* 1990; Alarcón 1994) In India, *E globulus* has been coppiced four times on a 10–15-year cutting cycle (Doughty 2000), but pulp-production plantations tend to be coppiced only two or three times on rotations of 8–12 years, before replanting (Eldridge *et al.* 1993). Coppice regrowth derives considerable benefit from an established root system. Biomass production is initially greater than seedlings (Blake 1980; Crombie 1997) and yield from the first coppice crop often exceeds that from the maiden crop (Hillis and Brown 1978). However, yield on a per hectare basis is usually reduced, particularly in later rotations, owing to cumulative mortality of stumps rather than loss of vigour in living stumps (Matthews 1992)

Manipulation of coppicing requires knowledge of the genetic control and interrelationship amongst traits directly or indirectly affecting coppice production. One such trait, amenable to early selection, is lignotuber development. Lignotubers are woody swellings found in the axils of the cotyledons (Boland *et al.* 1984) on seedlings, which become buried as they develop, providing trees with a bank of meristematic tissue protected from lethal fire temperatures by an overlying mantle of soil (Noble 2001). These organs have long been believed to enhance regeneration by coppice and, along with bark, enhance survival of catastrophic events such as fire, drought, frost and browsing of seedlings in

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Table 1. Details of the subrace classification (modified from Dutkowski and Potts 1999) used in this study

The number of families per subrace in the Massy Greene trial (MG), the number of families for which data on coppice production was available (coppice), the number of families with lignotuber formation (lig) and the total number of families providing data used in the study (total)

Subrace location	Number of families			
	MG	Coppice	Lig	Total
Far Western Otways	6	5		6
Western Otways	120	92		120
Cape Patton	18	17		18
Eastern Otways	23	17	8	24
Strzelecki Ranges	58	43	8	58
Strzelecki Foothills	8	7		8
Gippsland Coastal Plain	13	10		13
Gippsland Foothills	3	3		3
Flinders Island	61	48		61
Southern Furneaux	50	39	1	50
St Helens	11	9	7	11
North-eastern Tasmania	19	15	15	25
Inland north-eastern Tasmania	20	17	7	20
Dromedary	4	3		4
South-eastern Tasmania	61	51		61
Southern Tasmania	27	19	20	32
Tasman Peninsula	5	3		5
Recherche Bay	4	3	6	9
Port Davey	6	2		6
Western Tasmania	29	27	7	29
King Island	32	29	8	32
Total	578	459	87	595

eucalypts (Kirkpatrick 1975; Jacobs 1979; Blake 1983; Noble 1984; Webley *et al* 1986) Large genetically based differences in lignotuber development have been reported between (e.g. Burgess and Bell 1983; Noble 2001) and within (e.g. *E. viminalis*, Ladiges and Ashton 1974; *E. globulus*, Kirkpatrick 1975; *E. camaldulensis*, Jacobs 1979, and *E. gunnii*, Potts 1985) eucalypt species. Intraspecific variation in coppice production has also been reported for several species including *E. camaldulensis* (Grunwald and Karschon 1974), *E. grandis* (Reddy and Rockwood 1989) and *E. saligna* (Bowersox *et al.* 1990). However, few studies have examined the relationship between lignotuber development and coppice production

This study aimed to determine the genetic control of coppicing and lignotuber development in *E. globulus* (*sensu* Brooker 2000) and their genetic interrelationship. We examine the patterns of natural genetic variation in these traits in families sampled throughout the geographic range of the species, and provide the first estimates of their heritability in *E. globulus*. We also report the genetic correlations amongst these regenerative traits and other economically important traits such as later age growth and wood density (MacDonald *et al.* 1997, Dutkowski and Potts 1999).

Materials and methods

Genetic material

The genetic control of coppicing was investigated by using a common environment field trial at Massy Greene in northern Tasmania (41°05′S, 145°54′E), while a glasshouse trial with families in common with the Massy Greene trial provided a comparison between coppice production and seedling lignotuber development. Both trials were established from a range-wide collection of open-pollinated seed of *E. globulus* and intergrade populations, undertaken by the CSIRO Australian Tree Seed Centre in 1987 and 1988 (Gardiner and Crawford 1987, 1988). Genetic material within the Massy Greene trial in northern Tasmania represented a subset of the material used in previous studies of the genetic variation in *E. globulus* (MacDonald *et al.*1997; Dutkowski and Potts 1999; Jordan *et al.* 1999, 2000). The *E. globulus* population was arranged in 23 subraces (modified from Dutkowski and Potts 1999), reflecting the geographic origins of parent trees (Table 1). As with previous studies (e.g. Dutkowski and Potts 1999), samples from Wilson's Promontory Lighthouse were excluded from the analysis owing to atypical shrublike growth.

Coppice trial

The Massy Greene *E. globulus* base population trial was established by North Forest Products (now Gunns Ltd) in 1989. The trial consisted of five replicates in a resolvable incomplete block design (further details of the trial design are given in Jordan *et al.* 1994). The trial was converted to a seed orchard in November 1998, but cut stumps of culled trees were allowed to coppice. Of the nearly 6000 trees in the original

Table 2. Traits measured, the transformation used, overall means and their units

References refer to previously published studies in which the results of analyses included data for that trait from the Massy Greene trial; *n* is the number of measurements for each trait; and mean is the back-transformed whole trial mean for each trait

Trait	Description and transformation	*n*	Mean
	Field trial (Massy Greene)		
P/A	Presence (1) or absence (0) of coppice	3562	0.67
Cheight (cm)	$(cheight)^{0.85}$		
	Modal height of leaders coppicing from stump. Stumps not producing coppice were treated as missing values.	2443	85.6
Cstems	$(cstems)^{0.32}$		
	Number of major stems coppicing from the stump, counted at the base of stems. Stumps not producing coppice were treated as missing values.	2442	15.5
Pilo (mm)	Pilodyn penetration at 5 years. One tree per plot in two replicates, the average of two measurements per tree. See MacDonald *et al.* 1997.	1392	13.2
Dbh (cm)	Diameter at 1.3 m over bark at 8 years	4693	19.8
Bark (mm)	$(bark)^{0.71}$		
	Bark thickness, the average of two measurements Only in four replicates. See Dutkowski and Potts 1999.	4409	7.7
	Glasshouse		
Noligno	Number of nodes with lignotubers at 1 year	374	0.8
Ligwidth (mm)	Width across lignotubers at the cotyledonary node after 1 year	528	8.4
Stemdiam (mm)	Stem diameter at the cotyledonary node after 1 year	528	6.8
Rligno	(ligwidth – stemdiam)/stemdiam	528	0.2

trial, 3594 living trees were felled and available for assessment of coppice production. Measurement of coppice production was undertaken 15 months after felling. A low percentage of stumps covered with slash from felling were excluded, leaving 3562 stumps for analysis (Table 2).

Three measurements of coppice production were taken from each stump after 15 months: presence or absence (P/A) of coppice shoots; modal height of the coppice shoots (cheight), and the number of coppice shoots produced per stump (cstems). Other traits previously assessed at Massy Greene were incorporated into this study for cross-correlation and comparison of relative levels of heritability The additional traits included were diameter at breast height over bark prior to felling (dbh; 8 years); pilodyn penetration at 5 years (pilo) (Macdonald *et al.* 1997) and relative bark thickness at 4 years (bark) (Dutkowski and Potts 1999) (see Table 2). Pilodyn penetration is an indirect measure of wood density, with increased pilodyn penetration indicating decreased wood density (Greaves *et al* 1996, Raymond and MacDonald 1998). For modal coppice height, the number of coppice stems and bark thickness, the regression of log(standard deviation) on log(mean) indicated that power transformations were required to standardise the variances (Box and Cox 1964). The transformations are shown in Table 2.

Lignotuber trial

Sixty-six families were common to both the Massy Greene and glasshouse trials, allowing estimation of genetic correlations between seedling lignotuber formation and coppice production. The glasshouse trial contained 550 plants in all, from 87 open-pollinated families with 1–16 plants per family. The trial comprised 19 randomised blocks with between 4 and 81 families present in any block and between one and three non-contiguous plants per family occurring in a block. The genetic material in the glasshouse trial was selected from 10 subraces with families representing the extremes of genetic variation in bark thickness within *E. globulus* (Dutkowski and Potts 1999). After 12 months, the number of nodes with lignotubers was counted (noligno) and width across lignotubers including the stem (ligwidth) and stem diameter at the cotyledonary node, perpendicular to the lignotubers (stemdiam) were measured. In order to account for growth, the size of lignotubers relative to stem diameter (rligno) was calculated according to Ladiges and Ashton (1974):

$$\text{rligno} = \frac{(\text{ligwidth} - \text{stemdiam})}{\text{stemdiam}}$$

Statistical procedures

ASReml (Gilmour *et al.* 1995, 2002) was used to conduct mixed model analyses of the trial data. Residual maximum likelihood estimates of variances, covariances and correlations uniquely attributable to genetic and design effects in the trials were obtained.

General linear mixed model

An individual tree model with subrace and replicate as fixed effects was used. The univariate model was defined as

$$\mathbf{y} = \mathbf{X}\beta + \mathbf{Z}_1\mathbf{c} + \mathbf{Z}_2\mathbf{a} + \mathbf{e},$$

where $\mathbf{y}$ is the vector of n observations for the dependent variable, β is the vector of fixed effects including subrace and the replicate term (in the respective trials), $\mathbf{c}$ is the vector of random incomplete block effects (only for the Massy Greene trial), $\mathbf{a}$ is the vector of random additive genetic effects and $\mathbf{e}$ is the vector of random residuals. $\mathbf{X}$, $\mathbf{Z}_1$ and $\mathbf{Z}_2$ are incidence matrices relating observations to factors in the model The variance for each component is defined as

$$\text{Var}[\mathbf{c}] = \mathbf{C} = \mathbf{I}\sigma_c^2,$$

$$\text{Var}[\mathbf{a}] = \mathbf{G} = \mathbf{A}\sigma_a^2,$$

$$\text{Var}[\mathbf{e}] = \mathbf{R} = \mathbf{I}\sigma_e^2,$$

where $\mathbf{A}$ is the numerator relationship matrix for the additive genetic effects and $\mathbf{C}$, $\mathbf{G}$ and $\mathbf{R}$ represent incomplete block, additive and residual covariance matrices between the observations, respectively.

The expected values and variances of the model are as follows:

$$E\begin{bmatrix}\mathbf{y}\\ \mathbf{c}\\ \mathbf{a}\\ \mathbf{e}\end{bmatrix}=\begin{bmatrix}\mathbf{X\beta}\\ \mathbf{0}\\ \mathbf{0}\\ \mathbf{0}\end{bmatrix}, \text{Var}\begin{bmatrix}\mathbf{y}\\ \mathbf{c}\\ \mathbf{a}\\ \mathbf{e}\end{bmatrix}=\begin{bmatrix}\mathbf{V} & \mathbf{ZC} & \mathbf{ZG} & \mathbf{R}\\ \mathbf{CZ'} & \mathbf{C} & \mathbf{0} & \mathbf{0}\\ \mathbf{GZ'} & \mathbf{0} & \mathbf{G} & \mathbf{0}\\ \mathbf{R} & \mathbf{0} & \mathbf{0} & \mathbf{R}\end{bmatrix}$$

The phenotypic covariance matrix is

$$\mathbf{V}=\mathbf{Z}_1\mathbf{C}\mathbf{Z}_1'+\mathbf{Z}_2\mathbf{G}\mathbf{Z}_2'+\mathbf{R}.$$

In bivariate analyses **y**, **c**, **a** and **e** consist of vectors containing observations for two traits so that

$$\mathbf{y}=(\mathbf{y}_1',\mathbf{y}_2'),\ \mathbf{c}=(\mathbf{c}_1',\mathbf{c}_2'),\ \mathbf{a}=(\mathbf{a}_1',\mathbf{a}_2'),\ \mathbf{e}=(\mathbf{e}_1',\mathbf{e}_2'),$$

$$\mathbf{X}=\mathbf{X}_1+\mathbf{X}_2,\ \mathbf{Z}_1=\mathbf{Z}_{1_1}+\mathbf{Z}_{1_2},\ \mathbf{Z}_2=\mathbf{Z}_{2_1}+\mathbf{Z}_{2_2},$$

$$\mathbf{C}=\mathbf{I}_c\times\mathbf{C}_o,\ \mathbf{R}=\mathbf{I}_N\times\mathbf{R}_o \text{ and } \mathbf{G}=\mathbf{A}\times\mathbf{G}_o$$

The variance–covariance matrices for the incomplete block, additive genetic effects and residuals are represented by $\mathbf{C}_o$, $\mathbf{G}_o$ and $\mathbf{R}_o$, respectively:

$$\mathbf{C}_o=\begin{bmatrix}\sigma^2_{c_1} & \sigma_{c_{12}}\\ \sigma_{c_{12}} & \sigma^2_{c_2}\end{bmatrix}\ \mathbf{G}_o=\begin{bmatrix}\sigma^2_{a_1} & \sigma_{a_{12}}\\ \sigma_{a_{12}} & \sigma^2_{e_2}\end{bmatrix} \text{ and } \mathbf{R}_o=\begin{bmatrix}\sigma^2_{e_1} & \sigma_{e_{12}}\\ \sigma_{e_{12}} & \sigma^2_{e_2}\end{bmatrix}$$

OPAINV (Dutkowski *et al* 2001), a Fortran program for use with ASReml, was employed to form the inverse of the relationship matrix accounting for 30% selfing in open-pollinated progeny (Griffin and Cotterill 1988).

Narrow-sense heritabilities were calculated in ASReml as:

$$h^2=\frac{\sigma^2_a}{\sigma^2_a+\sigma^2_e}$$

The genetic correlation between an all-or-none trait and another normally distributed can be estimated without transformation so long as the incidence level of the all-or-none trait exceeds 10% (Olausson and Rönningen 1975). Thus, pairwise genetic correlations between the presence of coppice and other traits were calculated directly, as for quantitative traits. However, heritability of coppicing (based on presence/absence data) was estimated by using the general linear model with a probit link function. The significance of the heritability estimates and genetic correlations were tested with a *t*-test.

Least squares means for each subrace were estimated from the PREDICT statement in ASReml. Pilodyn penetration and bark thickness were not sampled in all replicates of the Massy Greene trial. In the case of cross-classified data with information absent in some cells, least squares means are not estimable from the PREDICT statement (Gilmour *et al.* 2002). Therefore, subrace least squares means for these variables were estimated by ignoring the effect of replicate Pairwise (Pearson's) correlations between subrace least squares means were estimated by using PROC CORR in SAS Version 8 (SAS Institute, 1999).

Results and discussion

Variation between subraces

Normally *E. globulus* coppices vigorously (Jacobs 1979; Turnbull and Pryor 1984; Matthews 1992; Wirthensohn and Sedgley 1998), but only 67% of the trees in the Massy Greene trial produced coppice Such low rates of coppicing contrast with the results of the coppicing trials conducted in Chile, where the success rate of coppicing in *E globulus* was found to be about 93%, 14 months after felling (Prado *et al.* 1990; Alarcón 1994). This could be due to factors such as differences in genetic material or season of felling. The starch content of *E obliqua* lignotubers shows significant seasonal variation (Cremer 1973) Coppice reproduction in eucalypts is reported to be maximal when trees are felled in late winter or spring and minimal when felled in summer (Blake 1983; Wirthensohn and Sedgley 1998). The Massy Greene trial was felled in November (late spring in Tasmania) and it is possible that the timing of felling was suboptimal for *E globulus*.

There was significant variation between subraces in the presence of coppice and the number of stems produced but not in coppice height (Table 3, Fig. 1). The proportion of stumps coppicing ranged from 43 (Strzelecki Foothills) to 73% (Recherche Bay) at the subrace level (Table 4). The least squares means for coppice height at 14 months after felling ranged from 63 (Foothills) to 94 cm, however, Foothills and Dromedary were the only subraces with least squares mean for coppice height of less than 80 cm. Despite significant genetic correlations between the three measures of coppicing within subraces (r_g = 0.39–0.63; Table 5), the patterns of geographic variation at the subrace level were statistically independent (0.27–0.42. n.s.). There does not appear to be any geographic trend in the variation in coppice production on the basis of presence/absence data, with the exception of a west–east clinal trend across the Otway Ranges (39°S, 144°E, Fig. 1*a*). The trend follows a rainfall gradient (Dutkowski and Potts 1999) and parallels local clines in increasing bark thickness (Dutkowski and Potts 1999) and drought tolerance (Dutkowski 1995) Subraces from south-eastern Victoria, including those from the Strzelecki Ranges, produce fewer stems when coppicing than do subraces from the Furneaux group of islands and the Tasman Peninsula (Fig 1*b*)

Significant variation occurred between subraces in the glasshouse trial for number of lignotubers, lignotuber width and relative size of lignotubers, but not seedling stem width (see Table 3). The number of nodes with lignotubers on a seedling ranged from zero to three over the period of the study (1 year). Lignotubers developed in every subrace studied; however, in the case of the Recherche Bay subrace, a mean of only 0 45 nodes had lignotubers per tree (Table 4) and only 33% of trees produced lignotubers (data not shown) The least squares means for relative lignotuber size ranged from 0.08 (Recherche Bay) to 0.53 (Eastern Otways) (Table 4 and Fig. 2*c*) There was strong genetic correlation between the three measures of lignotuber size both within (0.64–0.84) and between (0.95–0.97) subraces (Table 5). The most extensive lignotuber development could be found in the

Table 3. Variance components and narrow-sense heritabilities

For subrace, the denominator d.f. was taken to be equivalent to the residual d.f. in all cases Incomplete block is shown as iblock. The number of subraces was used as the denominator d.f. in the case of replicate. The values for the variance components are based on the transformed variable. Replicate in the Massy Greene trial is not equivalent to replicate in the glasshouse trial P/A is presence or absence of coppice; cheight is modal height of coppice leaders (cm); cstems is the number of stems coppicing from the stump; pilo is pilodyn penetration (5 years, mm), dbh is diameter at breast height (8 years; cm); bark is relative bark thickness (4 years); noligno is the number of nodes with lignotubers (1 year); stemdiam is diameter of the stem at the cotyledonary node (1 year; mm); ligwidth is the width across lignotubers at the cotyledonary node (1 year; mm), rligno is the lignotuber width relative to stem width as defined by Ladiges and Ashton (1974). Significance levels are based on F and T tests n s., not significant; $*P < 0.05$; $**P < 0.01$, $***P < 0.001$

	Trait	Variance components			Fixed effects							
					Replicate		Between subraces		Within subraces			
		Iblock	Additive	Error	F_{rep}	$P > F$	$F_{subrace}$	$P > F$	h^2	s.e. (h^2)	t	$P > T$
Field trial (Massy Greene)	P/A (probit)	0.06	0.07	1.00	23.33	***	2.03	**	0.07	0.03	2.36	*
	Cheight	5.91	29.69	151.08	12.37	***	1.36	n.s	0.16	0.05	3.58	***
	Cstems	0.01	0.04	0.20	49.24	***	5.14	***	0.17	0.04	3.79	***
	Pilo	0.04	0.89	1.70	2.16	n.s.	9.56	***	0.34	0.09	3.97	***
	Dbh	0.16	8.06	16.97	3.42	**	7.88	***	0.32	0.04	8.84	***
	Bark	0.05	0.09	0.27	6.66	**	12.17	***	0.25	0.03	7.19	***
Glasshouse	Noligno		0.11	0.23	1.39	n.s.	4.93	***	0.31	0.11	2.67	**
	Stemdiam		0.54	0.64	5.30	**	1.44	n.s	0.46	0.13	3.30	**
	Ligwidth		1.48	1.97	4.62	**	4.23	***	0.43	0.13	3.10	**
	Rligno		0.02	0.02	1.62	*	9.78	***	0.51	0.14	3.38	***

Table 4. Least squares means by subrace for all traits

Means for cheight, cstems and bark have been back transformed. P/A is presence or absence of coppice, cheight is modal height of coppice leaders; cstems is the number of stems coppicing from the stump; pilo is pilodyn penetration (5 years); dbh is diameter at breast height (8 years); height is tree height (4 years), bark is relative bark thickness (4 years); noligno is the number of nodes with lignotubers (1 year); stemdiam is diameter of the stem at the cotyledonary node (1 year); ligwidth is the width across lignotubers at the cotyledonary node(1 year); rligno is the lignotuber width relative to stem width as defined by Ladiges and Ashton (1974)

	Field trial (Massy Greene)						Glasshouse			
Subrace	P/A (probit)	Cstems	Cheight	Dbh (cm)	Pilo (mm)	Bark	Noligno	Ligwidth (mm)	Stemdiam (mm)	Rligno
Far Western Otways	0.55	17.70	94.05	18.60	15.16	7.54				
Western Otways	0.58	15.76	88.42	22.02	13.88	8.21				
Cape Patton	0 62	15.58	80.31	21.46	13.91	8.57				
Eastern Otways	0.68	15.35	86 15	20.45	13.32	8.75	1.33	10.44	6.84	0.53
Strzelecki Ranges	0.58	13.45	91.22	20.99	12.16	8.26	1.00	8.75	6.95	0.27
Strzelecki Foothills	0.43	12.25	86 93	21.98	12.65	8.19				
Gippsland Coastal Plain	0.54	11.09	87 44	21.36	13 86	7.47				
Gippsland Foothills	0.55	10.26	63.71	20.36	12.59	7.40				
Flinders Island	0.64	20.32	88.01	20.24	12.95	7.68				
Southern Furneaux	0.67	19.68	86.55	19.67	12.72	7.54	0.67	7.75	6.92	0.12
St Helens	0.69	16.84	87.57	19.07	13 83	8.66	0.78	8.46	6.44	0 31
North-eastern Tasmania	0.61	13.35	86.96	17.57	12.04	7.80	0.73	7.98	6.72	0.19
Inland north-eastern Tasmania	0.67	13.40	90.36	18.73	13.44	8.34	1.14	9 30	6.52	0.42
Dromedary	0.49	15.14	72.71	17.01	12.25	7.11				
South-eastern Tasmania	0.64	13.96	88.71	19 19	13.11	7.89				
Southern Tasmania	0.68	16.62	91.73	20 97	13.07	7.36	0.75	8.18	6.94	0 18
Tasman Peninsula	0.67	20.68	90.55	19.26	13.19	7.00				
Recherche Bay	0.73	15.78	84 72	19.20	12.10	7.46	0.45	6.76	6.25	0.08
Port Davey	0.51	15 21	88.88	16.86	13.33	6.20				
Western Tasmania	0.65	16.68	81.88	19.11	13.50	6.98	0.57	7.70	7.09	0.10
King Island	0.51	16 65	80.35	22.02	14 51	7.30	0.64	8.21	7 16	0 15

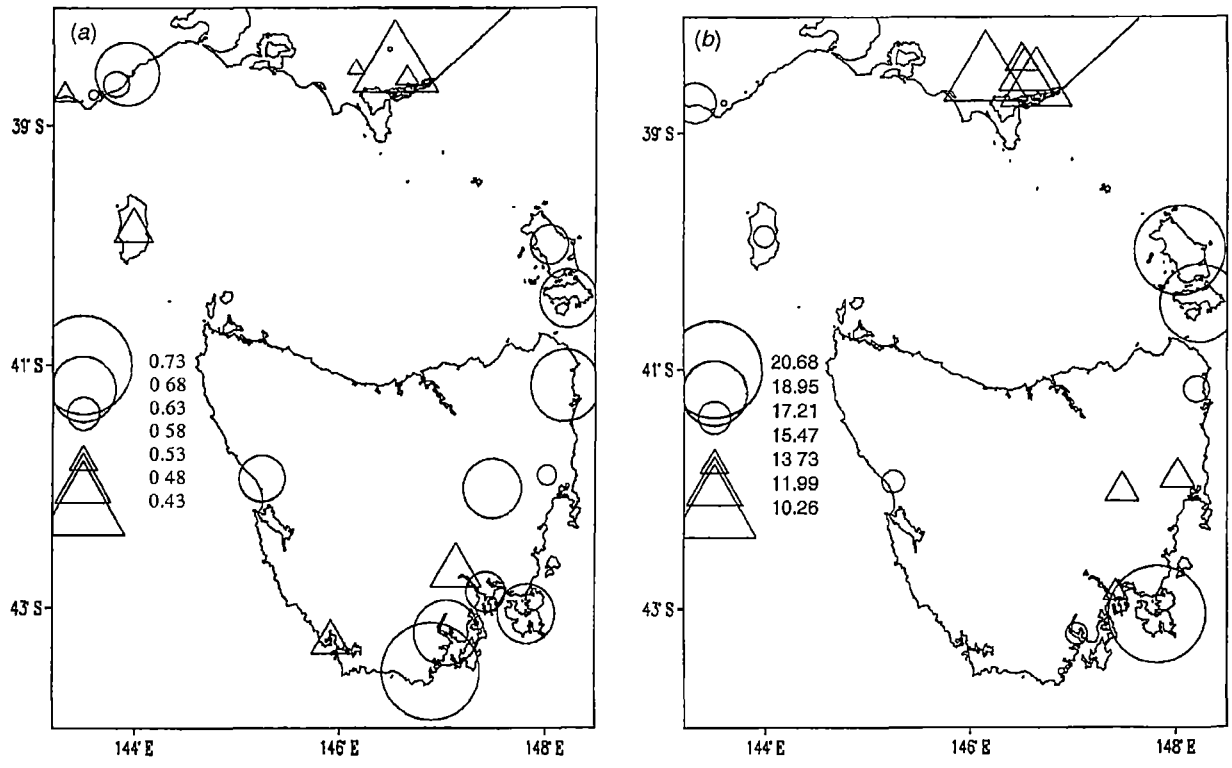

Fig. 1. Geographic variation in (*a*) the presence/absence of coppicing and (*b*) the number of stems coppicing from the stump Circles represent higher rates of coppice reproduction and more stems, triangles represent lower rates of coppice reproduction and fewer stems in (*a*) and (*b*), respectively. The marker scale is centred on the range midpoint of the subrace least squares means values.

Eastern Otways subrace, with a mean of 1.33 nodes with lignotubers per tree and 92% of trees producing lignotubers Western (Western Tasmania, King Island) and far south-eastern (Recherche, Southern Tasmania) Tasmanian subraces produced fewer lignotubers (Fig 2*b*). These subraces exist in wetter environments and have thinner bark (Kelly 1997; Dutkowski and Potts 1999). The latter trend is reflected in the significant correlation between lignotuber traits and relative bark thickness at the subrace level (Table 5). This result is consistent with previous reports of eucalypt species or populations from drier environments having greater lignotuber development (Gill 1997). There is limited correlation between lignotuber traits and relative bark thickness within subraces (0 13–0 46, Table 5), indicating that parallel selection may be acting on these traits.

Variation within subraces

Significant genetic variation was found within subraces for all coppice and lignotuber traits investigated (Table 3). The heritability of coppice characteristics was reported to range from 0.45 to 0.71 in *E. grandis* (Reddy and Rockwood 1989). In the case of *E globulus* the heritability of coppicing traits was the lowest of all traits measured. Heritabilities ranged from 0.07 for the presence of coppice, to 0.16 and 0.17, respectively, for modal coppice height and the number of coppice stems (Table 2). In contrast, lignotuber traits showed moderate heritability, ranging from 0 31 to 0.51, with relative lignotuber size the most heritable trait measured (Table 3). Other traits assessed in the field trial also exhibited moderate levels of heritability (h^2 = 0.21–0.34) and the heritability of variation in seedling stem diameter was the second highest (h^2 = 0.46) (Table 3). Despite extensive reports of heritability for growth and wood property traits (Lopez *et al.* 2002), these are the first estimates of heritability for coppice and lignotuber traits in the species.

Within subraces, the presence of coppice regeneration was positively genetically correlated with all traits measured in the Massy Greene trial, except for pilodyn penetration. No significant relationship was found between pilodyn penetration and coppice production, indicating that coppicing is genetically independent of wood density. Presence of coppice was significantly genetically correlated with tree size prior to felling (dbh *v.* P/A, r_g = 0.61; Table 5). However, there was little association of subsequent coppice growth with tree size prior to felling (dbh *v.* cstems, r_g = 0.26;

Table 5. Pairwise genetic (lower) and subrace (upper) correlations (Pearson's) for all traits

Genetic correlations with presence/absence (P/A) data were calculated without transformation to the probit scale. Statistically significant ($P < 0.05$) correlations are shown in bold. Correlations involving traits from the glasshouse trial are based on only 10 subraces; correlations between traits measured at the Massy Greene trial are based on 21 subraces. P/A is presence or absence of coppice, cheight is modal height of coppice leaders (cm); cstems is number of stems coppicing from the stump; pilo is pilodyn penetration (5 years; mm); dbh is diameter at breast height (8 years; cm); bark is relative bark thickness (4 years), noligno is the number of nodes with lignotubers (1 year); stemdiam is diameter of the stem at the cotyledonary node (1 year, mm), ligwidth is the width across lignotubers at the cotyledonary node (1 year, mm), rligno is the lignotuber width relative to stem width as defined by Ladiges and Ashton (1974)

	Field trial (Massey Greene)					Glasshouse				
	P/A	Cheight	Cstems	Dbh	Pilo	Bark	Noligno	Ligwidth	Stemdiam	Rligno
P/A		0.27	0 42	−0 11	−0 11	0.25	0	−0.08	**−0.69**	0.15
Cheight	**0.42**		0.36	0	0.24	0.16	0.48	0.31	−0.26	0.40
Cstems	**0.63**	**0.39**		−0.13	0.23	−0.17	−0.47	−0.35	0.24	−0.44
Dbh	**0.61**	0.12	**0.26**		0.24	**0.43**	0.12	0.21	0.57	0.01
Pilo	0.07	−0.04	−0.16	0 13		0.06	0 1	0 31	0 33	0.20
Bark	**0.33**	0.14	0.08	**0.57**	**0.25**		**0.79**	**0.75**	−0.41	**0.88**
Noligno	**0.66**	0.1	0.19	−0.34	**0.63**	0.13		**0.97**	0 03	**0.95**
Ligwidth	**0.89**	0 53	0.17	0.21	0.12	**0.46**	**0.77**		0 16	**0.95**
Stemdiam	**0.91**	0.49	−0.27	0.18	0.16	0.34	0 22	**0.64**		−0.18
Rligno	0.33	0.06	0.27	0 07	0 12	0.26	**0.84**	**0.66**	−0.15	

dbh *v.* cheight, $r_g = 0.12$; Table 5). This is consistent with previous reports that plant vigour prior to damage is a primary determinant of successful vegetative regeneration (Hillis and Brown 1978; Blake 1983, Noble 1984) However, the present study shows that this is only one of three mechanisms independently operating to determine the success of coppicing in *E. globulus*. Coppicing success is also strongly genetically correlated with seedling stem diameter (P/A *v.* stemdiam, $r_g = 0.91$) and less strongly correlated with the number of nodes with lignotubers (P/A *v.* noligno, $r_g = 0\ 66$). These two seedling traits are genetically independent of each other ($r_g = 0\ 22$. n.s.) and genetically independent of diameter at 8 years of age ($r_g = 0.18$. n s., and $r_g = 0.21$. n.s., respectively). The genetic correlation between the presence of coppice and relative lignotuber size was not significant, and while there was a significant correlation between the presence of coppice and lignotuber width (P/A *v.* ligwidth, $r_g = 0\ 89$; Table 5), this was solely due to covariation with seedling stem diameter. For example, the genetic correlation between the presence of coppice and lignotuber width was only 0.37 when seedling stem diameter was included as a covariate and was not significantly different from zero Similarly, the genetic correlation between relative bark thickness and the presence of coppice (bark *v.* P/A, $r_g = 0.33$) was not significant when dbh was included as a covariate (data not shown).

Lignotuber development has previously been suggested to enhance coppice production (Jacobs 1979; Webley *et al.* 1986; Bowersox *et al.* 1990; Noble 2001). The present study found the presence of coppice, and not subsequent coppice growth, to be correlated with lignotuber development in *E. globulus*. Bark thickness has no effect on coppice success at the age of 9 years, nor does wood density (as measured by pilodyn penetration; Table 5). Noble (2001) showed that lignotubers have an abundance of meristematic tissue available to differentiate into vegetative buds when the stem is damaged. The present study suggests that the probability of later-age coppicing in *E globulus* is not affected by the relative size of this organ, but the number of seedling nodes producing the organ. However, the strongest determinant of coppice success appears to be not the lignotuber *per se*, but the size of the seedling stem at the cotyledonary node.

It is clear from other observations that lignotubers *per se* are not essential for successful coppicing and the two closely related species *E. grandis* and *E. saligna* are a case in point (Gill 1997). *E. grandis* tends not to have lignotubers while most *E. saligna* seedlings develop lignotubers (Burgess and Bell 1983), yet coppicing of both species is believed to be equivalent (Eldridge *et al.* 1993; Gill 1997). Broad swelling of the basal portion of the stem of seedlings rather than discrete lignotuberous organs occur in some eucalypts (e.g. *E. pilularis*) and this is also believed to enhance vegetative regeneration (Boland *et al.* 1984). While most of the internal wood is lignified, peripheral vascular tissues in lignotubers are known to function as sinks for carbohydrates and water (Noble 2001). It is possible that swollen stem bases in seedlings also act as carbohydrate sinks, thus providing nutrients for improved coppice production. Alternatively, the presence of a swollen seedling stem base or many lignotubers in *E. globulus* may reflect an increased density of epicormic meristem strands (as described by Burrows 2002) available to produce regenerative buds In any case, the present study shows that these mechanisms are genetically independent, can co-occur in the same species (and potentially even in the same individual) and may represent primary storage and bud proliferation functions.

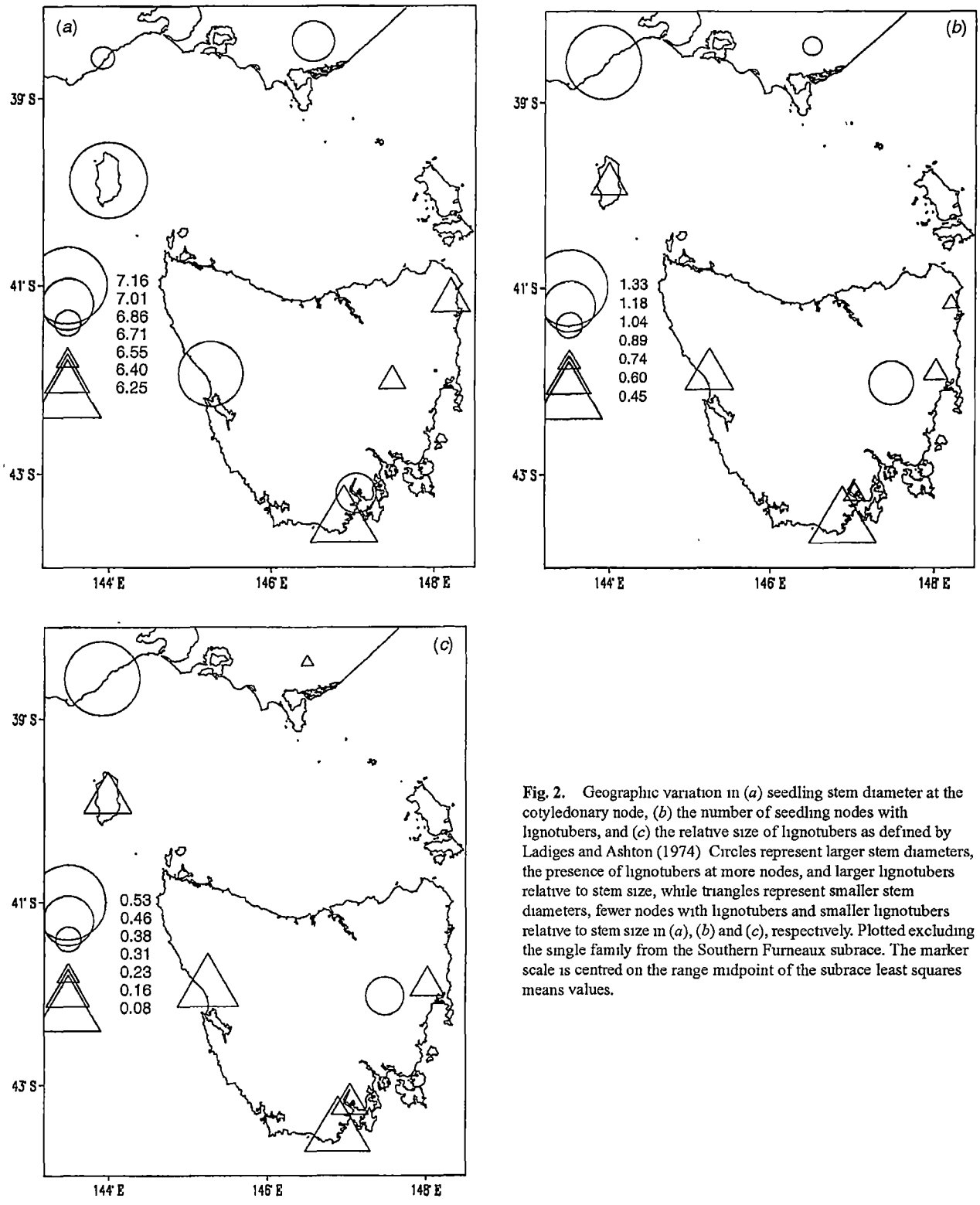

Fig. 2. Geographic variation in (*a*) seedling stem diameter at the cotyledonary node, (*b*) the number of seedling nodes with lignotubers, and (*c*) the relative size of lignotubers as defined by Ladiges and Ashton (1974) Circles represent larger stem diameters, the presence of lignotubers at more nodes, and larger lignotubers relative to stem size, while triangles represent smaller stem diameters, fewer nodes with lignotubers and smaller lignotubers relative to stem size in (*a*), (*b*) and (*c*), respectively. Plotted excluding the single family from the Southern Furneaux subrace. The marker scale is centred on the range midpoint of the subrace least squares means values.

Conclusions

There is significant genetic variation between and within subraces in their ability to reproduce by coppice and produce lignotubers, indicating both traits are amenable to artificial and natural selection Further, seedling stem diameter and the number of seedling nodes with lignotubers appear to be indicators of the ability of a tree to produce coppice and may provide useful selection traits to improve the success of coppice regeneration. This quantitative genetic approach has argued for three independent genetically based mechanisms impacting on coppice success. The success of coppice production in *E globulus* is dependent on tree vigour prior to felling, the number nodes with lignotubers in seedlings and finally the diameter of the stem at the cotyledonary node of seedlings.

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A cash flow model to compare coppice and genetically improved seedling options for *Eucalyptus globulus* pulpwood plantations

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Abstract

Coppice can provide a cheap alternative to replanting in the second rotation in *Eucalyptus globulus* Labill. plantations. However, replanting with genetically improved stock may provide a more profitable alternative A discounted cash flow model was used to compare the profitability of coppice and seedling crops in second rotation *E. globulus* pulpwood plantations, using incremental net present value (NPV). Using the model presented in this paper as a framework it is possible to say that a gain of 20% over the original seedling crop in dry matter production from second rotation seedlings through genetic improvement and provenance selection would result in equivalent NPV for second rotation seedling and coppice crops Sensitivity analysis showed that incremental NPV is strongly affected by the level of genetic gain available (and therefore the genetic quality of the first rotation stock relative to the available genetically improved stock), and the productivity of coppice relative to the first rotation crop. Any reduction in the basic density of coppice reduces the level of genetic gain required to make replanting with improved seedlings economically justifiable.
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Keywords: Coppice; Cash flow model; *Eucalyptus globulus*, Genetic improvement; Economic evaluation

1. Introduction

Eucalyptus globulus is one of the major hardwood species in temperate plantation forestry. Considerable effort has been expended on the domestication and genetic improvement of this species (Volker and Orme, 1988; Borralho et al., 1993; Greaves et al., 1997; Borralho and Dutkowski, 1998; Dutkowski and Potts, 1999; Harbard et al., 1999; Kerr et al., 2001). Genetic improvement in the form of provenance selection and breeding promises gains in productivity. Estimates of such gain in *E. globulus* range from 7 to 17% for volume (Volker et al., 1990), 20–47% for dry matter (Borralho et al., 1992) and up to 18% saving in total pulp costs (Greaves et al., 1997). Gains will be maximised where first rotation (1R) stock is based on seed collected from unselected natural stands.

E globulus regenerates readily through stump coppice following the removal of the stem and crown at harvesting (Blake, 1983; Opie et al., 1984). This ability to coppice and the fact that second rotation establishment costs are avoided have led many plantation managers to assume that the second rotation (2R) may be managed as a coppice crop. While a coppice

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crop may be optimal in some situations, potential increases in plantation productivity through genetic improvement may argue in favour of replanting in the second rotation.

Previous economic models of eucalypt coppice have dealt with the optimum number of shoots to retain (Agnihotri and Arya, 1994) or the number of coppice rotations and rotation length for optimum economics in a plantation (Nobre and Rodriguez, 2001), or charcoal production system (Platais and Betters, 1989). No direct comparison has been made between seedling and coppice crops in *E. globulus* pulpwood plantations for coppice stands thinned to one stem per stump. Such comparisons are complicated by the need to use the same genetic material for the establishment of first and second rotation crops. In the current study, a cash flow model is developed to allow an assessment of the level of genetic gain required to produce a second rotation seedling crop that exceeds the value of a second rotation coppice crop.

2. Methods

2.1. Model description

The model was developed in Microsoft Excel®, based on cost structures for managing *E globulus* plantations from seedlings in the first rotation, and from seedlings or coppice in the second rotation (Tables 1 and 2). All costs are in Australian dollars. Costs and the timing of costs differ between seedling and coppice crops. The model allows changes in productivity due to coppicing or genetic improvement to be investigated in terms of net present value (NPV). Incremental NPV (Irvin, 1978) was used to compare the two mutually exclusive options (Dasgupta and Pearce, 1972). A positive incremental NPV indicated that the NPV of coppice exceeded the NPV of seedlings in the second rotation, whilst a negative incremental NPV indicated that the NPV of a seedling crop exceeded the NPV of a coppice crop in the second rotation.

Two series of two 10-year rotations, representing a seedling crop established on an open paddock followed by either a seedling crop, or a coppice crop (Table 1) were considered. A lag time of 1 year

Table 1
The system used to calculate the incremental NPV of seedling and coppice crops

Year	Seedling (rotation 1, unimproved seedling)		Seedling (rotation 1, unimproved seedling)	
	Cost	Income	Cost	Income
0	Est1	1	Est1	1
1	Est2	2	Est2	2
2	Est3	3	Est3	3
3	4	4	4	4
4	5	5	5	5
5	6	6	6	6
6	7	7	7	7
7	8	8	8	8
8	9	9	9	9
9	10	H10	10	H10
	Coppice (rotation 2, coppice)		Seedling (rotation 2, improved seedling)	
	Cost	Income	Cost	Income
10	Man1	1	Fallow	0
11	Man2	2	Est1	1
12	Man3	3	Est2	2
13	4	4	Est3	3
14	5	5	4	4
15	6	6	5	5
16	7	7	6	6
17	8	8	7	7
18	9	9	8	8
19	10	H10	9	9
20			10	H10

'Est' indicates a cost associated with seedling establishment, 'man' indicates a cost associated with coppice management, 'H' indicates an income at harvest, 'fallow' the lag period of 1 year between harvest of the first rotation and establishment of second rotation seedlings, 'PV' the present value and 'NPV' the net present value. Numbers in the 'cost' and 'income' columns refer to the year in the rotation that the cost or income occurs

Table 2
Illustrative costs for the management and establishment of *E globulus* plantations

Activity	Cost per hectare (AU$ ha^{-1})		
	First rotation	Second rotation	
	Paddock	Seedling	Coppice
Administration	240 00	10 00	10.00
Preparation	1018 00	1468 00	5.00
First year	206.00	176.00	21.50
Second year	256.00	256 00	696.00
Third year	58 00	58.00	241.00
Annual costs	213 00	213.00	213.00

between clearfall and replanting seedlings built into the model (Table 1) meant that the lifespan of the two crop types (coppice or seedlings) differed by 1 year at the end of two rotations. Small differences in project lifespan should not impact significantly on the performance of financial models (Brigham and Houston, 2002). This was checked by converting the NPV of coppice and seedling crops to an equivalent annuity (Zerbe and Dively, 1994). The equivalent annuities system did not alter the interpretation of the results, and the results presented remain in the form of NPV or incremental NPV.

The net present value of systems was calculated as

$$\mathrm{NPV} = I_{\mathrm{PV}} - C_{\mathrm{PV}} \tag{1}$$

where I_{PV} is the present value of all incomes and C_{PV} the present value of all costs. All costs and incomes were discounted to the time of plantation establishment (year 0). Present value was calculated using the standard formula:

$$P = V\left(1 + \frac{d}{100}\right)^{a_V} \tag{2}$$

where P is the present value of a cost or income, (V), a_V the time (year) in which V occurs, and d the annual discount rate in percentage points. A discount rate of 7% was used in a study of fibre production from *E. globulus* in Australia (Selkirk and Spencer, 1999), and was adopted as the base rate in this study. 'Present' is the time of plantation establishment (year 0).

It was assumed the enterprise was selling timber as a standing crop. Income was calculated based on the value for an oven dried tonne of wood delivered (O) This was converted to a value per green tonne delivered using the basic density of the crop, and then transport and harvest costs were removed to give the stumpage price. This system allowed changes in basic density due to genetic improvement or coppice to affect the value of the standing crop at harvest.

Basic density was calculated separately for each series (seedling or coppice) in each rotation. The basic density of the first rotation crop (D) was altered by the gain in basic density from genetic improvement in percentage points (DGAIN) in second rotation seedling crops, and reduced by a small percentage (r) in a coppice crop. The base value (first rotation mean basic density) assumed was 530 kg m^{-3} (see Macfarlane and Adams, 1998; Schimleck et al., 1999; Miranda et al., 2001 for estimates of *E. globulus* basic density). Ferrari (1993) reported that the basic density of *E. globulus* coppice was up to 8% lower than the basic density of the original stem on the same stumps. A decrease in basic density was also reported in *E. camaldulensis* coppice (Sesbou and Nepveu, 1991).

The gross value per green tonne delivered was calculated as G_1, G_{2_s}, and G_{2_c}, in first rotation, second rotation seedling and second rotation coppice crops, respectively. The green specific gravity (S) was assumed to equal 1 t m^{-3} (Albertson et al., 2000).

$$G_1 = \frac{OD}{S} \tag{3}$$

$$G_{2_s} = \frac{OD(1 + \mathrm{DGAIN}/100)}{S} \tag{4}$$

$$G_{2_c} = \frac{OD((1 - r)/100)}{S} \tag{5}$$

The stumpage (net income per green tonne for the grower, I) was calculated by removing the harvest cost per green tonne (h) from the gross income per green tonne. The harvest cost (AU$ 17 per green tonne) given by Albertson et al. (2000) was used as the base value in this case. The number of stumps with multiple stems and form problems such as hooking towards the base of the stem will increase the cost of extraction and transport of a coppice crop. A penalty (f) was applied to reflect potential difficulties associated with the harvest of coppice material

$$I = G - h(1 + f) \tag{6}$$

Yield in metric tonnes (Y) for the first rotation was calculated as

$$Y = \mathrm{MAI} \times a_{\mathrm{R}} \tag{7}$$

MAI is the mean annual increment (merchantable volume) calculated as $m^3\ ha^{-1}$ per year, and a_{R} the rotation length in years. The base value applied for MAI was 20 $m^3\ ha^{-1}$ per year. Yield of a second rotation coppice crop (Y_c) was calculated as

$$Y_c = \mathrm{MAI}\left(1 + \frac{\mathrm{CPROD}}{100}\right) a_{\mathrm{R}_c} \tag{8}$$

where a_{R_c} is the rotation length (years) for a coppice crop, and CPROD describes the change in coppice productivity relative to the original seedling crop. Loss of stumps is a common cause of reduced MAI in

coppice crops (Matthews, 1992). However, there was insufficient information available on the effect of stump mortality on end of rotation yield to include it directly as a variable. The yield of coppice was considered only relative to the first rotation crop. The yield from a seedling crop in the second rotation (Y_s) was calculated as

$$Y_s = \mathrm{MAI}\left(1 + \frac{\mathrm{VGAIN}}{100}\right)(a_{R_s} - 1) \quad (9)$$

where a_{R_s} is the rotation length for a seedling crop, including the fallow period of 1 year between harvesting and replanting, and VGAIN the gain in volume production in second rotation seedlings. Genetic gain (GGAIN) in this case refers solely to increases in dry matter production directly attributable to provenance selection and breeding. GGAIN was made up of changes in volume production and gains in basic density (DGAIN) so that:

$$\mathrm{VGAIN} = X \times \mathrm{GGAIN} \quad (10)$$

and

$$\mathrm{DGAIN} = (1 - X)\mathrm{GGAIN} \quad (11)$$

where X is the proportion of genetic gain contributing to an increase in volume. The remainder of genetic gain contributes to increasing basic density.

All abbreviations used above are listed and described in Table 3.

2.2. Sensitivity analysis

The sensitivity of the model to variation in input variables was examined using Crystal Ball® 2000.2 (Decisioneering Inc., 2002) to fit probability distributions to variables and run Monte Carlo simulations. The base values in the model (Table 4) reflect realistic estimates derived from the literature and discussions with *E. globulus* plantation growers in Australia.

Sensitivity analyses looked at the impact changes in model variables had on the NPV of first and second rotation crops, and the incremental NPV of coppice and seedling crops in the second rotation. Sensitivity to changes in a particular variable was calculated as a rank correlation over 10,000 iterations. All variables, with the exception of the cost penalty at harvest (f) associated with a coppice crop and the proportion of

Table 3
A list of abbreviations used to describe of the model, and their meanings

Abbreviation	Description
NPV	Net present value
I_{PV}	Present value of incomes
C_{PV}	Present value of costs
P	Present value
V	Any cost or income
d	Discount rate
a	Time in years (a_V the time a cost or income occurs, a_0 the time of plantation establishment, a_R the rotation length, a_{R_s} the rotation length for seedlings, and a_{R_c} the rotation length for coppice)
G	Income per green metric tonne delivered (G_1 1R, G_{2_s} 2R seedling, G_{2_c} 2R coppice)
O	Income per oven dried metric tonne delivered
D	Basic density (metric tonnes per cubic metre)
DGAIN	Percentage genetic gain affecting basic density
r	Percentage reduction in basic density in coppice relative to maiden crop
S	Green specific gravity
I	Stumpage per green tonne
h	Harvest and transport cost per green tonne
f	A percentage of the harvest and transport cost, a penalty incurred when harvesting coppice
Y	Yield (green t ha^{-1}) (Y_c yield from coppice, and Y_s the yield from seedlings)
MAI	Mean annual increment (green t ha^{-1} per year)
CPROD	The percentage change in productivity of coppice in relation to first rotation yield
GGAIN	The percentage genetic gain in seedlings over the previous crop
VGAIN	The genetic gain in volume production
X	The proportion of genetic gain contributing to increased volume production

Table 4
Base values for model parameters, used in all cases where alternative values are not specifically stated

Assumption	Base value	Range	Reference
Discount rate, d (%)	7.0	5.6–8.4	Selkirk and Spencer (1999)
Basic density, D (t m^{-3})	0.53	0.42–0.64	
Reduction in basic density, r (%)	0	0–20	Ferrari (1993)
Harvest costs, h (AU$ t^{-1})	17	13.6–20.4	Albertson et al. (2000)
Coppice harvest penalty f (%)	10	0–20	
MAI (m^3 ha^{-1} per year)	20	16–24	
CPROD (%)	100	80–120	
GGAIN (%)	20	0–40	
Density:volume, X (proportion)	0.2	0–1	
AU$/oven dried tonne delivered, O (AU$ OD t^{-1})	115	92–138	WRI-Ltd. (2000)

Coppice productivity (CPROD) is relative to first rotation productivity.

density increases in genetic gain, were allowed to vary according to a triangular distribution with maximum and minimum values ±20% of the base value. The coppice harvest and transport penalty was fitted with a triangular distribution ranging from 0 to 20% with the likeliest value 10%. The proportion of density gain to volume gain in genetic gain was allowed to vary from 0 (all gain is in volume) to 1 (all gain is in density) with a uniform distribution.

3. Results and discussion

If the productivity of a coppice crop were equivalent to the first rotation seedling crop, then genetic gain of between 20 and 25% (dry matter production) would be required for a seedling crop to have an NPV equivalent to a coppice crop (incremental NPV is zero) (Fig. 1). This is due to the reduced establishment and management costs for a coppice crop. Changes in the productivity of coppice have a large effect on the choice of crop system in the second rotation. A coppice crop producing 90% of the dry matter of the original seedling crop will be outperformed by a new seedling crop with genetic gain of 15% (Fig. 1). Such levels of genetic gain through provenance selection and breeding are probably achievable in *E. globulus* (Borralho et al., 1992), as many first rotation plantations were established with open pollinated native forest seed.

At a discount rate of 7%, varying coppice productivity from 70 to 130% relative to the original seedling crop resulted in a range of incremental NPV of approximately AU$ 5000 ha^{-1} (Fig. 1). The range of incremental NPV resulting from variation in the productivity of coppice is more contracted at a discount rate of 12% (AU$ ~3000 ha^{-1}, Fig. 2). The influence of changes in productivity due to the performance of coppice or genetic improvement are minimised at high discount rates (Fig. 2). Genetic gain of approximately 35% would be required before a seedling regime was favoured at a discount rate of 12%, when coppice productivity was equivalent to that of the first rotation crop (Fig. 2).

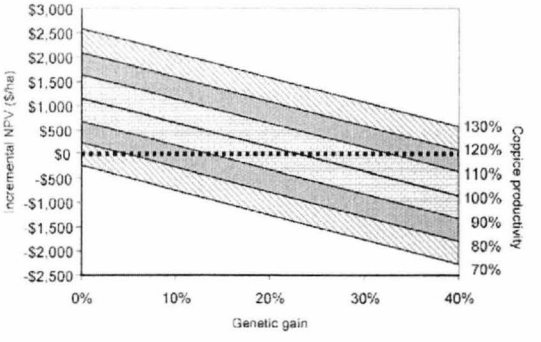

Fig. 1. Incremental NPV plotted against genetic gain (measured as percentage increase in dry matter production) showing the effect of increasing coppice productivity at the model base values. An incremental NPV of zero (broken line) indicates no difference in value between coppice and seedling crops in the second rotation. Incremental NPVs above zero indicate the value of coppice exceeding the value of seedlings, and incremental NPVs below zero indicate the value of seedlings exceeding the value of coppice. If the productivity of coppice crops is between 90 and 110% of the original seedling crop, then seedlings will start to become economically viable when genetic gain of 15–35% is available.

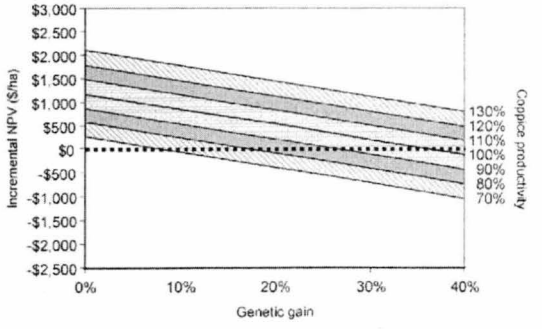

Fig. 2. Incremental NPV plotted against genetic gain (measured as percentage increase in dry matter production) showing the effect of increasing coppice productivity at high discount rates (12%). An incremental NPV of zero (broken line) indicates no difference in value between coppice and seedling crops in the second rotation. Incremental NPVs above zero indicate the value of coppice exceeding the value of seedlings, and incremental NPVs below zero indicate the value of seedlings exceeding the value of coppice. The reduction in cost of management combined with similar yields in a coppice crop when compared to a seedling crop mean that an increased discount rate drives the economics of plantation production towards using coppice in the second the second rotation.

Early growth of coppice is assisted by the established root system (Blake, 1983). The rapid growth of eucalypt coppice has led several authors (Jacobs, 1955; Carter, 1974; Matthews, 1992; Sims et al., 1999; Underdown and Bush, 2002) to suggest that coppice crops will produce up to 125% of the volume of the original seedling crop. Other authors (Skolmen, 1981; Prado et al., 1990; Alarcón, 1994; Whittock et al., 2003) have reported levels of stump mortality following harvest that would significantly reduce the productivity of a coppiced *E. globulus* plantation. Large differences in the ability of eucalypt species to regenerate through coppice (Blake, 1983; Sims et al., 1999; Little and Gardner, 2003) mean that yield information from other species may not apply in the case of *E. globulus*. In the absence of direct measurements, the broad range of coppice productivity covered in Figs. 1 and 2 realistically represents the possible range of *E. globulus* coppice productivity.

Sensitivity analysis showed that changes in basic density (*D*), MAI and the price paid for an oven dried tonne of chip (*O*) are the major factors affecting the NPV of first and second rotation crops (Table 5). Genetic gain and coppice productivity (CPROD) have rank correlations of a similar magnitude in second rotation seedling and coppice crops respectively (0.41 and 0.33) (Table 5), and a reduction in the basic density of a coppice crop (*r*) has a strong negative effect on its NPV (−0.48) (Table 5). The main variables driving changes in incremental NPV (the difference in value between coppice and seedling crops) are reduction in basic density (*r*), genetic gain and coppice productivity (−0.63, −0.52, and 0.44, respectively) (Table 5).

Table 5
Rank correlations for first rotation NPV (1R), second rotation seedling crop NPV (2R seedling), second rotation coppice crop NPV (2R coppice) and incremental NPV (iNPV)

Assumption	1R	2R seedling	2R coppice	iNPV
Basic density, *D*	0.58	0.52	0.46	−0.09
Reduction in basic density, *r*	–	–	−0.48	−0.63
Harvest costs, *h*	−0.16	−0.13	−0.15	−0.01
Coppice harvest penalty, *f*	–	–	−0.07	−0.10
MAI	0.42	0.39	0.32	−0.09
CPROD	–	–	0.33	0.44
GGAIN	–	0.41	–	−0.52
Density:volume, *X*	–	0.08	–	−0.12
AU$/oven dried tonne delivered, *O*	0.59	0.53	0.47	−0.09
Discount rate, *d*	−0.21	−0.21	−0.16	0.07

'Basic density' refers to the basic density of the first rotation crop, 'reduction in basic density' is the reduction in basic density of the wood in a coppice crop, 'harvest costs' include the cost of harvesting and transporting roundwood, 'penalty' is the cost penalty incurred when harvesting and processing a coppice crop, 'MAI' is the mean annual increment (m^3 ha^{-1} per year), 'coppice productivity' is the productivity of coppice relative to the first rotation seedling crop, 'genetic gain' refers to the increase in dry matter production from the first rotation crop to the second rotation seedling crop due to genetic improvement, 'density:volume' is the ratio of density gain to volume gain in genetic gain, 'AU$/oven dried tonne delivered' is the price paid for an oven dried metric tonne of wood delivered, and 'discount rate' is the discount applied.

This demonstrates that while the level of genetic improvement is an important consideration when choosing between coppice and seedlings in the second rotation, it will be very important to understand the factors affecting the productivity of a coppice crop.

The practice of varying underlying variables by ±20% for a sensitivity analysis does not take into account the likely variability of the underlying variables (Belli et al., 2001). The basic density of eucalypt coppice material has been found to be lower than that of the first rotation material (5%, Sesbou and Nepveu, 1991; 8%, Ferrari, 1993). However, the coppice material assessed was younger than the original stem material when tested (Sesbou and Nepveu, 1991), or as in the case of Ferrari (1993), the coppice growth had not been thinned. The sensitivity analysis conducted in this case may exaggerate the effect of a change in the basic density of coppice relative to the basic density of the initial seedling crop.

Coppice foliage in eucalypts typically shows higher stomatal conductance (Crombie, 1997; Reis and Reis, 1997), and higher stomatal number (Blake, 1980). *E. globulus* coppice foliage has a higher moisture content and increased carbon:nitrogen ratio when compared to seedling foliage (Steinbauer et al., 1998). Physiological changes in coppice foliage appear to leave it more susceptible to *Mycosphaerella* sp. (*E. marginata*, Abbott et al., 1993) and insect damage (*E. globulus*, Steinbauer et al, 1998) than seedling material. Replanting and turnover of genotypes may help to manage the risk of damage and loss due to pests and diseases. Coppice offers a plantation grower an opportunity to achieve a return for less investment. However, the risks associated with coppiced *E. globulus* plantations are likely to change over time. Where the NPV of coppice and seedling crops in the second rotation is equivalent, the grower should make their decision based on the crop that will incur less risk for the same NPV.

4. Concluding remarks

The use of a discounted cash flow model has identified situations where both seedling and coppice crops would be preferable in the second rotation. The current understanding of the productivity of coppice crops in *E. globulus* pulpwood plantations is inadequate to allow firm conclusions. However, the use of low quality genetic material to establish the first rotation will increase the relative level of genetic gain available in seedlings at the start of the second rotation, and make replanting more attractive. If it is assumed that a coppice crop will produce yields roughly equivalent to the first rotation crop, then a grower should start to consider replanting with genetically improved stock if the increase in dry matter yield would exceed 15% over the already established plantation.

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