# DEVELOPING A EUCALYPT RESOURCE: LEARNING FROM AUSTRALIA AND ELSEWERE

WOOD TECHNOLOGY RESEARCH CENTRE

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# PREFACE

The Farm Forestry Association has been a principal torchbearer for planting eucalypts in New Zealand. Many species have been advocated and trialled. Of these only *Eucalyptus nitens* and *E. fastigata* have been extensively planted, neither of which is naturally durable.

This workshop explores the issues that need to be covered where a new species is to be introduced outside its natural range. While the issues are general, those organising this workshop have a specific interest in naturally-durable eucalypts suited to New Zealand drylands.

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# GENETICS OF EUCALYPTS: TRAPS AND OPPORTUNITIES

## 1. INTRODUCTION

Eucalypts are amongst the most planted hardwoods in the world (Doughty 2000). They are native to Australia and islands to its north (Ladiges *et al.* 2003) where they occupy diverse ecological habitats ranging from sea level to the alpine tree line, from high rainfall to semi-arid zones, and from the tropics to latitudes as high as 43° south (Williams and Woinarski 1997). In habit they vary from shrubs and multi-stemmed mallees, to giant trees (Hickey *et al.* 2000; Nicolle 2006), and include the tallest flowering plants on earth (*Eucalyptus regnans* – 99.6 metres, http://www.gianttrees.com.au/). They are generally sclerophyllous, and adapted to low nutrient soils and fire (Ashton 2000; Eldridge *et al.* 1993; Florence 1996). In the broad-sense, eucalypts encompass species of the genera *Eucalyptus* L'Hérit., *Corymbia* Hill and Johnson and *Angophora* Cav. (Ladiges 1997; Appendix 1). A key feature of the majority of *Eucalyptus* (*sensu stricta*) and *Corymbia* (bloodwoods) is the fusion of either the petals and/or sepals to form an operculum from which the eucalypts derive their name (Eldridge *et al.* 1993; Ladiges 1997). The latest formal taxonomic revision of eucalypts (Brooker 2000) recognizes just over 700 species that belong to 13 main evolutionary lineages (subgenera/genera; Appendix 1), and EUCLID (Euclid 2006 - an important electronic resource for practitioners) lists 894 eucalypt taxa. The major subgenera exhibit different ecological and reproductive characteristics (Florence 1996; Ladiges 1997; Harwood 2011 this volume) and closely related species are usually ecologically differentiated (Florence 1996; Williams and Woinarski 1997).

Most eucalypt species belong to the subgenus *Symphyomyrtus,* and it is mainly species from three sections of this subgenus that are used in plantation forestry world-wide (Appendix 1; see Harwood this volume). This is certainly the case in Australia where there has been a major expansion of the eucalypt plantation estate in the last two decades. This eucalypt plantation estate reached 0.92 million ha in 2010 and is approaching the area of softwoods (Gavran and Parsons 2011). Most Australian eucalypt plantations occur in temperate regions and the estate is dominated by *Eucalyptus globulus* (58.4%; i.e. 538 000 ha) and *E. nitens* (25.5%, i.e. 235 000 ha) (Gavran and Parsons 2011). There are breeding and deployment programs in Australia and overseas for both *Eucalyptus globulus* (Potts *et al.* 2004) and *E. nitens* (Hamilton *et al.* 2008). These species are mainly grown for pulpwood. However there is increasing interest in producing solid wood products (e.g. sawn timber, veneer, composites) from these plantations (Nolan *et al.* 2005; Beadle *et al.* 2008; Wood *et al.* 2009; Washusen 2011; Welsford and Henson 2011). At least 7%

of the broadleaf plantations are managed for this purpose (Gavran and Parsons 2011), which includes Forestry Tasmania's solid wood estate of approximately 19 655 ha of *E. nitens* and 5462 ha *E. globulus* (Wood *et al.* 2009). We here overview some of the key genetic issues associated with the breeding and deployment of these industrial plantation species and recent research aimed at understanding the genetic opportunities for growing these species for solid wood products.

## 2. BREEDING OBJECTIVES

Tree breeding programs aim to improve the profitability and competitiveness of forest growers/processors through the genetic improvement of economically-important harvest-age traits. To maximize economic gains made though breeding it is important to i) identify the breeding objective (i.e. what you are breeding for); ii) identify the most important harvest-age traits affecting this objective (i.e. the objective traits); and iii) apply appropriate weights to each of these traits. This is best achieved through bioeconomic modeling of costs (land, establishment, management, silvicultural, harvesting, transport, processing) and revenues (potentially from different product classes of varying value) of production systems (Ponzoni and Newman 1989; Raymond and Apiolaza 2004). Traits such as pest and disease resistance, adaptability traits (e.g. frost resistance, drought resistance) and survival are only important as far as they impact on one or more objective traits and their incorporation into breeding programs requires an understanding of the frequency, intensity and impact of the associated biotic and abiotic threats across the plantation estate (Dutkowski *et al.* 2007).

Breeding objectives, objective traits and economic weights evolve with changes in understanding of production systems and harvest-age traits, silviculture (e.g. seedling to coppice (Whittock *et al.* 2004), pulpwood to long-rotation solid-wood), processing techniques/technology (e.g. backsawn vs quartersawn, changes in sawmilling and drying technology - Washusen 2011), environment (e.g. expansion into marginal zones prone to frost, drought, climate change - ABARES 2011; exhaustion of historic water and nutrient reserves; new pests/diseases (e.g. Myrtle rust]) or changed frequency/intensity of outbreaks), markets and products (e.g. solid-wood, carbon trading, bioenergy - Whittock *et al.* 2007). Some organizations have multiple objectives, reflecting the diversity of their estate and/or targeted products (e.g. cold and mild sites, disease-prone and less disease-prone sites, pulpwood and solid-wood silviculture). In such cases, targeted deployment is often preferred, as a lower cost alternative to maintaining multiple breeding populations, particularly in cases where objectives are closely aligned (i.e. favorably and strongly genetically correlated) or where some objectives are only relevant to a small proportion of the estate (i.e. it is not unusual for enterprises to have multiple 'deployment objectives', while maintaining only one breeding objective and population).

Bio-economic modeling has identified volume production per hectare, wood density and pulp yield as key objective traits for vertically integrated enterprises producing eucalypt kraft pulp (Borralho *et al.* 1993; Greaves *et al.* 1996; Dutkowski *et al.* 2007). The economic weight placed on each of these traits varies amongst Australian growers. For example, some wood chip exporters do not place an economic weight on pulp yield as a premium is generally not paid for high pulp yield (Whittock *et al.* 2007), although it may become a threshold trait affecting market access in the future. However, in Australia where *E. nitens* and *E. globulus* breeding may involve joint evaluation (McRae *et al.* 2004a; Hamilton *et al.* 2008) or cooperative breeding (e.g. through the Southern Tree Breeding Association - McRae *et al.* 2004b), such differences in objectives amongst growers are often applied at deployment. Secondary wood property traits of interest to pulp producers include the quantity or quality of extractives or lignin in the wood that affect the economic and/or environmental cost of pulping (Raymond and Apiolaza 2004; Stackpole *et al.* 2011).

Defining breeding objective traits and economic weights is more problematic for solid wood systems than for pulpwood systems, due to:

- a lack of an established plantation-eucalypt solid-wood processing industry in Australia,
- the array of products (e.g. sawn timber, veneer, residues), silvicultural regimes, processing systems, and product values to be accounted for, and
- longer rotation intervals and associated uncertainty (Greaves *et al.* 2004a; Greaves et al. 2004b; Greaves *et al.* 2004a; Shield 2004; Washusen 2011).

In the face of such difficulties, eucalypt growers targeting solid wood products have, initially at least, focused on generic traits (adaptability, form, etc), although numerous wood properties are known to affect the recovery and value of sawn timber, veneer and composite wood products (Table 1).

The yield of plantation logs suitable for solid-wood processing is strongly dependent upon silviculture (Washusen 2004; Nolan *et al.* 2005; Beadle *et al.* 2008) and there are few genetics trials of *E. globulus* and *E. nitens* that have been managed using solid-wood silvicultural regimes (e.g. thinning, pruning). This has restricted most genetic studies of potential solid wood traits to closely-spaced, unpruned trials (Hamilton *et al.* 2007; Hamilton *et al.* 2010b; Blackburn *et al.* 2010), which raises the possibility of genetic by silvicultural interactions for some traits (e.g. wood shrinkage and collapse - Hamilton *et al.* 2009). While key traits affecting the yield of logs suitable for a given processing system (e.g. survival, growth rate, forking, stem straightness, branch size, log taper) are usually under some degree of genetic control (Hamilton and Potts 2008; Callister *et al.* 2011; Blackburn *et al.* 2010), their impact on profitability will in part depend on whether adverse genetic effects are alleviated through routine silvicultural treatments such as thinning and pruning. Green recovery, drying defects and product value from logs are, in turn, affected by wood properties (Table 1), many of which are also known to be under a degree of genetic control (Kube and Raymond 2005; Greaves *et al.* 2004b; Hamilton *et al.* 2007; Hamilton *et al.* 2009; Hamilton *et al.* 2010b; Blackburn *et al.* 2010). Wood properties can impact multiple products in a favorable or adverse manner. For example, improvement in a trait such as wood density is likely to be favorable for multiple product types, at least in *E. nitens* (Kube and Raymond 2005).

*Table 1*. Wood properties affecting recovery and value for different product types (see also Raymond 2002).

| *Pulp and paper* | *Sawn timber* | *Veneer, plywood and laminated veneer lumber (LVL)* |
|---|---|---|
| Basic density, pulp yield/cellulose content, lignin content and composition, extractives content, fiber dimensions, | Green recovery (growth stress, log end splits, decay)<br>Dried recovery and value (knot size, checking, shrinkage, collapse, board distortion, strength and stiffness, density, hardness, dimensional stability, durability, sapwood-heartwood ratio, colour and colour variation) | Green recovery (growth stress, log end splits, decay)<br>Dried recovery and value (knot size, veneer splitting, shrinkage and shrinkage variation, density, strength and stiffness, bond strength and glue usage, roughness, colour and colour variation) |

## 3. CHOICE OF SPECIES

Choice of species based on breeding objectives and breeding objective traits (Table 2) may have a major impact on breeding and deployment. There are large differences in reproductive biology, potential for vegetative propagation and silvicultural options between *E. globulus* and *E. nitens* (Table 2). For example, as *E. globulus* coppices well, many plantations are not replanted but are managed as a coppice crop (Whittock *et al.* 2004). This option is not available with *E. nitens* which does not coppice as well (Little and Gardner 2003), and plantations are normally re-established using seedlings. Extensive studies of the reproductive biology and mating systems of these two species have been undertaken in order to optimise breeding and deployment (see *E. globulus* - Potts *et al.* 2008*; E. nitens* - Hamilton *et al.* 2008).

As with most eucalypts, *E. globulus* and *E. nitens* are animal pollinated, but the type and efficiency of pollinators may vary (Hingston *et al.* 2004c; Hingston *et al.* 2004b; Hingston *et al.* 2004a). For example, the large-flowered *E. globulus* is pollinated by both birds and insects, and the pollination behaviour of birds is thought to result in higher outcrossing in the upper canopies of both native and seed orchard trees in Tasmania. Birds were not observed feeding from the small flowers of *E. nitens* in Tasmanian seed orchards, and despite suggestions that the introduction of honey bee hives would increase outcrossing rates and seed set, honey bees were rarely observed feeding from small flowers of *E. nitens* in a study by Hingston *et al.* 2004a. Flowers however were consistently well pollinated by the suite of small native insects visiting the flowers.

Both *E. globulus* and *E. nitens* have a mixed mating system, but are generally preferential outcrossers. While average seed set is reduced following self-pollination

*Table 2.* Characteristics which favour the planting of *E. nitens* or *E. globulus* in Tasmania.

| *Eucalyptus globulus* | *Eucalyptus nitens* |
|---|---|
| Adaptive | |
| • More drought resistant[1]<br>• Greater water use efficiency[2]<br>• More resistant to *Phytophthora cinnamomi*[3]<br>• Less prone to copper deficiency[3] | • Generally more rapid site occupancy[4]<br>• Greater frost resistance and cold hardiness[5]<br>• Less prone to gum leaf skeletonizer[3]<br>• Greater resistance to Mycosphaerella leaf disease[6] |
| Pulping and paper making* | |
| • Generally greater kraft pulp yield[7,8,9,10]<br>• Higher wood basic density[8,9,10,11] | |
| Solid-wood, veneer and composite | |
| • Less internal checking in sawn boards[12,13]<br>• Greater wood strength, stiffness and hardness[11]<br>• Better shedding of dead branches[14] | • Less prone to tension wood formation and associated drying defects[13]<br>• Generally better early-age stem straightness[4,15] |
| Reproductive and deployment | |
| • Easier and quicker to grow seedlings in container nurseries (larger seed, easier to sow, grows larger seedlings in a shorter time)[14]<br>• Stronger coppicing ability[16,17]<br>• Easier to artificially pollinate[18,19] but exhibits unilateral cross incompatibility with smaller flowered taxa[20]<br>• Can be mass pollinated for deployment[18]<br>• Easier to propagate by hardwood cuttings [21] | • Easier to graft and less graft incompatibility[14,22]<br>• Open-pollinated seed orchards easier to manage[14]:<br>- More flowers and seed per tree or hectare[14]<br>- More overlap in flowering time[23,24] |

[1]White *et al.* 1996; [2]Honeysett *et al.* 1996; [3]Wardlaw 2010 (but see Potter and Stephens 2005); [4]pers. comm. D. Williams; [5]Hallam *et al.* 1989; [6]Mohammed *et al.* 2003; [7]Beadle *et al.* 1996 [8]Downes *et al.* 2006; [9]Kibblewhite *et al.* 2000; [10]Williams *et al.* 1995; [11]McKinley *et al.* 2002; [12]Innes *et al.* 2008; [13]Washusen 2011; [14]pers. comm. K. Joyce; [15]pers. comm. C. Harwood; [16]Little and Gardner 2003; [17]Whittock *et al.* 2003; [18]Venter and Silvlal 2007 [19]Williams *et al.* 1999; [20]Gore *et al.* 1990; [21]de Little 2004; [22]pers. comm. R. Griffin; [23]Jones *et al.* 2011; [24]Barbour *et al.* 2006.

* Other pulp and paper qualities of *E. globulus* and *E. nitens* are compared in Cotterill and Brolin (1997). While not cited as a consideration in Tasmania, overseas experience (pers. com. R. Griffin) suggests that *E. globulus* produces paper with higher tear strength and better porosity, whereas *E. nitens* is easier to refine and consumes less energy (see also Cotterill and Brolin 1997).

compared to unrelated outcrossing, open pollinated seed collected from native stand and seed orchard trees still contain significant proportions of self-pollinated seed. Averaged across 23 species the outcrossing rate in eucalypts in the wild is 0.74 (Byrne 2008), and recent native population estimates for *E. globulus* range from 65-89% (Mimura *et al.* 2009) and seed orchard estimates from 60 to 92% (Potts *et al.* 2008). Only seed orchard estimates of outcrossing rates have been published for *E. nitens* but these range from 0.75 to 0.87 (reviewed in Grosser *et al.* 2010). Both species exhibit severe inbreeding depression for growth and survival (Hardner and Tibbits 1998; Costa e Silva *et al.* 2010b; Costa e Silva *et al.* 2010a; Costa e Silva *et al.* 2011a). Virtually all *E. globulus* and *E. nitens* plantations in Australia are established using seed-derived plants and minimising the levels of self pollination has been an important objective. The cost of artificial pollination of *E. globulus* has been markedly reduced through the development of single-visit cut-style techniques (single-visit pollination, SVP - Williams *et al.* 1999; one-stop pollination, OSP - Harbard *et al.* 1999) which has allowed most breeding to be done through control pollination to provide full pedigree control. These techniques have also allowed the development of manual pollination techniques (e.g. mass supplementary pollination; MSP) for large-scale seed production to minimise selfing and to allow deployment of elite full-sib or mixed families (Potts *et al.* 2008). Despite numerous attempts, the cut style technique has not been successful with *E. nitens* (Williams *et al.* 1999), making it relatively expensive to control pollinate. While improved *E. globulus* seed is produced from open-pollinated (OP) seedling or grafted seed orchards as well as mass supplementary pollination, the later option is not available with *E. nitens*.

## 4. DEFINING THE GENEPOOL

The main breeding strategies used for genetic improvement of both *E. globulus* and *E. nitens* in Australia (McRae *et al.* 2004b; Li *et al.* 2007; Hamilton *et al.* 2008) and overseas (Griffin 2001) exploit genetic variability through single-species population genetic improvement. However taxonomically defining the base population used for genetic improvement is important (see, for example, Shepherd this volume) but has proved problematic in both species. Within species, marked genetic differentiation between populations is the norm rather than the exception (Pryor and Johnson 1971; Pryor and Johnson 1981; Potts and Wiltshire 1997). Genetic variation between populations in quantitative traits is often continuous and clinal, paralleling environmental gradients associated with changes in, for example, latitude, continentality or altitude (Pryor and Johnson 1981; Potts and Wiltshire 1997; Dutkowski and Potts 1999; Butcher *et al.* 2009). Many recognized eucalypt species intergrade resulting in complexes of closely related species where no clear morphological discontinuity is apparent (see Shepherd this volume). This is the case with *E. globulus* which is part of a complex of four closely related taxa (*E. globulus*, *E. pseudoglobulus*, *E. bicostata* and *E. maidenii* - Brooker 2000) variously given species or subspecies status (Jordan *et al.* 1993). The cores of these taxa are morphologically and geographically distinct, but linked by morphologically and geographically intermediate (intergrade) populations (Jordan *et al.* 1993; Jones *et al.*

2002). The main populations sampled for breeding programs around the world are core *E. globulus* and *E. globulus* intergrades (Jordan *et al.* 1993). Intergrade populations which are difficult to assign to a specific taxa caused problems in early seed collections where, for example, one collection locality was classified as *E. bicostata*, *E. globulus* and *E. pseudoglobulus* by different seed collectors (Jones *et al.* 2002). This issue is confounded by the fact that morphology often does not reflect underlying molecular affinities (Jones *et al.* 2002; Jones 2009). Three main molecular lineages have now been identified within the founder base population germplasm used in *E. globulus* breeding programs that strongly reflect geographic proximity (Jones *et al.* 2006; Steane *et al.* 2006). In the case of both *E. globulus* and *E. nitens* the broad-scale variation in the native gene pools has now been summarised using a hierarchy of geographic races, subraces and collection locality information based on quantitative genetic and geographic information (Dutkowski and Potts 1999; Hamilton *et al.* 2008).

In the case of *E. nitens*, two issues have complicated the exploitation of the base populations used for *E. nitens* breeding. Firstly, the founder native trees sampled in earlier collections encompassed phenotypes initially classified as *E. nitens* var *errinundra* by Pederick (1979), but subsequently classified as a separate taxon *E. denticulata* (Cook and Ladiges 1991). This taxon is mainly confined to the Errinundra region in eastern Victoria but some phenotypes are interspersed within predominantly *E. nitens* populations in central Victoria (Hamilton *et al.* 2008). More recent seed collections have avoided *E. denticulata*-like phenotypes (Dutkowski *et al.* 2001b), but their separation from *E. nitens* seed lots in data collected or reported from older trials has not always been possible (Hamilton *et al.* 2011). Secondly, further to characterising *E. denticulata*, Cook and Ladiges (1991), defined three genetically distinct races of *E. nitens* (i) Central and Northern NSW, (ii) Southern NSW and Mt Kaye, and (iii) Central Victoria. Dutkowski *et al.* (2001), later separated the Central Victorian race into three additional races - Northern, Southern and Connnor's Plain. The boundaries of these new races do not correspond neatly to those of the previous provenance classification of the same area (Pederick 1979), making exact comparisons across studies challenging.

Experience with the base populations of *E. globulus* and *E. nitens* has emphasised the importance of maintaining information on founder tree morphology as well as precise geographic origin. Such information is now easily collected and maintained with digital photographs (of tree habit and morphology) and accurate GPS information. Given the costs of field sampling and reducing costs of DNA studies, the collection and storage of foliar samples from trees sampled for seed collection is also warranted for assessing relationships (Shepherd this volume), future quality control (Vaillancourt *et al.* 1998; Faria *et al.* 2010) and potential use in molecular breeding (Section 8).

## 5. CHOICE OF PROVENANCE

Base populations for breeding *E. globulus* and *E. nitens* have been established from large-scale single-tree, open-pollinated seed collections from many localities within their native ranges (Eldridge *et al.* 1993; Potts *et al.* 2004; Hamilton *et al.* 2008). In many cases, these collections have been distributed across breeding organisations leading to numerous trials with shared pedigrees, and possibilities for joint analyses (Costa e Silva *et al.* 2006), cooperative breeding (McRae *et al.* 2004b) and/or joint evaluation (McRae *et al.* 2004a; Kerr *et al.* 2008). Genetic evaluations of base populations account for spatial genetic structure in the founder generation using genetic groups. Genetic groups are traditionally reported as "provenances" in forest tree studies, but in the case of both *E. globulus* and *E. nitens* where the native gene pools have been extensively studied, it is the race or subrace classification which is usually used (see Section 4).

Numerous studies of the quantitative genetic variation within *E. globulus* and *E. nitens* have been published from base-population trials (reviewed for *E. nitens* by Hamilton and Potts 2008 and for *E. globulus* by Dutkowski and Potts 1999; Potts *et al.* 2004; see also Stackpole *et al.* 2010b; Stackpole *et al.* 2011; Hamilton *et al.* 2010a). These studies provide information on the genetic architecture of the native forest gene pools as well as the basic information required for genetic improvement. As with most eucalypt species studied (Potts and Wiltshire 1997), there is considerable provenance (race/subrace) variation within *E. globulus* and *E. nitens* which impact on all stages of breeding and deployment from reproduction to product value. For example, during the rapid expansion of the *E. globulus* estate in Australia in the 1990's large amounts of seed were obtained directly from native forest due to the shortage of improved seed-orchard seed. As the subraces differ significantly in breeding objective traits for pulpwood production, Apiolaza *et al.* (2005) estimated that choice of subrace could alter Net Present Value (NPV) of plantations by as much as AU$2129 per hectare, effectively the difference between profit and loss. Notable examples of where genetic-based differences amongst native stand races or subraces impact the forest production system are given below.

### *5.1. Reproduction*

Studies of the reproductive biology (including pollination ecology) and breeding systems have been important for understanding the limits to genetic evaluation using open-pollinated seed lots as well as development of efficient pollination and deployment systems for these species (see Hamilton *et al.* 2008 and Potts *et al.* 2008 for references prior to 2008). These include studies of the pollination ecology, breeding system (outcrossing rates and gene flow - Grosser *et al.* 2010; Mimura *et al.* 2009), self-incompatibility (McGowen *et al.* 2010), flowering time (Jones *et al.* 2011) and abundance, pollination techniques, as well as seed production (Suitor *et al.* 2008; 2009a; Suitor *et al.* 2009b; Suitor *et al.* 2010) and seed germination (Nair *et al.* 2009; Rix *et al.* 2011).

While flowering time in *E. nitens* orchards is relatively synchronous, this is not the case for *E. globulus*. There may be up to 8 months difference in the peak flowering time amongst *E. globulus* genotypes, largely due to genetic-based differences between subraces (Gore and Potts 1995; Jones et al. 2011). This asynchrony has the potential to significantly reduce mating opportunities within open-pollinated seed orchards. A classic example relates to the two Bass Strait island races, King Island and Furneaux, which in early trials were grouped together into the same subline (Orme 1988) with a view to conversion to open-pollinated seedling orchards. These races have subsequently been found to differ in numerous traits (Dutkowski and Potts 1999) and the peak flowering of the King Island race is nearly 100 days later than Furneaux (Gore and Potts 1995). Genetic information is now available on flowering time, which has subsequently been used to better synchronize flowering within seed orchards. Flowering time limitations to cross-pollination are one of the advantages of mass supplementary pollination as opposed to relying on open-pollination in *E. globulus*. There is also evidence to suggest that subraces of *E. globulus* may differ in their degree of inbreeding depression (Costa e Silva *et al.* 2011a), which may differentially affect their performance under open pollination. Choice of provenance may also affect propagation costs. The subraces of *E. globulus* differ in flower and capsule size, as well as their reproductive output and seed characteristics in seed orchards. For example, one of the more favoured subraces - Strzelecki Ranges –has the smallest flowers and capsules, and in a seed orchard studied produced the smallest seed and lowest whole tree seed output (McGowen *et al.* 2004). This subrace has also been reported to be amongst the more difficult to propagate by hardwood cuttings (Cañas and Toval 2004).

### *5.2. Adaptability*

Growth and survival are fundamental to successful plantations, regardless of the product objective (Teulières *et al.* 2007). The longer the rotation and the greater the investment in plantation silviculture, the more important it will be to have well adapted germplasm. Often genetic effects may take several years to become evident following plantation establishment (Lopez *et al.* 2003; Costa e Silva *et al.* 2010b). While adaptive differences may be manifest early in the life cycle (e.g. frost susceptibility - Tibbits and Hodge 2003; Tibbits *et al.* 2006), there is increasing evidence of their ongoing expression, particularly with increasing competition following canopy closure and the onset of genetic-based size-dependent mortality (Chambers *et al.* 1996; Stackpole *et al.* 2010a; Costa e Silva *et al.* 2011a). Key pests and disease have been shown to impact growth and survival of both *E. nitens* and/or *E. globulus* (Battaglia *et al.* 2011), and when severe defoliation occurs their impacts will be embodied in later growth and survival measures both at a phenotypic (Rapley *et al.* 2009) and even genetic (Raymond 1995; Milgate *et al.* 2005; Jordan *et al.* 2002) level.

#### *5.2.1 Abiotic threats*

Large differences exist amongst the races of *E. globulus* and *E. nitens* traits associated with adaptation to the aboitic environment, and differences in susceptibility to factors such as frost and drought are evident. In *E. nitens* the more frost sensitive northern NSW races (Tibbits and Hodge 2003) grow better in summer rainfall zones, whereas the Victorian races perform better in winter rainfall zones

(Hamilton *et al.* 2011). The races of *E. globulus* differ in drought resistance (Dutkowski 1995), which in part explains their differential performance in trials across southern Australia (Costa e Silva *et al.* 2006).

### *5.2.1 Pests and diseases*

Variation in pest (insect and mammals) and disease risk occurs both temporarily and spatially across the plantation estates of *E. globulus* and *E. nitens* in Australia (e.g. Mohammed *et al.* 2003; Pinkard *et al.* 2010), as well as following silvicultural treatments such as pruning (Pinkard *et al.* 2004; Wiseman *et al.* 2006). Many of the Australian pests of these species have also become established overseas, including the brushtail possum in New Zealand (O'Reilly-Wapstra and Cowan 2010). Plantations within Australia are also at risk from introduced pests and diseases, no better exemplified by the recent introduction and spread of Myrtle Rust (*Uredo rangelii*) in Australia (http://www.dpi.nsw.gov.au/biosecurity/plant/myrtle-rust). This newly described pathogen of the family Myrtaceae has close links to the eucalypt guava rusts of South America which affects plants belonging to the family Myrtaceae, including eucalypts.

Provenance differences in susceptibility to pests (e.g. insects - Jordan *et al.* 2002, mammals - O'Reilly-Wapstra *et al.* 2002; Miller *et al.* 2011), diseases (e.g. Mycosphaerella leaf disease (MLD) caused by *Teratosphaeria* species - Milgate *et al.* 2005; Carnegie and Ades 2005) and susceptibility to wood decay have been reported in *E. globulus* (Poke *et al.* 2006; Hamilton *et al.* 2007). Decreased wood decay in one study (Poke *et al.* 2006) was associated with increased wood extractives at the provenance level (Stackpole *et al.* 2011). At an holistic community level, genetic-based differences between races of *E. globulus* have been shown to affect the composition of insect and fungal communities that develop on canopy foliage (Barbour *et al.* 2009c), under trunk bark (Barbour *et al.* 2009b) and even in decaying litter beneath trees (Barbour *et al.* 2009a).

Adverse genetic effects arising from such biotic factors can potentially contribute to genotype by site interactions and make some provenances unsuitable for planting in high risk areas. For example, the low defensive chemistry of the St. Helens provenance of *E. globulus* appears to account for its atypically high susceptibility to marsupial browsing (O'Reilly-Wapstra *et al.* 2002; O'Reilly-Wapstra *et al.* 2004; O'Reilly-Wapstra *et al.* 2005) and unsuitability for growth in southern Tasmania (Volker and Orme 1988). Several approaches are being used to reduce marsupial browsing damage in plantations, including seedling protection with stockings or repellent (Miller *et al.* 2008). However, genetic based differences in susceptibility are more persistent and there are direct and indirect (defensive chemistry) screening approaches for genetic improvement (Miller *et al.* 2009; Miller *et al.* 2011).

### *5.3. Pulpwood traits*

There are numerous studies demonstrating significant variation between the races of *E. globulus* and *E. nitens* in wood property traits affecting the pulpwood breeding objective. The key breeding objective traits related to wood properties are basic density and percentage pulp yield for both species. A review of published results from 11 trials (Hamilton *et al.* 2011) indicated that the significant differences in basic density between the *E. nitens* races were mainly due to the extreme low and high basic density of southern and northern NSW races, respectively. There was no consistent difference in basic density between the three Victorian races, which are the focus of *E. nitens* breeding for the winter rainfall zones in Australia. In *E. globulus* there is significant subrace variation within the base population for basic density with the mainland subraces tending to have higher basic density than King Island and most Tasmanian subraces (Dutkowski and Potts 1999; Stackpole *et al.* 2010a; Stackpole *et al.* 2010b). This has led to a focus on the mainland subraces of *E. globulus* for breeding (Jones *et al.* 2006). There are few published studies of the genetic variation in pulp yield in either species (e.g. *E. nitens* - Williams *et al.* 1995; Tibbits and Hodge 1998; Hamilton *et al.* 2011; *E. globulus* - Williams *et al.* 1995; Stackpole *et al.* 2010b). However, a recent study of an *E. globulus* base-population trial has shown significant variation in pulp yield between subraces with the highest pulp yield observed in the King Island and southern Tasmanian subraces (Stackpole *et al.* 2010b). Such large-scale information has not been previously available and if shown to be consistent at other sites will mean that the economic value of germplasm from these subraces may have been underestimated. This finding demonstrates the importance of large-scale studies, the potential changes in the economic value of germplasm which can occur as more information is obtained, and the value in long-term maintenance of base population trials.

### *5.4. Solid-wood traits*

There are few studies of the genetics of traits in *E. globulus* and *E. nitens* which are specific to a solid wood objective. Nevertheless, the few available suggest that the choice of provenance will not only affect solid wood product recovery but also quality. Recovery from trees or logs will be affected by stem straightness, forking, branchiness and taper. The three key Victorian races of *E. nitens* (Northern, Southern and Connors Plains) differ in stem straightness, log taper and predicted green board recovery, with the Southern race best on all traits (Blackburn *et al.* 2011a). A processing study also showed that the Connors Plain race produced boards of lower stiffness (Blackburn *et al.* 2010). While no significant race differences were detected for basic density, or board checking in Blackburn *et al.* (2010), studies of cores suggest that the *E. nitens* races do differ in the propensity for shrinkage (total volumetric) and collapse (McKimm 1985; Hamilton *et al.* 2011). Tension wood is one of the main factors believed to cause drying defects in *E. globulus* boards (Washusen 2011), and a study of 10-year old trees reported a higher proportion of tension wood and collapse in the Jeeralangs, one of the races with high basic density that is most favoured for pulpwood plantations, compared with the low density King Island race (Washusen and Ilic 2001). Board properties are altered by sawing pattern and in a study of 15-year old trees, Hamilton *et al.* (2010b) showed significant differences amongst races in the internal checking observed in quartersawn but not backsawn boards. Nevertheless, these genetic studies have been undertaken on unpruned and unthinned trials and the repeatability of observed differences in collapse, shrinkage and checking remain to be determined on other sites and under different silviculture regimes.

## 6. EXPLOITING VARIATION WITHIN PROVENANCES

While large and rapid genetic gains can often be made from exploiting the natural genetic variation which exists amongst provenances of a species (e.g. subraces/races - the genetic groups used in statistical analyses), substantial genetic variation also resides within provenances which can also be exploited for genetic improvement (Eldridge *et al.* 1993). From a quantitative genetics perspective, this variation may include both additive and non-additive genetic components. Only the additive genetic component can be exploited for ongoing population improvement but the non-additive genetic component in any one generation can be captured for deployment, along with the additive component, by cloning or use of full sib-families (e.g. mass supplementary pollination) (Eldridge *et al.* 1993). For base populations, the additive component of genetic variation is usually assessed from the pooled within-provenance variation amongst open-pollinated families and is assumed to represent the additive genetic variation which exists within a random mating population in the wild. The narrow-sense heritability ($h^2$) of a trait derived from such a partition represents the proportion of the phenotypic variation within provenances which are under additive genetic control. When the narrow-sense heritability has been estimated based on open-pollinated progeny the symbol $h^2_{\mathrm{op}}$ is used to indicate that the calculations make assumptions regarding the average relationship amongst open-pollinated sibs (i.e. they are not all unrelated half-sibs).

The reported heritabilities for a given trait may vary depending upon numerous factors, but meta-analyses are revealing a generalised picture of $h^2_{op}$ within base population trials of both *E. globulus* (Potts *et al.* 2004) and *E. nitens* (Hamilton and Potts 2008). While most traits and most trials tend to exhibit statistically significant $h^2_{op}$, on average the heritability of growth, survival, animal browsing and tree architecture traits tend to be lower than that of wood property, reproductive and developmental traits. For example, in *E. nitens* the average heritabilities for growth traits (e.g. average $h^2_{\mathrm{op}} = 0.26$ for diameter) were generally lower than those for wood property traits (e.g. average $h^2_{\mathrm{op}} = 0.51$ for basic density) (Hamilton and Potts 2008). Breeders also need knowledge of the stability of this genetic variation across ages (age-age correlations) and across sites (genotype x environment interactions – GxE) as well as an understanding of the genetic association amongst traits (Eldridge *et al.* 1993; Callister *et al.* 2011). This knowledge is usually obtained from calculating the additive genetic correlations ($r_a$) for the same trait measured at different ages or on different sites as well as between different traits. Age-age correlations for growth and wood density are relatively high (Borralho *et al.* 1992; Stackpole *et al.* 2010a; Hamilton *et al.* 2010b) and four-year DBH is commonly used as an early selection trait (Borralho *et al.* 1992). Additive genetic correlations across sites estimated from open-pollinated families also tend to be relatively high in both *E. globulus* – (MacDonald *et al.* 1997; Costa e Silva *et al.* 2006; Callister *et al.* 2011) and *E. nitens* (reviewed in Hamilton and Potts 2008), arguing that selections undertaken on one site will be reasonably suited for another site. However, in *E. globulus* lower genetic correlations have been reported for growth at the subrace level suggesting significant genotype by environment interaction (see section 4.2).

Large-scale assessments are required to obtain robust genetic parameter estimates, particularly for genetic correlations. While this is feasible with many traits obtaining large sample sizes for traits which are technically difficult or expensive to assess is problematic and often leads to relatively imprecise estimates (see discussions in Stackpole *et al.* 2010b; Hamilton and Potts 2008). Nevertheless, this situation is rapidly changing with the advances in phenotyping, such as near-infrared (NIR) spectroscopy (Downes *et al.* 2010a; Downes *et al.* 2010b) and acoustic (Blackburn *et al.* 2010) technologies that can now be used non-destructively on standing trees to predict traits relevant to pulpwood and solid-wood value (e.g. Blackburn *et al.* 2010; Stackpole *et al.* 2010b). For example, NIR models have recently allowed large-scale non-destructive studies of genetic variation in pulp yield (Stackpole *et al.* 2010b) and wood chemical traits (lignin, cellulose, extractives, lignin and its syringil to guacin ratio [S/G] – Stackpole *et al.* 2011) in *E. globulus*. Technologies for assessing wood colour have also been tested with *E. nitens* (Raymond and Bradley 2002). In addition, despite increasing efficiencies in sampling wood cores for density and other measurements (Raymond *et al.* 1998; Stackpole *et al.* 2010a), Pilodyn penetration is still being used as a rapid, indirect measure of wood density (MacDonald *et al.* 1997; Raymond and MacDonald 1998; Callister and England 2010).

Sample size has certainly limited genetic studies of solid-wood objective traits. Nevertheless, efficiencies have been made in tracking tree and log identities through processing systems (Blackburn *et al.* 2011b), allowing board and veneer properties to be linked to tree pedigrees and potential selection traits. Already, a recent study of 496 trees has shown the stiffness and checking of *E. nitens* boards are under strong genetic control and amenable to genetic improvement (Blackburn *et al.* 2010). Wood stiffness and checking traits were more-or-less genetically independent, surface and internal checking were only moderately positively correlated, but while basic density was positively correlated with stiffness it was adversely correlated with surface check length. NIR models for predicting specific solid wood traits from standing tree samples are yet to be developed. Nevertheless, in *E. nitens*, standing tree acoustic wave velocity is proving useful. It is strongly genetically correlated with board stiffness and moderately positively genetically correlated with basic density (Blackburn *et al.* 2010). While associations with non-destructive techniques are yet to be identified, a strongly positive genetic correlation between internal board checking and checking in wedges taken from disks removed from felled trees has been shown in *E. nitens* (Blackburn *et al.* 2010). However in *E. globulus*, board checking has yet to be shown to be significantly genetically correlated with potential selection traits assessed from standing trees (Hamilton *et al.* 2010b).

As is typical of eucalypt species, most reported estimates of genetic parameters in *E. globulus* and *E. nitens* are derived from base population trials. Base population trials tend to be more numerous, and have larger numbers of individuals and founder parents than trials comprising control pollinated families. However, there are inaccuracies associated with parameter estimates from the open-pollinated families due to the unknown male parentage. Open-pollinated families may comprise variable levels of selfing, biparental inbreeding and unrelated outcrosses (Eldridge *et al.* 1993; Hardner *et al.* 1998). The performance of open-pollinated families may thus be affected not only by the additive genetic worth of the female, but also the females' outcrossing rate and inbreeding depression (Costa e Silva *et al.* 2010a; Bush *et al.* 2011). In *E. globulus*, outcrossing rates tend to be higher in seed collected from the upper canopy compared with the lower canopy (Patterson *et al.* 2001; Hingston and Potts 2005). There is also marked tree-to-tree variation in outcrossing rates (Patterson *et al.* 2004), which tend to be lower in fragmented (low density) than continuous forest (Mimura *et al.* 2009). Self-incompatibility (McGowen *et al.* 2010) is likely to be a key determinant of tree-to-tree variation in outcrossing rates, and assessing self-compatibility through controlled pollination and collecting seed from self-sterile trees is one option to avoid inbreeding in deployment seed lots. While progress has been made in terms of accounting for average selfing rates in genetic evaluation of open-pollinated progenies of eucalypts (Dutkowski *et al.* 2001a), it is difficult to account for variable outcrossing rates without parentage analysis (Burgess *et al.* 1996; Gea *et al.* 2007; Bush *et al.* 2011). Even then the impacts of variable inbreeding depression at the individual level will be difficult to predict (Costa e Silva *et al.* 2010a; Costa e Silva *et al.* 2010b). In addition, there is some evidence to suggest that inbreeding depression may induce site stability in open-pollinated family performance that has resulted in an underestimation of the importance of environment x genotype interaction from an additive genetic perspective (Costa e Silva *et al.* 2011a). However, the effects of inbreeding depression appear to be more an issue for growth and survival traits (e.g. Costa e Silva *et al.* 2010a) and more reliable predictions of genetic parameters and breeding values are likely with other traits of economic interest (e.g. wood properties, disease susceptibility – Potts *et al.* 2004).

The non-additive (dominance, epistasis and maternal) components of genetic variation can only be captured through family or clonal deployment and estimation of these effects requires crossing designs with full-pedigree control. Understanding the relative importance and nature of non-additive genetic effects is now possible, particularly with *E. globulus* where control-pollinated (CP) trials are increasing in number and size. This information is required, for example, to help decide whether to shift from open-pollinated seed orchards to more expensive clonal and full-sib family deployment strategies. For growth traits, studies of control-pollinated trials in *E. globulus* have indicated that open-pollinated heritability estimates are inflated compared with control-pollinated estimates (Hodge *et al.* 1996; Volker 2002; Costa e Silva *et al.* 2010a), but to date this trend is not evident in *E. nitens* (Hamilton and Potts 2008). In *E. globulus*, breeding values for growth traits are poorly correlated between control- and open-pollinated populations (Hodge *et al.* 1996; Volker 2002; Costa e Silva *et al.* 2010a). Significant dominance variation has also been reported within many (Volker 2002; Li *et al.* 2007; Callister *et al.* 2011), but not all (Lopez *et al.* 2003; Costa e Silva *et al.* 2004), *E. globulus* populations studied. Non-additive effects for growth have also been reported for inter-provenance $F_1$ crosses of *E. globulus* which are positive, ranging from mid-parent (Volker *et al.* 2008) to better parent (Lopez *et al.* 2003) heterosis, and may partly reflect mild levels of inbreeding in local populations (Hardner *et al.* 1998). However the pattern of expression of inter-provenance $F_1$ heterosis needs to be better understood. It is also unclear whether these positive effects of inter-provenance crossing will persist in subsequent generations due to the possibility of outbreeding depression (see Shepherd this volume).

## 7. HYBRIDISATION

The major eucalypt subgenera do not hybridise but barriers to hybridization between species within subgenera are often weak (Griffin *et al.* 1988; Potts *et al.* 2003). Natural hybridization and introgression between recognized taxa is relatively common (Griffin *et al.* 1988; Potts and Wiltshire 1997; Butcher and Williams 2002; Field *et al.* 2011), and in some cases only detectable at the molecular level (McKinnon *et al.* 2001; McKinnon *et al.* 2004).

Artificial hybridisation has been widely used as a breeding strategy in eucalypts in subtropical and tropical regions of the world but to a lesser extent in temperate regions (Potts and Dungey 2004; see also Harwood this volume). While there has been extensive research on artificial hybridisation of *E. nitens* and *E. globulus* in Australia (Potts *et al.* 2000; Potts and Dungey 2004; Tibbits 2000; Meddings *et al.* 2003; Lopez *et al.* 2000), high costs of development and clonal propagation have meant that such germplasm has generally not been developed commercially in Australia. An exception is the 'Saltgrow' hybrids involving *E. globulus*, which have been developed for environmental plantings (Dale and Dieters 2007; Hardner *et al.* 2011).

While $F_1$ hybrid clones between *E. globulus* and *E. nitens* have been developed in Chile (Griffin 2001), attempts to develop such hybrids in Australia have not come to fruition, partly due to difficulties in clonal propagation (Tibbits 2000). However the genetics of this hybrid combination have been well studied. In the early 1990's large crossing programs were undertaken by both CSIRO and North Forest Products Ltd (now part of Gunns Ltd) to develop hybrids between these two species with the aim of developing germplasm with the pulpwood qualities of *E. globulus,* which could be planted on higher altitude colder sites. The first generation hybrids were expensive to produce as the cross could only be obtained using the small-flowered *E. nitens* as the female parent. This unilateral barrier appeared to be physical and due to the pollen tubes of *E. nitens* being unable to grow the full length of the large *E. globulus* style (Gore *et al.* 1990). The set of $F_1$ hybrid seed was low, high levels of abnormalities were observed in the nursery, the $F_1$'s exhibited increased susceptibility to possum browsing and poor survival in the field, although the success of hybridisation varied between the two *E. globulus* provenances tested (Dungey and Potts 2001; Volker *et al.* 2008). This crossing program is noteworthy as it used a relatively large number of parents of each species, and compared the performance of the hybrids against selfs, open-pollinated and unrelated outcrosses of the parental species. However, as the hybrids and pure species were planted in separate plots within each replicate of the field trial, high mortality of the hybrids resulting in a lower competitive environment for survivors biased later-age cross-type comparisons. Second generation hybrids (backcrosses and outcrossed $F_2$'s), were later produced and planted along with $F_1$ and pure species crosses at two sites, but using a single-tree plot design to avoid survival biasing cross-type means. At both sites the $F_2$'s exhibited poor mean survival compared to the pure species and the backcrosses were intermediate (Potts *et al.* 2003; Costa e Silva *et al.* 2011b) and at both sites the top families at age 14 were from the pure species (B. Potts unpubl. data). These hybrid populations exhibited severe outbreeding depression which increased with age, and appeared to be mainly due to adverse additive x additive epistasis (Costa e Silva *et al.* 2011b).

Another attempt to develop hybrid germplasm to extend the planting of *E. globulus* into colder areas involved crossing with the frost resistant species, *E. gunnii* (Potts *et al.* 2000). In this case trials were established along an elevation gradient. The $F_1$ hybrids in this case exhibited less abnormality and survival problems than the *E. nitens* x *globulus* hybrids but only outperformed *E. globulus* at the highest altitude site where the pure species was heavily damaged by frost. However at this highest altitude site, the performance of the $F_1$ hybrids were well below the routine *E. nitens* plantation seedlings included as a control.

## 8. MOLECULAR BREEDING

There have been major advances in eucalypt genomics and marker technologies in the last year which are leading to a rapid increase in our understanding of the eucalypt genome and opportunities to link genes to phenotypic variation of adaptive and economic significance (Poke *et al.* 2005; Grattapaglia and Kirst 2008; Myburg *et al.* 2008; Mamani *et al.* 2010). Following acceptance of a proposal from the international eucalypt genetics network EUCAGEN (http://web.up.ac.za/eucagen/), an assembled genome of *E. grandis* was generated and released into the public domain by the US Department of Energy's Joint Genome Facility in April 2011 and an *E. globulus* genome has been re-sequenced (see http://web.up.ac.za/eucagen/). There has simultaneously been increasing release of other genomic resources for eucalypts into the public domain (e.g. Rengel *et al.* 2009; Mizrachi *et al.* 2010; Faria *et al.* 2011; Neves *et al.* 2011; Paiva *et al.* 2011). This expansion has been coupled with the recent development of the Diversity Arrays Technology (DArT) for eucalypts (Sansaloni *et al.* 2010; Steane *et al.* 2011). DArT has allowed cost-effective generation of high-density linkage maps (Kullan *et al.* 2011) to provide a framework for comparative mapping (Hudson *et al.* 2011), generation of a multi-species concensus map (C. Hundson unpubl. data), and the expansion and integration of quantitative trait loci (QTL) studies (Thumma *et al.* 2010) across multiple species. The sequenced DArT markers allow QTL to be linked to the *E. grandis* genome sequence to help identify candidate genes for association genetic and other genomic studies. Association genetic studies aiming to identify the molecular change (e.g. single nucleotide polymorphisms – SNP) underlying the phenotypic variation in many wood property traits are well advanced in both *E. nitens* and *E. globulus* (Thumma *et al.* 2009; Southerton *et al.* 2010; Thavamanikumar *et al.* 2011), although the stability of marker trait associations across pedigrees and environments is becoming a key research issue (Southerton *et al.* 2010). We are at the threshold of major advances which will see an increasing number of validated markers/trait associations available for traits of interest to breeders, and potentially the development of genome-wide strategies for selection (Grattapaglia and Resende 2011). An important challenge ahead will be to integrate this molecular information into current breeding programs in a manner which is cost efficient and competitive with advances in phenotyping technologies (Kerr *et al.* 2011). The near absence of non-destructive tests and high costs of phenotyping breeding objective traits associated with solid-wood products (e.g. board checking-Sexton *et al.* 2010) combined with the longer rotation time of such plantations, would no doubt make solid-wood objective traits prime targets for molecular breeding.

## 9. SUMMARY

In summary, clearly defined breeding objectives are required to efficiently exploit the vast amount of genetic diversity which resides within eucalypts at multiple levels. While such objectives and associated traits are relatively well defined for pulpwood production, technological changes in solid-wood products and production systems argues for an initial focus on the more generic objectives and traits. Species and provenance choices offer key opportunities for gains in the early phase of domestication, impacting on not only product quantity and quality, but breeding and propagation options. Understanding the genetic architecture and economic weights of traits is important for breeding, but requires assessment under appropriate silvicultural regimes.

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## 11. APPENDICES

Major evolutionary lineages within the eucalypts (modified from Myburg *et al.* 2007). The alignment of Pryor and Johnson's (1971) genera and subgenera with

Brooker’s (2000) subgenera. Pryor and Johnson’s classification was informal, but widely used for 30 years. The number of species in each of Brooker’s subgenera is indicated and examples of well-known forestry species are given. Most species used in plantation forestry (see Harwood this volume), particularly outside Australia are from Brooker’s sections *Maidenaria* (e.g. *E. dunnii*, *E. globulus*, *E. nitens*), *Exsertaria* (e.g. *E. camaldulensis*, *E. tereticornis*) and *Latoangulatae* (e.g. *E. grandis, E. pellita, E. saligna, E. urophylla*) in the subgenus *Symphyomyrtus*.

| Pryor & Johnson’s subgenera/genera | Brooker’s subgenera | No. of species | Examples of well-known forestry species |
|---|---|---|---|
| *Angophora* (genus) | *Angophora*[1] | 7 | |
| *Blakella* | *Blakella*[1] | 15 | |
| *Corymbia* | *Corymbia*[1] | 67 | *C. torelliana, C. citridora, C. variegata, C. maculata* |
| *Eudesmia* | *Eudesmia* | 19 | |
| *Gaubaea* | *Acerosa* | 1 | |
| *Gaubaea* | *Cuboidea* | 1 | |
| *Idiogenes* | *Idiogenes* | 1 | *E. cloeziana* |
| *Monocalyptus* | *Primitiva* | 1 | |
| *Monocalyptus* | *Eucalyptus* | 110 | *E. regnans, E. delegatensis, E. obliqua, E. marginata, E. fastigata* |
| *Symphyomyrtus* | *Cruciformes* | 1 | *E. guilfoylei* |
| *Symphyomyrtus* | *Alveolata* | 1 | *E. microcorys* |
| *Symphyomyrtus* | *Symphyomyrtus* | 474 | *E. camaldulensis, E. dunnii, E. exserta, E. globulus, E. grandis, E. nitens, E. paniculata, E. pellita, E. robusta, E. saligna, E. tereticornis,E. urophylla, E. viminalis,* |
| *Telocalyptus* | *Minutifructus*[2] | 4 | *E. deglupta* |

[1] The subgenera *Blakella* and *Corymbia* had previously been treated as a separate genus *Corymbia* Hill and Johnson and the subgenus *Angophora* treated as a genus (Hill and Johnson 1995) and this approach has been adopted in the text

[2] A recent molecular study suggests that these species belong within subgenus *Symphyomyrtus* (Whittock 2003)

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MICHAEL HENSON

# FAST-TRACKING GENETIC IMPROVEMENT

## 1. INTRODUCTION

The value of any tree improvement program is realised only when the genetically-improved material is deployed operationally, and the cash return is realized only upon the harvest of that material. The costs of the tree improvement program have to be carried by the company, co-operative or institute until the harvest of the improved material. For a tree improvement program to be viable, the annualised economic return from the program must be greater than the risk-adjusted discount rate for the project. Therefore, the quicker any genetic gain is deployed operationally the more profitable the tree improvement program.

Some tree improvement programs work in isolation of the commercial plantations, and the risk-averse nature of some researcher may result in a reluctance to deliver material for operational deployment until the material has been extensively tested. Many tree improvement programs follow rigid predefined recipes and a result often fail to take advantage of less traditional opportunities. There are risks in deploying material that has not been fully tested, but there are strategies that can be used to mitigate these risks as part of a well-designed and executed deployment strategy. The risks increase with a narrowing genetic base of the material being deployed; monoclonal blocks are very impressive when they work but are equally impressive when they do not. Developing an appropriate and economically-viable deployment strategy at the commencement of a genetic improvement program is essential to ensure the genetic gains realized can be delivered into operations. Researchers often focus on the newest or more complex technologies such as controlled pollination, biotechnology and clonal forestry, often paying less attention to simpler techniques that could deliver gains earlier in the life of the program.

Methods for delivering gain in a “greenfield” start-up genetic improvement program will differ from those used in a mature advanced-generation program. In the mature program the development of biotechnologies, such as genomics, can be used to accelerate the rate that genetic gain is transferred to operations.

## 2. TRADITIONAL TREE IMPROVEMENT

Most pedigree tree improvement programs follow a simple well-tried and tested recipe of testing and selection, which is then repeated for each generation. Material is tested as families. That is, seed from a know mother and a “random” father (half sib) or known mother and a known father (full sib). The trials are assessed at specific ages for characteristics of interest (selection traits) that relate to economically-important traits at rotation. Superior genetic material is then selected using a range of analytical methods, from simple visual selection to more complex multiple-trait and multiple-generation analysis. This material is used to form the base for the next generation of trials, often with other infused material. The very best genetic material is selected to produce material for operation deployment.

The level of genetic gain is a factor of numbers; the greater the number of individuals tested and the fewer the number of individuals selected for deployment the greater the genetic gain. However, with fewer individuals selected for deployment the higher the risks, as genetic diversity is reduced. A tree improvement program needs to balance genetic gains against risk when making any deployment decision; the decision should be influenced by the level and certainty of information of each genotype. Many researchers, in order to mitigate risks, seek to comprehensively test material for multiple traits and across sites and ages prior to recommending material for deployment. This results in high testing costs and extended periods of time for material to be developed prior to being deployed operationally.

The benchmark for short rotation high yielding hardwood plantations are the clonal eucalypt plantations in Brazil. The majority of Brazilian clones are hybrids such as *Eucalyptus grandis x urophylla*, and even today many of the clones deployed operationally in Brazil have not been selected from structured pedigreed tree improvement programs. Many of the clones have been selected from open pollinated hybrid seeds collected from historic mixed species plantings or from purpose-designed hybridising orchards. Large numbers of individuals were screened, with few selected for further testing and eventual deployment commercially. This has resulted in high selection intensities and associated genetic gains. It is interesting to note that, even today, clones originating from seed collected from trees planted in the early 1900s in Rio Claro, Sao Paulo state are being deployed commercially. Many of the genetics gains seen in Brazilian forestry are a result of opportunistic selection after the screening of large numbers of individuals and have not a resulted from structured pedigreed tree improvement programs. The Brazilian are using pedigreed tree improvement programs with the hope of delivering further genetic gains, but combine this with more opportunistic and "non-traditional" techniques. RIMA, a medium sized company (approx. 60,000ha) in northern Minas Gerais, which grows hybrid eucalypts to produce charcoal for use in the mineral reduction process, has successfully developed new clones with significant growth gains from selections made in stands grown from seed collected from monoclonal plantations (i.e. selfed seed). The collection of seed from monoclonal stands wouldn't be considered by most of the tree improvement programs operating in Australia and or New Zealand.

## 3. FAST TRACKING DELIVERY OF GENETIC GAIN

Advanced-generation tree improvement programs are normally managed to deliver relatively continuous genetic improvements for operational deployment. Although there are normally quantum changes in genetic gains between generations, organisations use a range of techniques to deliver interim gains between generations. In Vietnam the Forest Science Institute establish clonal trials of *Eucalyptus* and *Acacia* species that included clones selected from progeny trials. These clonal trials serve the purpose of identifying clones for commercial deployment. They are also being thinned, with the poorer performing clones removed from the trials. The trials are then used to produce seed for deployment which they consider as an interim improvement between generations.

In tree improvement programs serving a new plantation program, the rapid delivery of improved genetic material for commercial deployment is a bigger challenge. A greenfield operation needs to establish significant areas of commercial plantations early after the project's commencement to be commercially viable and attract investment. In this situation, the supporting tree improvement program needs to rapidly identify and/or develop improved material for commercial deployment. In a typical greenfield operation, the majority of the first rotation plantations will have been established prior to the first improved genetic material being developed by a traditional tree improvement program. Greenfield operations develop a variety of strategies to fast-tract the deployment of improved genetic material into their commercial plantations, these include:

- *Purchase of improved seed*. In many cases, improved seed can be purchased. Where possible, it is best to source the seed locally, but when this is not possible seed produced in areas with similar environmental conditions should be sourced. Seed from a variety of sources should be purchased and tested to identify the best seed source for commercial deployment. For bulk seed, early results from trials are often quite reliable. Where possible, improved family seed lots should be purchased to be included in, and fast-track the organisation's tree improvement program.
- *Utilisation of historic trials and information*. In many areas historic trials are available that can be utilised to obtain data on the performance of species and seedlots. In many cases, the trials have been abandoned and some detective work is required to obtain the best value from the trials. Seed and/or cuttings can be made from superior trees in these plantings. The seed can be multiplied in the nursery using mini cuttings.
- *Collection of seed from superior trees in plantations*. In many areas there are existing historic plantations. Normally, an agreement can be made to allow access to the plantations for the selection of superior trees. Seed can be collected from these trees and possibly felled to produce coppice for rooted cuttings for trials as clones. This selection technique has been shown to deliver significant gain to operational plantings. The seed is normally bulked prior to planting.
- *Development of seed stands*. If approval can be obtained from third-party plantation owners, then a stand of trees can be converted into a seed stand. Superior trees are selected and the other trees felled. If required, the seed can be bulked up in the nursery using cuttings.
- *Family forestry*. Seed collected from plantations, trials and seed stands can be established at a family level in progeny trials. These can be assessed relatively early, and groups of superior trees selected for deployment with the seed bulked, and multiplied in the nursery as rooted cuttings. The families should be deployed

as bulked seed lots to manage risk. The selections can be narrowed as the trials age and there is more certainty about the genetic worth of the material.

- *Use of tested clones*. In some regions with a well-developed plantation industry, it is possible to license or purchase tested clones that can deliver immediate genetic gains. It is also possible to import tested clones from other regions or countries but these should be tested in designed trials prior to commercial deployment.

In all the above, there is a degree of risk as the genetic material deployed often has not been comprehensively tested on the sites or with the silviculture of the commercial plantations. In most cases the risk can be mitigated by deploying a bulk/mixture of families or clones in each compartment, thus mitigating any potential losses if one or more of the selections have inferior performance. As more information is obtained regarding the individual genotypes' performance the mixture can be narrowed, increasing the potential genetic gain. This strategy has been applied in several greenfield operations and has yielded significant gains in the field.

The most highly improved seed is always the seed in least supply. In many species, small quantities of seed can be "bulked up" using family forestry strategies. The strategy is well developed with pines where often improved, controlled-pollinated families are bulked up using rooted cuttings. This method is now widely used for tropical acacia species in Asia, as *Acacia mangium* and *A. crassicarpa* demonstrate similar maturations issues as the pines. Some eucalypt species can successfully be cloned and maturation does not seem to be an issue in many species, even with mother plants in production over extended timeframes. Forest NSW did find probable maturation issues with *E. pilularis* where mother plants in mini-hedges developed from selected clones produced significantly less shoot material than mini-hedges produced from seed. The cuttings from the clonal mini-hedges also were slower to develop and had a lower rooting success than those taken from seedling hedges. This maturation issue presented a severe bottleneck for commercial clonal deployment of *E. pilularis* and to address this the company adopted a family forestry deployment strategy.

Clonal propagation has evolved from its inception in the 1970s when the French in the Congo and the Australians first began trialling root cuttings as a method of clonal propagation of eucalypts. The method was commercialised by the Brazilian company Aracruz and rapidly adopted across Brazil, originally relying on extensive clonal gardens where cuttings were collected from trees felled in commercial plantations, evolving to intensively-managed clonal gardens located in the nursery to the mini-cutting systems used by most operations today.

In China most eucalypt plantations are clonal and the much of the clonal planting stock is produced using tissue culture (*in-vitro* propagation). Labour costs are relatively low and economies of scale in large tissue culture labs make tissue culture an economically-viable option. Relatively few different clones are used in commercial plantations throughout China, and many of the commercial clones are related, sharing common ancestry. Not all clones perform well in tissue culture, and new protocols for *in-vitro* propagation may have to be developed for each new clone. China's reliance on tissue culture can present a significant barrier to the deployment of a new clone commercially, and may be part of the reason why the majority of commercial clones used in China were developed in the late 1980s and early 1990s. With rising labour costs and the entrance of large multi-national pulp companies in China it will be interesting to see if tissue culture remains the preferred propagation method for the production of commercial planting stock.

## 4. THE IMPORTANCE OF DEVELOPING THE APPRORIATE DEPLOYMENT STRATEGY

When designing a genetic improvement program it is essential to develop a deployment strategy in parallel. The deployment strategy will depend on factors such as:

- Can the species be cloned? If it can what percentage of genotypes can be cloned?
- Do clones of the species show signs of maturation that may result in reduction in performance and/or rooting?
- Does the species flower in the environment where it is grown? If not where does the species flower?
- How easily can the species be graft?

Three examples are presented below where tree improvement programs have failed to deliver early gains operational as a result not taking the deployment issues into account and the start of an improvement program.

- Shell Forestry developed a well planned and managed progeny trials of *E. dunnii* in Uruguay. The trials were assessed, and superior genotypes identified. *E. dunnii* does not root easily and commercial clonal deployment is not viable, nor does the species flower early or reliably in Uruguay. As a result the delivery of genetic gains to operations were considerably delayed, and 20 years on companies in Uruguay still use a proportion of wild seed for commercial deployment. In neighbouring Argentina, there are sites where *E. dunnii* flowers reliably at a young age. Had the Uruguayan companies established a replicate of their progeny trials or grafted clonal seed orchards in Argentina, the delivery of gains to the field would have dramatically improved. In Australia, Forests NSW as well as other companies planted commercial *E. dunnii* plantations in northern NSW, but located the clonal seed orchards on the NSW/Victorian border where the species reliably flowers at a young age. A similar strategy is adopted in China with the seed orchards located further north of the regions where *E. dunnii* is planted commercially.

- Some naturally occuring hybrids of *Corymbia variegata* and *Corymbia torrelliana* performed extremely well in some lower rainfall marginal sites of northern NSW and southern Queensland. The hybrid has also been reported to perform well in drier areas of Brazil. In the late 1990s there was a lot interest in the hybrid as a candiate for commercial plantations in northern NSW and southern QLD. The Queensland state government funded a program to develop the hybrid for commercial plantations. A tree improvement program, based on controlled crosses and progeny tests, resulted in the identification of superior hybrids. Rooting the hybrid and species as cuttings was known to be poor. However, several clonal trials were established. From these trials, a subset of the superior clones were selected for commercial deployment. The clones were provided to several commercial forestry nurseries for production. *Corymbias* in general do not root well as cuttings and few commercial plantations of the hybrids have been established in Australia due to the difficulties in producing planting stock in the nursery. One of the main advantages of the hybrid was its tolerance to shoot blight (*Quambaleria* sp.). However, heritability for shoot blight tolerance in the pure species *Corymbia variegata* is relatively high, and it is expected that improved seedlings from clonal seed orchards of the pure species selected for productivity and shoot blight tolerance will result in seed that is suitable for commercial plantations in areas impacted by a high incidence of shoot blight.

- A commercial pulp company in SE Asia, commenced a tree improvement program in the mid 1990s for *A. mangium* focused solely on the commercial deployment of commercial clones. Due to the poor coppicing ability of the species, the selection of superior trees was made in very young stands (18 months), and the trees pollarded at about 2m with cuttings collected from the pollard shoots. The material was established in clonal trials. In most of these trials the seedling controls perfomed better than the clonal material. In the mid-1990s there was some existing knowledge regarding maturation issues with *Acacia*. Yet the strategy implemented did not take account of this information and parallel progeny trials and orchards were not established. In 2003, the company reviewed its clonal program and developed a new tree improvement strategy that based on family forestry using improved seed. Unfortunately, as the company had previously solely focused on the development of clones, effectively the program had to start from zero and the company lost significant time in deploying genetically improved material.

In all of the three cases, the genetic improvement strategies would have differed if the deployment issues had been considered from the outset.

## 5. SUMMARY

Many tree improvement programs in Australia and New Zealand are very rigid, following a fixed recipe, and in many cases, more focus needs to be made on reducing the time to deliver gains to operations. Pedigreed progeny trials should form the back bone of any genetic improvement program. However, there is a range of opportunistic paths that can be investigated to deliver early gains. Researchers should look beyond their trials more often to identify superior material and deliver genetic gains to operations. Risk management strategies should be developed to allow researchers to make decision to deploy improved genetic material before the full testing cycle is complete. Biotechnology will provide a range of tools that can be used to fast track genetic improvement.

When developing any genetic improvement strategy, a deployment strategy should be developed in parallel to ensure that the genetic improvement can be deliver operationally in a cost effective manner. The strategy should be developed to suit the size and budget of the grower, as the goal of the tree improvement should be to deliver economic as well as genetic gains to the grower. In some cases, a single generation of improvement will provide the optimum level of economic return.

## 6. AFFILIATIONS

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## DAVID CLIFFE

# BEST NURSERY PRACTICE

## 1. INTRODUCTION

Over the last twenty-five years there has been an increase in large-scale plantings of *Eucalyptus* species in Australia as well as South Africa, Chile, Uruguay, Brazil, China and Portugal. This interest in the use of the genera, mainly for pulp production, has placed unprecedented demands on nurseries in these countries to produce high quality containerised seedlings and clones.

This paper attempts to present the experiences of one Australian nursery, Narromine Transplants, in it's efforts to better understand the idiosyncrasies of germination and propagation of the genera in an endeavour to produce high quality transplanting material for the Australian plantation industry.

## 2. PROPAGATION

### *2.1. Seedlings*

*Eucalyptus* seedling production in Australia, prior to the mid 1980s, followed the practice of sowing uncleaned and ungraded seed into community nursery trays. After germination, and approximately six weeks after sowing, the seedlings were “pricked in” to a final container. These containers were originally either wood or metal, usually a metal cylinder with an open bottom.

Eventually, plastic forestry tubes, usually with a semi-open bottom and later with integrated root trainers, replaced metal cylinders. Despite this development, nearly all seedlings were still pricked into the final container and there was still widespread incidence of root malformation due to the transfer process.

With the advent of the Speedling© tray in the late 1970s, designed for the propagation of vegetable seedlings which prior to this point were grown in seed beds or wooden flats, it seemed possible that trees could also be grown in small individual cells. South African nurseries were the first to test this theory in the mid 1980s and modified the polystyrene trays with a standard cell volume of 22 $cm^3$ and a depth of 75 mm to a volume of 50 $cm^3$ and a depth of 125 mm. Seedlings were still pricked in. In some instances the roots of *Eucalyptus* seedlings penetrated the polystyrene, however coating of the trays with copper paint limited this problem.

Narromine Transplants learned of this advance via a connection with the Speedling Corporation in America and also of the adaptation by the South Africans of the Fluid Drill system developed in the UK. This technique involved the pre-germination of seed, separating the non-germinated material from that which had germinated usually in sugar solutions and then sowing it via a fluid system, one germinated seed at a time into the final container.

At Narromine Transplants we figured there had to be a better way of germinating and transferring seedlings. The first step we took was to separate the actual seed from the abundant amount of extraneous matter that comes when *Eucalyptus* seeds are collected. Initially we did this with sieves but we also had access to a fractionating aspirator and for many of the species we were dealing with we managed to finish with a very clean sample. For others, particularly those of the subgenus *Monocalyptus*, mechanical separation was almost impossible and we incorporated a process of seed priming with sugar separation prior to the seed starting to germinate.

Sugar separation involves imbibing the cleaned seed either in aerated columns or under mist, in a controlled temperature environment. Treatment times vary according to species but anything between 48 and 120 hours may be required always to a point where the radical is on the verge of emerging. The seed is then immersed in a sugar solution, typically a concentration of 1kg per litre of water. The unimbibed seed and extraneous matter falls to the bottom and imbibed seed forms a layer near the surface, which can be skimmed off. The seed is then washed, surface-dried and sown. Bulk, partially cleaned samples of *E. pilularis* seed treated in this way increased germination from 12% to 53%.

Our next step was to try and sow single seeds using a needle seeder, either after mechanical separation or from the priming/sugar separation method, direct into the final container. This was only partially successful, mainly due to problems of intermittent germination that seem inherent with many *Eucalyptus* species.

By the late 1980s, new containers had come on the market that were specifically designed for tree propagation. As well, developments in the ornamental nursery industry had produced cell trays with a volume of only 7 $cm^3$ and 512 cells to a tray. These became known as plugs. By the mid 1990s at Narromine Transplants, we were germinating all of our tree production in 512 cell plug trays and transferring by hand into the final container, in our case the Swedish Hiko tray, having 40 cells of 93 $cm^3$ each. Initially, many of our competitors thought we had added an extra and unnecessary process into the propagation system but later realised the benefits of such a change particularly in regard to final uniformity and the lack of root distortion this process offered.

### *2.2. Improvements in germination techniques*

Following our discovery of the techniques for mechanically and fluid separating seed and of the possibilities for single direct seeding, we made a number of improvements to our processes. Researchers working for AMCOR Plantations in Victoria, developed a technique to increase the seed energy and vigour of *E. globulus* a species used extensively in their plantation estate. The technique uses a 2% solution of potassium nitrate contained in aerated columns for a period of up to 120 hours at 22ºC. The treatment has the effect of osmotically priming the seed, enhancing germination vigour and promoting a higher incidence of initial germination.

We were able to adapt this process, with changes in timing and treatment temperature, to a range of other *Eucalyptus* species to a point where nearly all seed that we deal with is subjected to this process.

Of particular interest is the use of this process for the treatment of *E. nitens*. This species was normally stratified for a 21-day period to overcome dormancy. In our case, our temperatures were too high at the time of sowing (December/January) and germination was intermittent and the stratifying process was messy and prolonged.

We found that if *E. nitens* seed was primed using a 2% solution of potassium nitrate and kept at a constant temperature of 18ºC for 110 hours dormancy could be broken and the uniformity of germination was enhanced. Ultimately this process allowed us to propagate *E. nitens* even during high temperature conditions and at the same time achieve a much more uniform end product.

Further enhancements to the propagation process have been made with the introduction of vacuum seeders, injection moulded plug trays and robotic transplanters. This equipment in conjunction with a great deal of attention to growing medium and nutrition, has allowed us to produce high quality seedlings exhibiting a high degree of uniformity and with excellent root systems.

### *2.3. The growing medium*

We are one of the few nurseries in Australia still using peat as a major portion of our growing mix. We will probably change this in the next year or so and start using a pine bark based medium supplemented with some peat and coir. Unfortunately this change will be driven by cost.

Currently, we use a medium containing the following ingredients:

| | |
|---|---|
| Peat | 63% |
| Vermiculite | 30% |
| Perlite | 7% |

Fertiliser is added at mixing as follows:

Gypsum
Superfine super phosphate
Lime
Dolomite
Iron sulphate
Trace elements
Wetting agent

No nitrogen is added at this stage but it is applied during the growing phase as a mixture of calcium nitrate and potassium nitrate via the irrigation system. This strategy allows us to determine the rates of growth we require and at the same time match them to species, weather and customer delivery timing requirements.

Our proposed pine bark based medium is:

| | |
|---|---|
| Composted pine bark 3mm | 60% |
| Fine coir | 15% |
| Hardwood sawdust | 15% |
| Perlite | 10% |

Base fertiliser will also be added and will include some nitrate to ensure there is no nitrogen draw down from the pine bark.

Plug production uses a peat based medium but with lower air-filled porosity via the use of a finer grade of peat. Growing time for plugs varies according to species but it is usually between six and eight weeks before the seedlings are large enough for transplanting. Once again nitrogen application is via irrigation and starts at week four using a predominately urea based soluble fertiliser at low rates.

### *4.4. Transplanting*

Transplanting via the use of TEA Transplanters has revolutionised our production and reduced our labour costs. However, these machines are only efficient if plug germination and quality are very high (Table 1).

*Table 1.* Germination, degree of difficulty.

| Species | Degree of difficulty 1 = difficult 5 = easy | Comments |
|---|---|---|
| *E. argophloia* | 4 | |
| *E. benthamii* | 3 | |
| *E. cladocalyx* | 4 | |
| *E. cloeziana* | 1 | Pre treatment and separation |
| *E. delagatensis* | 3 | |
| *E. fastigata* | 3 | |
| *E. globulus* | 5 | Pre treatment |
| *E. grandis* | 5 | |
| *C. maculata* | 4 | |
| *E. laevopinea* | 4 | |
| *E. melliodora* | 4 | |
| *E. nitens* | 2 | Pre treatment |
| *E. pilularis* | 1 | Pre treatment and separation |
| *E. regnans* | 3 | Pre treatment |
| *E. saligna* | 4 | Pre treatment |
| *E. viminalis* | 3 | Pre treatment |

We are presently considering the purchase of a 'replugger'. This machine is capable of determining which cells in a tray have not germinated and deplugging the cell and transplanting a viable plug from another tray into that cell. This will allow us to put plug trays through the transplanters and reduce by three the number of people downstream of each machine who would normally be required to infill missed cells.

## 3. CUTTING PRODUCTION

### *3.1. Background*

We made two visits to South America in the early and mid 2000s and visited nurseries in Chile, Brazil and Uruguay as well as three trips to South Africa, to investigate the propagation of *Eucalyptus* hybrids and single species. We found that stock plants were being maintained via a number of different treatments. These included in-ground, sand beds with drip lines and ebb-and-flow systems. The methods being employed in the latter two cases incorporated the use of hydroponic solutions both as run to waste systems and as ebb-and-flow.

In addition, the stock plants were physically treated in such a way that they retained juvenility thus maximising the number of propagules that eventually formed roots. The comparison between in-ground grown stock plants spaced at one metre, which were essentially used for the production of macro-cuttings, was in stark contrast to sand bed and ebb-and-flow culture where the stock plants were grown at densities of up to 340 plants per square metre.

The adaptation of this system to suit Australian conditions, as well as reducing the capital outlay and ongoing costs associated with both sand beds and ebb-and-flow, has been quite successful and has now been further adapted to other genera.

### *3.2. Materials and methods*

Since the late 1990s we had grown our *Eucalyptus* stock plants in 50 litre bags and harvested a range of cutting material without much concern for the age of that material. It took another twelve years before we fully realized the significance of maintaining the stock plant in a continual state of juvenility. We adapted our system, still in 50 litre bags, so that we could use what is now termed mini-cuttings mainly by constantly taking cuttings from the stock plants.

However after the two visits to South America and an escalation in demand for clonal hybrids, we needed to dramatically increase our strike rates and our production volumes.

We initially approached the problem by costing the purchase of an ebb-and-flow system or constructing sand beds both of which would need to be under cover. These systems proved to be expensive and as well, in the case of sand beds, the medium needed to be replaced every two years. The ebb-and-flow system required the renewal of the nutrient solutions periodically and therefore necessitating the dumping of the old solutions in an environmentally acceptable way.

A friendly competitor, Jayfields Nursery, was also searching for a way of economically producing *Eucalyptus* clones and on a visit to Ball Australia happened to see New Guinea *Impatiens* stock plants in coir-filled bags. These bags are routinely used in Australia by the hydroponic greenhouse tomato industry. They were readily available and at low cost, so we decided to adopt this medium using a Netafim drip system.

We had learned in South America, particularly from Teotonio de Assis, at the time a plant breeder and propagator with the pulp and paper company Aracruz and the University of São Paulo, of the need to carefully treat *Eucalyptus* stock plants with the correct nutrient solutions. The reasoning for this was that the propagules that were subsequently produced under this regime would have just the right degree of hardness and maintain their turgidity under mist, would not need supplemental nutrition while under mist, would not require the use of hormone to assist callus and eventual root initiation and would produce a high percentage strike rate.

As most of the literature on the subject in the early stages of our experimentation was in Portuguese, we had to rely on a translator who had no training in chemistry or nutrition, to decipher what little information we had. We started with a very basic A and B solution that we gradually refined, initially through trial and error and eventually with the help of Teotonio de Assis and Aracruz (Table 2).

*Table 2*. Stock solutions for *Eucalyptus* stock plant maintenance.

| Stock solution A | g/L | Stock solution B | g/l |
|---|---|---|---|
| $Ca(NO_3)_2$ | 32.0 | $KNO_3$ | 4.0 |
| $KNO_3$ | 4.0 | $KH_2PO_4$ | 7.25 |
| Fe (as EDTA) | 2.0 | $MgSO_4$ | 7.25 |
| | | Mn | 0.05 |
| | | Zn | 0.05 |
| | | Cu 0.005, B 0.15, Mo 0.00125, Co 0.0005 | |

We found that to fine-tune these solutions we needed to take regular tissue samples for analysis and to continually monitor the EC and pH of the delivered nutrient solution (Table 3).

Stock plants were fed on a daily basis via drippers spaced at every second plant. Flushing with pure water every 10 days ensured that there was no accumulation of salts in the coir bags.

We commenced full production using hybrids of *E. grandis x E. camaldulensis*, probably two of the easiest species to propagate, using the mini-cutting system where stock plants are kept small and as juvenile as possible. With only a few errors along the way, we managed to launch into a production run of three million rooted cuttings produced trees over a six-month period.

*Table 3*. Desired nutrient levels of leaves of *Eucalyptus* stock plants.

| Macro-nutrients (%) | | | | | | Micro-nutrients (mg/kg) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| N | P | K | Ca | Mg | S | B ppm | Mn ppm | Zn ppm | Fe ppm | Cu ppm |
| 2.5 | 0.2 | 1.5 | 1 | 0.25 | 0.15 | 40 | 100 | 50 | 100 | 10 |
| to | to | to | to | to | to | to | to | to | to | to |
| 3 | 0.4 | 2 | 1.5 | 0.4 | 0.25 | 70 | 500 | 60 | 200 | 15 |

As we proceeded we found that we were able to dispense with the use of hormone and that our strike rates increased as well, from an initial 70% to as high as 92% in the middle of summer. We also found that bottom heat (22ºC) was essential to increase throughput, with rooting occurring within twelve days in mid-summer and cuttings able to be removed from mist within 20 days. Without bottom heat these times increased to 18 and 28 days respectively.

Without doubt this system works exceptionally well where plants are kept as juvenile as possible. As we have subsequently found, not all *Eucalyptus* hybrids are as easy to propagate as *E. grandis x E. camaldulensis* and they are not so prolific if the stock plants are derived from cutting material rather than from seed. Cutting-derived material does not develop a lignotuber from which we are able to harvest the most juvenile material.

In the case of the new *Corymbia* hybrids, namely *C. torelliana x C. citriodora* subsp. *variegata*, we have had difficulty in increasing strike rates above 50% but have concluded that these hybrids need to be propagated from extremely juvenile material. We have now been able to achieve strike rates of 80% by ensuring we take only sprouts from the base of each stock plant. We may need also to use tissue culture to ensure we create stock plants with better juvenility.

We have also had success in propagating cuttings of *E. argophloia, E. globulus*, and a range of other experimental hybrids. We believe that despite a current lack of demand for hybrids that disease pressure, e.g. myrtle rust *Uredo rangelii/Puccinia psidii* and *Kirramyces eucalyptii*, as well as a drive for higher productivity and improved form and fibre quality, will reinvigorate this market.

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CHRIS HARWOOD

# NEW INTRODUCTIONS – DOING IT RIGHT

## 1. INTRODUCTION

The history of eucalypt introductions and subsequent domestication in exotic environments up to 1990 is reviewed by Eldridge *et al.* (1993). This book describes the wealth of different eucalypt species, and how to exploit the genetic resources that exist within species so as to produce genetically improved planting stock matched to target planting environments and intended end uses.

Various approaches have been taken to eucalypt introduction. A commonly advocated method has been to start with testing 1-3 “best bet” provenances of a range of candidate species in species elimination trials. These trials are of short duration, and use relatively small plots: six replicates of ten-tree line plots for each seedlot under test is a good starting point. The aim is to quickly eliminate those species that are poorly adapted. Careful selection of trial sites, which should be truly representative of the target environment, is very important. Philip Smethurst discusses in these proceedings the significance of local landscape position in relation to the intensity of frost and water-logging. Better information will be obtained from several such species elimination trials, spanning the range of target environments, than by putting the same resources into one huge trial which may turn out to give an uncharacteristic result.

This species elimination testing phase is then followed by more extensive provenance trials of one or more of the most promising species using larger plot sizes and extending the testing period to at least half of the planned rotation, and importation of broad-based populations of the best provenance or provenances of the species finally selected for planting, so as to support a breeding program leading to production of improved planting stock. Growers may conduct two or more of these steps in parallel to save time, although this can lead to wasted effort when major resources are directed to intensive testing and breeding for a species that is subsequently abandoned.

Eldridge *et al*. (1993) document numerous cases of informal, “unscientific” eucalypt introductions involving an overly narrow genetic base of a species, leading to unsatisfactory outcomes. For example, inferior land races have developed after introduction of seeds collected from one or a few trees of an inferior provenance, leading to subsequent inbreeding and loss of vigour. In India a slow-growing eucalypt land-race, Mysore Gum, has developed, based largely on a very early and narrow introduction of *E. tereticornis*. Subsequent introductions based on best tropical provenances of *E. camaldulensis* and *E. tereticornis* have performed much better and enabled the development of more productive plantations (Varghese *et al.* 2009).

The area of eucalypt plantations has increased from about 6 Mha in 1990, to over 20 Mha today. We now have an additional 20 years of experience of eucalypts as exotics, subsequent to production of the Eldridge *et al*. book. What new knowledge of and approaches to eucalypt introduction have emerged? I will endeavour to bring out lessons relevant to New Zealand, but will draw heavily on experience from Australia and elsewhere.

## 2. THE "BIG NINE" *SYMPHYOMYRTUS* SPECIES AND THEIR HYBRIDS

It is instructive to examine the GIT Consulting World Eucalyptus Map (**http://git-forestry.com/download_git_eucalyptus_map.htm**) and consider the species being planted worldwide. I estimate, based on visits to the major grower countries and discussions with grower agencies, that nine eucalypt species in the subgenus *Symphyomyrtus* (Brooker 2000) and clonal plantations of various interspecific hybrids among these species account for over 90%, and probably 95%, of the world's planted eucalypts. The small number of dominant plantation species is remarkable when compared with estimates of the total number of species (over 900 species - Boland *et al*. 2006) in the genus *sensu lato* (including *Corymbia* species).

*Table 1.* Nine eucalypt species and their hybrid combinations dominate the world's eucalypt plantations.

| Species | Approximate range of mean annual temperature ($^{o}$C) for good growth in plantations |
|---|---|
| *E. camaldulensis* | 18-28 (northern provenances) |
| | 13-22 (southern provenances) |
| *E. dunnii* | 14-22 (Jovanovic *et al.* 2000) |
| *E. globulus* | 9-18 |
| *E. grandis* | 14-25 |
| *E. nitens* | 9-18 |
| *E. pellita* | 20-27 |
| *E. saligna* | 14-23 |
| *E. tereticornis* | 17-27 (northern provenances) |
| *E. urophylla* | 18-28 |

Most of the world's eucalypt plantations are located in tropical, subtropical and warm temperate climates. Table 1 indicates the range of mean annual temperature required by each species for good growth in plantations, derived from bioclimatic niche studies (Jovanovic *et al.* 2000). Differences in adaptability within species makes these ranges approximate at best. Individual provenances will generally have narrower ranges of temperature adaptability than Table 1 would suggest. However, of the species in Table 1, only *E. camaldulensis* (southern, winter rainfall provenances), *E. globulus* and *E. nitens* thrive in winter/uniform rainfall, cool temperate climates, and only they are planted widely at latitudes further than 35° north or south from the equator, corresponding to New Zealand's climates and location.

Of the species listed in Table 1, *E. dunnii* and *E. pellita* have emerged as plantation species only in the last two decades. *E. dunnii* is now grown in summer-rainfall subtropical/warm temperate climates in South America, southern Africa and China, while *E. pellita* is probably the eucalypt best able to thrive in year-round humid lowland equatorial climates, and is now being planted on an industrial scale in Indonesia. *E. benthamii* (also belonging to subgenus *Symphyomyrtus*) has also recently emerged as an important pulpwood species in Latin American countries such as Uruguay, because of its cold tolerance combined with rapid growth and ability to grow well in climates with a summer-uniform rainfall distribution.

Clonal forestry has been successfully developed for the majority of the species listed in Table 1. Exceptions are *E. dunnii*, *E. globulus* and *E. nitens*, which are hard to propagate from stem cuttings (*E.nitens* particularly so), even using advanced "mini-cutting" technologies. (Assis *et al.* 2004). Many interspecific hybrid combinations among the nine species listed have been produced by controlled pollination, and individual hybrid clones adapted to climates and conditions "intermediate" between those that favour the pure species of Table 1 have subsequently been identified. Hybrids between *E. grandis* and *E. urophylla*, for example, are well adapted to tropical-subtropical humid climates, display vigour and disease resistance that are superior to the pure species, and dominate the eucalypt plantations of Brazil. However, an attempt to develop plantations of this hybrid combination in what appeared to the proponents to be similar climates in lowland Sumatra and Borneo failed (Dr E. Hardyanto, *pers. comm.*). In elevated regions of South Africa where frost risk prevents use of pure *E. grandis* the hybrid combination *E. grandis* x *E. nitens* is planted commercially, and this combination has also been tested in New Zealand. Similarly, *E. nitens* x *E. globulus* hybrid clones have been developed for frost-rpone sites in Chile. On sites in South Africa and Latin America considered too dry for pure *E. grandis*, hybrids between *E. grandis* and *E. camaldulensis* display superior drought tolerance to pure *E. grandis*, and superior growth to pure *E. camaldulensis*. Another aim of hybrid breeding involving the species in Table 1 is to combine complementary traits, for example to produce hybrids with both the desired high wood basic density and pulp yield of *E. globulus* and the adaptability to summer-rainfall subtropical climates of *E. grandis* and *E. urophylla* (Bison *et al.* 2007).

So we have arrived at a situation where the “Big Nine” species of Table 1 and their hybrids dominate eucalypt plantation forestry worldwide, and huge investment has been made in the evaluation and development of their genetic resources in recent decades. There is extensive variation among provenances within most of these species that can be exploited by breeders (Eldridge *et al.* 1993). *E. dunnii* is an exception. There are, with the exception of pure-species *E. globulus*, *E. dunnii* and *E. nitens*, the advantages of greater stand uniformity associated with clonal foresty, and the ability to select and deploy clones with wood properties matched to desired end uses.

Why then should we look beyond them to find other eucalypt species adapted to New Zealand conditions?

## 3. AUSTRALIA: *SYMPHYOMYRTUS* VERSUS THE REST AND HYBRIDS

Ecologists have for many years argued over the ecological characteristics of species of the different eucalypt subgenera. *Monocalyptus* species dominate the majority of Australia’s native forests, particularly in the temperate climatic zones of interest to New Zealand, whereas *Symphyomyrtus* species have succeeded best as exotics worldwide (Adams 2000; Noble 1989; Stone *et al.* 1998). Florence (1996) provides some evidence that the *Symphyomyrtus* species grown in plantations for wood production, such as *E. globulus, E. grandis* and *E. nitens*, are “sprinters” relative to *Monocalyptus* species that attain the same stature. In natural stands they display very rapid early growth, followed by a major decline in current annual increment (CAI) from as early as 10-15 years, while *Monocalyptus* species that are candidates for temperate plantation forestry have slower initial growth but maintain their peak growth rates over longer periods of 20+ years. Florence also makes the comparison within *Monocalyptus* between *E. regnans***,** a species with a high early peak in CAI, and *E. obliqua*, which lacks this initial rapid growth phase but may maintain its peak CAI for as long as 40-50 years. Such comparisons become important when we are considering embarking on long plantation rotations to produce large-dimensioned sawlogs – a different situation to that for most of the world’s eucalypt plantations that are growing on short (less than 10 year) rotations, primarily for pulpwood.

Pure-species plantations of *E. globulus* and *E. nitens* dominate in Australia, comprising 55% and 24% respectively of the total hardwood plantation area of 1M ha (Gavran and Parsons 2011). In Tasmania, efforts to develop plantation forestry initially focussed on the *Monocalyptus* species *E. delegatensis* and *E. regnans* that provide most of the timber from the State’s natural forests (Tibbits 1986). Major provenance testing and breeding programs to support plantation forestry for these species were commenced by CSIRO (Griffin et al. 1982). This genetic research, along with silvicultural research and operational plantation programs, was abandoned in the 1990s when it became clear that *E. nitens* (and *E. globulus* in low-elevation, less frost-prone areas), were much more reliable in terms of successful plantation establishment and rapid early growth (Turnbull *et al.* 1993). Recent re-examination of some of the original species trials and pilot plantings in the Esperance Valley in southern Tasmania indicates that more than 25 years after planting, *E. delegatensis* and *E. regnans* are performing on a par with *E. nitens* and *E. globulus*, in contrast to the clear superiority of the latter two species at age 5 years. However, the devastating attack by defoliating insects experienced in many young *Monocalyptus* species plantations at around the time of canopy closure was a major problem that would mitigate against a revival of their popularity as plantation species in Tasmania.

Australian experience with interspecific eucalypt hybrid plantations has been decidedly mixed. Hybrids between *E. globulus* and its more cold-tolerant relatives *E. nitens* and *E. gunnii* have proved very susceptible to herbivore attack, making them unsuitable for deployment (Potts and Dungey 2004). Interspecific hybrids among *E. grandis, E. globulus* and *E. camaldulensis* have been developed successfully for low-rainfall, inland environments in the Murray-Darling basin, including soils with elevated levels of salinity (Hardner et al. 2011), and *Corymbia torellina* x *C. citriodora* hybrids show promise in Queensland (Lee et al. 2009). However, a 20 000 ha plantation estate of clonal of *E. grandis – E. camaldulensis* hybrids in high-rainfall regions of eastern central Queensland was recently abandoned because of destructive defoliation by leaf blight diseases – an outcome that could have been avoided by careful testing of pilot plantings before embarking on operational planting. Taxa trials in northern NSW (Listyanto *et al*. 2010) and southern Queensland (Lee *et al*. 2010) found that interspecific hybrids and pure-species seedlots of *Symphyomyrtus* were particularly susceptible to attack by stem boring insects, rendering them unsuitable for solid-wood applications. Spotted gums (*Corymbia* species) appeared to be the best prospects for Australian subtropical plantations targeting solid-wood products, despite their somewhat slower early growth. Testing in Western Australia (Barbour 2004) found that pure-species *E. globulus* outperformed interspecific hybrid combinations on sites where growth of the pure species was acceptable for commercial plantations. At lower rainfalls, hybrid combinations *E. grandis* x *E. camaldulensis* and *E. camaldulensis* x *E. globulus* outperformed pure *E. globulus*, but growth rates in these environments do not appear sufficient to make plantation forestry an attractive investment in the absence of substantial co-benefits such as payments for hydrological services or carbon sequestration. Another factor discouraging clonal forestry in Australia is that high labour costs have resulted in the per-plant costs of clonal planting stock being as much as 3-4 times higher than seedlings.

Overall, the Australian plantation experience suggests to me that *Symphyomyrtus* species with fast early growth will not necessarily win out in the long run as the best plantation species, particularly when we are targeting solid-wood products grown over longer rotations. Furthermore, given that interspecific hybrids appear to be more vulnerable than the parental species to pests and diseases when planted in the natural ranges of the parent species (Potts and Dungey 2004), there are serious risks in growing hybrids in Australian and nearby New Zealand environments where most of the pests and diseases of the parental eucalypt species may be expected to eventually make their appearance.

## 4. ALTERNATIVE TESTING AND DEPLOYMENT PATHWAYS

### *4.1. Conventional approaches*

The conventional approach of species introduction and testing followed by development of a genetic improvement program typically takes at least ten years from commencement to the production of genetically improved seed from seed orchards based on identified best provenances. This has been the experience in a collaborative breeding program of the Australian Low Rainfall Tree Improvement Group (ALRTIG) that has been developing improved seed sources of eucalypt species for low-rainfall environments of southern Australia's wheat-sheep belt (Harwood *et al.* 2007). This program focussed on improving eucalypt species (*Corymbia. maculata*, *E. camaldulensis*, *E. cladocalyx*, *E. occidentalis, E. sideroxylon* and *E. tricarpa*) which were selected in 1998 from among many candidate species on the basis of their performance in existing plantings in the target environments, via collective expert opinion distilled at a multi-agency workshop and subsequent detailed review (Harwood *et al.* 2001). All of these species merit evaluation for planting in New Zealand's drylands, although their frost tolerance is less than that of species from Australia's coldest natural environments such as *E. nitens and E. gunnii*. We still lack comprehensive comparative testing comparing these selected species in trials throughout the target planting environments (Bush *et al.* 2009), although some of them have been compared in species trials throughout New South Wales (Johnson *et al.* 2009).

The ALRTIG breeding program has required investment of at least $250,000 per species, excluding additional major in-kind support such as the provision of land for field trials and seed orchards (David Bush, *pers. comm.*). Most of the cost arises in setting up and managing pedigreed breeding populations (provenance-progeny trials at multiple locations within the target planting area). A substantial plantation estate of some thousands of hectares is required to justify this level of effort and resources to genetically improve a species. Large-scale plantings of these were anticipated to achieve hydrological management for salinity mitigation in dryland landscapes of southern Australia. The logic of the genetic improvement program was to enable these plantings to provide greater commercial returns from wood production, thus improving the economics of environmental tree plantings (Harwood, *et al.* 2007).

For many candidate eucalypt species, seed from seed orchards of documented provenance origin and pedigree is now available internationally. For example, orchard seed is now available from all of the species listed in Table 1, and for the dryland eucalypt species developed by ALRTIG. Typically, seed orchards are established from a mix of known best provenances (best, that is, for the target set of environments and end uses). Where such orchard seed sources are available, it certainly makes sense to include them in species/provenance testing, along with selected natural provenances. If they perform well, they can provide a quick route to deployment of improved seed. Growers often baulk at the cost of orchard seed, but it is seldom a major component of establishment cost – for example a price of $0.05

per seed for orchard seed equates to only $100/ha, assuming 50% of seeds make it through to planted-out seedlings.

### *4.2. Clonal approaches*

Sets of tested eucalypt clones, both pure species and hybrid, displaying good growth in a characterised range of environments and with well-understood wood properties, are now being marketed internationally and can be moved between countries in tissue culture for propagation and re-testing in regions with similar environmental conditions. Importing, testing and then rapidly deploying such “designer sets of clones”, typically interspecific hybrids, developed elsewhere in similar climate and soil conditions, appears to provide an attractive alternative route for circumventing the lengthy multi-stage process of species and provenance testing followed by in-country breeding. Some large-scale growers in tropical and subtropical environments are now using this strategy in parallel with, or instead of, conventional species-provenance testing and breeding approaches. However, this strategy is prone to failure in the absence of thorough testing of the clones in the new environment, as discussed above. In comparison with tropical and subtropical environments, the strategy is less applicable to New Zealand, particularly to cooler dryland environments in the South Island, because less effort has gone into development of clones for such environment. *E. nitens* is one of the most cold tolerant of the eucalypts, Tasmanian plantations being able to tolerate extreme winter minima as low as -8$^{o}$C, but requires an annual rainfall in excess of 900 mm for good plantation development, and is not amenable to clonal propagation as a pure species. Interspecific hybrid clones (*E. nitens* crossed with *E. grandis* and *E. globulus*) have been developed for operational forestry in South Africa and Chile respectively.

### *4.3. Low-cost alternatives for small-scale planting programs*

Low-cost, simple approaches seem particularly appropriate for the New Zealand’s drylands environments, where there are quite a number of candidate eucalypt species worthy of testing, and where plantation areas are unlikely to be high in the short to medium term. The basic approach is to test one or more “likely-to-succeed” provenances of a number of candidate species, commence operational plantings using purchased seed from the best provenances of the best species identified in the trials, and set up one or more unpedigreed seed production areas based on these best natural provenances for longer-term seed production. The following questions immediately arise:

- How many species should one test, and how many provenances per species?
- What constitutes a good sample of a provenance, for testing?
- How does one set up and manage a seed production area?

There is no easy answer to the first question. The species’ natural distributions must be examined (see the species digests in Boland *et al.* (2006) as a good starting point for most candidate species) and a sensible decision made, based upon the distribution, and review of any available literature relating to testing of the species in cultivation. Where there is a specific product requirement, such as production of durable wood for external use, review of wood quality information and elimination of unsuitable species will narrow the range of candidates, as will be discussed by David Bush at this workshop.

For initial testing, no more than 1-3 provenances per species should be required, and for species with limited geographic distributions of less than say 200 km in extent, one provenance should suffice. As ability to tolerate frost seems to be a success-limiting factor for eucalypts in New Zealand's drylands, I would recommend high-elevation provenances, as these are generally likely to be superior in their frost tolerance. As an example, the highest-elevation provenances of *E. camaldulensis* from near Yass, New South Wales are likely to have the greatest frost tolerance for this species, although their growth performance would likely be poorer than that of the well-known and widely used southern *E. camaldulensis* provenance of Lake Albacutya in Victoria. For species with a wide geographic range, it is sensible to test at least two provenances, but focus on provenances from latitudes south of $35^{\circ}$S. If a seed orchard source, based on likely provenances, is available, then an orchard seedlot should be included in the trials.

As a general rule of thumb, a provenance sample for testing should comprise a mix of seed from a minimum of 5, and preferably 10 or more parent trees. These should be spaced more than 100 m apart from one another, to minimise the chances of mother trees being related by recent common descent and maximise the genetic sample under test. Seed from each mother tree will derive from pollination by a number of nearby father trees, and there will typically be a proportion of selfed seed. Ideally, equal weights of seed of equivalent viability from each mother tree should be mixed together to constitute the provenance bulk sample for testing. Reputable seed supplier should be able to supply these details.

General guidelines for seed production areas (SPAs) are provided by Eldridge *et al.* (1993, Chapter 21.1). A stand of trees of at least 0.5 ha, raised from a well-comprised provenance bulk comprising at least 10 mother trees, as described in the previous paragraph, will provide a sufficiently broad genetic base for a SPA. If an orchard seed source was found to be the best performer for a species, it could in principle be used instead, provided that the genetic base of the orchard was similarly broad. The SPA will be planted at "typical" initial stocking of around 1000 stems per hectare, and subjected to 2-3 selective thinnings at 50% intensity as it develops, retaining the better trees in each thinning, to reduce stocking to about 100-200 stems per hectare by the time seed production commences, which will usually be at around 6-10 years or longer, depending on the species.

If the species has already been planted in the target region, it is helpful to observe existing plantings to determine patterns of flowering and seed production and determine whether particular soils and landscape positions favour heavy seed production – these situations would then be chosen for establishing the SPA. In some cases in Australia it has been possible to convert an existing pilot plantation of known provenance origin into an SPA. The selective thinning, and the mixing of seed from multiple parents, reduces "neighbourhood inbreeding" (Eldridge *et al.* (1993) and can give a modest genetic improvement in vigour and stem straightness as a result of the selective thinning. Most eucalypts are insect-pollinated, and beehives can be introduced to boost seed set and cross-pollination. Judicious use of the flower promoter paclobutrazol can stimulate seed yields in shy-flowering species such as *E. nitens* (Moncur *et al.* 1994). The SPA strategy has been tried many times and has often succeeded. However, good seed production is not always achieved, because local climates may not be conducive to flowering – an example is *E. dunnii* in southern China, where the species grows well but does not flower heavily, and seed has to be produced elsewhere to meet the large planting targets for this species in this region.

Unfortunately, the recent arrival of eucalypt rust (*Psidium psidii*) in eastern Australia may make seed transfer from Australia to New Zealand increasingly problematic.

## 5. LINKING GENETICS, SILVICULTURE, PRODUCTS AND PROCESSING

The requirement to produce wood for desired product classes complicates and lengthens the processes of introduction and testing. Papers by Beadle *et al.* (2008) and Washusen *et al.* (2009) and a series of technical reports of the Cooperative Research Centre for Forestry (CRC Technical Report Nos 168, 188, 200, 201, 209, 211) downloadable at **http://www.crcforestry.com.au/publications/technical-reports/index.html**, outline the tortuous 30-year path towards developing *E. nitens* as a species for sawn timber production in Tasmania; a journey not yet completed. I would emphasise here that this is not just a question of genetics (searching for the ideal species and provenance and then further genetic improvement of wood quality). What is required is a multi-disciplinary approach where improvements in genetics, silviculture and processing all interact and adjustments are made so as to achieve a profitable growing and processing value chain, as outlined in CRC Technical Report No. 188. For species introduced on a small scale, with unpedigreed management of genetic resources and in the absence of clonal forestry, I would not hold out much hope of genetic selection having a major impact on wood quality and processing. Under such circumstances, if wood production systems cannot cope with good natural provenances of a species, it is better to switch to growing another species to meet the desired product requirements. Even for a major plantation species with pedigreed breeding, changes in plantation wood quality resulting from breeding will be modest and relatively slow, particularly when the aim is to improve value-limiting traits that are expressed and can be assessed only at a relatively mature age, such as internal checking in *E. nitens* (Blackburn *et al.* 2010).

Rapid changes in processing methods, particularly for engineered wood products, may overtake the plans of breeders and silviculturalists. A good example is can be seen in southern China, where the recent rapid expansion of small-scale rotary veneering and associated plywood manufacture has led to eucalypts that had been grown on short (4-5 year) rotations for pulpwood being diverted to veneer producers who are prepared to pay a higher price for logs and now process up to 80% of the available eucalypt wood resource in Guangxi and Guangdong provinces. The wood traits of importance for pulpwood and veneer production are different; veneer manufacturers favour high stiffness, stem straightness and cylindricity and minimal end-splitting, and have no interest in pulp yield (Roger Arnold, *pers. comm.*). I rather think that those setting out to grow sawlogs over long rotations in Australia and New Zealand may face similar shifts in demand for their forests.

## 6. ACKNOWLEDGEMENTS

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# DEVELOPMENT OF *E. ARGOPHLOIA* IN QUEENSLAND: LESSONS LEARNT

## 1. INTRODUCTION

*Eucalyptus argophloia* has great potential as a plantation species in low rainfall areas of northern Australia. It exhibits frost hardiness, adaptation to drought, good form and reasonable growth and produces a durable timber. This paper reports on the current knowledge of the species, focussing on the tree improvement and wood properties charcterisation work, underway in Queensland.

## 2. WHAT IS *E. ARGOPHLOIA*?

*Eucalyptus argophloia* Blakely (Queensland western white gum or Chinchilla white gum) is endemic to south eastern Queensland and has very limited distribution (Brooker and Kleinig 2004) northeast of Chinchilla in south-eastern Queensland. This species is classified as 'vulnerable' under the Queensland Nature Conservation Act (1992) so harvesting or clearing of naturally occurring trees is restricted. Recent studies (unpublished data) indicate that approximately 1000 mature wild trees remain with little natural regeneration as most of the species habitat has been cleared for agriculture.

It is a large tree (40 m) that produces strong durable timber (Boland *et al.* 2006; Hopewell 2010) with attractive red-brown heartwood. Currently approximately 5000 hectares of *E. argophloia* plantation have been established on marginal agricultural land in Australia's subtropics for timber production, for the on site beneficial use of the saline waste water from coal seam gas mines, and for carbon sequestration purposes.

## 3. SELECTION AND GROWTH OF *E. ARGOPHLOIA*

In north-eastern Australia approximately 130 000 ha of hardwood plantations have been established in the last 15 years. As a result of poor taxa selection approximately 30,000 ha has failed due to drought, pest and disease incursions and extreme weather events mainly drought and cyclones (Lee *et al.* 2011). Much of the rest of the plantation estate was planted with sub-optimal species so the growth and/or potential to turn the trees into products is limited. In southern Australia and New Zealand mistakes were also made with poor taxa selection in the progress to the current estate in which growers settled on *Pinus radiata*, *E. globulus* subsp. *globulus* and *E. nitens* as appropriate. In north-eastern Australia development of a viable hardwood industry can only be achieved if species can be identified with acceptable growth rates, with desirable wood properties; and with plantations positioned near processors and markets to allow economically viable utilisation in the timber.

One of the main considerations for expansion of the plantation sector in north-eastern Australia is the large increase in the price of land in the higher rainfall zones (>1000 mm) due to urbanisation and competition from other land uses, resulting in a reduction in the amount of land available for plantation establishment. Subsequently, hardwood plantation expansion in north-eastern Australia is primarily in the 700 to 1000 mm MAR rainfall zone in areas not previously considered suitable for production forestry. In subtropical Australia, this zone has potentially millions of ha of marginal agricultural land that could be converted to forests to either sequester carbon or grow timber and poles. The low rainfall, high evaporation rates, pest and diseases, and the frequent frosts in this zone have limited the species and hybrids that can be considered for plantation forestry.

Work was initiated on *E. argophloia* in 1997 based on its performance in amenity plantings and a few older trials around Queensland (Lee *et al.* 2010; Lee *et al.* 2001) and New South Wales (Johnson *et al.* 2009). The early promise of the species in Queensland has been confirmed in a recent study of the adaptation, growth, form, survival, stem borer attack and wood properties of 38 replicated large block taxa trials spread throughout Queensland and northern NSW. In this study *E. argophloia* was identified as one of five core species for on-going tree-improvement work based on its growth, form, survival, stem borer resistance, and wood properties performance on marginal sites in north-eastern Australia (Lee *et al.* 2011). This recent study has shown *E. argophloia* to be a drought adapted species suitable for frost prone, low rainfall environments e.g. 600 to 800 mm MAR confirming earlier finding (Lee *et al.* 2005; Ngugi *et al.* 2003; Ngugi *et al.* 2004). Another advantage of *E. argophloia* over many species in these low rainfall environments is that it can grow on low to high salinity soils (2-8 dS/m) with moderate growth and survive on very highly saline soils (8-12 dS/m (House *et al.* 1998).

*Eucalyptus argophloia* is very slow out of the blocks in the first few years, with total standing volume MAI in the first three years in the order of 0.3 to 1.4 $m^3$/ha/annum (Figure 1) on low rainfall sites (500 to 650 mm average during the trial period; Table 1). By age 18 however, the volume MAI at these sites had increased to 6.7 - 10.4 $m^3$/ha/annum and had not peaked (Figure 1).

*Table 1.* Location and climatic variables for three taxa trials containing *E. argophloia* in Queensland.

| Location | Average trial yearly rainfall (mm) | Latitude | Longitude | Wetness index (rainfall / evaporation*) |
|---|---|---|---|---|
| Stanwell | 631 | -23.45º | 150.45º | 0.30 |
| Morgan Park | 618 | -28.25º | 152.05º | 0.37 |
| Goondiwindi | 506 | -28.15º | 149.87º | 0.23 |

* Open pan evaporation.

Note: Brisbane's latitude -27.47º and longitude 150.02º.

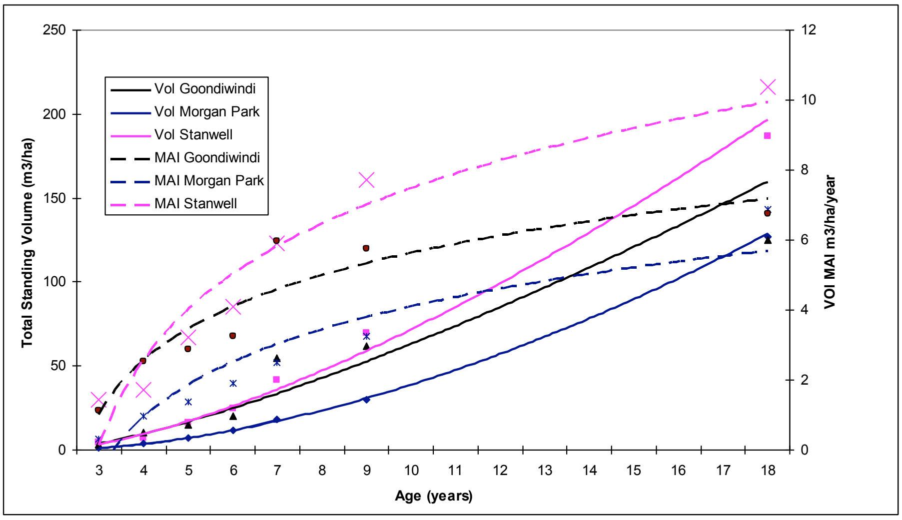

*Figure 1.* Growth of the *E. argophloia* in three taxa trials in terms of total standing volume and volume MAI up to age 18 years.

## 3. *E. ARGOPHLOIA* GENETIC IMPROVEMENT

*Eucalyptus argophloia* tree improvement is ongoing across three organisations in Australia with small programs being managed by Forest NSW (established in 2004-2005 with 4 x 20 seed parent progeny trials) and CSIRO (established in 2002, a single 42 tree progeny trial; *pers. comm.* Paul Warburton September 2011) and a larger program managed by the Queensland Government (established in 1997 with 85 seed parents planted across 3 x 50 tree progeny trials and an 85 seed parent tree ex-situ seed orchard and conservation stand). The genetic base for *E. argophloia* in the Queensland captures approximately 10% of the mature wild trees from across the species current range (Figure 2). In the Queensland trials, heritability for growth traits (height and diameter) was relatively low at ages five (pre thinning) and 13 years (post thinning; range 0.08 to 0.15) and there was little genotype × environmental interaction across the four trials (trial details are provided in Table 2). Breeding values have been determined from a REML analysis of the trials and elite high growth families and individuals have been identified and grafted to establish a high growth clonal seed orchard. Seed production commenced in the first generation seed orchards and progeny trials at age six. In 2009 a mass flowering occurred in these seed orchards (following thinning to final stocking) and sufficient seed is now in store to meet industry needs. In addition the ‘high growth’ clonal seed orchard has also flowered and seed is also available.

*Figure* 2. Distribution and location of the trees included in the genetic base of *E. argophloia* in Queensland. Satellite images accessed from Google Earth. Location of seed parents locations mapped by Rob Lamont (USC).

*Table 2.* Location of the *E. argophloia* progeny trials and seed orchards and genetic base established in each.

| Trial | Average trial yearly rainfall (mm) | Latitude | Longitude | Number of seed parents |
|---|---|---|---|---|
| 460a | 733 | -27.52 | 151.08 | 50 |
| 460b | 676 | -27.26 | 151.37 | 50 |
| 460c | 871 | -26.08 | 152.25 | 50 |
| 460e | 733 | -27.52 | 151.08 | 85 |

### *3.1. Characterising the wood properties*

Sixty-seven of the best growth and form trees across 41 families have been non-destructively evaluated for wood properties at age 13.5 years. In this study, large variations in heartwood proportion (28% to 66%; Figure 3) and basic density (680 to 820 kg/m$^3$ for the heartwood; Figure 4) have been measured using increment core samples (a validation population is now being assessed). The variation in wood properties detected in this study indicates there should be good potential for selection of trees with elite wood properties for inclusion in a new elite growth and wood property *E. argophloia* clonal seed orchard planned for 2012. Seed should be available from this seed orchard approximately three years after the trees are grafted.

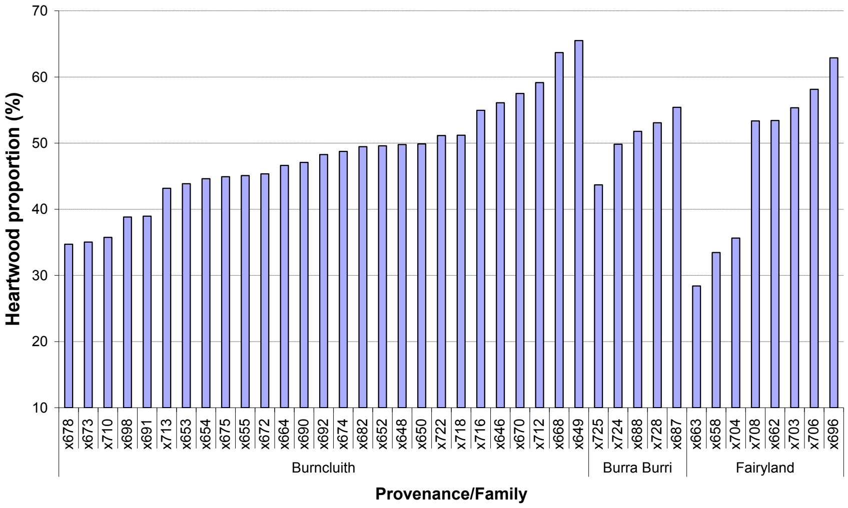

*Figure 3*. Heartwood proportion based on the cores of 13-year-old *E. argophloia* samples across provenances and families.

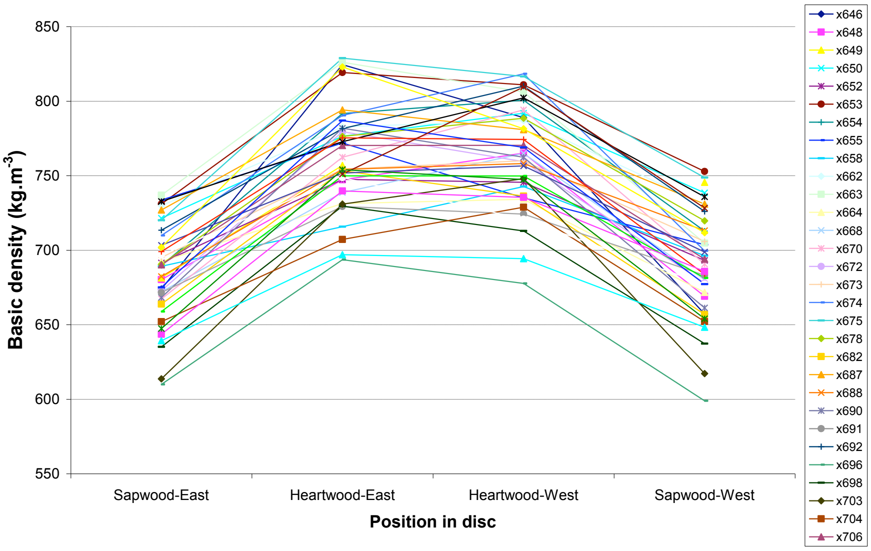

*Figure 4*. Distribution of basic density of 13-year-old *E. argophloia* samples across provenances and families.

### 3.2. Propagation

Vegetative propagation is widely used for maximising growth, quality and uniformity of trees in clonal production systems. It is also used when seed supply is limited or where seed production is constrained in a hybrid production program (Eldridge *et al.* 1993; Leakey *et al.* 1982). *Eucalyptus argophloia* coppices well with most trees producing abundant coppice when juvenile seedlings are hedged. Similar results have been achieved with thinned plantation trees and selection age trees (up to age 10). However the species is not generally considered to be amenable to propagation by rooted cuttings as survival is in the order of 10% at five weeks using conventional in-ground hedges (Baker and Walker 2005). Coppice from five year-old plantation trees, managed as hedge plants in a nursery, had similar rooting values (*pers. comm.* Steve Barker August 2011). Based on this, deployment of *E. argophloia* hybrids may also be difficult unless the other parent of the hybrid (e.g. *E. bosistoana* in New Zealand) brings in acceptable rooting into the mixture. As a general rule acceptable rooting (> 70% for eucalypt species (Eldridge *et al.* 1993) is associated with more northern species (e.g. *E. pellita* and *E. camaldulensis*), so a breeding program aimed at hybrid production should first evaluate the propagation of the species involved before a controlled pollination program begins.

### 3.3. Pollination biology

The pollination biology of *E. argophloia* has recently been evaluated under an Australian Research Council grant to Wallace and Lee (LP0562678). In this study stigma receptivity did not commence until six days after anthesis (Randall *et al.* in prep). Stored (desiccated and stored at +4ºC) *E. argophloia* pollen did not result in pollen tube growth whereas freshly extracted pollen resulted in abundant pollen tube development. The three-stop pollination method (Van Wyk 1977) was effective at producing pollen tubes, whereas both the one-stop pollination technique (Harbard *et al.* 1999) and protogyny treatments (de Assis *et al.* 2005) resulted in little or no pollen tube development. In a controlled pollination program, *E. argophloia* readily selfed, outcrossed and hybridised with other Symphyomyrtus species including iron barks, box species and red mahogany (unpublished data).

## 4. *E. ARGOPHLOIA* PESTS AND DISEASES

One of the reasons we have persisted with working with *E. argophloia* is its generally low susceptibility to many pests and to date, an absence of major disease occurrences. The most important pest of *E. argophloia* is the plate galler caused by the larvae of *Ophelimus sp.* (tiny wasps) that feed off the upper leaf surface. This pest is unique to *E. argophloia* and can cause severe damage with 100% of leaves affected and associated defoliation in young plantations (Carnegie *et al.* 2008). A list of the known main pests of *E. argophloia* is provided (Table 3). As indicated above, no significant diseases of *E. argophloia* have been recorded in plantations as yet.

However, seedlings grown in nurseries in far north Queensland for use in south-eastern Queensland plantings have been found to be susceptible to Cylindrocladium leaf blight (*Cylindrocladium quinqueseptatum*).

*Table 3*. The most common pests of *E. argophloia* in plantations and trials in north-eastern Australia (adapted from Carnegie *et al*. 2008).

| Common Name | Species | Susceptibility | Occurrence |
|---|---|---|---|
| Gum leaf skeletoniser | *Uraba lugens* | Moderate | Uncommon |
| Flea beetles | *Chaetocnema* sp. | Moderate | Uncommon |
| Wingless grasshopper | *Phaulacridium vittatum* | High | Uncommon |
| Leaf spotting bug | *Rayieria* spp. | Low | Uncommon |
| Plate galler wasp | *Ophelimus* sp. | High | Common |
| Giant wood moth | *Endoxyla cinereus* | Low | Uncommon |
| Culama wood moth | *Culama* spp. | Low | Uncommon |

## 5. WOOD PROPERTIES OF *E. ARGOPHLOIA*

The wood of *E. argophloia* is not well known by the Queensland timber industry and wood produced under a plantation regime is understood even less. The wood of *E. argophloia* is an attractive and uniquely coloured timber, suitable for clear-finished high-value applications such as furniture, joinery and flooring (Armstrong *et al.* 2003). The sapwood is described as contrasting, white in colour, and has the potential to be used to provide a striking visual feature in some styles of appearance applications. The heartwood colour is described as orange-brown to deep red-brown. The wood is described as having a fine to medium textured grain that is variable from straight to interlocked.

The basic density of wood from native forests is reported to be 855 kg/m$^3$ (Department of Primary Industries and Fisheries 2006), while (Armstrong *et al.* 2003) reported the basic density for 32 year-old and 10 year-old plantation grown wood to be 838 kg/m$^3$ and 726 kg/m$^3$ respectively. Unfortunately the reporting is unclear with some conflicts between the report data and text, and it is suspected that these values represent outer heartwood basic densities. Average basic densities are believed to be somewhere in the vicinity of 767 kg/m$^3$ and 714 kg/m$^3$ for the 32 year-old and 10 year-old material respectively. More recent studies (Kennedy *et al.* 2011) reported a basic density of 663 kg/m$^3$ for 12 year-old plantation wood sourced from Gatton, west of Brisbane. These results are comparable to other mid to high density eucalypts such as spotted gums (*Corymbia* species) at these various ages.

The sapwood of *E. argophloia* is reported as being provisionally susceptible to *lyctus sp.* (Department of Primary Industries and Fisheries 2006) suggesting that susceptibility has not been accurately determined by reliable laboratory testing. For most product applications, the sapwood would therefore need to be preservative treated to ensure protection against lyctine attack.

The natural heartwood durability of *E. argophloia* wood is reported to be durability class one for both above-ground and in-ground applications (Anon. 2010). Accelerated durability bioassay testing of 32 year-old and 10 year-old plantation grown wood has performed well, being highly resistant to fungal decay with performances similar to other durability class one timbers tested (Armstrong *et al.* 2003).

### *5.1. Sawn timber*

Published strength group information for *E. argophloia* lists the green (unseasoned) strength group as S2 and SD3 for seasoned wood (Armstrong *et al.* 2003). Both of these values however are provisional, indicating that the values have been based on the density data and/or limited mechanical properties data. Structural sawn timber from an S2 strength group in an unseasoned condition has the potential to be graded as high as F22. The same timber in a seasoned condition has the potential to grade as high as F27. These values however would most likely be applicable to mature native forest wood only. Armstrong *et al.* (2003) report, lower strength group values from limited testing performed on small-clear wood samples sourced from 32 year-old and 10 year-old plantations. In their study, estimated strength group values of S3 and S5 were reported for the older plantation wood and younger plantation wood respectively. Their report also highlighted an effect of sloping grain within the test samples but does not confirm whether the problem was restricted to sample preparation or to the wood resource in general.

There is very limited information published on the grade recovery of sawn timber products from *E. argophloia*. A small study by Leggate (1998) details that the green-off-saw recovery was 33.75%, with only 7.8% of the log volume meeting the requirements for an appearance-sawn product (in accordance with AS2796, however exact product category not specified).

In a study reported by Armstrong *et al.* (2003), green-off-saw recoveries of 47% and 42% were measured for 32 year-old and 10 year-old plantation logs respectively. Visual grading in accordance with AS2796 (same standard as adopted by Leggate 1998), yielded up to 30% of the log volume from the older plantation resource being recovered for the flooring product category. For the sawn timber produced from the younger 10 year-old trees, only 14% of the log volume could be recovered for the same flooring product category.

While the physical and mechanical properties of plantation sourced *E. argophloia* make the wood suitable for sawn timber applications for either structural or appearance type products, the low-grade recoveries would make the economics of production marginal. This would be especially true when competing in commodity type markets where alternative forest resource with similar properties is available in a form that can produce higher recoveries. Opportunities to attract a premium value may exist in some niche markets however the volume demanded would be minimal.

### *5.2. Wood-based composite products*

Wood-based composite products can include a large range of products. In simple terms and excluding fibre panel type products (e.g. medium density fibreboard, particle board etc), these products are usually constructed from a feedstock of sawn timber or veneer. Wood-based composite products may potentially allow production of higher quality products while potentially using a broader range of feedstock qualities.

Specifically for veneer applications, the log size produced in short rotation plantations is traditionally regarded as being too small in diameter for consideration in rotary veneer operations. However, the recent emergence of advanced technologies allows logs to be peeled to very small peeler core diameters (by using retractable spindles with back-up roller support or spindleless lathes) and the opportunity for small-log processing has become more attractive. This is of course also influenced by the general reduction in available log qualities forcing industry to adapt to lower quality resources.

Preliminary findings from rotary peeling trials of 12 year-old plantation *E. argophloia* provide some encouraging results. A total of 12 trees provided the trial with 34 billets which were peeled at a billet length of 1300 mm using a spindleless veneer lathe (Kennedy *et al.* 2011). Total billet volume was 1.15 $m^3$ and 3.2 mm dry veneer thickness was targeted. A green recovery of 73% was achieved, almost double that expected from a sawn timber process. When graded to Australian and New Zealand standard AS/NZS 2269:2008, (Standards Australia 2008), 44% of the log volume was found to have produced veneer that meet the structural veneer quality of D-grade (the lowest structural grade) or better. While panel mechanical properties were not reported, modulus of elasticity (MOE) of the veneer indicates an average MOE of above 12.5 GPa. This suggests that even at such an early age, the mechanical properties are potentially superior to commonly available final rotation softwood resources.

While the effort towards evaluating *E. argophloia* in wood-based composite products has been limited, the findings reported by Kennedy *et al.* (2011) indicate that veneer processing can achieve much higher recoveries of usable product than sawn timber processing. The mechanical properties and grade recoveries lend the resource towards the existing large structural product market. Within this market, a premium is attached to veneer with high mechanical properties which *E. argophloia* veneer may be able to meet.

While there are some positive indications from the work reported by Kennedy *et al.* (2011), manufactured plywood panel mechanical properties, adhesive performance and the economics of production need to be evaluated further.

## 6. CARBON SEQUESTRATION OF *E. ARGOPHLOIA*

Given the moderate growth rates of *E. argophloia* and its high density, the species has good potential to sequester carbon and then to store it as a durable timber. The results reported here support the findings of by Lee *et al.* (2011) that *E. argophloia* has good potential to sequester carbon in marginal rainfall areas in north-eastern Australia and the same may apply for New Zealand.

## 7. SUMMARY

This endangered species has great natural form and potential to grow with MAIs reaching 6.7-10m$^3$/annum by age 18 under plantation conditions in low rainfall environments. The Queensland Government has established a broad genetic base of the species in seed orchards and progeny trials and seed production has commenced. The species is not considered amenable to propagation as a rooted cutting with only *ca.* 10% rooting success. It also is difficult to pollinate unless the traditional three-stop pollination technique is employed.

Wood property evaluations show that plantation grown *E. argophloia* produces durable timber and there is potential to select trees that have elite growth, density and heartwood percentage. The physical and mechanical properties of plantation sourced *E. argophloia* make the wood suitable for sawn timber applications for either structural or appearance type products. However, the low-grade recoveries may make the economics of production marginal. A recent evaluation of the potential to use *E. argophloia* in composite products indicated that it may have potential to be processed into veneer based products where grade recoveries are high and products can capitalize on the high mechanical properties of the timber. The research work presented here is preliminary, so all results should be treated accordingly.

## 8. ACKNOWLEDGEMENTS

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MERV SHEPHERD

# EARLY DECISIONS IN EUCALYPT DOMESTICATION; SPECIES DELINEATION, GEOGRAPHIC VARIATION, INBREEDING AND OUTBREEDING DEPRESSION

## 1. INTRODUCTION

Often the success of a tree breeding program is fixed by the early decisions on the species and sources chosen for improvement (White *et al*. 2007). Large gains for many traits of economic importance can often be obtained early by identifying the best provenances and selecting within those provenances. Other early decisions surround the need to manage both inbreeding and outbreeding depression, and how to rapidly and cost effectively generate propagules for deployment.

This paper looks at some of the ways genetic markers have been used to help with early decisions in the domestication of eucalypts. The scope is restricted to applications for neutral genetic markers, i.e. those such as microsatellite markers, which are generally not subject to natural selection and therefore are most useful for exploring evolutionary relationships and the effects of demographic (e.g. migration) or neutral processes (e.g. genetic drift) on the distribution of genetic variation among and within species. The paper does not consider the many important applications of markers in forward genomic approaches, i.e. where markers are identified that are linked with traits of economic value in populations where strong linkage disequilibrium is induced (see Grattapaglia and Kirst 2008 for a recent review). These applications usually become more important only as the large initial gains in the first few generations following domestication decline, and an understanding of the underlying genetics becomes necessary, or the potential for gains from marker aided selection comes more attractive. Examples were chosen to show how markers have contributed to applied tree improvement and include; species delineation in the Blackbutts (*E. pilularis* and *E. pyrocarpa*), a revision of race classification in *E. globulus*, testing of hypotheses of inbreeding in *E. pilularis*, and optimisation of *E. grandis* x *E. urophylla* seed orchard design and management.

## 2. SPECIES DELINEATION

One of the first challenges when embarking on a domestication program for a tree species is the circumscription of the relevant taxa. This may be particularly so for groups like the eucalypts with more than 900 species, many of which are poorly studied in terms of taxonomy and distribution, show extensive clinal variation, and are promiscuous, with hybridisation common among closely related species (Potts and Wiltshire 1997; Ashton 1958).

A genic species concept, which focuses on adaptively significant differentiation and the gene (speciation genes) as the unit of species differences (Wu 2001), may be particularly useful in groups like the eucalypts, where the biological species concept of full reproductive isolation rarely applies to closely related species.

Increasingly, genetic markers have been used to delineate species for breeding or conservation purposes as they allow decisions on a phylogenetic (evolutionary) rather than taxonomic footing (White *et al.* 2007a). Evolutionary relationships often provide a better indication of the degree of reproductive isolation between individuals and thus the fitness of their offspring. This can be helpful in assessing the fitness consequences due to outbreeding depression for offspring from both interspecific and interprovenance crosses. Avoiding the unwitting production of crosses subject to outbreeding depression is a major motivation for resolving taxonomic uncertainties in populations used for tree breeding and restoration plantings (Frankham *et al.* 2007, p.385; Potts and Dungey 2004; Dundash and Fenster 2000).

Outbreeding depression reduces reproductive fitness and increases abnormalities in the $F_1$ and subsequent generations in crosses between individuals from different populations. Most evidence of outbreeding depression comes from plants, where dispersal is limited, and more frequently occurs between populations that have undergone significant adaptation (ecotypes) to local conditions (Frankham *et al.* 2007, p.386). Outbreeding depression has two modes, the first, an extrinsic or local adaption mode where survival of hybrids depends on their interaction with the environment (Edmands and Timmerman 2003). The second mode is intrinsic, where fitness is reduced due to internal factors, either a breakdown in co-adapted gene complexes (i.e. fitness depends on epistatic interactions) or where a detrimental intra-locus interaction occurs (i.e. under-dominance or a heterozygote disadvantage) (Edmands and Timmerman 2003). Outbreeding depression is clearly exhibited as depressed germination rates and abnormalities in $F_1$ and advanced generation interspecific eucalypt crosses (Potts *et al.* 2003, Table 4; Griffin *et al.* 2000).

### *2.1 Blackbutts*

The Blackbutts exemplify a classification problem facing eucalypt taxonomists and gene pool managers. Two species may be distinguished using morphological and ecological criteria but not genetically. *Eucalyptus pilularis* is a widespread species whose distribution spans both subtropical summer- and temperate winter-rainfall dominated climates, ranging between latitudes 25-37°S from Fraser Island, Queensland (Qld) in the north to near Bega in southern New South Wales (NSW) (Slee et al. 2006, Figure 1). *Eucalyptus pyrocarpa* (large-fruited Blackbutt) is very similar to, and forms a mosaic with *E. pilularis*, but prefers less fertile and higher elevation sites, and although locally abundant, has a more restricted patchy distribution from around Woodburn (NSW) (29.07°S) in the north to Wauchope (NSW) (31.46°S) in the south. *Eucalyptus pilularis* is the focus of the Blackbutt improvement programs in NSW and QLD but it is regarded as a fussy species that requires high quality sites that are increasingly unavailable for forestry purposes

(Smith *et al*. 2004; Johnson and Nikles 1997). It is of interest therefore, whether the adaptive range of germplasm from Blackbutt breeding programs might be broadened by infusion of *E. pyrocarpa* genetic background.

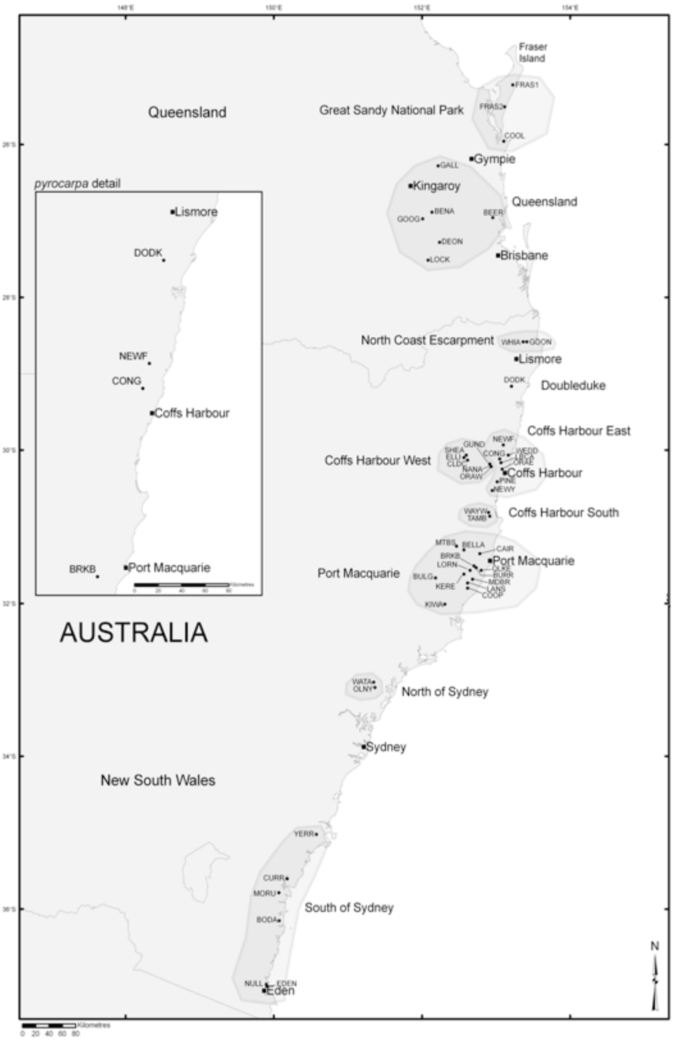

*Figure 1*. Locations of *E. pilularis* and *E. pyrocarpa* (insert) sampled for a study of species delineation. Locality names and coordinates are provided in Shepherd and Raymond (2010). NB Both taxa were sampled at each four *E. pyrocarpa* locations. Ten regions of *E. pilularis* were identified based on rainfall and population disjunction and are highlighted.

Genetic analysis of the Blackbutts suggested *E. pyrocarpa* and *E. pilularis* are not "good" species, with less genetic differentiation between taxa than within taxon for paired-samples of Blackbutt species from four locations spanning the range of the more narrowly distributed *E. pyrocarpa* taxon (Shepherd and Raymond 2010). Furthermore, range-wide analysis of *E. pilularis* revealed significant regional-scale differentiation in molecular and adaptive variation (Shepherd et al. 2010). This suggested a new regionally-based subdivision should be recognised within *E. pilularis* (southern and northern subspecies) and the two Blackbutts species might be better classified as ecotypes because although genetically indistinguishable, they are discernable on ecological grounds (Shepherd and Raymond 2010).

This reassessment of relationships in the Blackbutts should help inform future decisions with the breeding populations. High levels of contemporary inter-taxon gene flow indicate the genomes of the two taxa are broadly permeable to genetic exchange and suggest reproductive isolation between the taxa should be minimal. Outbreeding depression due to intrinsic factors (i.e. due to a breakdown in co-adapted gene complexes) would not be expected to be strong in crosses between *E. pyrocarpa* and northern *E. pilularis* provenances. Nonetheless, field observations reveal sharp transitions in ecotype distributions corresponding with changes in soil type and elevation, suggesting strong selection for parental genotypes at some locations. Adaptation appears to be occuring at a landscape level, giving rise to morphological differentiation and probably inducing allele frequency differences at adaptive loci. Selection against inter-ecotype hybrids is outbreeding depression imposed by extrinsic factors (i.e. a GxE mode of outbreeding depression). The results of the genetic studies suggest, therefore, that *E. pyrocarpa* might be introduced into the Blackbutt breeding population without penalty from outbreeding depression due to intrinsic factors. But whether a potential advantage is realised by broadening the adaptive base will depend on the match between the prospective plantation landbase and the drier ridge sites *E. pyrocarpa* naturally occupies.

## 3. GEOGRAPHIC STRUCTURING

Over the past few decades there has been increasing awareness of the need to adequately sample within species variation when planning for conservation management or tree improvement (Millar 1983; White *et al*. 2007b). The study of geographic variation is a logical first step in domestication of a tree species if breeding populations and deployment zones for applied tree improvement programs are to be both genetically sound and logistically efficient (White *et al*. 2007b). Using genetic markers to study geographic variation has the advantage that samples of tissues can be acquired directly from trees growing in the wild. Hence information on genetic structuring can be obtained without the delays associated with growing progeny in common garden trials. Inferences about structure are at the genome rather than locus scale, as structuring of neutral genetic markers should primarily reflect evolutionary forces other than selection i.e. drift and migration. However, as studies based on genetic markers generally do not inform on patterns of adaptive variation they clearly cannot replace long-term provenance trials (White *et al.* 2007b).

Studies of geographic structuring in *E. globulus* highlight how describing patterns of genetic structuring alleviate some of the problems of using phenotypes for racial classifications (Steane *et al.* 2006). The race classification system for *E. globulus* is valuable in the prediction of breeding values for this species (Dutkowski *et al.* 1997). However, classifications based on quantitative characters may be misleading about true genetic relationships because of convergent or divergent selection.

Comparison of $Q_{st}$ and $F_{st}$ values in a study of *E. globulus* sampled from across 34 localities in Victoria, the Bass Strait and Tasmania, showed that there is a significant but low correlation between phenetic and genetic distance matrices, and that genetic similarities among localities showed a strong association with geographic proximity (Steane *et al.* 2006). $Q_{st}$ is a measure of racial differentiation based on quantitative data and is equivalent to $F_{st}$, a measure of racial differentiation based on molecular data. Divergence between these two estimates of population differentiation can be indicative of selection; i.e. where $Q_{st} > F_{st}$, divergent selection may be occuring, and when $Q_{st} < F_{st}$, stabilising selection may be occuring. Equivalence suggests no selection (Spitze 1993). Because $F_{st}$ values are based on genetic markers, they are assumed to provide a baseline of divergence due to neutral evolutionary forces (i.e. migration and drift).

Probable cases of both divergent and stabilising selection were identified. The significance of the correlation between quantitative and molecular distance matrices was attributed to correspondence at the regional level i.e. mainland or island races but discrepancies between quantitative and molecular distance matrices could also be large within regions. Traits such as leaf size and bark thickness showed evidence of diversifying selection due to local adaptation within regions as indicated by $Q_{st} >> F_{st}$. On the other hand, Furneaux and Western Tasmanian races that both have relatively small leaf sizes, were divergent by neutral markers, suggesting convergent selection rather than shared ancestry may account for phenetic similarity in this trait for these races (Steane *et al.* 2006). In these situations, true evolutionary relationships may be masked, and inter-race cross performance based on these measures may be misleading.

Countering the types of discrepancies revealed in such studies of genetic structure should allow breeders to better predict performance in their crossing programs. For example, outbreeding depression may be occuring in the *E. globulus* breeding program that is now in its third selection cycle. Accounting for frequency and degree of impact of inter- and intra-lineage crosses among the three somewhat independent evolutionary lineages identified in the study of *E. globulus* would help to manage negative fitness consequences of wide hybrids. Accounting for racial or population differentiation in tree breeding populations is also important in assessing the significance of association studies. In the near future, it will be feasible to use information from association studies that identify variation at the gene level linked to economic or adaptively significant traits in forest trees for marker aided selection in breeding program (e.g. Thumma *et al*. 2005; Sexton *et al*. 2010). However, false inferences can arise if population structuring is not controlled during analysis (Neale and Savolainen 2004). This will be particularly important for species like *E. globulus* with strong geographical patterns of variation (Steane *et al*. 2006).

## 3. WITHIN POPULATION STRUCTURE (STAND STRUCTURE; INBREEDING)

A study of the Fraser Island provenance of *E. pilularis* provides an example of how molecular markers can test hypotheses surrounding the levels of inbreeding in natural stands and its influence on the growth of offspring in progeny trials. A coastal ecotype of *E. pilularis* from Fraser Island was first recognised on the basis of flowering time and mature and juvenile leaf morphology (Florence 1969), and speculation has remained as to whether inbreeding in this small isolated population, or adaptation, better explained poor growth relative to mainland provenances from northern NSW (Burgess 1975; Johnson and Nikles 1997).

This hypothesis was examined in a study of genetic structuring and diversity in *E. pilularis* using microsatellites (Shepherd et al. 2010). It was shown that Fraser Island material was not more inbred than nearby mainland provenances or those from other regions. This suggested that adaptation to extreme environments better explained the poor performance of the Fraser Island provenance than inbreeding (Table 1).

*Table 1.* Genetic diversity (Mean (SE)), sample numbers, number of alleles and fixation indices for 10 regions of *E. pilularis* trees (n = 424). Region names; GSNP = Great Sandy National Park (incl. Fraser Is); Qld = Queensland; NCE = North Coast Escarpment; DODK = DoubleDuke SF; CHW = Coffs Harbour West; CHE = Coffs Harbour East; CHS = Coffs Harbour South; PM = Port Macquarie and SSYD = South of Sydney. *See* Shepherd *et al.* (2010) for further details.

| *Region* | *N* | $N_a$ | $N_e$ | $H_o$ | $H_e$ | *F* |
|---|---|---|---|---|---|---|
| GSNP | 20.5 (1.2) | 9.6 (1.1) | 5.4 (0.9) | 0.68 (0.07) | 0.71 (0.07) | 0.04 (0.05) |
| QLD | 31.7 (0.5) | 12.9 (1.6) | 7.1 (1.2) | 0.66 (0.06) | 0.77 (0.05) | 0.17 (0.03) |
| NCE | 45.1 (0.4) | 14.5 (1.9) | 7.5 (1.3) | 0.76 (0.05) | 0.79 (0.05) | 0.05 (0.02) |
| DODK | 9.6 (0.2) | 8.3 (1.2) | 6.1 (1.0) | 0.74 (0.08) | 0.73 (0.07) | -0.02 (0.04) |
| CHW | 38.3 (0.5) | 14.4 (1.8) | 7.6 (1.3) | 0.80 (0.03) | 0.81 (0.04) | 0.00 (0.03) |
| CHE | 62.9 (0.5) | 16.7 (2.2) | 8.4 (1.4) | 0.74 (0.05) | 0.80 (0.05) | 0.08 (0.03) |
| CHS | 12.8 (0.1) | 9.9 (1.1) | 6.6 (0.9) | 0.79 (0.04) | 0.80 (0.04) | 0.00 (0.02) |
| PM | 116.1 (1.2) | 18.3 (2.3) | 8.8 (1.4) | 0.80 (0.04) | 0.82 (0.04) | 0.01 (0.01) |
| NSYD | 7.7 (0.1) | 6.8 (0.7) | 5.0 (0.7) | 0.76 (0.03) | 0.74 (0.05) | -0.07 (0.06) |
| SSYD | 61.5 (2.2) | 14.3 (1.5) | 6.8 (1.2) | 0.76 (0.04) | 0.79 (0.04) | 0.03 (0.03) |
| Total | 40.6 (2.9) | 12.6 (0.6) | 6.9 (0.4) | 0.75 (0.02) | 0.78 (0.02) | 0.03 (0.01) |

N = sample size; $N_a$ = No. of alleles; $N_e$ = Effective number of alleles; $H_o$ = Obs. heterozygosity; $H_e$ = Expected heterozygosity; F = Fixation Index.

## GEOGRAPHIC STRUCTURE, SPECIES DELINEATION AND AVOIDING INBREEDING

It seemed most likely the Fraser Island ecotype arose by local adaptation, following colonisation of the sand mass. The ecotype probably evolved parapatrically in response to local site conditions (i.e. soil fertility and depth, rainfall, elevation), and differentiated despite extensive ongoing gene flow from the mainland (the Fraser Island populations are not well differentiated from nearby Queensland localities (Gallangowan) (Shepherd *et al*. 2010). Lower diversity levels for the Fraser Island and more northerly provenances in Queensland generally, however, suggested, occupation of this northern region is either more recent than regions to the South in Northern NSW, or it represents an extremity of the adaptive range of the species, as diversity is often reduced in populations at the limits of a species range or following range expansion. Parallel examples of the effect of adaptation to poor site quality on growth have been noted in many tree species including other eucalypts such as *E. globulus*. Material of *E. globulus* from extremely hostile environments such as the Lighthouse population from Wilson's Promontory retains a stunted form and poor growth in common garden trials (Dutkowski and Potts 1999).

## 5. MARKER-ASSISTED BREEDING; INCREASING THE QUALITY OF SEED FROM SEED ORCHARDS USING PARENTAL RECONSTRUCTION

Marker assisted breeding and parental reconstruction are probably the areas where genetic markers currently have the greatest impact in applied tree improvement. DNA fingerprinting is now conducted in a number of countries around the world including South Africa, Chile, Brazil and Australia, in some cases on a large scale (i.e. ~ 8000 trees per year). Genetic markers provide unrivalled power for resolving relationships and establishing parental identity; this is most useful in a tree improvement context where it is used to restore full pedigree information. The use of open pollinated seed for production plantings or progeny testing is common practice in early stages of many tree breeding programs as it is often impractical or too costly to use controlled pollination (Eldridge *et al*. 1994). However, by retrospectively recovering the identity of the pollen parents of OP progeny by parental reconstruction, progeny tests retain their informativeness as BV can be obtained for pollen parents (Hansen and McKinney 2010; Grattapaglia *et al*. 2004). Marker assisted breeding tactics that employed parental reconstruction have been variously referred to as quasi-field trials when used to estimate breeding values from OP progeny in operational stands of *Picea* in Denmark (Hansen and McKinney 2010), or polymix breeding with parental analysis (PMX/WPA) when considered as an alternative to full-sib breeding of loblolly pine (Lambeth *et al*. 2001). Parental analysis also allows testing of many of the assumptions used in estimating gains from a seed orchard and the effectiveness of seed orchard management practices i.e. the use of isolation buffers, evenness of pollen parent contributions and checking levels of inbreeding due to selfing or crossing among relatives.

Grattapaglia *et al*. (2004) showed that realised gains of 24% in the growth of operations stands of *E. grandis* x *E. urophylla* hybrids were obtained by renovating a clonal seed orchard and implementing improved seed orchard management practices. Most of the genetic gain in this case accrued from simple changes to management practices that minimised pollen contamination (addition of nutrients to promote flowering; introduction of bee hives to encourage pollinations within the orchard). Although clones with low-reproductive output were culled from the orchard, this was not expected to have greatly altered the genetic merit of progeny from the orchard in this case; nonetheless, removing paternal parents of poor genetic merit may be a key step for orchard improvement in other situations.

By comparing DNA fingerprints from samples of select, high performing individuals with random samples of six year-old progeny growing in operational stands, Grattapaglia *et. al.* (2004) were able to show that the pollen contributions of the six paternal clones was highly uneven (due to asynchrony in flowering time), and that some clones contributed to significantly more individuals in select samples than individuals in random samples. Twenty-nine percent of pollen contributing to offspring in the operational planting originated from outside the orchard. Although the genetic merit of progeny resulting from pollen outside the orchard could be high, (55% of progeny were in the select samples and none were in a sample of stunted trees), contaminating pollen did not have the genetic merit of the best clone (which contributed to 92% of select progeny). The study also found that selfing occurred at a rate of 8.3%, which was consistent with the mixed mating system of eucalypts. Selfing had a profound influence on the performance of stock produced from the orchard as selfed progeny were stunted, and made up almost half of non-select trees at six years of age in the production stand. These direct estimates of inbreeding confirm the effect of inbreeding depression on the growth of eucalypts and provide a measure of the gains that may be achieved by moving to controlled pollinated crossing programs. Outcrossing rates have been found to be relatively stable across eucalypt species but may have been underestimated in the past where studies were based on isozymes which have lower power to detect selfs (Byrne 2008; Potts and Wiltshire 1997). Genetic markers, such as microsatellites, have proven to be valuable tools in providing better estimates of mating system parameters, and for the design and management of seed orchards, aiding the productivity from early steps in the domestication of eucalypts.

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CHRIS BEADLE, JANE MEDHURST AND DAVID FORRESTER

# LINKING SILVICULTURAL MANAGEMENT TO SOLID-WOOD VALUES

## 1. INTRODUCTION

Of the >20M ha of plantation eucalypts worldwide (Iglesias-Trabado and Wilstermann 2009), at least 5% have saw-log potential (FAO 2005). The species planted most commonly are those with fast early growth rates. The short rotations (<20-30 yr), even for saw-logs, that are feasible with these species are often associated with the development of internal growth stresses and tension wood that lead to end-splitting at harvest and limit the recovery of wood during processing (Washusen 2005). On the one hand, these issues are being addressed through the use of new sawing and drying technologies (Washusen 2011), and by developing an understanding of genotypic variation in wood properties (Blackburn *et al.* 2010; Blackburn *et al.* in press). This paper asks the question, can they also be addressed through silvicultural management. Besides high levels of growth stress, plantation timber usually has lower wood density, hardness and stiffness than that of slower-growing native-forest trees of the same species; this is an issue for *E. nitens* which in Australia, particularly in Tasmania, has been the most commonly planted species managed for solid-wood production (Beadle *et al.* 2008). The other major species planted in Australia is *E. globulus*, particularly as an exotic in the Mediterranean climates found in Western Victoria, south-east South Australia and south-west Western Australia. These species are the major focus of this paper. Subtropical species such as *E. pilularis*, and more recently *E. dunnii* and *Corymbia citriodora* ssp. *variegata*, have also been planted and managed for solid-wood production in Australia (Nichols *et al.* 2010). In New Zealand, *E. saligna* has been processed for solid-wood products (Poole 2009).

## 2. OPTMISING SILVICULTURAL INPUTS

### *2.1. Background*

Eucalypt plantations to be managed for solid wood are established at stockings around 1000 stems ha$^{-1}$. This is done for two main reasons. High rates of growth lead to the rapid development of intra-specific competition which has positive effects on form, particularly by reducing branch size. For *E. globulus* and *E. nitens*, which do not naturally shed branches, this is particularly important; pruning large branches in these species can be associated with the development of stem defect (Mohammed *et al.* 2000). The second reason is that even at these planting densities, current eucalypt planting stock can be associated with variation in growth rate and form; the higher stocking allows for selection of retained trees that are good in both respects (Beadle *et al.* 1994). Improved seed from breeding programs is addressing this issue in *E. globulus* and *E. nitens*.

In an ideal world it makes sense to do nothing that prejudices characteristic rapid early growth rates. As these are very much compromised in eucalypts by inter-species competition (Adams *et al.* 2003), weed control is essential. Thinning regimes are a necessity in plantations managed for solid wood; these and fertiliser application can be used to maintain growth rates, particularly those of the selected final-crop trees. Pruning is essential in *E. globulus* and *E. nitens* to produce clear wood and realise commercial wood-quality outcomes (Nolan *et al.* 2005). However, care must be taken not to prune so severely that the value gained by increasing wood quality is outweighed by reductions in stand value due to reduced growth rates. High rates of growth *per se* mean that getting the timing of interventions right can be a fraught process; being aware of what you might be doing to wood values at the same time adds complexity but should lead to better decision-making.

### *2.2. Responses to treatment - stand*

Thinning, pruning and fertiliser application alter canopy structure and physiological function in different ways. In commercial plantations, these inputs may or may not be undertaken simultaneously but often are. It is therefore instructive to examine how potential interactions between these treatments are expressed. Such an experiment has recently been completed in an *E. nitens* plantation at Carrajung in Victoria (Forrester *et al.* submitted, a). Two levels of each treatment were applied, unthinned (900 stems ha$^{-1}$) and thinned to 300 stems ha$^{-1}$; unpruned or pruned removing 50% of the live crown length of the largest 300 potential sawlog crop trees ha$^{-1}$ ($SCT_{300}$); and no fertiliser or 300 kg N ha$^{-1}$. The pruning removed 75% of the leaf area. The treatments were applied at age 3.2 years.

The effect of each treatment on growth efficiency defined as volume periodic annual increment (PAI; m$^3$ ha$^{-1}$ year$^{-1}$) per unit leaf area index, LAI (Waring 1983) was examined. In the first year after treatment, LAI accounted for 61-87% of the variation in stand PAI (Figure 1a, c, e). Pruning had the strongest influence on this relationship and significantly increased the growth efficiency of the stands (Figure 1c); the relationships show that initial responses to treatment were both structural and physiological. Four years after treatment, as stand leaf areas developed and stabilised, the relationships between LAI and growth efficiency became much stronger (Figure 1b, d, f) and subsequently there were no treatment effects. This reduction in the contribution of physiological responses to treatment with time is consistent with parallel studies on other species (Cannell 1989; Albaugh *et al.* 1998).

Thinning and pruning can also be used to manage the use of water. At Carrajung, thinning and pruning reduced stand transpiration by 45 and 12%, respectively, while fertiliser application increased transpiration by 21% (Forrester *et al.* submitted, c). Thinning and pruning also increased water-use efficiency (WUE) defined as annual above-ground biomass increment per unit transpiration, by 23 and 21%, respectively; fertiliser application had no significant effect on WUE. Using thinning and pruning to reduce stand transpiration, while also increasing WUE, could be useful where water resources are in high demand and on sites that are subject to periodic drought.

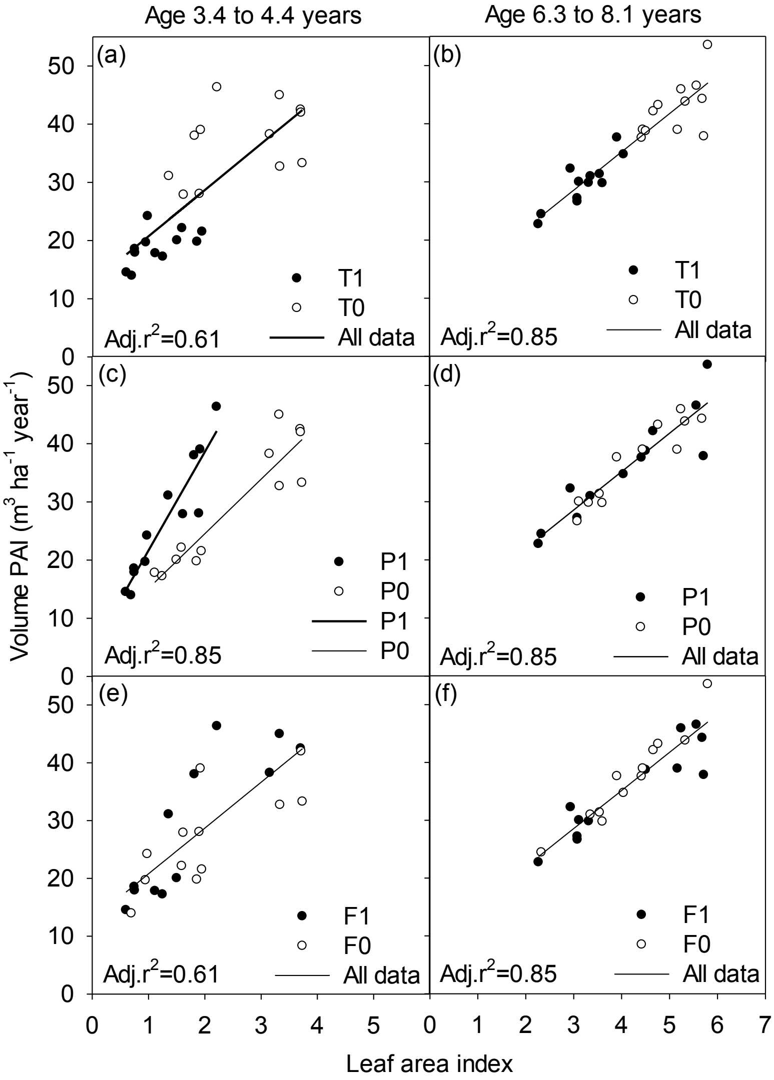

*Figure 1*. The effect of thinning (T; a, b), pruning (P; c, d) and fertiliser application (F; e, f) on the relationships between total-stand volume periodic annual increment (PAI) and leaf area index (LAI) at the beginning of each increment period. The slopes and intercepts are significantly different for (c) only. 0 and 1 refer to without or with the treatment, respectively (Forrester *et al*. submitted, a).

### *2.2. Responses to treatment – final-crop trees*

Because of the commonly found high variability in growth rate and form of fast-growing eucalypts, thinning and pruning focus on specific size classes *viz*. the top 200-300 stems $ha^{-1}$. As trees in different dominance classes cannot be assumed to respond structurally and physiologically in the same way to these treatments (Binkley *et al.* 2010), examining these mechanisms should focus on these final-crop trees.

The crucial lesson learnt from the Carrajung experiment is that thinning played a dominant role in realising the potential of final-crop trees. Thus thinning increased above-ground biomass (AGB) of the $SCT_{200}$ by 24% and this was associated with significant increases (24%) in the absorption of photosynthetically active radiation (APAR) and light-use efficiency (LUE, 13%) measured as AGB growth/APAR; fertiliser also increased these variables but by a smaller amount (Forrester *et al.* submitted,b). Because APAR and tree leaf area are linearly related, this finding presents a very strong case for maximising tree leaf area and keeping it well lit when aiming to increase the growth and value of saw-log crop trees (Shield 2008). They also support the argument that thinning regimes should be commensurate with the maximisation of crop-tree light interception and therefore growth of the selected trees (Beadle *et al.* 2008).

### *2.3. Second-lift pruning*

High-pruning systems require multiple lifts (Neilsen 1990). On productive sites, lift pruning which removed 50% of the green-crown length and 55% of the leaf area from fast-growing *E. nitens* trees had no significant effect on subsequent growth (Pinkard and Beadle 1998). Such findings are linked to pruning triggering physiological changes that increase biomass production to a level that is significantly greater than in similar unpruned trees in the same environment (Pinkard and Beadle 2000). However there remains less confidence that this will be repeated in second and subsequent lifts.

At the Carrajung experiment, first-lift pruning (P1) which removed 50% of green-crown length and retained 25% of leaf area reduced mean diameter of the $SCT_{300}$ by 5% at age 8.1 years; second-lift pruning (P2) 1.5 years later at age 4.7 years which also removed 50% of green-crown length and retained 28% of leaf area reduced the mean diameter a further 8% relative to P1 and 13% relative to P0 (Figure 2) (Forrester *et al*. submitted, a). Significant differences in diameter >3 years after this second pruning suggest that the trees had not recovered from first-lift pruning; differences in diameter between P2 and the other pruning treatments were still increasing. While this effect would have been less severe if less crown length had been removed, very high rates of growth often mean that pruning intervals will be less than the time required for the tree to recover if live-branch removal is to stay ahead of crown lift. On low quality sites, multiple-lift pruning may also prejudice height growth (Pinkard 2002).

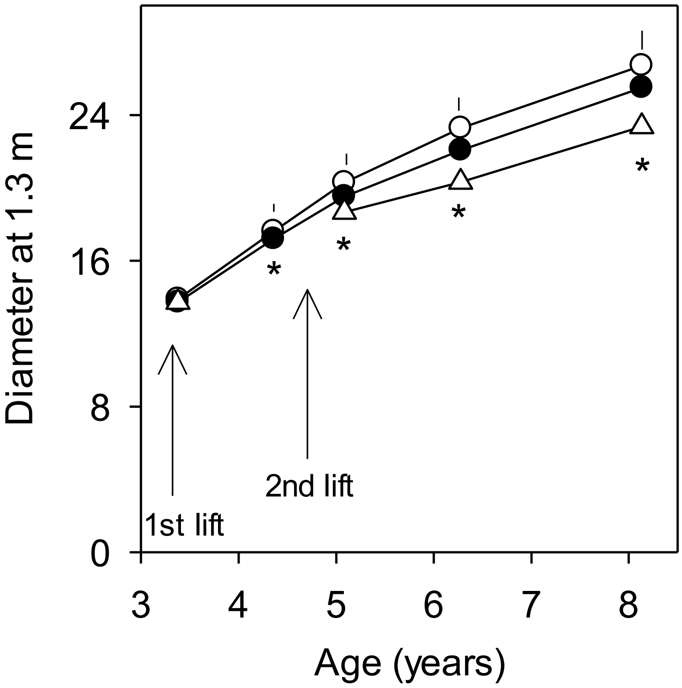

*Figure 2*. The effects of no (P0), first- (P1) and second-lift (P2) pruning treatments which removed 50% of green-crown length and approximately 75% of leaf area on mean diameter at 1.3 m of the largest-diameter 300 sawlog crop trees $ha^{-1}$ ($SCT_{300}$). Data are averaged across thinning and fertiliser treatments. Error bars are standard errors of difference. Asterisk denotes significant differences ($P<0.05$).

## 3. LOG AND WOOD PROPERTIES

### *3.1. Background*

A comprehensive survey of the literature thirteen years ago concluded that wood and paper properties were unaffected by silviculture (Raymond 1998); the author also noted an absence of any strong relationships between tree growth *viz*. height, diameter and volume, and wood properties. Given that the manipulation of wood properties through the smart use of silviculture might be considered an attractive tool to apply in plantation management, these findings were not encouraging.

Since then there has been a more concerted effort, often through the use of new technologies, to re-examine whether silviculture can have a role in the manipulation of wood properties and wood value. Also stem shape is an important consideration in the recovery of wood value. Basic density and microfibril angle (MFA), which together determine wood strength and stiffness, dimensional stability, shrinkage and collapse, tension wood, incidence of decay, spiral grain and end splits have been identified as the key traits that contribute to the quality of sawn timber and veneer (Raymond 2002). Some of these variables are now examined in the context of thinning, pruning and fertiliser application.

### *3.2. Stem shape*

The stem shape of plantation eucalypts can be altered by silvicultural decisions made throughout the rotation. An understanding of the effect of silvicultural operations on stem shape is crucial as this plays a major role in determining the recovery of select grade solid-wood products from eucalypt plantations (Shi and Walker 2006).

Indices of stem form such as the ratio of tree height to tree diameter at breast height, stem form or taper, and cross-sectional eccentricity of growth rings reflect the requirements of a tree for mechanical stability in response to its growing conditions. There is a general consensus that stem taper is a function of growth response to bending stresses applied to the stem as a result of wind action in the canopy (Jacobs 1954; Larson 1965; Osawa 1992; Valinger 1992). Reduced wind exposure and decreased stem sway were suggested as a possible reason for wood stiffness (MoE) of six-year-old *E. cloeziana*, *E. pilularis* and *E. dunnii* increasing by 11% from stockings of 714 to 1250 trees ha$^{-1}$; MoE was also significantly correlated with stem slenderness (Warren *et al.* 2009). Slender *E. nitens* trees, i.e. those with greater height:diameter ratio, were more elliptical in cross-section than stocky trees regardless of thinning treatment (Medhurst *et al.* in press); in addition this study showed that pith eccentricity was linked to the dynamic loading imposed on the stem by the prevailing wind (Figure 3). Thus decisions regarding initial stocking and thinning intensity have important wood-quality implications for forest owners in these respects.

Low initial stocking and thinning promote the growth of tree diameter in eucalypts but generally do not alter height growth (Neilsen and Gerrand 1999). Changes to height:diameter ratios can affect wood quality. In a study of 10-year-old *E. globulus* plantations, Washusen *et al.* (2008) found that slender trees in unthinned plots had lower MFA than stocky trees in thinned plots. A study of a 22-year-old *E. nitens* thinning trial showed that while stem taper tended to increase with thinning, significantly greater taper of the bottom six-metre log was only apparent in heavily thinned stands of 100 trees ha$^{-1}$ (Wang *et al.* 2007).

Pruning of the green crown to improve wood quality can potentially alter stem shape or taper by concentrating stem growth above the pruned height. However, pruning at intensities of 50% or less of green crown removal has not altered stem form in a range of eucalypt plantation species (Pinkard and Beadle 1998; Alcorn *et al.* 2008).

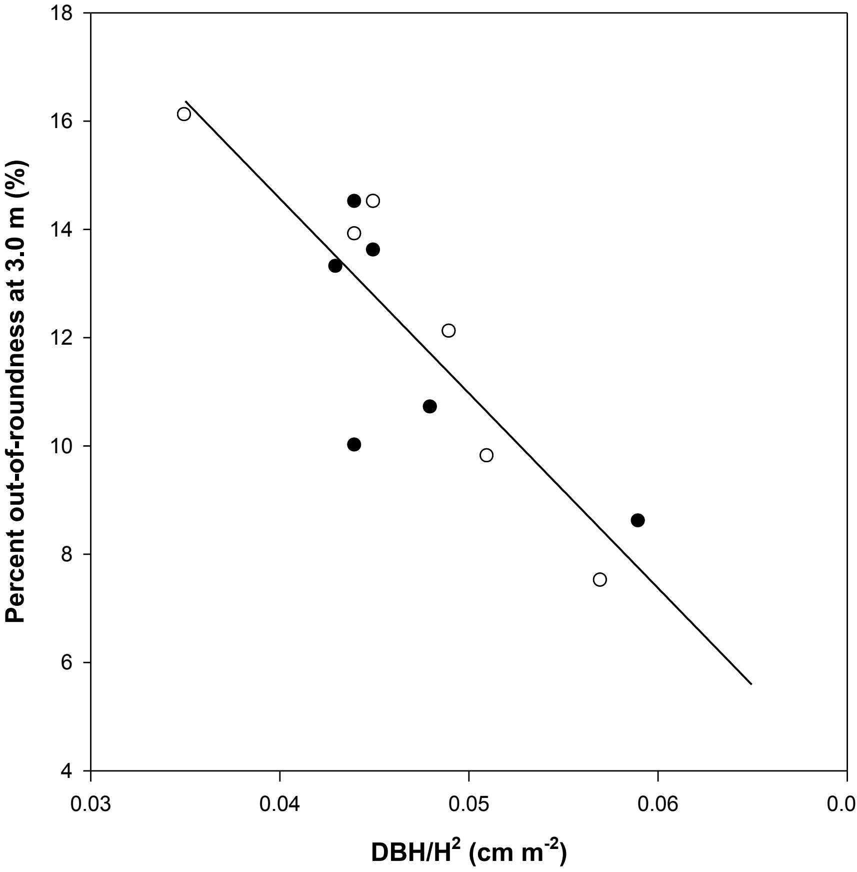

*Figure 3*. Relationship between out-of-roundness (non-circularity) at 3.0 m stem height and DBHob:height² used as a stem shape index (Moore and Maguire 2004) at age 22 years in an *E. nitens* thinning trial. Open and closed symbols are trees from thinned (200 trees ha$^{-1}$ at age 6 years) and unthinned treatments, respectively. Regression line generated using pooled data ($r^2 = 0.75$) (Medhurst et al. in press).

### *3.3. Basic density*

Wood density is a measure of cell wall material per unit volume. While relatively straightforward to measure, basic density is an expression of complex relationships between cell wall thickness, cell diameter, earlywood-to-latewood ratio, and chemical content. Nevertheless, there is a view that of all the traits that define wood, basic density is one to which all end-users can relate (Walker 1993). This is justified because basic density often correlates well with other wood properties, such as strength and stiffness (Alexiou 1994), dimensional stability (Chafe 1990) and permeability (Kollman and Côté 1968).

The basic density of wood within a eucalypt tree is not uniform. In a study of *E. globulus* and *E. nitens*, basic density initially declined from the base and then increased up the tree in a linear fashion: minimum density was recorded at 50% height level (Raymond and Muneri 2001). Basic density also increases from pith to bark (Harwood *et al*. 2005). In concert with these changes, as with most species, basic density of eucalypts increases with age (Hein and Brancheriau 2011).

Our understanding of the environmental variables that influence the wood density in eucalypts has improved with detailed studies that link wood production to climate (Drew and Downes 2009; Drew *et al*. 2009a; Drew *et al*. 2009b; Drew *et al*. 2011). The wood density of plantation-grown *E. globulus* appears to be particularly sensitive to soil water availability; reduced water availability leads to an increase in wood density (Drew *et al*. 2009a); these authors also found that the average wood density formed each month was strongly correlated with the average air temperature of that month. Taken together, soil water availability and air temperature explained 65% of the variation in wood density of *E. globulus* (Drew *et al*. 2009a). In *E. nitens* the seasonal variation in wood density is reduced if the variation in water stress is also low. There are marked decreases in wood density coincident with rainfall/irrigation to relieve drought stress (Drew *et al.* 2009b). Large changes in basic density from pith to bark and within the annual growth cycle are generally undesirable for solid-wood processing. Silvicultural interventions such as thinning and fertilising that aim to maintain relatively continuous individual tree growth throughout the rotation will produce wood that is of significantly more homogenous density compared with stands of more fluctuating periods of growth (Drew *et al*. 2011). While wood density is a heritable trait in eucalypts (Stackpole *et al*. 2010), the importance of soil water availability and air temperature in driving wood density suggest site-specific tailored silvicultural regimes are needed to control wood density variation.

### *3.4. Tension wood*

Tension wood in eucalypts is formed by the production of cells with distinct anatomical and chemical properties that allow a tree to react to changes in its environment that have caused a non-optimal orientation of stem or branches. A distinctive characteristic of tension wood is a thick, gelatinous inner layer of the cell wall. This non-lignified layer is loosely attached to the other layers of the cell wall and the orientation of the microfibrils is nearly parallel to the fibre axis (Du and Yamamoto 2007). During maturation, the tension wood fibres contract strongly in the longitudinal direction, thereby creating a very strong tensile stress to "pull" the leaning stem upright (Du and Yamamoto 2007). In *E. globulus*, tension wood is detected by the presence of these gelatinous fibres using microscopy and by high longitudinal and tangential shrinkage during drying (Washusen and Ilic 2001). Although this shrinkage appears similar to collapse in normal wood, there is no recovery following stem reconditioning as occurs with collapse (Washusen *et al.*

2002). This is thought to be related to the absence of lignin in the S2 layer as lignin is a necessary part of the recovery process (R. Washusen, *pers. comm.*).

Tension wood is a major factor limiting the recovery of wood processed from eucalypt plantations, and when located at the periphery is associated with very high growth stresses that result in board distortion (Washusen 2005) and poor accuracy during sawing and sizing. When it is located anywhere within the log or board, tension wood results in high transverse and longitudinal shrinkage (drying defect) during drying (Washusen 2000). The role of silviculture in mitigating the prevalence of tension wood deserves careful attention. A study of peripheral growth strain in *E. nitens* between ages three and 14 years suggested that stem slenderness is correlated with growth stress at a young age, while other factors such as crown symmetry are more influential in older stands (Biechele *et al.* 2009). Tension wood formation in *E. globulus* was correlated with form factor and stem taper (Washusen 2002). These results suggest that manipulation of stand density by thinning early in the rotation can reduce the formation of tension wood. On the other hand, later-age thinning, or a poor growth response to thinning may contribute to tension wood formation in eucalypt plantations (Washusen *et al.* 2005; Washusen *et al.* 2008). The combination of increased exposure to wind and slower stem diameter growth to improve stability may contribute to tension wood formation in these plantations. Studies of silvicultural effects on tension wood in *E. globulus* suggest that fertiliser application at time of thinning may be a useful strategy in minimising tension wood formation (Washusen *et al.* 2005; Washusen *et al.* 2008).

### *3.5. Microfibril angle*

Cellulose occurs as long crystalline microfibrils in the cell wall that have great stiffness in the direction of the microfibril axis. Microfibril angle (MFA) is the winding angle of these cellulose microfibrils in the dominating $S_2$ layer of the secondary cell wall. Wood stiffness is a function of cellulose content and its distribution in the cell wall. Microfibril angle is an important characteristic for sawn timber because the stiffness of the cell increases approximately linearly as MFA decreases (Cave 1968): at the same time, longitudinal shrinkage decreases, though in a highly non-linear manner, and tangential shrinkage increases (Walker and Butterfield 1995). Microfibril angle alone accounted for 87% of the variation in wood stiffness, expressed as Young's modulus of elasticity (MoE), in plantation-grown *E. globulus*, *E. nitens* and *E. delegatensis* (Yang and Evans 2003).

The MFA of eucalypts tends to start at about 20° at the pith (Evans *et al.* 2000). The MFA declines rapidly throughout the earlywood and tends to reach a relatively stable value by the fifth growth ring; the MFA of the outer wood of eucalypts typically ranges between 10 and 15° (Donaldson 2008). The MFA of eucalypts also declines rapidly with tree height to a height of approximately 10 m or 60% of merchantable height beyond which it then increases rapidly (Evans *et al.* 2000; Kibblewhite *et al.* 2004).

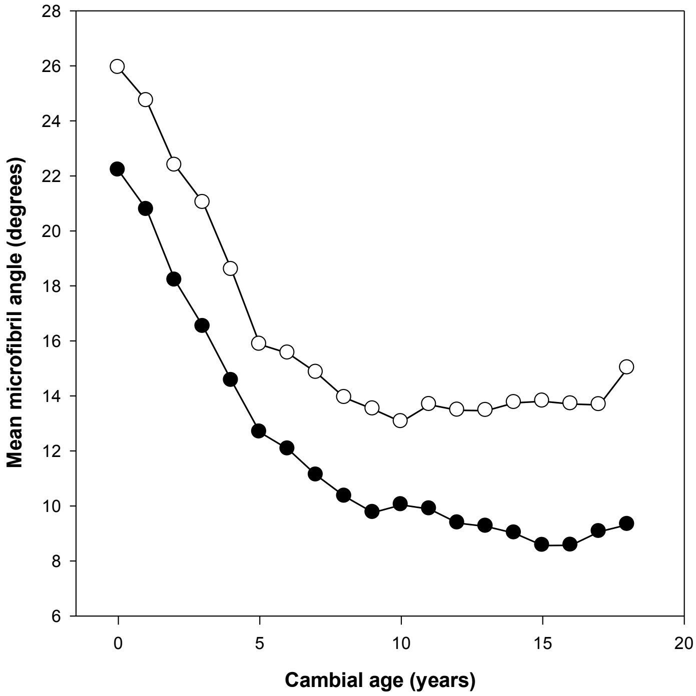

*Figure 4.* Radial pattern of mean microfibril angle (MFA) at stem height of 1.3 m for *E. nitens* trees from a fast-growing (open symbols; *n* = 12) and slow-growing plantation (closed symbols; *n* = 12). (Medhurst et al., unpublished data).

Both growth rate and seasonal growth pattern influence MFA of eucalypts (Wimmer *et al.* 2002; Drew *et al.* 2009b). From this we can expect that site selection and silvicultural practices that alter the growing conditions and the growth patterns of plantation eucalypts also have the potential to influence MFA. While the bulk of research to date has focused on softwood species, indications are that the age-related radial pattern of MFA and MoE of eucalypts can also be manipulated through judicious silviculture. A number of studies have shown a positive relationship between tree growth rate and MFA (Donaldson 2008). Thus MFA was higher in *E. nitens* at a fast- than slow-growing site (Figure 4; Medhurst *et al.* unpublished). Thinning from 1000 trees ha$^{-1}$ to 200 trees ha$^{-1}$ in plantation-grown *E. globulus* at age eight years significantly increased mean MFA and lowered the mean density of wood produced during the following four years (Washusen *et al.* 2005). Applying fertiliser had the same effect on MFA and density as thinning (Washusen *et al.* 2005). Higher MFA values were also found in 10-year-old *E. globulus* thinned from 1200 trees ha$^{-1}$ to 300 trees ha$^{-1}$ and/or fertilised with nitrogen at age two years

(Washusen *et al.* 2008). The unfertilised trees had lower MFA than those receiving 250 kg ha$^{-1}$ of N-fertiliser (Washusen *et al.* 2008). No silvicultural effect on wood density was found in this study. However, outer wood density increased with decreasing soil water availability across the three Western Australian sites used in the study (Washusen *et al.* 2008). The effect of pruning on wood properties such as MFA and MoE has not been extensively examined for softwoods or hardwoods.

High MFA is associated with increased drying distortion in sawn timber (Briggs and Smith 1986; Zhang 1997). Does the silviculturally-induced increase in MFA of outer wood pose significant solid-wood processing problems for plantation-grown eucalypts? Probably not as the values appear to fall within the range associated with high stiffness (Apiolaza *et al.* 2009); increasing MFA from the low values, around 10°, associated with tension wood through thinning and site selection may also be desirable (C.E. Harwood, *pers. comm.*).

## 4. SUMMARY

This paper asked the question "can the development of potentially deleterious wood properties in fast-growing eucalypts being managed for solid wood be addressed by silvicultural operations like thinning, pruning and fertiliser application?"

A mantrum for solid-wood production from fast-growing eucalypt plantations has been a perceived need to minimise rotation length, and thereby the costs of production. Simultaneous application of thinning, pruning and fertiliser which will often be associated with solid-wood regimes has shown that these practices can be used to meet this requirement; thinning is the most powerful and should be used to maximise the leaf area of crop trees and their absorption of photosynthetically active radiation as soon as good practice allows. Such an approach has been heavily promoted for eucalypts being managed for solid-wood production in Uruguay (Shield 2008). In Australia, regimes have also been developed that delay thinning until tree size allows a commercial pulpwood harvest, both in Tasmania (Beadle *et al.* 2008) and sub-tropical Australia (Glencross *et al.* 2011). Whether this practice is commercial has been questioned (Volker *et al.* 2005); intra-species competition almost certainly means that growth rates of final-crop trees are compromised. However, even on dry sites in the subtropics, significant growth responses two years after treatment have been demonstrated in *E. dunnii* and *C. citriodora* ssp. *variegata* plantations when thinning was delayed until age 7-8 years (Glencross *et al.* 2011). The Carrajung experiment has shown that such responses are linked to thinning not only reducing transpiration, but also increasing the water-use efficiency of above-ground dry mass production. How to manage sequential lift prunings so as not to prejudice growth rate of crop trees remains unresolved.

Although stem shape affects the recovery of solid-wood products, in the first instance this is determined by bending stresses and dynamic loading imposed by the prevailing wind. Thus spacing and thinning intensity inevitably have implications for stem shape. However increasing stem taper in response to thinning may have little effect on the bottom log. Pruning appears not to affect stem shape in the eucalypts examined to date.

Basic density is generally directly associated with increased value (Raymond and Muneri 2000), though species adapted to dry environments may already have basic densities commensurate with those required for solid-wood products. Given that 65% of the variation in basic density may be accounted for by water availability and temperature in *E.globulus*, is there still room to make a difference through silvicultural inputs? Yes, there is if they can be applied to reduce the natural variation in basic density, primarily caused by fluctuations in water stress. This is likely to demand site-specific regimes. However, even on relatively mesic sites, intra-ring density range may still vary between 450 and 700 kg $m^{-3}$ (Jane Medhurst, unpublished data).

Tension wood that can result in severe board distortion and drying defect has received the most attention in Australia in *E. globulus*. Results to date support the view that early thinning can reduce its formation, and that fertiliser application at thinning can assist this process; conversely a poor response to thinning may exacerbate the problem. Last but not least is microfibril angle (MFA), the most important determinant of wood stiffness. On the positive side, MFA decreases and then remains fairly stable and within an acceptable range in the lower part of the stem once cambial age is > 5 years. While fast-growing conditions, thinning and fertiliser all lead to increases in MFA, it still remains within this acceptable range. Nevertheless, an understanding of the effect of silviculture on MFA is an important step in tailoring management regimes for the production of solid-wood products.

## 5. ACKNOWLEDGEMENTS

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## PHILIP SMETHURST

# GENOTYPE-SITE MATCHING AND MANAGING FOR ABIOTIC CONSTRAINTS: DRYLAND EUCALYPTS FOR THE SOUTH ISLAND

## 1. INTRODUCTION

The New Zealand Dryland Forests Initiative aims to establish the knowledge base and genetic resources necessary for developing plantations of eucalypts on drought prone and erodible pastoral land in the Marlborough-Canterbury regions of the South Island (Millen 2009). Products initially might be vineyard poles, but most value is expected to come from the later production of other solid wood products. Many factors affect the attainment of these product goals, including plantation growth rates, wood quality, markets, labour and other resources. This paper evaluates the issues that need to be taken into account when selecting and managing genotypes to cope with the abiotic constraints of the region.

Eucalypts for commercial plantations have been introduced to many environments outside their home range. This has always involved a degree of trial and error, but most introductions have included a level of deliberate selection and management. Once genotypes have been selected that grow reasonably well on the range of sites of interest, abiotic factors might remain a constraint to production. These limiting factors in some cases can be partially or completely removed by management. Hence, I have been guided in this paper by the questions:

- What general guidance is there for matching genotypes to a new environment?
- How can these principles be applied to this initiative?
- What abiotic constraints are likely to be important for this project?
- What are the management options for coping with these constraints?

## 2. GENERAL CONSIDERATIONS

Genotype-site matching relies on a description of site conditions in the new region of interest, and location of similar conditions in the home range of species that might be suitable.

### *2.1. Sites*

In Australia, several climatic descriptors are commonly available daily: rainfall, temperature (maximum and minimum), maximum wind gusts (direction, speed and time), and relative humidity. Interpolations are also usually available for evapotranspiration, solar radiation, and vapour pressure deficit. Monthly summaries include frosts below 0.0, 1.0 and 2.5°C, average temperature, and rain days. Several weather stations might exist across the home range of a species, which together define the range of climates suitable for the range of provenances of that species. Gaps in this information arise however due to the time periods of measurements, parameters measured, instrument, operator and interpolation errors, and variations in the density, uniformity and spatial representativeness of the distribution of weather stations. Across a home range, uncharacterised micro-climates might exist to which particular provenances might have specifically adapted.

Many of these errors in the climate description of the home range also apply to the new range. Topography and other landscape factors can also affect micro-climate in ways not always well-represented in weather measurements in the home or new range, e.g. cold air drainage for frost, and aspect for drought.

There are also various ways to assess the importance of drought, frost, wind, temperature and humidity extremes that have implications for inferring impacts on plant growth. A recent climate analysis of extreme events in Tasmania, Australia, listed 16 indices of extreme temperature, and 11 indices of extreme precipitation (White *et al*. 2010). Frost measurements provide an example of the complication that can arise, as temperature measurements are usually recorded at 1.2-1.3 m in a Stevenson screen, but these temperatures are generally 1.8-2.2°C above those at ground level (Holz *et al*. 2010). Hence, a screen measurement of 2°C can infer a frost (0°C) at ground level, but not all 2°C events will be frosts. Holz *et al*. (2010) suggest that a screen temperature of 0 or -2°C might be a better predictor of frost damage for tree crops. The choice of index can have important implications for inferring the impacts on crop growth, yet the exact climate conditions that cause irreversible tissue damage or plant death in eucalypts or other trees are not well defined (Fensham and Holman 1999, McDowell *et al*. 2008, Mitchell *pers. comm.*). Some eucalypts also have a tenacious ability to regenerate even after they are perceived to be dead.

Soils can vary enormously within a landscape. Geology is an important determinant of soils that, together with topography, climate, biology and management, determine the physical, chemical and biological characteristics of soil. Rock or soil type information is commonly available in all or part of the home and new ranges, but it is often a challenge to infer the salient characteristics for plant growth. Many eucalypts, like most crop plants, grow best in deep soils with good aeration, low compaction and soil strength, few rocks, and adequate water and nutrient availability. Few soils have this ideal array of attributes, and various eucalypts in their home range appear to grow well on soils that are variously shallow, poorly aerated, compact, rocky, or of low water and nutrient availability. A factor for survival in their home range, though, is their relative competitive ability with other native plants. In a new environmental range, site selection or management can control some of these factors.

### *2.2. Genotypes*

The aim in this type of genetic screening is to start with a base population of genetic material that is likely to cover the full potential of capability in the new range of plantings. However, logistics and costs limit the breadth of this population. The challenge is to keep the number of genotypes manageable, whilst retaining enough genetic variability. In practice, initial selections are made at the provenance-within-species level, based on site characteristic matches between the new and home ranges of the eucalypt species.

Databases are available that show the distribution of eucalypt and other native Australian species in their home range. Seed selections can be made in the field from selected localities to provide provenances that might have environment-related differences in their genetic composition.

Genotypic variability can be increased by hybridisation, and where permitted genetic engineering and mutations. Hybridisation of species leads to many individuals of intermediate phenotypic expression for quantitative traits, and quantitative traits mostly determine environmental suitability. There is a chance with hybridisation, genetic engineering or mutations that individuals beyond the known current extremes of phenotypic expression will also be produced. Some combinations of genes can be rearranged and tested using traditional plant breeding methods.

Large numbers of plants (individual genotypes) can be screened in growth chambers and glasshouses for tolerance of some growth conditions, e.g. drought, frost, humidity. Laboratory DNA screening technologies are not yet advanced enough to be useful in this broad-scale screening step. Eventually, selected genotypes progress to screening experiments in the field.

During field screening, it is important to use management to eliminate or minimise as many abiotic constraints as possible, e.g. minimise soil strength and maximise aeration using cultivation, and minimise nutrient and water stresses by using herbicides and fertilisers. By controlling these factors at favourable levels, uncontrollable factors such as weather extremes that occur during the screening phase will be the primary screening factors. Management options can be refined later after genotypes have been identified that can cope with the prevailing, uncontrollable environmental conditions. Although genotype-by-management effects also exist, currently there are few operational plantations in the world where this interaction is exploited, i.e. genotype-specific management prescriptions, because the knowledge base is too limited and associated expenses are too great. The exceptions I know of are a few anecdotal examples in South America where local managers have built up experience with particular clones that provides them with confidence to vary fertilizer prescriptions between clones. The chance to build such experience though is limited, as each clone in these circumstances is deployed for only a few years. It is quite common within broad genotypic classes, however, like all clonal hybrids or open-pollinated seedlings of a species in a region, to tune management regimes to soil and climatic conditions.

### *2.3. Practical Genotype-Site Matching*

From the discussion above, we can define two main factors that limit the extent to which the theory of genotype-site matching can be put into practice:

- Incomplete knowledge of micro-climates and other site conditions in the home and new regions.
- Inability to collect or create the full range of genotypic possibilities.

In practice, these limitations are partially overcome by collecting or creating a few individuals each of a broad range of genotypes, screening them in nurseries, breeding, and further testing a subset in field experiments at several sites that cover a large proportion of site variability in the new region. Screening is then followed by management optimisation for cultivation, pests (animals, insects, diseases and weeds), fertilisers, irrigation, wind, and frost.

## 3. ENVIRONMENT OF THE CANTERBURY AND MARLBOROUGH REGIONS

### *3.1. Climate*

Mean annual rainfall in the Canterbury and Marlborough regions ranges from 500 to 2000 mm, but the Dryland Forests Initiative targets the drier end of this range, i.e. 500-800 mm. In the South Island, variability in annual rainfall exceeded ± 200 mm on 20 occasions in a 44 year period, i.e. in 45% of years, but in the Marlborough-Canterbury regions the variation in wet or dry years is ± 100 mm on average (Ummenhofer and England 2007). Some locations of these regions have experienced quite cold temperatures, e.g. Hanmer Forest -13.7$^{o}$C. Although this location is of higher elevation and rainfall than the zone targeted by the initiative, it is an indication of the potential severity of frost risk (Table 1). Recordings at the Marlborough Research Centre at Blenheim (one location of field screening for this initiative) during the winter of 2010 indicated that on 20 occasions the frost at ground level was more severe than -2$^{o}$C and on one occasion reached -6.2$^{o}$C (Figure 1). These data characterise the regions as prone to severe frosts, drought and winds.

*Table 1.* Summary of three climate stations in the Canterbury-Marlborough regions. The Marlborough Research Station is in the north and coastal, Hanmer Forest is central and inland, and Christchurch Gardens is coastal and in the south.

| Station | Blenheim Research Centre | Hanmer Forest | Christchurch Gardens |
|---|---|---|---|
| Elevation (m) | 4 | 387 | 7 |
| Rainfall (mm mean annual) | 689 | 1158 | 635 |
| Wet days (>1.0mm) | 78 | 116 | 84 |
| Sunshine hours (mean annual) | 2470 | 1809 | 2035 |
| Mean July max/min temp ($^{0}$C) | 12.7/2.1 | 9.7/-1.4 | 11.3/1.7 |
| Mean Jan max/min temp ($^{0}$C) | 23.6/12.6 | 22.9/8.9 | 22.5/12.2 |
| Extreme temp max/min ($^{0}$C) | 33.9/-3.3 | 37.1/-13.2 | 41.6/-7.1 |
| Screen frost days | 21 | 88 | 29 |
| Ground frost days | 65 | 123 | 69 |
| Wind mean speed (km/h) | 11 | - | 15 |
| Gust days (>93 km/h) | - | - | 3 |

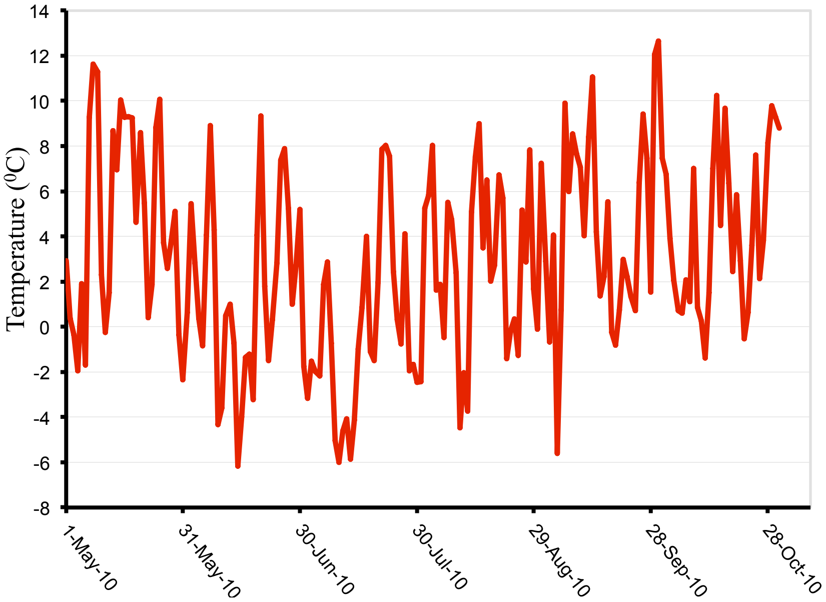

*Figure 1.* Daily minimum temperature at ground level at the Marlborough Research Centre May-October 2010.

### *3.2. Soils*

Soils in this region are predominantly classified as Pallic or Brown soils in the New Zealand soil classification system (http://soils.landcareresearch.co.nz/). Brown Soils are the most extensive soils covering 43% of New Zealand. They have relatively stable topsoils with well-developed structure. They have moderate natural fertility, and contain large, active populations of soil organisms, particularly earthworms. Fertilised Brown soils, such as those on the plains of the region, are sought after for sheep, beef and dairy farming.

Pallic soils cover 12% of New Zealand. They are called Pallic because of the subsoils' pale colour. New Zealand Pallic soils are derived from loess and have compact, deep subsoils. Use of Pallic soils is mostly limited to sheep grazing. Although dry in summer, the soil can be waterlogged in winter or spring. Younger Pallic soils are not so dense and have a range of agricultural uses.

These soil descriptions alert us to potential nutritional and physical limitations for plant growth of soils in the region.

*Figure 2*. Photos of a Brown soil and a Pallic soil, with labelled horizons. (http://soils.landcareresearch.co.nz/contents/SoilNames_NZSoilClassification_SoilOrders.aspx?currentPage=SoilNames_NZSoilClassification_SoilOrders&menuItem=SoilNames).

## 4. IDENTIFIED EUCALYPT GENOTYPES FOR THE REGION

Several eucalypt species have been identified as having potential for this region, i.e. *Eucalyptus argopholia*, *E. bosistoana*, *E. camaldulensis*, *E. globoidea*, *E. quadrangulata*, and *E. tricarpa* (J. Walker *pers. comm.*). As an example of climatic comparison, mean annual rainfall across the range of *E. bosistoana* is in a range of 500-1600 mm rainfall, which is comparable with the Canterbury-Marlborough regions (Figure 3). While this sort of comparison is a reasonable basis for selecting these species, there is a chance that provenances might not have evolved to cope adequately with the full range of climatic and soils conditions that will be encountered at any location in the new range, i.e. severe drought, frost, and wind and poor soils. This can only be determined by field testing in the new range.

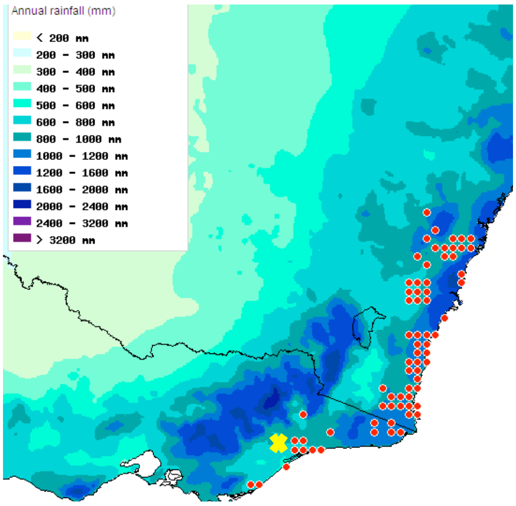

*Figure 3.* Annual rainfall in relation to the distribution of *E. bosistoana* (http://www.chah.gov.au/avh/public_query.jsp). The location of the Stockdale cultivation experiment is indicated by a yellow cross.

## 5. LIKELY ABIOTIC CONSTRAINTS AND MANAGEMENT OPTIONS

From the above analysis it is reasonable to predict that the main abiotic limitations for eucalypt growth in the Canterbury-Marlborough regions will be drought, frost, wind, high soil strength, poor aeration, and low nutrient availability. There are several management options that might assist in alleviating these limitations, i.e. position within the landscape, cultivation, weed control, fertilisation, wind risk management, and frost risk management. Some of these factors are taken into account in process-based models that can be used to predict plantation growth in a wide variety of circumstances.

### *5.1. Landscape Position*

Micro-climate and soils are related to landscape position, which can in turn be defined by elevation, aspect, slope and topographic position. Higher elevations are associated with lower temperatures, as there is a decrease of 4-7°C/km of elevation increase. However, a temperature inversion when the air mass is relatively calm can result in a cold air mass flowing down-hill along drainage lines to an area where it ponds. These cold air drainage lines and frost hollows are the locations of the most severe frosts. South facing slopes in the southern hemisphere receive less radiation and are cooler and more humid than north facing slopes.

Soil depth, rock content and texture usually vary with slope position, and these variations can be reasonably predicable (and therefore can be mapped) within a region of relatively uniform geology and climate. Bottom-slope positions are most prone to waterlogging and frost hollow effects.

Landscape position also affects wind exposure. Rating systems for wind risk can be developed based on climatic, soil and topographic factors (West 2004, Wood *et al*. 2008).

### *5.2. Cultivation*

Cultivation can reduce soil strength, increase aeration, stimulate organic matter decomposition and nutrient availability, and reduce competition from weeds. Mounding during cultivation, and planting on the tops of mounds, can raise seedling height above the local ground surface by 20-40 cm and thereby reduce the frost effects of cold air drainage. Mounding can also alter seasonal patterns of soil temperature, and thereby root activity and the length of the growing season. Mulching can also affect soil temperature and frost severity. However, mounding to reduce soil strength for promotion of root growth can reduce the ability of the soil to anchor the tree during high winds, leading to toppling. Toppling risk, I suspect, is greatest in mounded, wet soils in the presence of high or strong winds from an unusual direction.

Deep ripping has a history of overuse in plantation forestry in Australia. Improving access of roots to subsoils using cultivation will only lead to better tree growth if it increases root access to water or nutrients that are limiting growth, or if it improves tree anchorage. An analysis of thirteen cultivation experiments in southern Australia indicated that surface cultivation was very important, but deep ripping (> 40 cm deep) usually provided no statistically significant additional benefit to tree growth at 2-16 years of age (Smethurst 2004). On average, a combination of ripping and mound-ploughing provided best growth, but there was no benefit of ripping deeper than 40 cm, and there was no benefit to tree growth of using wings or leading tines on the ripper. On ex-pasture sites, ripping can assist cultivation of surface soil containing a sod of pasture roots. The best responses to ripping and mounding were seen on poorly drained, poorly structured, or nutrient-poor soils.

If soils are too wet, cultivation will be ineffective, which might explain the limited usefulness of deep ripping in soils with heavy clay sub-soils, even if the clay horizon was shallow enough to be reached by the ripper. An example of this limitation was observed at the Stockdale site in eastern Victoria, Australia (Smethurst 2004); its location is shown in Figure 3. This site is at the southern end of the range of *E. bosistoana*. Rainfall during the 4 years prior to cultivation had been below average, which constituted a major drought and would have favoured dry soil conditions. The nearby Briagalong weather station has a mean annual rainfall of 668 mm. The site had supported a rotation of *Pinus radiata*, which had been harvested less than a year before cultivation. Despite the drought and the drying effect of the previous, mature plantation, the shallow subsoil remained too moist for effective ripping. The ripper did not shatter the subsoil, but instead sliced through it (Figure 4), and, consistent with other experiments, it did not lead to a significant improvement in tree growth. Another problem limiting the effectiveness of deep ripping is that the disturbed soil in the rip line can re-settle over a few wet seasons to a soil strength similar to that prior to ripping.

*Figure 4*. Photo of two contrasting soil profiles after winged ripping with mounding. The shallow clay subsoil at the Stockdale site (top) was not effectively cultivated as it remained too moist despite 4 years of drought and supporting a crop of *P. radiata* until about a year prior to cultivation. The well-structured clay-loam soil at the Mt Worth site (bottom) shows the zone of cultivation shatter; the shovel in this photo indicates the level of the original soil surface. Both these sites are reported in Smethurst (2004), and ripping did not significantly improve tree growth at either site.

### 5.3. *Water and Nutrient Management*

Apart from locating plantations to minimise the risks of water-logging and drought, water availability for trees can be managed by stocking (planting density and thinning) and canopy management (pruning) to reduce leaf area and transpiration, irrigation to increase water supply, cultivation (particularly contour cultivation) to increase infiltration, and weed control to reduce transpiration by competing species. Mulches, if available, can be used to reduce evaporation from the soil surface and suppress competing vegetation. Some companies in Brazil use water absorbent polymers to enhance water supply to seedlings during establishment under droughty conditions. Grazing can be used to reduce the level of competing vegetation, but cattle and sheep compact surface soils, which reduces infiltration rates, increases overland flow and reduces available soil water.

Weed control is also an important means of decreasing competition for nutrients, and of enabling easier movement of nutrients to plant roots through increased soil water content. Fertilisers increase nutrient availability, but system-specific knowledge (fertiliser history, soil nutrient availability measures, and the effects of type, rate, placement and timing of fertilisation) is needed to develop local fertiliser prescriptions. If there is over use of fertilisers, financial resources are wasted, environmental risks develop, and wood quality and value can be reduced. In contrast, under use of fertiliser is an opportunity cost. As the cost of fertiliser is usually a significant input for plantation growers, the incentives are high for optimising its use. An overview of fertiliser practices in Australian plantation forestry is provided by May *et al*. (2010).

### *5.4. Wind Risk Management*

Apart from locating plantations in areas of low wind risk, vulnerable young trees can be supported by stakes. Otherwise, experience-based guidelines used in Tasmania are: plant fewer than 1200 trees/ha where thinning is planned; and avoid thinning stands taller than 20 m (Wood *et al*. 2008).

### *5.5. Frost Management*

Siting base populations in a new region is especially critical as they need to be representative of prospective planting sites and avoid high frost-risk areas. It would be wise to avoid establishing base populations in cold air drainage lines or frost hollows. Small-scale species trials might be planted on such sites to evaluate comparative frost-tolerance or the effects of waterlogging. In view of the cost of establishing base populations it is generally wise to include on-site weather stations to record precise conditions rather than to rely on interpolation from more distant weather stations.

### *5.6. Process-Based Growth Modelling*

Growth of some plantation species can be well-predicted in moderately variable climates and typical soils, e.g. 3PG (Almeida *et al*. 2007) and CABALA (Battaglia *et al*. 2004). These models are improving in their capability to include climate-change effects associated with carbon dioxide and temperature increases, and rainfall variability. However, their ability to predict growth during and after extreme events is quite limited. These models rely heavily on subjective ratings and empirical factors of mortality to incorporate drought, frost, and wind limitations. These models rely on species-specific parameters that define physiological responses to environmental variables, but the parameters for the species being considered for this initiative have not yet been developed.

## 6. SUMMARY

Genotype-site matching is imprecise because of limitations in matching the range of micro-climates in the region of interest with those in Australia where eucalypts are native. In practice, regions are matched on general climate criteria, and seeds of various provenances of eucalypts selected for testing. The range of genotypes can be increased by breeding, hybridisation, genetic engineering, mutations, but the number of genotypes eventually available for testing is limited by finances and regulations. Growth chamber, glasshouse, and nursery screening is possible, and field screening is essential. Weather monitoring at the field sites enables a comparison of the climate experienced during screening with what might be expected in the longer-term. Once prospective genotypes are identified, management options for coping with abiotic limitations can be evaluated. In the Marlborough-Canterbury regions, management for drought, frost, wind and poor soils will probably be needed. Locating plantations will be important, as well as optimising cultivation, weed control, fertilisation, wind risk management, and frost risk management.

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## TIM WARDLAW

# MANAGING BIOTIC RISK

## 1. INTRODUCTION: EMERGENCE OF BIOTIC THREATS WITH PLANTATION EXPANSION

Australia's eucalypt plantation estate is predominantly first generation: the great majority has been established in the 15 years since 1996 (Gavran and Parsons 2011). *E. globulus* plantations, established as a short-rotation crop for pulpwood, have fuelled most of the recent expansion, and plantings have been concentrated in the southern mainland states with Mediterranean climates. *E. nitens* has been the dominant species planted in Tasmania and the cooler areas of central/east-Gippsland and the northern tablelands of NSW. A more diverse mixture of *Eucalyptus* and *Corymbia* species have been planted in the warmer coastal areas of northern NSW and south-east to central – east Queensland, although *E. dunnii* has been the dominant species planted during the past decade. *Eucalyptus* has only been a minor component of the relatively small area of plantations established in the tropical areas of northern Queensland and Northern Territory.

While the number of pest species recorded from the developing plantation estate has increased in proportion with the growing size of the estate (Grimbacher *et al.* 2011) there have been few instances of catastrophic damage, particularly in the southern temperate *E. globulus* and *E. nitens* plantations.

Pest problems in the greenfield areas of south-west Western Australia and the Green Triangle emerged in synchrony with the aging plantations. Thus the first significant pest problems encountered were during the initial establishment phase and were dominated by polyphagous insect pests (Aftrican black beetle, scarbs) carried over from the previous pasture crop (Bulinski *et al.* 2006). A succession of defoliating insect pests moved into these plantations from the surrounding native forests or as exotic introductions from other states, e.g. *Gonipterus platensis* in Western Australia from Tasmania (Mapondera *et al.* 2011). The temporal pattern of damage by post-establishment pests in these greenfields plantation areas was consistent with new colonisation events: a progressive expansion in range was followed by an increase in the intensity of damage over 3-4 years before reaching stable equilibria after which the intensity of damage fluctuated from year to year (Grimbacher *et al.* 2011). The overwhelming majority of the biotic damage in the southern *E. globulus* plantations is from insect herbivores; fungal pathogens, while present and increasing in incidence as the plantation estate matures, have caused little damage (Barber *et al.* 2008).

The recent plantation expansion in Tasmania, by contrast, added to a more mature pre-existing plantation estate and was generally embedded in a matrix of native forest. The suite of pests and pathogens affecting the plantations was similar to those in native forest and changed little during the recent expansion. Moreover, there was little difference in the number of pests and pathogens affecting the two main species, *E. globulus* and *E. nitens*, even though the latter was not native to the state (de Little *et al.* 2008). The temporal pattern of pest and disease damage within the plantations reflects an equilibrium state, with the range fully occupied and the intensity fluctuating from year to year (Grimbacher *et al.* 2011). By contrast with the temperate *E. globulus* plantation estate in the southern states of mainland Australia, a broader mix of biotic agents contribute to damage with fungal pathogens, browsing mammals and insect herbivores equally important biotic threats (Wardlaw 2010).

The expansion of eucalypt plantations into the warmer, peri-coastal areas of northern NSW and Queensland progressed more slowly than in the southern states. Initial plantings were for solid wood and favoured species such as *Corymbia maculata* and *E. grandis*. Each had critical biotic threats that had moved across from the native forests – Quambalaria shoot blight on *C. maculata* and giant wood moth (*Endoxyla cinerea*) in *E. grandis*. More recent and extensive plantings for pulpwood have favoured *E. dunnii*. As well as the suite of pests and pathogens known to attack *E. dunnii*, a previously minor psyllid pest, *Creiis literatus*, became particularly damaging, causing repeated episodes of severe defoliation in certain situations (Carnegie and Angel 2005). Further north near Cairns, clonal plantations of *E. grandis* x *camaldulensis* were established in the period since the mid-2000s. Soon afterwards a previously unknown species of *Kirramyces* – *K. viscidus* – was isolated from leaf lesions on trees suffering severe defoliation. *E. grandis* x *camaldulensis* proved particularly susceptible to this pathogen resulting in the abandonment of that plantation development. As distinct from southern Australia, the development of eucalypt plantations has been typified by each species having a critical biotic threat not easily amenable to management.

As distinct from Australia, biotic threats of eucalypt plantations New Zealand develop from a much smaller pool of pests and pathogens – just those that have crossed the Tasman Sea and become established; pests and pathogens native to New Zealand have caused little damage to eucalypts (Withers 2001). Eucalypts of the sub-genus *Monocalyptus* have experienced relatively few biotic threats compared with species from the sub-genus *Symphyomyrtus* (Fry 1983, Shelbourne *et al.* 2002), a finding also reported in Australia (Stone *et al.* 1998). However commercial plantings for pulpwood production have predominantly used *E. nitens,* which is cold tolerant and performed well in many species trials (Shelbourne *et al.* 2002). However, *E. nitens* has proven remarkably susceptible to defoliation by the leaf beetle, *Paropsis charybdis,* and the fungal pathogen *Kirramyces eucalypti*.

## 2. SIGNIFICANT BIOTIC THREATS

Eucalypt plantations in Australia and New Zealand support a large diversity of pests and pathogens (Wylie and Peters 1993, Stone *et al.* 1998, Yuan 1999, Withers 2001, Loch and Floyd 2001, Carnegie 2007a, de Little *et al.* 2008, Whyte *et al.* 2011). Only a small proportion of these pests and pathogens have caused sufficiently severe

*Table 1*. Significant pests and pathogens of *Eucalyptus* species in Australian and New Zealand plantations.[1.] Five-year average.

| **Pest/pathogen** | **Location** | **Host** | **Damage** | **Impact** | **Reference** |
|---|---|---|---|---|---|
| *Heteronychus arator* | WA | *E. globulus* | Stem girdling | Replant once mortality >30%, a threshold often exceeded | Bulinski *et al.* (2006) |
| Browsing mammals | TAS | *E. nitens, E. globulus* | Shoot browsing | ≥30% mortality after 4 weeks in 25% unprotected plantations | Walsh and Wardlaw (2011) |
| *Phytophthora cinnamomi* | TAS | *E. nitens* | Root rot | 150 ha with moderate / high incidence of mortality annually (on SF) | Forestry Tasmania records |
| *Creiis literatus* | NSW, Q'LD | *E. dunnii* | Defoliation | >75% leaf loss in 400 ha resulting in mortality (2003) | Carnegie and Angel (2005) |
| *Paropsisterna bimaculata* | TAS | *E. nitens, E. globulus* | Defoliation | Damaging populations in 6,900 ha; moderate / severe defoliation in 1,500 ha (on SF)[1] | Forestry Tasmania records |
| *Paropsis charybdis* | NZ | *Eucalyptus* sub-genus *Symphyomyrtus* | Defoliation | Stands subject to repeated defoliation become moribund with appreciable mortality. | Fry (1983) |
| *Mnesampela privata* | TAS, VIC | *E. globulus, E. nitens* | Defoliation | Localised outbreaks cause severe defoliation resulting in mortality and significant growth losses | Rapley *et al.* (2009) |
| *Phoracantha acanthocera* | AUST | *E. grandis* | Wood boring | Losses of up to 15% in *E. grandis* trial plantings | Wylie and Peters (1993) |

*Table 1 continued on Pg 109*

damage to threaten the commercial viability of plantations (Table 1). It is this subset of significant pests and pathogens that critically impact decisions on plantation developments. This generally means a predicted high risk of plantation failure unless the specific pest or pathogen is effectively managed.

Some pests, most notably *Gonipterus platensis* (*syn. G. scutellatus*), were considered significant threats during their initial colonisation of new plantation estates but subsequent research has shown impacts to be lower than expected (Fry 1983, Loch and Matsuki 2010). A small number of pests and pathogens, have not yet had sufficient time post-colonisation to determine the threat they pose to plantation eucalypts. *Uraba lugens* in New Zealand, and *Uredo rangelii* (of the *Puccinia psidii* complex) in eastern Australia are two examples.

## 3. MANAGEMENT OF BIOTIC THREATS

Wardlaw (2008) outlines a general framework for the management of biotic threats, particularly highlighting how management is delivered at the strategic, tactical and operational levels. Strategic management that can be used to modify biotic threats includes: species-choice decisions, selection and deployment of resistant seedlots / clones, quarantine embargos, the introduction of biological control agents (for exotic pests), and the determination of priorities for research investment. Tactical management provides a framework for delivering specific management decisions: site-species matching, demarcation of hygiene areas, and the use of site-hazard to guide the delivery of management interventions are three examples. Strategic and tactical management deliver their outcomes at the country / state and estate levels and continue to modify pest/pathogen risk over medium to long timeframes.

Operational management, by contrast, delivers outcomes at the stand-level in response to immediate and (usually) short-term threats. Operational management can be either pest/pathogen-focussed or crop-focussed. Pest/pathogen-focussed management is used for those pests and pathogens that regularly threaten a significant proportion of the crop. It generally involves targeted monitoring, timed to coincide with predictable periods of threat, to guide decisions on the need for management intervention. Crop-focussed management is appropriately used to manage threats capable of causing significant damage, but intermittently and in an unpredictable manner. Early detection is the critical aspect of crop-focussed management and is best provided through formal surveillance using methods of inspection appropriate for the types of damage of most concern for management (Wardlaw *et al.* 2008).

The degree to which the adverse impacts from the significant pest and pathogen threats can be managed varies enormously. The introduction of mesh stockings to protect newly transplanted *E. globulus* seedlings from stem-girdling damage by *Heteronychus arator* was a simple and cost-effective solution that limited losses from that pest to within acceptable levels (Bulinski *et al.* 2006). At the other extreme are those, notably the wood-boring insects and many of the fungal leaf pathogens, that are currently intractable. For these, the planting of susceptible species on sites conducive to the pest or pathogen represents a high risk of

*Table 1 continued from pg 107*

| **Pest/pathogen** | **Location** | **Host** | **Damage** | **Impact** | **Reference** |
|---|---|---|---|---|---|
| *Endoxyla cinerea* | Q'LD, NSW | *E. grandis* | Wood boring | Losses of up to 50% in trial plantings | Wylie and Peters (1993) |
| *Teratosphaeria nubilosa* | TAS, VIC, NSW | *E. globulus* | Defoliation | Widespread epidemics causing severe defoliation during favourable years | Pinkard *et al.* (2010) |
| *Kirramyces eucalypti* | NZ | *E. nitens* | Defoliation | Severe defoliation of plantations in peri-coastal areas | Hood *et al.* (2004) |
| *Quambalaria piterika* | NSW, Q'LD | *C. maculata* | Shoot blight | >25% shoot damage in 59 / 117 FHS records | Carnegie (2007) |
| *Kirramyces viscidus* | Nth Q'LD | *E. grandis x camaldulensis* | Defoliation | >95% defoliation; write-off of 6,000 ha plantation asset | Andjic *et al.* 2007;<br>ABC (2010) |

catastrophic failure. Two examples of such failure are: (i) chronic severe defoliation of peri-coastal *E. nitens* pulpwood plantations on the central North Island of New Zealand by *Kirramyces eucalypti* (Hood and Alexander 2006); (ii) write-off of approximately 6,000 ha of young *E. grandis x camaldulensis* plantations at Mareeba in northern Queensland due to recurring severe defoliation by the newly-discovered pathogen *K. viscidus* (Primary Industries and Fisheries, Queensland 2010). Most of the significant pest and pathogen threats lie between these two extremes of manageability.

### *3.1. Establishment phase*

The establishment phase is generally completed within the first growing season following transplanting, although on colder sites, notably in Tasmania, establishment may extend into the second growing season. Poor survival requiring replanting is the main threat during the establishment phase and the generalist herbivores pose the greatest threat of this.

Browsing by mammalian herbivores poses the largest threat in eucalypt plantations during the establishment phase, with most of that threat in Tasmania. During the mid-late 2000s when nearly 20,000 ha were being established annually in Tasmania, the annual cost for browsing management was in excess of $6M. The high cost is due to the need for regular culling of target species (brushtail possum, Bennett's wallaby and Tasmanian pademelons) beginning prior to plantation establishment and continuing until the seedlings reach a "safe" height of about 1 metre. This cost is incurred in virtually all plantations established. While many plantations could be successfully established with minimum intervention, attempts to develop a site-hazard rating to predict plantations likely to suffer high levels of browsing have been unsuccessful (Walsh and Wardlaw 2011). Research into non-lethal tactics has shown three – plastic mesh seedling stockings, grit-based repellent and genetic selections for high levels of plant secondary compounds – provide significant protection (Miller *et al.* 2011a, b) and are amenable to operational adoption. Seedling stockings are already routinely used and their use has allowed a reduction in the intensity of post-plant culling (Wardlaw 2009). An integrated pest management strategy combining the non-lethal tactics with pre-plant culling and monitoring-directed post-plant culling should provide a more cost-effective and socially-acceptable approach to managing browsing mammals. This approach is currently being tested by the Co-operative Research Centre for Forestry.

Several polyphagous insect pests that primarily live in pastures or native grasslands pose a threat to establishing plantations. Damage by the African black beetle (*Heteronychus arator*) and swarming scarabs of the genera *Heteronyx* and *Liparetus* in Western Australia was sufficiently severe during the recent phase of plantation expansion to require controls to be developed to reduce the area requiring replanting because of excessive mortality. Below-ground feeding on the root collar of transplanted seedlings by the African black beetle was not effectively managed by the traditional agronomic method for this pest using a soil application of chlorpyrifos (Bulinski and Matthiessen 2002). However, a plastic mesh sleeve enclosing the transplant, including the root plug, reduced mortality from this pest by nearly 80% (Bulinski *et al.* 2006) – a level sufficient to avert replanting. The operational adoption of mesh sleeves on ex-pasture sites supporting a population of African black beetles was calculated to provide a benefit-cost ratio of at least 7:1 in the 5500 ha protected with the sleeves during the early 2000s (Bulinski *et al.* 2006).

Mortality following severe or repeated defoliation by swarming scarabs was reported as a significant problem during the early phase of the recent plantation expansion in Western Australia. A slow-release tablet formulation of imidacloprid (Initiator™ Bayer CropSciences) was developed to protect seedlings from defoliating insects during the establishment phase. The levels of operational use of this product are not documented, however, swarming scarabs have not been reported as a damaging pest in young plantations during the past decade (Research Working Group 7 – Forest Health - Annual Pest and Disease Status Reports for Australia and New Zealand).

Root rot diseases are the main pathogens of concern during the establishment phase. Three are regularly reported: *Armillaria* spp. (Carnegie 2007, de Little *et al.* 2008, Wardlaw 2010), *Phytophthora cinnamomi* (Carnegie 2007, Wardlaw 2010) and *Macrophomina phaseoli* (Carnegie 2007). *P. cinnamomi* is the most widespread and damaging of the three (mainly on *E. nitens* and *E. pilularis*) although mortality rarely reaches a level to necessitate replanting. However, in Tasmania, a strong association between mortality from Phytophthora root rot during the establishment phase and later-age windthrow (Wardlaw 2010) suggests pathogenic activity may extend beyond the establishment phase. Growth rate reductions exceeding 40% have been reported for other root rot diseases in plantations and native forests. A study is currently underway in Tasmania to detect and quantify any such ongoing growth rate reduction from chronic *P. cinnamomi* infection in surviving *E. nitens*. A simple option for managing Phytophthora root rot is to use a resistant species such as *E. globulus* on sites where the disease is a concern.

### *3.2. Established young plantations*

At this stage the now established young trees are building their crowns, reaching canopy closure and beginning the process of crown-lifting. Crops managed for solid wood are pruned during this period. It is also the period that heteroblastic species switch from the juvenile to adult leaf form. Pests and pathogens that cause shoot mortality resulting in multiple stems or stem kinks, and those that cause defoliation pose the main threat during this period.

#### *3.2.1. Fungal diseases*

Fungal shoot blights and leaf diseases pose a significant threat in areas where periods of high moisture coincide with active shoot growth. Quambalaria shoot blight (QSB) affecting *Corymbia* species, and Mycosphaerella leaf disease (MLD), particularly that caused by *Teratosphaeria nubilosa* infection of *E. globulus*, are the most damaging fungal diseases. Chemical control of these diseases using fungicides is not practical nor cost-effective because of the difficult weather conditions (wet and/or windy) coinciding with the periods of high disease risk, and the extended periods of infection that require protection during epidemics. For both diseases the selection of genotypes for higher resistance to the disease is the main approach for management. Studies have found that resistance for both diseases is heritable and is correlated with disease pressure experienced by the natural populations of the host species (Dickinson *et al.* 2004; Hamilton *et al.* submitted), although note that Pegg *et al.* (2011) conclude that selections made at the provenance-level were poor indicators of QSB resistance in open-pollenated families of *Corymbia* species.

The scope for marked improvements in resistance, beyond that achieved from selections made to date, appear limited for both diseases. Lee *et al.* (2011) reported significant variation in resistance to QSB among clones of *C. citriodora* var *variegata* but that virtually all of that variation was non-additive. This result, they concluded, indicated that previous selections had been successful in selection for resistance but very little within-family variation remained. Similarly, past and recent screening has found significant family variation in MLD (Milgate *et al.* 2005) but an elite breeding population developed after selecting for favourable wood properties and growth traits was neutral in it's selection for MLD resistance (Dean Williams *pers. comm.*). An alternative approach to selection for resistance is to select instead for disease tolerance. A large *E. globulus* progeny trial in northeastern Tasmania has been exposed recently to a severe MLD epidemic. Future growth measurements will identify progeny that are able to maintain high growth rates regardless of the severity of disease they suffer.

The remaining strategy for avoiding losses from severe shoot/leaf disease is to avoid planting susceptible species/clones on high hazard sites. Pinkard *et al.* (2010) used bio-climatic niche modelling to predict a site-hazard rating for MLD based on the frequency of recurrence of years with weather conditions favouring severe disease. However, the low spatial resolution of that model (due to low number of sites with records of epidemic MLD events) limits the capacity for fine-scale mapping of site hazard.

### *3.2.2. Defoliating insects*

Several defoliating or sap-sucking insects have the potential to regularly cause severe defoliation to young eucalypt plantations.

The psyllid *Creiis literatus* emerged during the early 2000s as a significant threat to *E. dunnii* plantations established for pulpwood in the warm, peri-coastal areas of northern NSW – southern Queensland. While soil application of the insecticide imidacloprid and supplementary fertilisation assisted recovery after defoliation (Carnegie and Angel 2006), the strong association of damage with particular sites appeared to offer better prospects for management. In most *E. dunnii* plantations, *C. literatus* was present in low populations. However, populations became high on trees growing in stressed sites either due to drought or water-logging (Carnegie and Angel 2006). Stone *et al.* (2010) demonstrated experimentally, that slower-growing *E. dunnii* seedlings that had been subjected to periodic water-logging were more attractive to *C. literatus*. Thus site selection to avoid planting *E. dunnii* on stressful sites, in particular water-logged sites, would avoid damaging *C. literatus* outbreaks.

Autumn gum moth (*Mnesampela privata*) causes severe defoliation of blue gums, particularly *E. globulus*, in the juvenile leaf stage. Severe defoliation, particularly during the latter period of the growing season, can result in appreciable mortality resulting in a reduction in productivity for the remainder of the rotation (David de Little, unpublished data). Such damage can be easily prevented by a foliar insecticide spray using either broad-spectrum insecticides such as α-cypermethrin or biological insecticides such as tebufenozide (Mimic™) or *Bacillus thuringiensis* var. *kurstaki*. The challenge with managing autumn gum moth is to detect populations before the damaging later larval stages. Developing autumn gum moth populations are easy to detect by visual monitoring done at the appropriate time (mid- to late-summer). However, pheromone lures may provide a more sensitive way to detect populations in plantations. Walker *et al.* (2009) have isolate two volatile compounds, a C19-triene and a C21-triene, from female autumn gum moths that are strongly attractive to male moths when combined at the ratio of 16:1. Operational evaluation of pheromone-laced delta-traps as a monitoring tool commenced in 2011. Delayed mating of either male or female moths significantly reduces both the number and viability of eggs (Walker and Allen 2010), suggesting the option of mating disruption as an alterative to chemical control. However, this method is not likely to be cost-effective given the high cost of synthesising the pheromone.

### *3.2. Mid to late rotation plantations*

The middle and latter period of the rotation is when the trees grow into merchantable size. This period is particularly important in plantations managed for solid wood as most of the growth increment of pruned trees is in the valuable clearwood section produced outside the knotty core. Biotic threats that reduce survival or wood quality of trees that have reached merchantable size, particularly if those trees have been pruned, can significantly reduce the value returned from the crop. Similarly, biotic threats that reduce growth increment, particularly if that increment is clearwood, can have a greater impact on financial returns compared with growth impacts sustained earlier in the rotation, which affect mainly the juvenile wood or knotty cores. Importantly, because of the length of this period, there is a stronger likelihood of multiple damage events, which for defoliators may result in sustained reductions in growth rates.

#### *3.2.1. Defoliating insects*

Chrysomelid leaf beetles are an important biotic threat in the mid and late rotation, or earlier. The two most significant are *Paropsisterna bimaculata*, a Tasmanian endemic, and *Paropsis charybdis*, another native of Tasmania that was accidentally introduced into New Zealand in the early 20th century (Withers 2001).

Ash species from the subgenus *Monocalyptus* are the natural hosts of *P. bimaculata* (de Little 1983). Ongoing defoliation by this species was the main reason for the failure of attempts in Tasmania to grow *E. regnans* and *E. delegatensis* in plantations. *P. bimaculata* became adapted to *E. nitens* soon after the commencement of large-scale planting of this species in Tasmania.

Despite high levels of egg predation and, to a lesser extent, larval parasitism by a suite of natural enemies (de Little *et al.* 1990), populations of *P. bimaculata* still regularly cause severe defoliation. Integrated Pest Management (IPM) of *P. bimaculata* in Tasmania was developed in the late 1980s (Elliott *et al.* 1992) and introduced operationally there in the early 1990s to protect plantations from damaging defoliation. The leaf beetle IPM relies on fortnightly monitoring of target plantations during the late-spring and summer months to detect and measure egg and/or young (1st and 2nd instar) larval populations. A leaf beetle population - damage model for *E. nitens* has been developed for *P. bimaculata* (Candy 1999), which enables the population corresponding to an economic injury threshold (value of losses exceed cost of management) to be set. This threshold forms the basis for determining whether a measured population requires an insecticide spraying operation to prevent economic injury. The spray decision aims to ensure spraying, if required, is done before the leaf beetle population transitions to 3rd instar, as the 3rd and 4th larval instars cause the majority of the larval defoliation (Greaves 1966). An important aspect of the IPM is the aim to get maximum benefit from natural control events, thus if a predator population or severe weather event (e.g. heavy rain and/or wind) was recorded from a plantation with an above-threshold population an additional monitoring would be done before making a final spray decision. Between 15-20% of above-threshold populations decline naturally to below-threshold levels (Wardlaw *et al.* 2011, Forestry Tasmania records).

Wardlaw *et al.* (2011) have calculated that the leaf beetle IPM currently provides a benefit:cost ratio of about 1.8:1. Importantly, that analysis identified that the IPM provides sub-optimal protection to older plantations that are beyond age-classes the IPM was originally developed for. In addition, the majority of moderate/severe insect defoliation detected in plantations was due to leaf beetle feeding in older plantations that were not included in the IPM. A model has been recently developed to classify plantations as low, medium and high risk of supporting above-threshold leaf beetle populations (Edgar 2011). This is enabling a switch from age-based to risk-based targeting of plantations to include in the leaf beetle IPM and will provide a greater focus on protecting older plantations. While analyses have shown considerable financial benefit from individual spray decisions, each additional year through the rotation requiring protection from leaf beetles will reduce the overall financial viability of the crop. This may result in future species changes in high leaf beetle risk areas where *E. nitens* is currently grown. *P radiata* is one option, but the decision will need to balance the cost and effectiveness in managing Spring Needle Cast (≈Cyclaneusma needle cast) in *P.radiata* by genetics and silviculture versus the cost and effectiveness of managing *P. bimaculata* in *E. nitens* using the leaf beetle IPM.

In the absence of its natural enemies in New Zealand, *P. charybdis* regularly caused severe defoliation of eucalypts within the subgenus *Symphyomyrtus* through until the 1990s. The egg parasitoid, *Enoggera nassaui* (Western Australian strain), was first released in New Zealand in 1987-88, with second release of *E. nassaui* (Tasmanian strain) in 2000 (Murray *et al.* 2008). This parasitoid was effective in reducing *P. charybdis* populations in many, but not all areas (Murphy and Kay 2000). *E. nassaui* was particularly effective in parasiting the late season egg population of *P. charybdis* (Murphy and Kay 2000). In 2001, the status of the *P. charybdis* biological control became uncertain following the detection and subsequent establishment of *Baeoanusia albifunicle*, a hyperparisite of *E. nassaui* (Jones and Withers 2003). Peak hyperparasitism of *E. nassaui* by *B. albifunicle* occurred towards the end of the *P. charybdis* season, the period where previously *E. nassaui* provided peak levels of parasitism (Jones and Withers 2003). In the same year, a second *P. charybdis* egg parasitoid, *Neopolycystus insectifurax,* appeared in New Zealand, possibly the result of an accidental introduction, as earlier attempts to introduce this parasitoid were unsuccessful. Subsequent monitoring has found that *N. insectifurax* reaches peak levels of egg parasitism at the end of the *P. charybdis* season (Jones and Withers 2003) filling the void previously occupied by *E. nassaui* until the appearance of the hyperparasite. Thus it is possible that the net effect of the two recent introductions will be neutral, with the high levels of parasitism initially provided by *E. nassaui* alone being maintained.

While the biological control has greatly reduced the need for insecticides (α-cypermethrin) a gap in effectiveness remains during the early part (November – December) of the *P. charybdis* season (Murphy and Kay 2000, Jones and Withers 2003). The predatory ladybird, *Cleobora mellyi*, could cover this gap. However, previous attempts at introduction have met with limited success (Murray *et al.* 2008).

## 4. ACCOUNTING FOR BIOTIC THREATS IN SPECIES CHOICE DECISIONS

Where more than one species is available for the range of sites for plantation investment, a decision needs to be made on which to recommend. An ideal species will have wood properties suited to end-use; have favourable growth and form traits on the sites available for planting; be amenable to to the vicissitudes of operational management; and, have a low risk from biotic threats. Invariably though, no one species will be the best in all of these attributes so the choice of one species over another will need to compare trade-offs against each attribute. Financial analysis is an objective way of doing this when each attribute can be valued.

### *4.1. A case study (based on Wardlaw 2010):*

Forestry Tasmania manages a eucalypt plantation estate of about 50 000 ha across a wide range of sites. The production of solid-wood products is the management priority. The current estate comprises *E. nitens* and *E. globulus* in the ratio 81:19 by area. *E. nitens* has been favoured because of its cold tolerance, perceived growth and form advantages, and resistance to Mycosphaerella leaf disease (MLD). However, *E. globulus* has superior wood properties both for solid-wood and pulp. Price premiums are beginning to appear in the market-place for superior wood properties.

Financial analysis was used to understand the magnitude of price-premiums for the superior wood properties of *E. globulus* that would be needed to offset the cost associated with MLD and lower growth rates. Because *E. nitens* and *E. globulus* are affected by other pests, pathogens and abiotic factors an analysis was done to identify the most important biotic and abiotic threats influencing the species-choice decision.

A climate analysis (Wardlaw 2011) found that 26 600 ha of the estate was warm enough to plant both *E. nitens* and *E. globulus*: 70% of that area is currently planted to *E. nitens*. Forest health surveillance records were used to identify the main damage agents causing moderate or severe damage (as defined in Stone *et al.* 2003). Further analysis of the fourteen most prevalent damage agents identified the subset most important for the species-choice decision. That analysis was based on:

- The strength of their association with one host or the other;
- The overlap of their distribution with climate envelope of that section of the plantation estate available for planting both *E. globulus* and *E. nitens*;
- The contribution of plantation areas within the distribution of the damage agent to the expected future yield of the estate.

Of the fourteen most prevalent damage agents, four (MLD, *Gonipterus*, gum-leaf skeletoniser and moderate chrysomelid defoliation) were strongly associated with *E. globulus*, and three (Phytophthora root rot, copper deficiency and drought death at or soon after transplanting) were strongly associated with *E. nitens* (Figure 1).

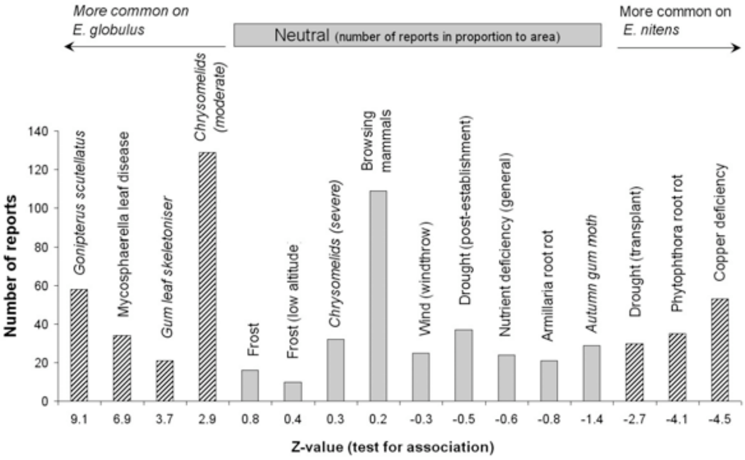

*Figure 1.* Degree of association of the most common agents of damage in *E. nitens* and *E. globulus* plantations within the climate cells occupied by those damage agents. Cross-hatched columns indicate damage agents that were significantly more commonly detected on *E. globulus* (left side of graph) or *E. nitens* (right side of graph).

Moderate defoliation by chrysomelids and *Gonipterus* often occured together making it difficult to identify which was the main agent responsible for damage. This co-occurrence is the likely reason for moderate chrysomelid damage being more strongly associated with *E. globulus* while severe chrysomelid defoliation, which rarely occured together with *Gonipterus*, had a neutral host association. The strong association of MLD with *E. globulus* and Phytophthora root rot with *E. nitens* was unsurprising: *E. nitens* is virtually immune to infection by *Teratosphaeria nubilosa*, the main pathogen associated with MLD, while *E. globulus* is resistant to infection by *P. cinnamomi*. An interesting finding was a strong association between records of Phytophthora root rot, during establishment, and windthrow at a later-age. This was evidence suggestive of ongoing root damage to trees that survived infection during establishment. The degree of overlap between the distribution of the damage agents and that part of the plantation estate suitable to plant both *E. nitens* and *E. globulus* varied considerably. Damage agents with distributions that were concentrated in that part of the estate suitable for both eucalypt species included MLD (Figure 2a), Phytophthora root rot (Figure 2b), *Gonipterus*, autumn gum moth, windthrow, copper deficiency and general nutrient deficiency. Severe chrysomelid defoliation was the only damage agent with a distribution that was concentrated in the colder parts of the estate suitable to plant only *E. nitens* (Figure 2c). The remainder, including severe browsing mammal damage were distributed uniformly throughout the plantation estate (Figure 2d).

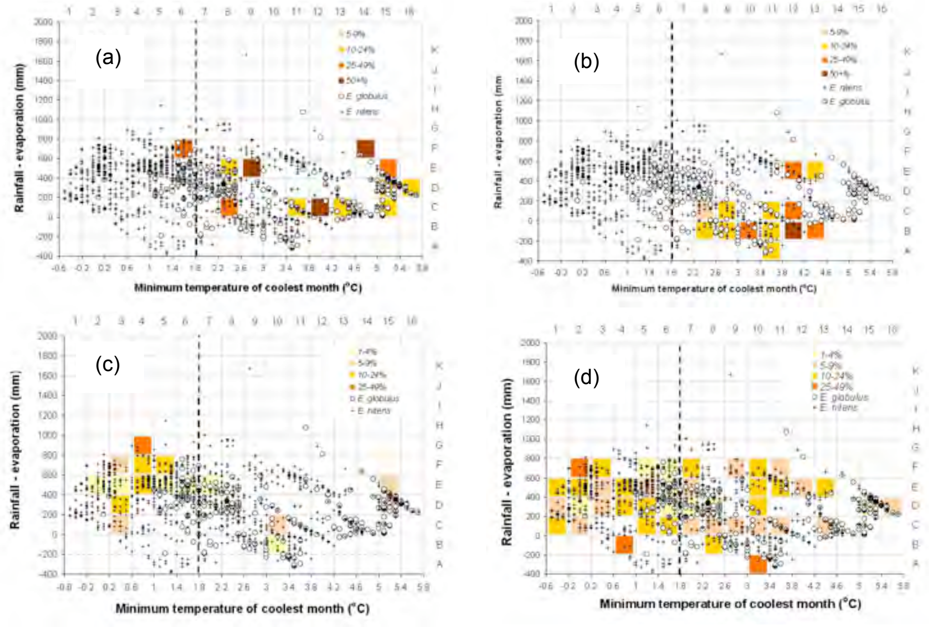

*Figure 2.* Distribution of (a) Mycosphaerella leaf disease, (b) Phytophthora root rot, (c) severe *Paropsisterna bimaculata* defoliation, and (d) mammal browsing within the climate envelope of the eucalypt plantation estate on State forest in Tasmania. The vertical dashed line represents the recommended minimum temperature threshold for *E. globulus*. Shading indicates the prevalence (% of plantations recording damage) of the pest/disease within that climate cell.

The damage agents most important for the species-choice decision were strongly associated with either *E. globulus* (MLD and *Gonipterus*) or *E. nitens* (Phytophthora root rot, copper deficiency and drought death soon after transplanting), and had distributions strongly concentrated within that part of the estate that was climatically-suitable for planting both eucalypt species. Five climate regions (Figure 3), within that part of the estate climatically suitable for both species, were delineated based on their climatic and geographic proximity, and records of moderate or severe damage by any of the five targeted damage agents. Those climate regions can be summarised as follows:

| | |
|---|---|
| Climate Region 1: | Coastal lowland areas of mid-northwestern Tasmania and the Tasman Peninsula in southeastern Tasmania with a warm-moist climate; |
| Climate Region 2: | Coastal lowland plantations in the far northwestern corner of Tasmania with a warm-wet climate; |
| Climate Region 3: | Inland lowland plantations in northwestern Tasmania with a mild-wet climate; |
| Climate Region 4: | Mid-altitude plantations in northeastern and northwestern Tasmania and lowland areas of southern Tasmania with a cool-moist climate; |
| Climate Region 5: | Dominated by plantations in lowland areas northeastern Tasmania with a mild-dry climate. |

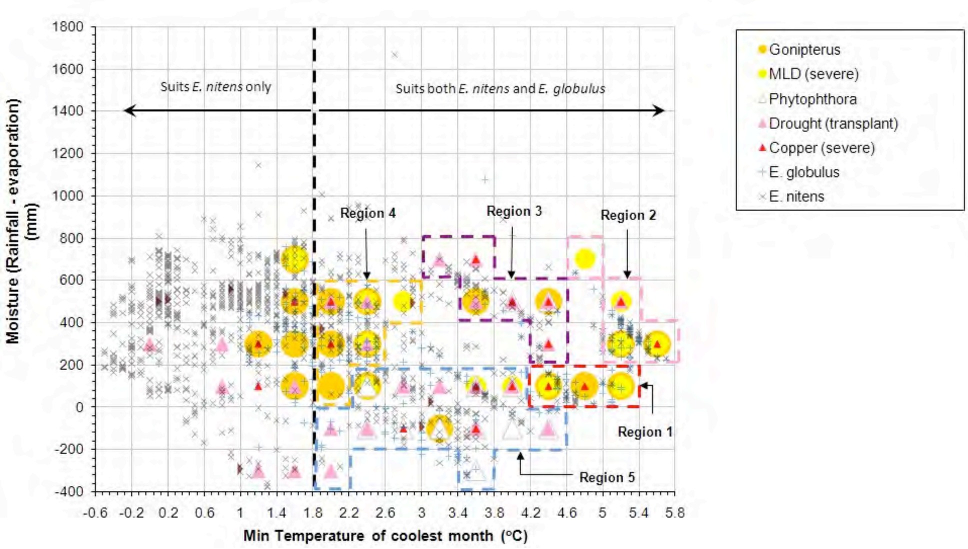

*Figure 3.* Climatic distribution of the *E. nitens* and *E. globulus* plantations on Tasmanian State forest show climate cells with records of moderate or severe damage by one or more of the five targeted damage agents. The boundaries delineating five climate regions are shown.

The prevalence of records of moderate or severe damage for each of the five damage agents important for the species-choice decision was summed for each of the delineated climate regions (Table 2). Analysis of operational pruning records found that the adverse form consequences from copper deficiency were effectively ameliorated by including copper in the fertilizer mix applied to seedlings soon after planting. Because of this copper deficiency was excluded from the tally. In three Climate Regions (1, 2 and 4) damage agents preferentially affecting *E. globulus* predominated, while in the other two Climate Regions (3 and 5) damage agent preferentially affecting *E. nitens* predominated.

*Table 2*. Sum of the prevalence of damage agents within Climate Regions that preferentially affect either *E. nitens* or *E. globulus*. Blue shading indicates Climate Regions where damage agents affecting *E. nitens* are most prevalent, pink shading indicates Climate Regions where damage agents affecting *E. globulus* are most prevalent.

| | | Climatically suited to *E. nitens* and *E. globulus* | | | | | |
|---|---|---|---|---|---|---|---|
| Damage agent | Climatically suited to *E. nitens* only | Not blocked | Climate Region 1 | Climate Region 2 | Climate Region 3 | Climate Region 4 | Climate Region 5 |
| ***Damage agents preferentially affecting* E. nitens** | | | | | | | |
| Drought -transplant | 6 | 3 | | 1 | 8 | 3 | 9 |
| Copper | (3) | | (14) | (11) | (11) | (4) | (10) |
| *Phytophthora* | | | | | 6 | 1 | 28 |
| Sum | 6 | 3 | 0 | 1 | 14 | 4 | 27 |
| ***Damage agents preferentially affecting* E. globulus** | | | | | | | |
| *Mycosphaerella* | 3 | 1 | 4 | 13 | 1 | 6 | 6 |
| *Gonipterus* | 13 | 1 | 11 | 4 | 4 | 21 | 1 |
| Sum | 16 | 2 | 15 | 17 | 5 | 27 | 6 |

The impact of the damage agents on the financial returns from *E. nitens* or *E. globulus* plantations in each of four productivity classes (based on estimates from inventory plots or "best guess" using local knowledge) were calculated using Farm Forestry Toolbox (Private Forests Tasmania 2001) using the following regimes:

- High site quality - standard three-lift pruning of 300 sph to 6.2 m, mid-rotation commencial thinning to pruned stocking and clearfelling at 23 years
- Medium site quality - standard three-lift pruning of 300 sph to 6.2 m, secondary nitrogen application at age 2 and every 3 years thereafter, mid-rotation commencial thinning to pruned stocking and clearfelling at 23 years;
- Low site quality – single pruning lift to 2.7 m of 300 sph, secondary nitrogen application at age 2 and every 3 years thereafter, commercial thinning at age 11 and clearfell at age 23;
- Very low site quality - secondary nitrogen application at age 2 and every 3 years thereafter; no pruning; no commercial thinning; clearfell at age 20 for pulpwood-only crop.

The impact of the damage agents was based on empirical data from research plots, extrapolation of measured impacts from similar types of damage or sensitivity analysis where impacts had not been quantified (Table 3). The proportion of plantations in each Climate Region affected by *Gonipterus,* Phytophthora root rot and drought deaths soon after transplanting over a full rotation were calculated from Forestry Tasmania's forest health surveillance records between 2003-2009. The frequency of severe MLD epidemics in each Climate Region over a full rotation was based on Pinkard *et al.* (2010). Net present values each of the site quality-based regimes and damage agents were calculated for *E. nitens* using Forestry Tasmania's base log values, and for *E. globulus* using Forestry Tasmania's base log values as well as 0-40% price premiums for pulpwood and 0-20% price premiums for peeler logs. The results of these analyses found that:

- In Climate Regions 1, 2 and 4 the impact of *Gonipterus* and Mycosphaerella leaf disease on *E. globulus* required a 40% pulpwood price premium to match the returns from *E. nitens*. For *E. globulus* to deliver clearly superior financial returns than *E. nitens* in these three regions, it would need to attract a price premium for solid wood in addition to a pulpwood premium. A density-based price premium of one percent for each percent increase in basic density above *E. nitens* would provide a 10-20% price premium for peeler logs based on predicted gains in wood density from the current breeding program. This would be sufficient for *E. globulus* to deliver clearly superior financial returns than *E. nitens* after accounting for the impact of MLD and *Gonipterus*.
- In Climate Regions 3 and 5, plausible growth rate reductions from sub-lethal infection of *E. nitens* with *Phytophthora* in 50% of low and very low quality sites would be sufficient to reduce the financial returns from *E. nitens* to below that of *E. globulus*. Even in the absence of *Phytophthora* impacts, *E. globulus* would be the favoured species in these two regions if genetic selection delivered gains in pulpwood properties sufficient for *E. globulus* to attract a 40% price premium.

*Table 3*. The damage caused by each of the four damage agents important for the species-choice decision, and the method for simulating that damage in Stand Manager (Farm Forestry Toolbox 2001).

| Damage agent | Damage description | Method of simulation |
|---|---|---|
| MLD | Severe defoliation (>50% leaf loss) sustained for one growing season. | CAI reduced by 100% for year of epidemic and 50% for year following (Wardlaw unpublished data) |
| *Gonipterus* | Moderate defoliation (25-50% leaf loss) in late season sustained for one growing season. | Growth impact of a late season defoliation event of comparable severity caused by chrysomelid leaf beetles (Candy 1999). |
| Phytophthora root rot | Opportunistic growth measurements in several *E. nitens* stands infested with *P. cinnamomi* found growth rates 30-40% less than expected. | Sensitivity analysis for 0-40% reduction in MAI (based on review of growth impacts of other root rot diseases). |
| Drought death soon after transplanting | Reduction in survival to levels below set standards (90% at stand-level) necessitates replanting. | Replanting after autumn survival survey done by adjusting regime to double nursery and planting costs and reducing CAI for the first year by 100%. |

## 5. SUMMARY

The recent rapid expansion of eucalypt plantations in Australia has resulted in an increase in the number of pests and diseases causing damage. However, only a small number of these pests and pathogens regularly cause severe damage that warrants management or threatens the viability of some plantation developments. Procedures for managing the majority of the significant biotic threats have been developed and are being used operationally. Where the biotic threats impact different eucalypt species unequally, financial analysis of the wood values and pest impacts for each species provides a way to quantitatively evaluate species choices.

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DAVID BUSH

# SELECTING AND BREEDING EUCALYPTS FOR NATURAL DURABILITY

## 1. INTRODUCTION: THE NEED FOR NATURALLY DURABLE WOOD

The desirability of wood as a naturally renewable, greenhouse gas friendly 'green' architectural material is increasing (Grealy 2008). The appeal is practical, and in some cases there are additional aesthetic or emotional reasons to use wood. Also the growing demand for organically produced food is likely to favour chemical–free production environments, providing further impetus for untreated wooden materials to be used in agriculture and horticulture. However, in situations exposed to the weather, such as outer cladding of buildings, in-ground posts and poles and marine pilings, a serious downside of wood is the natural deterioration that it undergoes.

There are various strategies that can be employed to protect wood and lengthen its service life. Outer coatings such as paints and stains are the most obvious and effective in the short-term, but since the 1950s the use of highly effective, long-lasting, chemically impregnated woods has increased, especially in Australasia where naturally non-durable softwoods are in plentiful supply. There are numerous chemicals, but the most widely used for preserving softwood is copper/chrome/arsenic (CCA) solution. CCA-treated softwood is commonly used is construction (for example barge boards, fascia and other exposed/wet areas), in domestic and municipal landscaping (e.g. retaining walls, garden border edging) and on farms for fence posts and strainers. Another major user is in vineyards. By far the majority of vineyards in Australia and New Zealand as well as a significant proportion in South Africa and Chile use CCA-treated vine trellis posts and strainers. The use of toxic materials such as arsenic is controversial and has now been discontinued in some applications. However the use of CCA-treated wood continues on many farms and vineyards: though the material is quite inert and there is no evidence of it entering the soil or food crops in harmful amounts, disposal of broken posts is certainly a problem. The opportunity to substitute naturally durable timber is significant.

The Australian market for naturally durable timber is significant and growing. The demand for Class 1 (the most durable class) poles in New South Wales is projected to increase by 75% to 87 000 poles between 2004 and 2014 (Grealy 2008). The majority of supply in Australia is sourced from native forests in New South Wales and Queensland, which are rich in naturally-durable species in both the coastal and inland forests. As forests in these States are progressively placed within the national reserve system, the supply is dwindling and the opportunity for plantation development increasing. The value of durable timbers can be substantial, with a premium paid for Class 1, large section and/or long lengths. For timbers used in the round for poles, piles girders and similar, prices in 2008 were between \$60-450/m$^3$, and for sawn timbers \$1,800-3,000/m$^3$ (Grealy 2008).

In Australia, the area in vines is substantial (though declining since 2007), and is estimated to cover 157 000 hectares (O'Donnell *et al.* 2011). Cookson *et al.* (2002) estimated that around 5.5 million trellis posts per year are required, placing the market at that time in the order of $33 million per year. Pine posts have low strength per cross-sectional area compared to hardwood posts and up to 15% are broken or need replacing due to decay each year (Cookson *et al.* 2002). New Zealand also has a large area (circa 32 000 ha) of vineyards (New Zealand Winegrowers 2010). Post breakage rates in New Zealand may actually be slightly higher than in Australia because of the lower strength of faster grown *P. radiata* there. The opportunity to substitute higher strength, naturally durable posts is substantial.

## 2. WHAT IS NATURAL DURABILITY?

Natural durability is a property of wood that allows it to resist biodeterioration caused by bacteria, fungi, termites, borers and marine organisms without treatments of preservative chemicals or coatings. There is a significant amount of variation in natural durability properties among and within genera and species. This is certainly true within the eucalypt genera. There are numerous *Eucalyptus* and *Corymbia* species that have long been known to have good in-ground durability, making them suitable for fence posts, poles and other structural applications involving contact with soil. Traditionally, Australian farms used local resources of eucalypts for their fencing requirements. However there are many non-durable eucalypts, so choosing the right species is important if naturally durable products are the aim. In Australia, native and commonly available exotic timbers are assigned natural durability ratings under Australian Standard 5604-2005. The four-class system is based on the probable life expectancy of heartwood under three classes of exposure (Table 1). Termites are an additional problem, and the Standard also gives information on whether each species' heartwood is susceptible or non-susceptible to such attack.

*Table 1.* Australian standard natural durability ratings corresponding to probable life expectancy (in years) in-ground, above ground and in southern marine waters.

| Class | In-ground | Above-ground | Marine (southern waters) |
|---|---|---|---|
| 1 | >25 | >40 | >60 |
| 2 | 15-25 | 15-40 | 41-60 |
| 3 | 5-15 | 7-15 | 21-40 |
| 4 | 0-5 | 0-7 | 0-20, usually <5 |

Table 2 includes data from the Standard giving ratings for a range of eucalypt taxa and other commonly used species. Clearly there is wide variation among the eucalypts. There are some apparent trends, for example the ash group are generally non-durable in in-ground applications, whereas some of the hardy woodland species such as the boxes and ironbarks tend to be in the most durable group. The conifers are much less durable, with the exception of redwood (*Sequoia sempervirens*).

*Table 2***.** Natural durability ratings (AS 5604-2005) (1 for most durable to 4 for least durable, corresponding to ratings given in Table 1) and basic climate information for some eucalypts and other species. W=winter, U=uniform and S=summer peak rainfall.

| | Durability Class | | | Climate adaptation | | |
|---|---|---|---|---|---|---|
| Species | In-ground | Above ground | Marine | Drought | Rainfall seasonality | Cold |
| Ash group | | | | | | |
| *E. delegatensis* | 4 | 3 | 4 | Poor | W | Excellent |
| *E. fastigata* | 4 | 3 | 4 | Poor | W | Excellent |
| *E. obliqua* | 3 | 3 | 4 | Poor | W | Good |
| *E. regnans* | 4 | 3 | 4 | Poor | W | Good |
| Boxes | | | | | | |
| *E. bosistoana* | 1 | 1 | 3 | Good | W/U | Good |
| *E. molucanna* | 1 | 1 | 2 | Good | U/S | Good |
| *E. quadrangulata* | 2 | 2 | ? | Poor? | U/S | Good |
| *E. argophloia* | ? | ? | ? | Excellent | U/S | Good |
| Grey gums | | | | | | |
| *E. major* | 1 | 1 | 2 | Excellent | U/S | Good |
| *E. propinqua* | 1 | 1 | 2 | Excellent | U/S | Good |
| *E. punctata* | 1 | 1 | 2 | Excellent | W/U | Good |
| *E. longirostrata* | 1 | 1 | 2 | Excellent | U/S | Good |
| Ironbarks | | | | | | |
| *E. crebra* | 1 | 1 | ? | Excellent | W/U/S | Good |
| *E. sideroxylon* | 1 | 1 | 2 | Excellent | U/S | Good |
| *E. tricarpa* | 1 | 1 | 2 | Excellent | W/U | Good |
| Stringybarks | | | | | | |
| *E. globoidea* | 2 | ? | 3 | Poor-Fair? | W/U | Fair-Good |
| *E. macrorhyncha* | 3 | 2 | 3 | Fair | W/U | Good |
| *E. muelleriana* | 3 | 2 | 3 | Poor | W | Fair-Good |
| Corymbia | | | | | | |
| *C. torelliana* | 2 | ? | ? | Good | S | Fair |
| *C. maculata, henryi, citriodora* | 2 | 1 | 4 | Good | W/U/S | Poor |
| Miscellaneous eucalypts | | | | | | |
| *E. camaldulensis* | 2 | 1 | 2 | Good | W/U/S | Good |
| *E. cladocalyx* | 1 | 1 | ? | Excellent | W | Poor |
| *E. cloeziana* | 1 | 1 | ? | Poor | S | Poor-Fair |
| *E. dunnii* | 4 | ? | 4 | Poor | U/S | Excellent |
| *E. nitens* | 4 | 3 | 4 | Poor | W | Excellent |
| *E. pellita* | 2 | 1 | 2 | Poor | S | Poor |
| *E. saligna* | 3 | 2 | 3 | Fair | W/U/S | Poor |
| Conifers and other genera | | | | | | |
| *P. radiata* + all other pines | 4 | 4 | 4 | Mixed | Mixed | Mixed |
| *Pseudotsuga menziesii* | 4 | 4 | 4 | Poor | W | Excellent |
| *Sequoia sempervirens* | 2 | 1 | 4 | Poor | W/U | Excellent |
| *Acacia melanoxylon* | 3 | 3 | 4 | Poor | W | Excellent |
| *Tectona grandis* | 2 | 1 | ? | Poor | S | Poor |
| *Syncarpia* spp. | 2 | 1 | 1 | Poor | U/S | Fair-Good |

These ratings were first determined in the 1950s and were based upon laboratory trials often involving very small sample sizes, the experience of foresters and those writing the standard (Tamblyn 1966). Durability is based upon the resistance of the outer heartwood of mature timbers. The sapwood of all species is considered non-durable, and for many timbers the inner heartwood and pith is also of lower natural durability than the outer heartwood (Gambetta *et al.* 2004; Giordano 1981; Windeisen *et al.* 2002). The ratings given by the Standard serve as a useful guide, but revisions on the basis of comprehensive re-testing would be required to confirm, especially for lesser-known and used species. Such revisions have occurred for some species, *E. cladocalyx* is an example – it was moved from Class 2 to Class 1 in 2005. There can also be a considerable range of variation within classes, for example *E. sideroxylon* is noticeably more resistant to decay than *E. cladocalyx* in test and practice (Kevin McCarthy, former CSIRO biodeterioration scientist, *pers. comm.*). In this paper, following Grealy (2008), 'durable' timbers are defined as those that are Class 2 in-ground or better.

## 3. FACTORS RESPONSIBLE FOR DURABILITY

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

## 4. HOW IS DURABILITY TESTED?

The ultimate test of durability can only be done in-service, a very time consuming process that is difficult to replicate and monitor, especially for the more durable species that don't show appreciable decay even after twenty years in-ground or 40 years above ground. Such long-term tests are fraught with many difficulties ranging from accidental destruction to the ravages of research organisational change. There are various ways to accelerate the biodeterioration process, and these can be correlated with some success to in-service life. One technique is to establish a 'fungal cellar' laboratory facility, where large sections of timber can be buried in soil inoculated with specific strains of fungi. Temperature and humidity can be controlled to maximise fungal attack, and the test can run over the course of years rather than decades. An even quicker method, the 'soil-jar' technique involves placing a small block of wood in an inoculated, soil-filled jar that is maintained in ideal conditions to decompose the sample for a short period, typically of 12 weeks.

Mass-loss is measured after this period, and as a guide <5% is considered to be a performance benchmark for chemical treatments. This technique is clearly far quicker than the alternatives, but is still very expensive for large experiments.

A survey of the few research papers published that deal with family-level genetic variation of decay resistance revealed that sample sets are seemingly limited to around 300 samples or fewer. This is probably because of practical limitations on space and equipment required to simultaneously carry out large soil jar experiments. The use of rapid screening tools such as near-infrared reflectance (NIRA) that relate laboratory-measured parameters to variance in reflected light spectra caused by the chemical composition of the sample would be highly beneficial, especially for studies involving a large number of samples as would be required in genetics studies. While Gierlinger *et al.* (2003) found that NIRA was an effective predictor of decay in *Larix* spp., Bush *et al.* (2011) found that, though an useful predictor of extractives, NIRA is not very effective for predicting decay mass-loss in *E. cladocalyx*. This finding, if more widely applicable to eucalypts, presents a significant obstacle to selection and breeding for fungal resistance, and the cost is only likely to be justifiable in breeding programs that are backing plantation programs of significant scale.

## 5. IS EARLY-AGED WOOD DURABLE?

There is a common perception that heartwood of younger trees, especially those that are faster grown, will be significantly less durable than 'old-growth' wood. However, CSIRO research has shown that younger aged plantation heartwood from Queensland (Johnson *et al.* 1993) and southern Australian low rainfall eucalypts (McCarthy *et al.* 2009) is not necessarily much less durable than old-growth material. A probable reason for this misperception is that younger trees, especially those that are rapidly growing and have a vigorous crown, will have a relatively high proportion of sapwood, and this of course will be non-durable unless treated. Recent studies by Palanti *et al.* (2010) and Bush *et al.* (2011) provide additional evidence that the heartwood of plantation-grown wood of less than 10 years of age can be moderately to highly durable. Though this is an encouraging finding, dealing with the sapwood is a technical challenge that can't be ignored. One approach would be to remove it by peeling. With the appropriate technology, it might even be possible to produce valuable sapwood veneer from small logs (*see* Harwood 2011 in these proceedings). The alternative would be to treat it, which would defeat the 'clean green' objective, but would at least produce a highly durable product.

## 6. CHOOSING NATURALLY DURABLE SPECIES

The ratings of Table 2 provide a reasonable guide to the natural resistance of various species. An interesting point is that some timbers "known" to be highly resistant to decay in the Australian building industry are significantly inferior to many of the more durable eucalypt species. The in-ground rating of teak (*Tectona grandis*) is 2, the above ground rating of western red cedar (*Thuja plicata*) is 2, and Oregon

(*Pseudotsuga menziesii*) – a favourite in Australia for outdoor structures such as pergolas etc though reputed to be more durable than *P. radiata* only achieves a rating of 4 for above ground applications. As a general strategy it is probably best to focus on those genuinely durable species that are rated 1 or 2 for in-ground use. For applications such as vineyard posts, a 25-year in-ground service life is required, so rating 1 is probably best. For above ground applications such as decking timbers and cladding, Class 2 may be adequate.

Of course the choice of species largely has to be determined by what will grow on the available sites. Many of the fast growing species in Australia and New Zealand are not very durable. *E. globulus*, *E. nitens*, *E. dunnii* and *E. fastigata* are essentially non-durable. Drought and cold tolerance are additional limiting factors on many Australia and New Zealand sites. Table 2 provides some guidance on the environmental attributes of species likely to be of interest. The most durable species tend to be slow growing – *E. sideroxylon* is an example. One exception is *E. cloeziana*, which is grown in plantations in Queensland. This species however requires high rainfall and deep, well-structured soils. In Australia, the Australian Low Rainfall Tree Improvement Group (ALRTIG) commenced in the late 1990s to genetically improve species suitable for environmental remediation in the low rainfall sheep-wheat belt (Harwood *et al.* 2007). A small number of “key species” (*E. cladocalyx*, *C. maculata*, *E. sideroxylon/tricarpa*, *E. occidentalis* and *E. camaldulensis*) were chosen on the basis of their natural tolerance of drought and other stressors. From Table 2 it can be seen that all of these species with the exception of *E. occidentalis* which is unrated except in marine environments, are significantly durable (though see later case study). Some of these species may also be suitable for dry environments in New Zealand, though cold is limiting to establishment of *E. cladocalyx* and especially *Corymbia* spp. However for high-value durability applications, New Zealand may have some climatic niches where some of the more durable coastal species such as *E. bosistoana* and *E. quadrangulata* might be grown with relatively high growth rates.

## 7. WITHIN-SPECIES DURABILITY VARIATION

That within-species durability variation exists in most tree species is well known (Hillis 1987). This prompts the question of whether a component of this variation is genetic, and then whether it might then be improved by selection and breeding. Genetic variation in natural durability traits has been studied for a number of taxa including *Larix* spp. (e.g. Gambetta *et al.* 2004; Gierlinger *et al.* 2004; Paques 2001; Venalainen *et al.* 2001), *Picea glauca* (Yu *et al.* 2003), *Pinus sylvestris* (Ericsson and Fries 1999; Fries et al. 2000), P. taeda (Schmidtling and Amburgey 1982), *Quercus* spp. (Mosedale *et al.* 1996) and *Tectona grandis* (Kjaer *et al.* 1999). Until recently, *Eucalyptus* species, which are very variable in their natural durability properties (Rudman 1966), have been relatively unstudied except in relation to heartwood/sapwood ratio (e.g. dos Santos *et al.* 2004; Nicholls and Matheson 1980) and extractive content (Poke *et al.* 2006; Washusen *et al.* 2001), the latter usually in connection with low durability species suited to pulping. Recently Palanti *et al.*

(2010) examined variation in the natural durability properties of *E. camaldulensis* and *E. camaldulensis* x *botryoides* clones, finding significant variation in durability among species and clones within species. The following section describes recently completed work on some low rainfall species from Australia.

## 8. CASE STUDY – PROSPECTS FOR BREEDING EUCALYPTS FOR IMPROVED EARLY EXPRESSION OF NATURAL DURABILITY TRAITS

A project carried out by CSIRO in Australia examined the prospects for genetically improving the natural durability traits for three of the ALRTIG key species. The original objective of the ALRTIG project was to produce small sawlogs on a circa 20 year rotation from southern Australian sheep-wheatbelt sites that would also benefit from the addition of deep-rooted woody perennials to control saline ground water problems. None of the woodland/open-forest species chosen by ALRTIG are suitable for pulp production as they are too dense, and most are also rich in extractives, a negative for pulp production. The idea of producing naturally durable vineyard trellis posts was seen as attractive as it might provide an early return for prospective growers, Australia has extensive vineyards where weak CCA-treated radiata post breakage and disposal is a problem, and the vineyards in many cases are located in or around the places where the low rainfall species might be grown.

Initially two species, *E. cladocalyx* (durability Class 1) and *E. occidentalis* (unclassified) were chosen. The study examined a range of genetic resources grown in provenance-progeny trials at age 8-12, when the trees were of pole size. The following questions were asked:

- Is sufficient heartwood formed by age 8-12 to make a suitable vineyard trellis post of circa 75-100 mm diameter?
- Is the young-age wood sufficiently durable for a vine post application?
- Is there within-species variation in heartwood proportion, extractive content wood density, and (soil jar) resistance to three aggressive brown and white rot strains?
- Can near-infrared reflectance (NIRA) be used as a tool to assess the other traits more cost-effectively and quickly?
- Do beneficial or deleterious inter-trait correlations exist?

In the first stage of the experiment a small number of test blocks of the two species were exposed to an initial 12-week soil jar test of one white rot fungus (*Perenniporia tephropora*) and two brown rot fungi (*Gloeophyllum abietinum* and *Fomitopsis lilacino-gilva*) alongside some commercial preservative treated softwood. The results of this test showed mixed promise: the *E. cladocalyx* samples held up well (as well or better than the preservative treated samples with less that 5% mass loss), while the *E. occidentalis* was aggressively attacked (9-20% mass loss) (Bush and McCarthy 2008). The decision was made to continue with *E. cladocalyx* and substitute spotted gum (*Corymbia* spp.) for *E. occidentalis* in the full study. Though only Class 2 durable, *C. maculata* is an excellent decking timber, and plantation-grown wood might find a ready market in that segment if sufficiently durable.

Results of the study were broadly encouraging, especially for *E. cladocalyx*. Heartwood development (defined as heartwood diameter as a proportion of diameter at breast height over bark) was quite strong in both *E. cladocalyx* and the *Corymbia* species studied at 8-10 years after planting. Significant genetic variation in heartwood proportion indicated that genetic improvement by species/provenance selection in the *Corymbia* and both provenance and family-within-provenance selection in *E. cladocalyx* should be possible. Increased heartwood proportion would also be desirable for sawlog production. The accelerated decay study showed within-species genetic variation in both *Corymbia* spp. (Figure 1) and *E. cladocalyx* (Figure 2) for resistance to both brown and white rotting fungi. Strong *E. cladocalyx* provenance differences were indicated for all three of the fungi, with high estimated narrow-sense heritability ($\hat{h}^2$=0.5-0.6) for two and low ($\hat{h}^2$=0.1) for the most aggressive brown rot fungus, *F. lilacino-gilva*. However perhaps the most important finding was that while the *E. cladocalyx* (particularly the South Flinders Range provenances) has good overall resistance to fungal deterioration, the *Corymbia* heartwood was attacked severely, particularly that of the *C. maculata* samples. The best families of *E. cladocalyx* experienced < 5% mass loss for all three fungi, whereas nearly all samples of *Corymbia* suffered > 5% mass loss for at least one fungus and usually > 10% for *F. lilacino-gilva.*

Significant genetic variation in basic density in both the *E. cladocalyx* and *Corymbia* spp. was indicated. Density is usually strongly related to strength properties and sometimes durability. However, the range of density was quite low. Both species have dense wood even at young age (over 600 kg.m$^{-3}$) which means that post strength will be high, relative to *P. radiata*. Correlations between the different wood traits studied were in many cases significant, though no undesirable correlations were identified. Extractive content was, in both taxa, negatively correlated with mass loss associated with decay caused by the three fungi, as was basic density in all but one case. The strength of the correlations varied from weak to strong.

Disappointingly, while NIRA showed good promise for predicting extractives content in *E. cladocalyx*, it was not a sufficiently good predictor of decay mass-loss to be a useful tool for tree breeding selection purposes (Bush *et al*. 2011).

The study concluded that while heartwood formation was adequate in *E. cladocalyx* and the spotted gums, only the young-age wood of *E. cladocalyx* (which has a mature Class 1 rating) would be sufficiently durable in-ground. The spotted gum heartwood had a generally high extractive content, and there was significant variation among species and provenances in decay resistance. Durability might be improved by selection and breeding, but it would probably be better to start with an alternative species if in-ground applications are the aim. For above-ground applications of the *Corymbia* species, straightforward provenance level selection would probably give an adequately durable product.

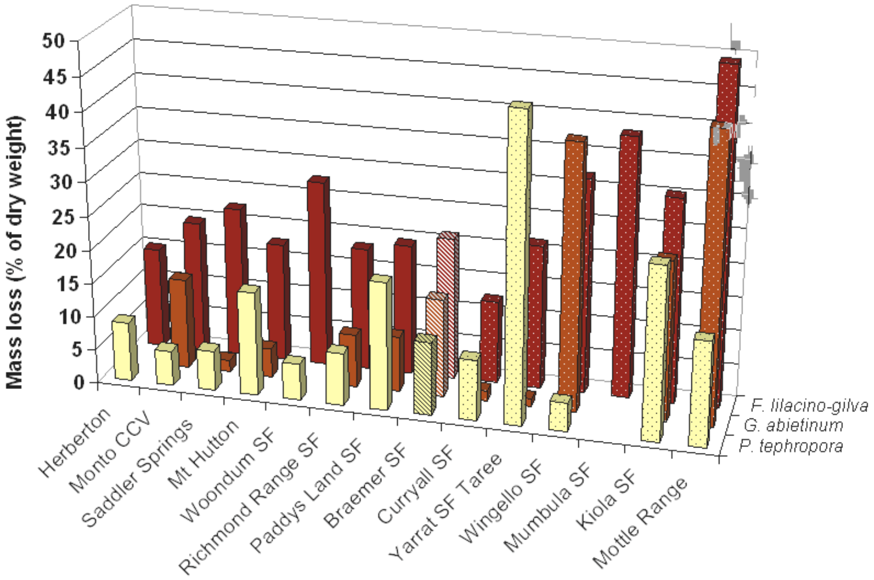

*Figure 1.* Percentage mass loss of *Corymbia* spp. heartwood provenances exposed to one white rot [7904, *P. tephropora* ] and two brown rot [13851, *G. abietinum*; 1109 *F. lilacino-gilva*] fungi. Solid bars= *C. citriodora* ssp. *citriodora/variegata*; diagonal stripes=*C. henryi*; stipple=*C. maculata*. (Bush and McCarthy 2008).

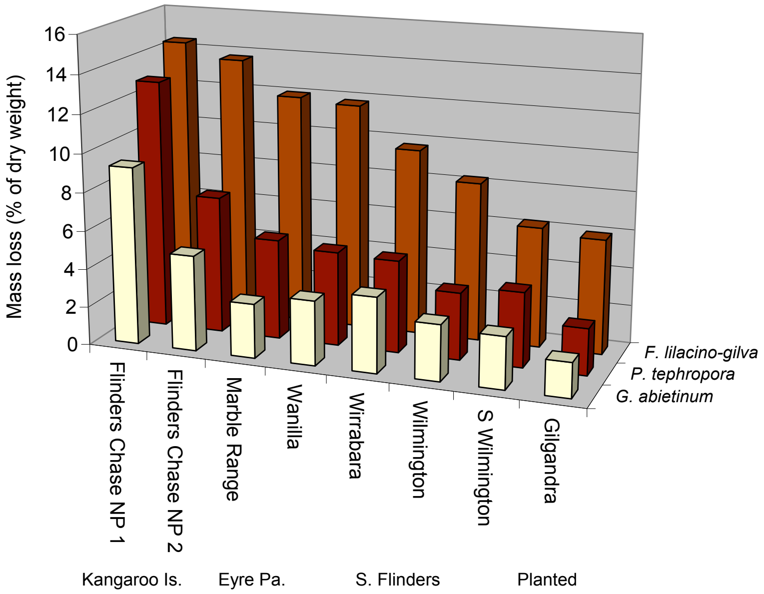

*Figure 2.* Percentage mass loss of *E. cladocalyx* heartwood samples exposed to two brown and one white rot fungus (Bush and McCarthy 2008).

## 9. CONCLUDING REMARKS

Natural durability is a desirable property found in many, but not all, eucalypt species. Naturally durable products have the potential to command a significant price premium, and a societal move towards 'clean, green' products is likely to increase demand for them. In Australia, supply has traditionally been from native forests, but these are becoming increasingly inaccessible. A significant opportunity exists there to grow species with good natural durability properties, either on quite short rotations of circa 8-10 years for small posts and poles and small roundwood, or on longer rotations for sawn timber and larger poles in areas of the extensive low rainfall sheep-wheat belt. In New Zealand, several of the most durable species might be grown in areas where cold is not limiting to establishment. There is substantial within-species variation in eucalypts; however selection of known Class 1 or 2 durable species is likely to be a critical first step. The small amount of research that has been conducted into within-species variation of durability traits in eucalypts indicates that provenance selection and recurrent selection and breeding hold promise for creating specialised durable breeds, but the cost of such programs would need to be justified by a significant plantation base. There is increasing evidence that young-aged eucalypt heartwood is nearly as, or as durable, as that of older trees. Sapwood is never durable, and treating or removing the relatively high proportion of sapwood found in younger aged trees is a challenge for research and utilisation.

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# INTRODUCING DURABLE SPECIES TO NEW ZEALAND DRYLANDS: GENETICS OF EARLY ADAPTATION OF *EUCALYPTUS BOSISTOANA*

## 1. INTRODUCTION

New Zealand plantation forestry is dominated by conifers, with radiata pine (*Pinus radiata* D. Don) and Douglas fir (*Pseudotsuga menziesii*) accounting for 95% of the 2 million ha estate. These species display considerable environmental plasticity, but they face problems when grown in increasingly dry conditions, as well as having end-uses limited by their wood properties.

Drylands – defined as areas receiving a rainfall of 500 to 1000 mm/year – cover large parts of New Zealand (Apiolaza *el al. 2011, Appendix 1*). The productive use of drylands is dominated by agriculture and sheep farming, but land owners are actively looking for alternative uses. Besides wood values, dryland plantations have the potential to bring environmental benefits influencing the carbon, water and energy exchanges (Schimel 2010).

*Eucalyptus* species play only a minor role in New Zealand forestry, with plantations of *E. nitens* in the South Island as the only resource of industrial-scale use. There have been a myriad attempts at introducing eucalypts in the country, but they have failed with all plantings being small scale. On one hand, small plantations have not had sufficient "critical mass" to sustain commercial use of the species. On the other, species introductions have failed to obtain a large enough collection of samples to, firstly, characterize the potential of the species and, secondly, perform selective breeding exploiting between- and within-family variation.

*Eucalyptus bosistoana* F. Muell. (Coast Grey Box, Gippsland Grey Box) is a medium-sized to tall forest tree of the subgenus Symphyomyrtus (Brooker and Kleinig 1999) with a reputation for highly durable wood. This species presents us with an interesting challenge, as very little is known about it from a genetics and tree-breeding point of view. Tree breeding programs rely on the existence of exploitable variability for traits of commercial importance. If traits are not variable, or heritable or we cannot assess them in a cost-effective manner there is little we can do through breeding. Therefore, a successful breeding program requires characterizing variability and estimating the degree of genetic control of each trait, as well as the association between different traits. This information is often referred to as the "genetic architecture" of the species.

This paper presents early results for growth and survival of 66 *E. bosistoana* families growing on three sites in the South Island. We present the degree of genetic control for both traits as well as the magnitude of the change in rankings for growth between sites. Finally, we discuss the prospects for selection of superior genotypes within this species.

*Figure 1.* Location of the *E. bosistoana* plus trees represented in the progeny tests. There are a substantial number of overlapping labels in the southern part of the map.

## 2. MATERIALS AND METHODS

Three open-pollinated progeny tests, representing 66 plus trees from the southern coastal distribution of *E. bosistoana* (see Figure 1), were established in the South Island. The Cravens and Lawsons sites are located in the Marlborough region, while Martins is in the Canterbury region. Table 1 presents a summary of climatic data for the trials.

The trials also included three bulk-seed controls: 997 *E. globoidea* (from Swifts Creek), 998 *E. quadrangulata* and 999 *E. globoidea* (from Cann River). Control seedlots were fitted as additional fixed effects in the statistical models, as they did not have a family structure.

*Table 1.* Climatic data for trial sites (NIWA Cliffo database).

| Site | Mean annual rainfall (mm) | Mean annual maximum temperature (C) | Mean annual minimum temperature (C) | Minimum annual temperature (C) |
|---|---|---|---|---|
| Cravens | 668 | 18.3 | 7.6 | 2.3 |
| Lawsons | 590 | 17.1 | 9.3 | 4.2 |
| Martins | 750 | 17.0 | 5.9 | 1.7 |

Estimates of genetic parameters and predicted breeding values for tree height were obtained by fitting generalised linear mixed models. First we fitted a univariate family model to the vector of phenotypic observations $\boldsymbol{y}$:

$$\boldsymbol{y} = \boldsymbol{Xm} + \boldsymbol{Z_1 b} + \boldsymbol{Z_2 f} + \boldsymbol{e} \qquad (1)$$

where $\boldsymbol{m}$ is the vector of fixed effects (overall mean, control effects), $\boldsymbol{b}$ is the vector of random block effects, $\boldsymbol{f}$ is the random effect of the open-pollinated families and $\boldsymbol{e}$ is the vector of random residuals. $\boldsymbol{X}$, $\boldsymbol{Z}_1$ and $\boldsymbol{Z}_2$ are incidence matrices linking $\boldsymbol{y}$ to the fixed and random effects. The expected values and variances were $\mathrm{E}[\boldsymbol{y}] = \boldsymbol{Xm}$, $\mathrm{Var}[\boldsymbol{b}] = \sigma_b^2\boldsymbol{I}$, $\mathrm{Var}[\boldsymbol{f}] = \sigma_f^2\boldsymbol{I}$ and $\mathrm{Var}[\boldsymbol{e}] = \sigma_e^2\boldsymbol{I}$. In addition we assumed that all covariances were zero.

The previous model was later extended to a multivariate family model by stacking up the data vectors. The variances were then $\mathrm{Var}[\boldsymbol{b}] = \boldsymbol{B} = \boldsymbol{B}_0 \otimes \boldsymbol{I}$, $\mathrm{Var}[\boldsymbol{f}] = \boldsymbol{F} = \boldsymbol{F}_0 \otimes \boldsymbol{I}$ and $\mathrm{Var}[\boldsymbol{e}] = \boldsymbol{R} = \boldsymbol{R}_0 \otimes \boldsymbol{I}$, where $\otimes$ is the Kronecker product and

$$\boldsymbol{B}_0 = \begin{bmatrix} \sigma^2_{b_{11}} & 0 & 0 \\ 0 & \sigma^2_{b_{22}} & 0 \\ 0 & 0 & \sigma^2_{b_{33}} \end{bmatrix} \quad \boldsymbol{F}_0 = \begin{bmatrix} \sigma^2_{f_{11}} & \sigma_{f_{12}} & \sigma_{f_{13}} \\ \sigma_{f_{21}} & \sigma^2_{f_{22}} & \sigma_{f_{23}} \\ \sigma_{f_{31}} & \sigma_{f_{32}} & \sigma^2_{f_{33}} \end{bmatrix} \quad \boldsymbol{R}_0 = \begin{bmatrix} \sigma^2_{e_{11}} & 0 & 0 \\ 0 & \sigma^2_{e_{22}} & 0 \\ 0 & 0 & \sigma^2_{e_{33}} \end{bmatrix}$$

Heavy tree mortality was due to frost in Cravens and water-logging at Martins. Therefore, survival data were analysed as separate traits with a logistic mixed model following equation (1). However, the model used a binary response variable (0 dead, 1 alive) following a binomial distribution and a logit link function.

Heritability ($h^2$) and genetic correlations ($r_{\mathrm{ij}}$) were estimated using the standard formulas:

$$h^2 = \frac{4\sigma_f^2}{\sigma_f^2 + \sigma_b^2 + \sigma_e^2} \qquad r_{ij} = \frac{\sigma^2_{f_{ij}}}{\sigma_{f_{ii}}\sigma_{f_{jj}}}$$

The heritability for survival used the residual variance for the logit link ($\sigma_e^2 = \pi^2/3$). Standard errors for heritabilities and genetic correlations were approximated using a Taylor series. All model fitting was done using ASReml-R, an implementation of ASReml in the R statistical system (Gilmour et al. 2002, Development Core Team 2008).

## 3. RESULTS

There were large among-trial differences for average survival, ranging from 38.2% for Martins to 98.5% for Lawsons (Table 2). The average differences for Cravens and Martins mask large between-family differences. In addition, there was a significant difference between the survival of the 998 (*E. quadrangulata*) and the 997 and 999 (*E. globoidea*) controls. The survival of 998 was equal to (in Cravens) or better than (in Martins) the average family performance.

*Table 2.* Average tree height (cm) and status (number of dead and alive) by site, percentage survival and main cause of mortality.

| Site | Height | Dead | Alive | Survival | Cause of mortality |
|---|---|---|---|---|---|
| Cravens | 137.0 | 1703 | 1997 | 54.0% | Frost |
| Lawsons | 149.9 | 69 | 4424 | 98.5% | |
| Martins | 132.8 | 2317 | 1433 | 38.2% | Water-logging |

There were significant site-level differences for average tree height, with Lawsons — the driest site but with warmest minimum temperatures, see Table 1 — showing the best growth.

Heritabilities for height were low, ranging between 0.10 and 0.14, which is a common result for early growth of trees. This indicates that most of the observed variability potentially corresponds to within-site environmental variability and non-additive genetic effects. Interestingly, the site with the highest survival displays the lowest heritability.

The genetic control for survival presented high heritabilities for Cravens (0.50, mostly affected by Frosts) and Lawsons (0.61, high overall survival). Martins, which was plagued by water-logging problems, presented a much lower heritability (0.11), reflected the underlying environmental effects that caused patched mortality.

*Table 3.* Estimated genetic parameters for tree height and survival at age 2: degree of genetic control (heritability), genetic correlations between sites and their standard errors (between pathentheses).

| Site | Trait | Heritability | Cravens | Lawsons | Martins |
|---|---|---|---|---|---|
| Cravens | Height | 0.13 (0.04) | | | |
| Lawsons | Height | 0.10 (0.02) | 0.74 (0.14) | | |
| Martins | Height | 0.14 (0.05) | 0.99 (0.21) | 0.80 (0.19) | |
| Cravens | Survival | 0.50 (0.10) | | | |
| Lawsons | Survival | 0.61 (0.09) | | | |
| Martins | Survival | 0.11 (0.03) | | | |

Figure 2 summarizes predicted height and survival (Best Linear Unbiased Predictions—BLUP—plus the overall mean) for each site, complementing the story presented in Table 2. Lawsons displays very small between- and within-family variability for survival, while there is a large spread in survival for both Cravens and Lawsons, with a 60% difference between best and worst survival families.

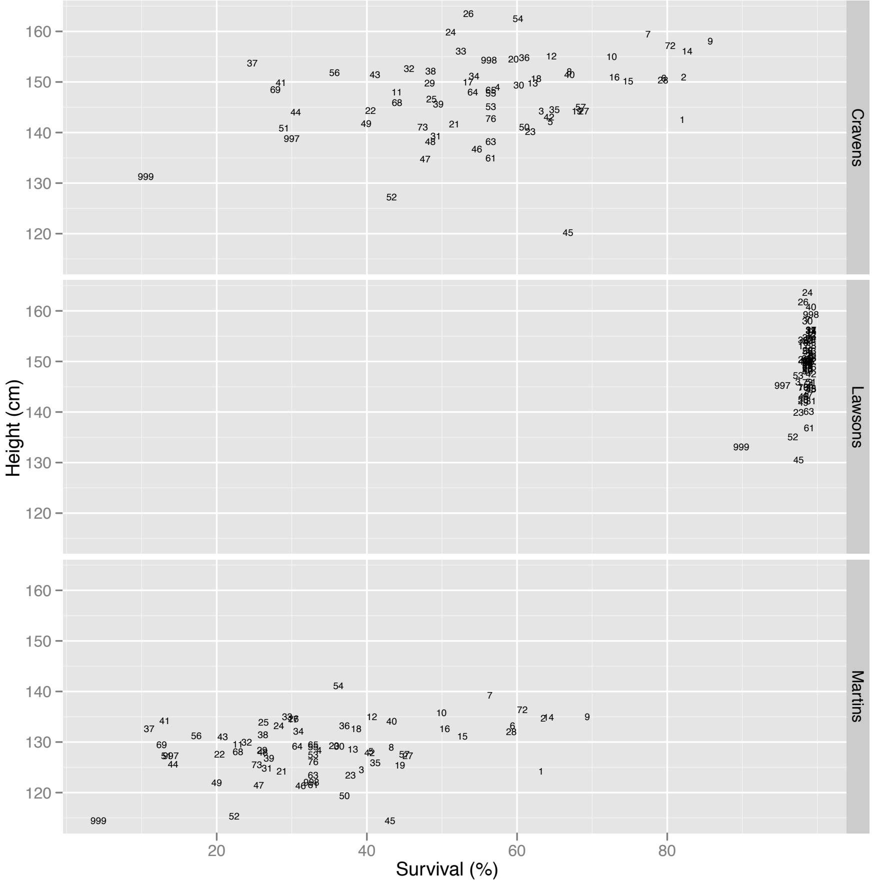

*Figure 2*. Breeding values for tree height and survival of *E. bosistoana* growing in three sites. Numbers correspond to family IDs, with 997, 998 and 999 referring to bulk seedlot controls. Notice the similarity of height variability for all sites, and contrast with the narrow variability of survival in Lawsons.

The situation is different for tree height, with all sites displaying similar levels of variation, a spread of roughly 30 cm between top and bottom families. However, if we consider the degree of genetic control for height (8-13%, see Table 2), much of the observed variability is of environmental rather than of genetic nature.

Another important question for breeding programs is how consistent are rankings across sites. Figure 3 displays family rankings; that is, BLUPs simply expressed as deviations from each site mean. Rankings are very consistent between Cravens and Martins (as indicated by the high genetic correlation between sites), and show some interaction in Lawsons, although the correlation is still very high (between 0.74 and 0.80).

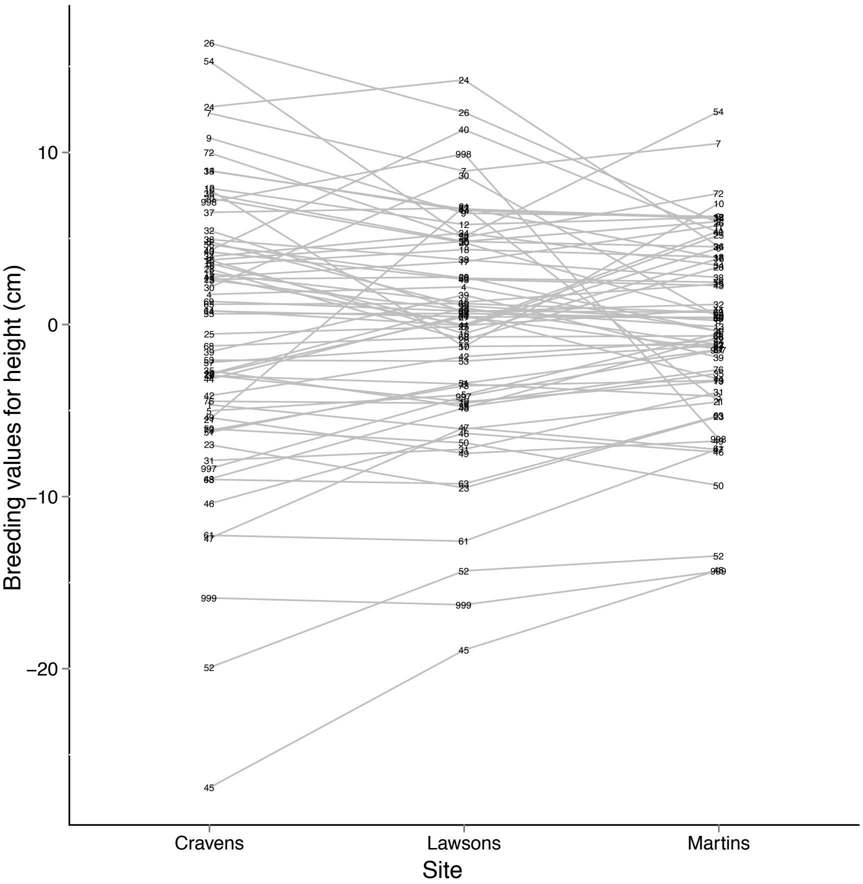

*Figure 3*. Family ranking for tree height (expressed as deviation from the site mean). There is high between-site correspondence, which suggests no need to create site-specific breeding and deployment populations at this stage.

## 4. DISCUSSION

In principle, a formal definition of breeding objectives should precede any serious work in a breeding program. In practice, when introducing new species to an environment—as is the case of *E. bosistoana* in New Zealand—the first priority is to screen for adaptation: growth rate, survival and tree health.

Our results correspond to *early* adaptation (tree height and survival) without any consideration to forest health and wood properties. A cursory view of Figure 2 reveals opportunities for selection; with the best trees in each panel (site) located in the top-right corner; that is with high growth and good survival. Except for Martins (affected by water-logging) the degree of genetic control for survival is high (~55% on average), which suggests room for selection. In addition, these results highlight the importance of working with relatively large samples, both on the number of trees under testing and on the coverage of natural populations growing in contrasting environments.

Heritability estimates assumed that, on average, we were dealing with ideal half-sib families and used a coefficient of relationship of 1/4. Nevertheless, studies in other species have used larger coefficients, e.g. 1/2.86 for *E. camaldulensis* (Apiolaza 1994) based on Squillace (1974) and between 1/3 and 1/2.5 for several species (Eldridge *et al.* 1993) to account for deviations from ideal conditions. As an example, *E. globulus* presents varying family-level selfing and small-scale spatially structured populations, almost guaranteeing deviations from ¼. Unfortunately, there is very little published information on both the reproductive biology and population structure of *E. bosistoana* as to make any realistic assumption. Nevertheless, heritabilities presented in this paper can be easily scaled to represent alternative coefficients of relationship. Estimated genetic correlations between traits will not change when assuming different coefficients of relationship among siblings.

Genotype by environment interaction is a common preoccupation in breeding programs, particularly for growth traits, (e.g. Wei and Borralho 1998; Costa e Silva *et al.* 2006, Costa e Silva *et al.* 2008). At least at this stage, there is little evidence for strong changes of ranking that would require more complex (and therefore expensive) breeding and deployment strategies. In general, wood properties tend to be less susceptible to GxE interaction, although changes of scale (as opposed to ranking) are not unusual (e.g. Raymond *et al.* 2001, Apiolaza 2011).

Genetic evaluation models did not include provenance or locality effects to account for different genetic populations, (e.g. Dutkowski and Potts 1999). At this stage, there is not enough data available to delineate these populations that would result in better fitting models. The accuracy of the predicted breeding values could also be improved by fitting within-site spatial patterns (e.g. Gilmour *et al.* 1997), as there are strong environmental gradients in some of the trials, relating to slope and aspect. Improved genetic-statistical models are under development.

One of the main objectives of the NZDFI is to generate a forest resource with naturally durable wood, i.e. that does not require preservatives. Durability in eucalypts is directly related to the presence of extractives in heartwood, which is not possible to evaluate—at least phenotypically—at this early stage.

## 5. FINAL REMARKS

Tree breeding is a numbers game and, as shown by these results, there is a need to screen large numbers of families and trees within families to find some winners. Domesticating a new species requires, first, finding subpopulations of good enough adaptation as to permit screening for other objective traits like growth and wood properties.

Therefore, having selected the best-adapted material from this series of trials, we can start investigating and understanding the variability of durability and tree health. The characterization of wood properties, particularly of durability, will require new tools and techniques. Developing these will require additional R&D funding.

Given that there is no much experience with *E. bosistoana* in New Zealand, the trials that we establish serve both for tree breeding and to discover the appropriate environmental conditions for optimal growth of the species. This situation carries some additional risks, as discovered at the Martins site.

The NZDFI expanded the *E. bosistoana* collection in 2010 by planting another 36 families on a further three sites, with progeny of mostly plus tree collections within the Northern natural populations. Our expectation is that Southern populations will be more successful in New Zealand drylands and on this basis, we have just completed seed collection from a further 86 plus trees that will be put to the nursery to propagate seedlings for planting in 2012. However we will also watch with interest the performance of our Northern collections as international experience with other species has delivered some surprises. These additional collected trees are not part of this series of sites, but they will be linked to this work in future trials.

## 6. SUMMARY

This article presents early results on the genetics of adaptation for *Eucalyptus bosistoana* growing in New Zealand drylands. A progeny trial established in 3 sites in Marlborough and Canterbury was analyzed for growth and survival at age 2 years. There was substantial variation for both height growth and survival both between- and within-family. However, only a small proportion of height variation was under genetic control ($h^2$ ranging from 0.10 to 0.14), while survival was under strong genetic control ($h^2$ from 0.50 to 0.61), except in Martins, a site damaged by water-logging. There was a low degree of genotype by environment interaction for tree height, with genetic correlations ranging between 0.74 and 0.99. This high correlation suggests that there would be no need to create breeding and deployment zones for this species.

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# NZ DRYLAND FORESTS INITIATIVE: LEARNING FROM OTHERS

## 1. INTRODUCTION

There is more to forestry than radiata pine and average quality wood. We all know it but, as an industry, have mostly struggled to materialise successful alternatives. Bootstrapping a new plantation species from scratch is no small feat, but we also know that it is perfectly feasible, as it has been done before in New Zealand and other countries (at least we did it before we became too complacent and settled for our current dominant species). Knowing that we can make do with the *status quo* has had a paralysing effect: at first, we tend to see large drawbacks for alternative species, while minimising their (potentially transforming) positives.

We would still be arguing from a completely academic point of view if it had not been for the determination (some would say stubbornness) of one of our co-authors. His perseverance lead to a series of encounters that would become the NZ Dryland Forests Initiative (NZDFI) and to the collection and establishment of large populations of naturally durable eucalypts in the country.

The NZ Dryland Forests Initiative has its beginnings in 2003 when Paul Millen, a forestry consultant in Marlborough, was asked to source alternative material to CCA-treated radiata pine posts for some vineyards (Millen 2009). The immediate problem was unacceptably high post breakage during mechanical harvesting as well as a perceived groundwater risk posed by the large-scale use of CCA-treated posts. Subsequently the Marlborough Research Centre co-ordinated an investigation as to the potential for contamination of soil and groundwater due to leaching from CCA-treated posts (Robinson *et al.* 2006; *see* Bush 2011). Millen looked for sources of NZ grown naturally durable timbers to address these needs, but very little was available.

While disappointed by the lack of any significant regional resource, Millen was encouraged by the interest in naturally durable timbers and saw the potential to establish new plantings. He set up Vineyard Timbers Ltd and over the next three years established some 80 small trials of 25 durable eucalypt species in collaboration with the Marlborough District Council, several local landowners and Proseed NZ Ltd. Concurrently Scion established and reported on a series of multi-species trials (McConnochie *et al.* 2008) which included class 1 or 2 durable eucalypts. Also, in 2004 and 2005 NZ Farm Forestry Association's Eucalypt Action Group members undertook trials of several durable eucalypt species. Data from all these trials provided the foundation for NZDFI to build on.

Thus NZDFI's initial key focus was on genetically improving naturally-durable eucalypts suited to grow on the drier eastern areas of Marlborough that could meet the needs of local vineyards. NZDFI was supported by regional government as it offered the potential for a regional supply on non-toxic posts/poles, and a short rotation cash crop that dryland farmers could grow to diversify land-use.

## 2. CAPTURING THE STRATEGIC HIGH GROUND

In the broadest possible sense, the strategic aim for the NZ Dryland Forests Initiative, and for New Zealand (and Australia), is to be a world leader in breeding, management and production of elite naturally-durable eucalypts that are suited to dryland conditions and produce high value roundwood and sawn timber. Underpinning NZDFI's strategy is a commitment to the establishment of a durable hardwood industry capable of supplying the eco-certified timber products being demanded by international markets and thereby displacing demand for unsustainably harvested tropical timbers. The potential of dryland eucalypts to displace tropical hardwoods on world markets has universal appeal at a cultural, economic, political, scientific and societal level.

However, a claim of the moral high ground with sweeping strategic goals has to defer to logistical needs. Harwood (2011) addressed the high cost of *ab initio* breeding programmes, noting that the ALRTIG breeding program has required investment of at least $250,000 per species, excluding additional major in-kind support such as the provision of land for field trials and seed orchards (David Bush, *pers. comm.*). This investment is broadly in line with our experience, namely that by 2013 NZDFI will have spent some $2 million in establishing its broad-based breeding populations for some six species, probably including *Eucalyptus argophloia* (S), *E. bosistoana* (L), *E. camuldulensis* (S) *E. globoidea* (L), *E. quadrangulata* (S) and *E. tricarpa* (S), where (S) and (L) refer to small and large collections of families at the current time, i.e. our largest broad-based populations are of *E. bosistoana* and *E. globoidea.* In addition, a further six durable eucalypt species are being monitored in small-scale, multi-species trials across the drylands of eastern New Zealand from the East Cape to Canterbury. *E. cladocalyx* would be a most desirable addition if it were not for its susceptibility to the expected frosts on much of New Zealand drylands. We are tempted to trial it on dry, frost-free coastal sites.

All these species have elite properties (Grealy 2008), including exceptional natural durability, hardness and a fine range of colour; but some survive only in remnant stands and have never been bred because their inherent durability was too easily and cheaply replicated in the 1940s by copper-chrome-arsenate (CCA) treated pine, as well as by supply of other hardwoods from unmanaged native forests.

Today NZDFI holds the largest collection of *E. bosistoana* and *E. globoidea* families from across their natural range and *de facto* is an archivist and steward for these species.

The NZDFI's objectives will contribute to New Zealand's sustainability goals:

### *2.1 Economic*

- Despite a $1 billion invested by the State on pine research the intrinsic quality of the wood of radiata pine being planted today is little better than that planted in the 1920s. Its markets are modest and pine's inherent wood qualities will always remain mediocre even when compared to run-of-mill hardwoods (US$200/m$^3$ for pine *versus* $394/m$^3$ for hardwood export lumber) (FAO 2008).
- By diversifying New Zealand's timber supply with high quality durable eucalypts that will substitute for imported hardwoods ($270 million/yr). Our timbers will match elite species like mahogany, rosewood and teak. They are highly durable and very stiff/strong, so are ideal also for posts, poles and utility cross-arms.
- By developing the resources needed for landowners to invest in growing eucalypt woodlots that will be more profitable than pine on drylands (broadly 600-1000 mm rainfall/year and prone to summer drought).
- By reducing New Zealand's dependence on CCA-treated pine, so forestalling international market resistance to the use of CCA in agricultural systems growing food.

### *2.2. Societal*

- By contributing to regional development; and
- Income diversification, by offering an appropriate and sustainable opportunity for small growers and pastoral farmers who account for 35% of the world's forestry (including NZ). Traditionally these growers have had access to only the poorest forest germplasm.
- By creating a resource that can thrive on poor quality, low rainfall lands such that it does not compete with food production systems.
- By creating a mosaic of woodlots on farms that are dispersed throughout the regions such that forestry becomes less obtrusive.

### *2.3. Environmental*

- By developing a resilient forestry option for New Zealand drylands. These regions are predicted to experience more frequent and prolonged droughts as a result of climate change. *See* NIWA annual rainfall map (Appendix 1).
- By developing a high value tree crop that provides diversification for pastoral farmers using only their most erosion-prone land – recognizing that these eucalypts have extensive root systems that coppice (resprout) following harvesting or after fire.
- By encouraging the planting of durable eucalypts that also have rapid growth rates and high wood densities offering the potential for rapid carbon sequestration rates even on NZ drylands.

- By encouraging regional councils to support the development of sustainable hardwood forestry that will diversify land use and local regional economies.
- By providing year round nectar/pollen for native biodiversity and bee keeping.
- By producing naturally durable timber that will substitute for treated pine and thereby reduce hazardous wood waste flows. For example, in Marlborough broken posts during the harvesting of vines create up to 24 000 $m^3$/yr of hazardous waste for which no acceptable disposal facilities exist other than secure landfill. Landfill costs in Marlborough are \$21/$m^3$.

## 3. PROBLEMS AND OPPORTUNITIES

New Zealand's failure to develop a large eucalypt estate is in stark contrast to other Southern Hemisphere countries, both in temperate and sub-tropical regions (Apiolaza *et al.* 2009). Many of the new projects involve very high biomass productivity (either for pulp or energy production). These are cutthroat businesses where New Zealand has little prospect of competing on equal terms with countries like Brazil or Chile. However around the world there has been less progress with solid wood products and therein lies an opportunity.

New Zealand is overly reliant on radiata pine which accounts for 90% of plantations. Eucalypts account for only 1% of timber production. NZ has demonstration plantings of many eucalypts but only *Eucalyptus nitens* and *E. fastigata* have been planted on any scale. Both are not durable and are unsuited to drylands. Other eucalypt species planted in NZ have not been improved and existing stands are a very narrow genetic resource that severely limits screening to remove undesirable features.

Yet, New Zealand's primary industries need sustainable land use options that are resilient to the effects of climate change. This is particularly so for NZ drylands where, in recent years, there has been an increase in prolonged droughts. Drylands can sustain productive forest, e.g. Yatir pine forest planted in 1964 in Israel, with rainfall < 500 mm/yr, sequesters carbon as rapidly as pine forests in continental Europe (Schimel 2010).

Durable eucalypts are likely to sequester carbon at higher rates than pine. Their rapid growth rates together with their wood being roughly twice as dense, age for age, as radiata pine makes them highly eligible as species for NZ's Emissions Trading Scheme (Walker 2008, for NZDFI).

One of the purposes of this workshop is to address our failure to make much progress with eucalypts. Indeed, it is with trepidation that we must acknowledge that eucalypt pests and diseases have lead to past failures, and that our proximity to Australia is a significant biosecurity threat to any new venture. Such difficulties have been contrasted with the ease of growing and processing pine everywhere around New Zealand.

Historically, the risk-reward balance in favour of pine was unchallenged with pine displaying little downside risk compared to the (soluble) complexities of growing and processing eucalypt. But the harsh realities of modest financial returns for many years, poor wood quality issues and the high biosecurity risk posed by being reliant on a single species are compelling reasons for taking a contrary view. Besides, in the 21st Century, diversification of our forestry resource with durable eucalypts has strong market appeal as it offers the aesthetic and environmental benefits of being an eco product.

We believe that, despite the excellent work by ALTRIG (Bush 2011), the opportunity for growing naturally-durable eucalypts on drylands in temperate regions has largely passed unnoticed giving us international first mover advantage to capture and establish broad-based breeding populations of elite dryland hardwoods. The NZDFI partners have established their R&D programme to capture such opportunities and believe New Zealand's farm foresters and corporate forestry growers will adapt their skills and resources in growing pine to growing durable eucalypts. Our selected species are drought tolerant and highly durable (Class 1 and 2 Australian Standard, AS5604-2005/Amdt-2008). CCA-treated wood is now banned for many uses in Europe and the USA, so there are significant international and domestic markets for naturally-durable timbers.

We have chosen to work with multiple species for a number of reasons.

- Diversification reduces risk.
- Individual species are site specific, having evolved in niche environments in Australia. A suite of species is needed to cover the diversity of NZ dryland sites.
- Outcrossing of species will create elite hybrids that capture the best traits of each species and extend the range of sites able to successfully grow durable eucalypts.

Tree breeding and forestry are long-term ventures. NZDFI seeks to shorten the time horizon by:

- Making improved germplasm available for planting within 3-5 years through the use of innovative early selection procedures when trees are only age 2-4.
- Capturing the immediate multiple-use benefits of these species for growers – combating erosion, carbon sequestration, habitat for native fauna and bee keeping – while offering potential for commercial sale of post/pole thinnings (age 8-10) and sustainable harvesting of high value sawlogs (age 24–30).
- Developing rapid, bulk screening assessments for heartwood.

The programme leverages off the existing interest shown by potential growers and those seeking sustainable products for use in their business or communities – electrical network companies, winegrowers, organic farmers and regional government.

## 4. TACTICS AND BEST PRACTICE

Discussions in Wellington made it clear that R&D funding would not be forthcoming until NZDFI had the trees on which to undertake research. Since 2009 the priority has been, and remains, to collect seed and establish broad-based populations for half a dozen species, alongside small multi-species trials of possible contenders, across our dryland regions. By the end of 2012 some 150,000+ trees will have been planted consisting of broad-based single-species in blocks of up to 10,000 trees, each replicated on sites across our dryland regions, as well as multiple small multi-species trials on both representative and demanding sites.

The initial selection for survival, growth and form should be straight-forward, however, the costs of measurement, assessment and thinning 150,000+ trees will be significant. In addition, we are aware that there are further large costs and are looking to this workshop for ideas that will allow NZDFI to use its resources most effectively – making do with less than we would like in an ideal world.

NZ farm foresters and forest growers are interested in planting durable eucalypts. They are asking for information and advice regarding the siting of these species, how to manage them, and what growth and biomass production they might expect to achieve. This information is needed to ensure new plantings are successful and to evaluate the potential economic returns for growing durable eucalypts under various forest models including a roundwood coppice regime and a European-style coppice and standard regime. Measurement and analysis of our breeding populations and species trials will contribute to developing these models. Also we need eco-physiological studies so as to better understand and quantify the effects on productivity that result from variations in site conditions. In the medium term NZDFI plans to investigate and understand the ecology of each species in Australia so as to better assess their performance in New Zealand.

The technical issues that have most constrained our planning have been:

### *4.1. Availability of seed in Australia*

Proseed has co-ordinated the collection of seed in Australia. NZDFI now has a reasonably complete collection of families across its range for *E. bosistoana*, but has, as yet, largely failed to collect *E. quadrangulata.* In effect NZDFI has had to be opportunistic collecting seed when and where it becomes available. This remains an on-going constraint to rapid deployment of species.

### *4.2. Drought, frosts and pests and diseases*

Our chosen eucalypt species can be relatively site specific having evolved under differing geographic and climatic influences in niche Australian environments (Boland *et al.* 2006; Janovic & Booth 2002). Where possible we have collected some closely related eucalypts with the view to being able to develop some useful hybrids. Thus multiple species, multiple sites and large populations are indispensible; to contribute variation to better adapt to distinctive dryland conditions, and to mitigate risks of out-of-season frosts, and of pests and diseases, and provide the broadest affordable genetic base from which to create elite breeding populations by selecting *ca.* 1 tree in 300.

Both Harwood (2011) and Shepherd (2011) are cautious about eucalypt hybrids, particularly in Australia and New Zealand with ready access their natural diseases and pests. This is despite successes such as Aracruz in Brazil with *E. grandis* x

*E. urophylla*, where the latter provided resistance to canker and greater drought tolerance. Our choice of species allows us to retain the hybrid option.

With regard to diseases and pests, NZDFI must better understand and promote the careful matching of species with specific sites to ensure healthy plantations; while also relying on New Zealand's biosecurity controls and Scion's Forest Health Monitoring Unit.

### *4.3. Durability, early heartwood formation and colour*

Trees are amongst the most variable of all living organisms, and this applies to wood properties as much as to forest growth and forest health. Once trees have been screened for early growth and form the next major task will be assessing the heartwood. To stress the point, some heartwood of a class 1 durable species will fail prematurely while some heartwood of a class 2 durable species will exceed expectations. Developing a viable mass-screening system for early heartwood formation and for durability is essential to the success of this programme. Further, it would be desirable to produce honey-coloured heartwood to mimic teak (as with *E. bosistoana*) and dark, blood-red heartwood to mimic rosewood (as with *E. camuldulensis*), species prized in India and China respectively (Figure 1). Consistent colour is important for marketing high valued products.

*Figure 1.* Sawmill offcuts: (a) from old-growth riverine *E. camuldulensis* from Mildura on NSW/Vic border

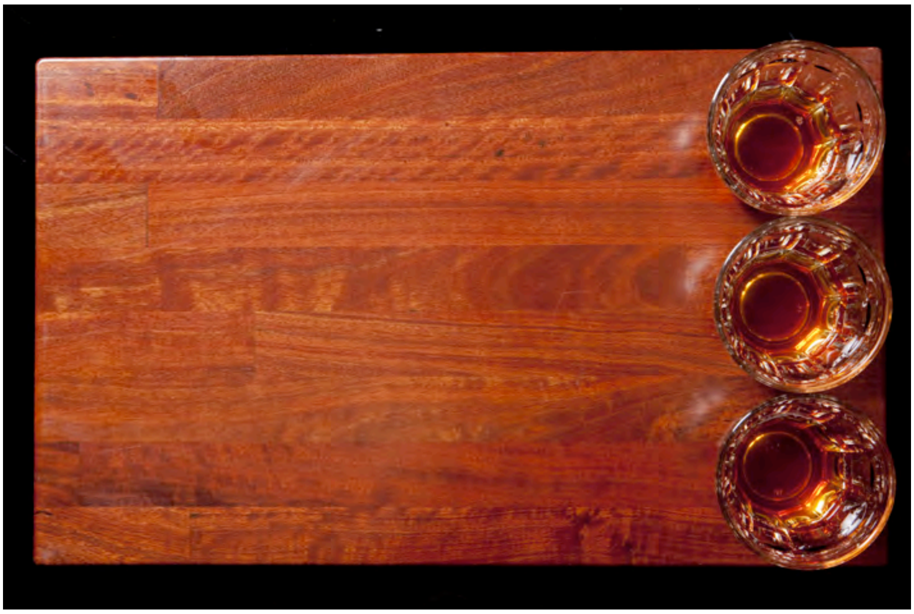

*Figure 1.* (b) from old-growth riverine *E. camuldulensis* from Mildura on NSW/Vic border

*Figure 1.* (c) from New Zealand grown *E. bosistoana*.

## 5. LOGISTICS: CUTTING EDGES

Selecting a new breeding population for survival, growth and form comes at a considerable cost. Just spending a minute looking at 120,000+ trees equates to a year's work (40hr/week; 50weeks/yr) so early thinning to waste is essential. With large populations one has to keep one's procedures simple, quick, repeatable and robust.

When screening large numbers of specimens for multiple properties, it is not necessary to obtain accurate absolute values. It is sufficient to be able to rank and so select only the top few percent from the broad population. In addition, there will need to be an ongoing collecting of further seed in Australia once the best families have been identified.

Within this programme there are a number of bottlenecks that will require new approaches. The most critical revolve around early heartwood formation, its durability, and the within-species variability. We suspect that we will need to:

- Develop a high-torque electric drive unit to use with a conventional hand-held 5 mm diameter increment corer to examine sapwood.
- Develop a new coring tool to effortlessly (*sic*) extract 25 mm diameter dimetral cores from selected trees that form early heartwood.
- Develop new procedures to rank 25 mm diameter increment cores for durability. We would like to investigate a bioreactor/digester system that could take either thin radial strips cut from the heartwood in the increment core, or 5 mm thick LT-oriented discs cut successively to give outer- and inner-heartwood samples.

A complementary quantitative approach might be to screen the sapwood of very young trees for small quantities of monoterpenes, ellagic acid, flavonoid compounds *etc.* for durability, and polyphenols and tannins for colour. One would have hoped to rely on tools such as near-infrared reflectance spectroscopy as it is fast, although Bush (2011) is pessimistic.

Other critical tasks would include:

- Establishing effective nursery propagation and deployment technologies.
- Investigating and understanding the ecology of each species in Australia so as to better assess performance and risk management in New Zealand.
- Developing hybrid mensurational/physiological growth and yield models for dryland site species.
- Initiating a hybrid breeding programme. For example, one would expect to be able to cross *E. argophloia* and *E. bosistoana*, and probably *E. tricarpa.* This could be an area for a trans-Tasman partnership.

This is a formidable list of "choke points" or, from a more positive perspective, an alignment of challenges to be overcome. These in turn must be subservient to the management demands of the newly established broad-based populations. Hence the need to be cunning and learn from others.

## 6. CONCLUDING REMARKS

With a new programme, one might expect something that is long on strategy and short on tactics and even briefer on logistics. This workshop was conceived as a way to address this by inviting some of the foremost experts on eucalypts to Marlborough in the expectation that this meeting will crystallize opportunities and build valuable trans-Tasman partnerships.

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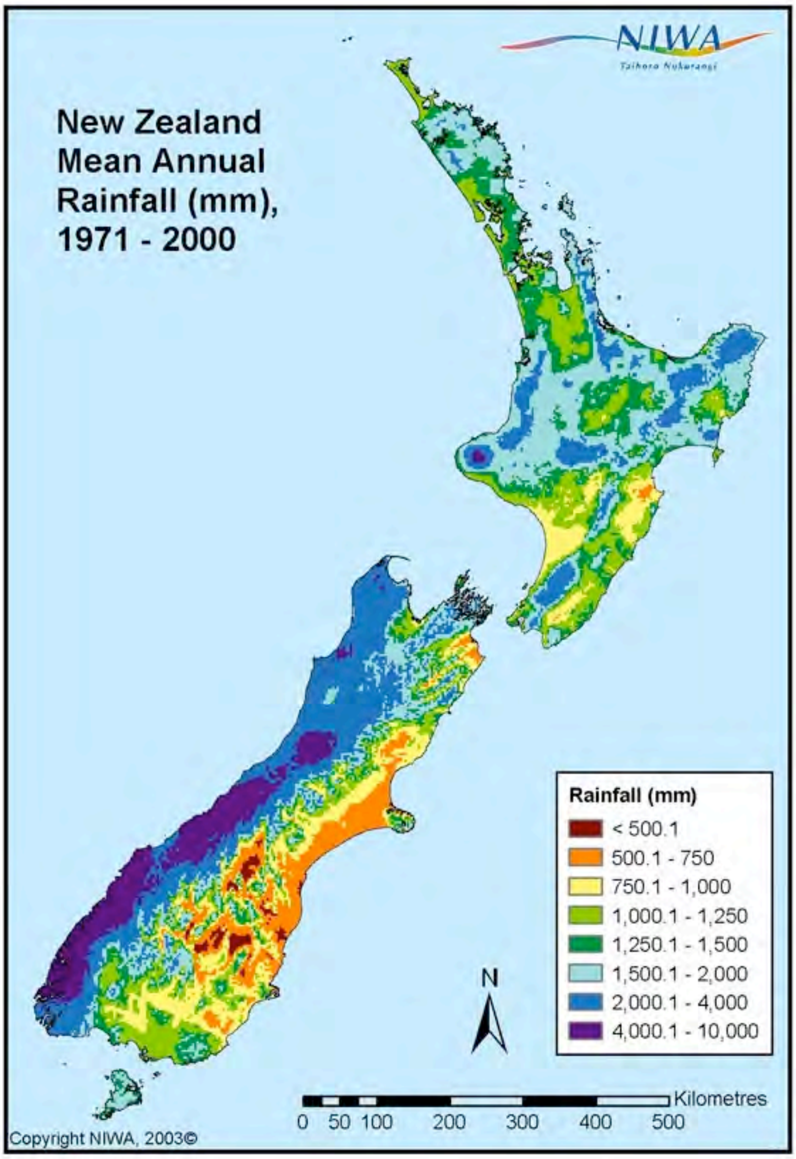
# APPENDIX 1



Source: NIWA, National Climate Centre, Wellington