DURABLE EUCALYPTS ON DRYLANDS: PROTECTING AND ENHANCING VALUE

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WORKSHOP PROCEEDINGS 2017

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New Zealand, April 19th 2017.

PREFACE

The workshop "Durable Eucalypts on Drylands: Protecting and Enhancing Value" was held on the 19 April 2017 at the Marlborough Research Centre in Blenheim. On the 20 April 2017 a field visit followed to one of the NZ Dryland Forests Initiative's (NZDFI) breeding trials, located on land owned by the Marlborough District Council near Blenheim, and then to Nelson Pine Industries Ltd's LVL processing plant in Richmond, Nelson.

The main aims of the workshop were (i) to inform our supporters and the wider public of the recent progress in establishing a forest industry based on durable eucalypts and (ii) to enable international experts to review our research programme. While the challenges associated with growing and processing durable eucalypts are general, those organising this workshop have a specific interest in addressing local issues and uncertainties.

The workshop attracted participants spanning a broad range of nationalities, interests and expertise, and we gained valuable feedback on the NZDFI research programme. The workshop enabled NZDFI to strengthen and expand domestic and international collaborations.

We thank all the speakers and their companies/organisations for their support. The speakers' time in preparing material for the proceedings and their participation at the workshop was greatly appreciated.

We thank those who helped to organise the workshop and the field trip, in particular Gerald Hope and Mandy Mitchell (Marlborough Research Centre); Harriet Palmer, Ash Millen and Ruth McConnochie (NZDFI); Vicki Wilton and Jeanette Allen (University of Canterbury) and Richard Barry (Nelson Pine Industries Ltd).

We acknowledge all the sponsors of NZDFI's research, and those who supported our workshop: AGMARDT, MPI Sustainable Farming Fund (SFF project 407602), Neil Barr Foundation, Nelson Pine Industries Ltd, Proseed, Ernslaw One, Kaingaroa Timberlands, Vineyard Timbers, Marlborough Lines, Forest Grower Levy Trust, MBIE's Specialty Wood Products Research Partnership (SWP) and Juken New Zealand.

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Videos of the talks are available at http://nzdfi.org.nz/news-and-events/resources/workshop-durable-eucalypts-protecting-and-enhancing-value/.

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S. VAN BALLEKOM AND P. MILLEN

NZDFI: ACHIEVEMENTS, CONSTRAINTS AND OPPORTUNITIES

Abstract We believe the development of a durable eucalypt resource in New Zealand is a transformational opportunity, and the NZDFI has the vision and the resources to make it reality.
Using areas of dry, marginal farmland, the NZDFI aims to create a naturally durable, highly coloured eucalypt resource. The timber will mimic the most valuable tropical hardwoods. Our aim is that New Zealand will compete on innovation and excellence rather than price; our work is underpinned by increasing scarcity of tropical timbers and environmental constraints limiting their supply. New Zealand should enjoy a comparative advantage in that relatively low-value, marginal pastoral dryland can be used to grow high-value timber. With our elite breeding populations we will have 'first mover' advantage. In addition, we believe New Zealand will become the partner of choice for international dryland ventures.

1. INTRODUCTION

The New Zealand Dryland Forests Initiative (NZDFI) was established in 2008 as a collaborative tree breeding and forestry research project. The NZDFI's aim is to select and improve drought tolerant eucalypts that produce high-quality naturally ground-durable hardwood. The NZDFI vision is for New Zealand to be a world-leader in breeding ground-durable eucalypts, and to be home to a valuable sustainable hardwood industry based on 100,000 hectares of eucalypt forests, by 2050.

Markets for naturally ground-durable wood exist in New Zealand's agricultural, transport and energy sectors. There is also potential for high-value specialty wood products for export to international markets (Millen, 2009).

NZDFI's unique research focus and strategic vision will benefit future generations of New Zealanders by delivering the plants and knowledge to forest growers, enabling them to select and grow eucalypt species suited to their site.

NZDFI is providing landowners with a new option: that is, to grow eucalypts that will produce a high-quality durable timber that meets the requirements of domestic and international markets, and in doing so, diversify farm income. NZDFI eucalypts will also enhance environmental sustainability by combating soil erosion thanks to the trees' extensive root systems and eucalypts propensity to coppice (regrow from a cut stump) following felling. The new hardwood forests envisaged will offer other benefits beyond wood production – for example, carbon sequestration, and nectar, pollen and habitat for bees and other fauna. NZDFI species also have a low wilding risk.

NZDFI pursues a strategy that involves carefully matching species to site and to end-products. The focus is on geographic regions with less than 1000 mm/year average rainfall, especially regions where new land-use options are needed to diversify economic development. Therefore, rather than looking for generic species, we are looking for species that complement New Zealand's main plantation species and have the potential to produce high-value products. At the same time, we need to help growers learn how to successfully establish these new species to ensure our target of 100,000 hectares is reached to produce a sustainable resource for a new hardwood industry.

2. DURABLE HARDWOOD MARKETS

NZDFI's inception came as a result of the project manager, Paul Millen, recognising the huge potential market in Marlborough for vineyard posts. The wine industry's standard posts, made of CCA-treated radiata pine, cause a number of problems. They have high rates of breakage as a result of mechanical harvesting and their toxicity means they are very difficult to dispose of safely.

This brought the identification of species which could produce timber 'fit for purpose' as vineyard posts into focus. Natural durability and strength are the two essential wood properties that made durable eucalypts an obvious choice.

In addition, it soon became apparent that there were other potential market opportunities. New Zealand's current annual timber imports exceed $500M; timber imported goes into markets well-suited to durable eucalypt timber including:

- cross arms for electricity networks
- sleepers for rail networks and urban landscaping
- wharf timbers for ports and marinas
- decking, outdoor landscaping and furniture.

Further to this, there is significant export potential for both naturally durable solid wood products and high-strength laminated veneer lumber (LVL) increasingly being demanded in international timber construction markets.

Knowledge of these potential markets has led the NZDFI into a product-focused research programme. It is envisaged that growers will benefit from two income streams, by harvesting at different ages:

- roundwood thinnings from around age 12 onwards: timber suitable for preservative-free posts and poles for vineyards, horticulture and organic enterprises, and potentially for rotary peeled veneers
- sawlog harvest at around age 24 onwards: timber for cross-arms, sleepers (rail and outdoor landscaping), small wharves and marinas, furniture and interior fittings (Asia), and engineered wood products.

3. PAST RESEARCH INITIATIVES

The early experiences with growing eucalypts for solid wood products in New Zealand are summarised by (Barr, 1996). Two New Zealand eucalypt research initiatives in the early part of the 21st century are worth mentioning. Both of these projects were undertaken with scarce resources, and although done as well as possible given the resource constraints, ultimately are not suitable as the foundation for a serious breeding programme.

3.1. FRI/Scion stringybark trials

A good start was made by Scion (formerly the NZ Forest Research Institute, FRI) to investigate the stringybark eucalypt group for solid wood uses (Shelbourne et al., 2002). Proseed NZ Ltd assisted with seed collections, with seed from 12 species and 69 provenances being supplied. In 2003, Scion planted a set of research trials of 12 species from the stringybark group. This research was focused on testing a selection of durable species for survival and early growth. Unfortunately this work was curtailed due to a lack of funding.

3.2 NZFFA stringybark trials

Then in 2003-2004 the NZ Farm Forestry Association (NZFFA) established a network of eucalypt evaluation trials, funded by the Ministry for Primary Industry’s Sustainable Farming Fund. These trials were established on some 40 sites throughout New Zealand, and comprised 15 tree row plots of 10-15 species per site. These sites are still occasionally monitored, but there is no on-going formal research programme associated with them.

3.3. Lessons from Australian tree breeders

There are lessons the NZDFI can take from Australian tree breeders (Eldridge, 1993). Eldridge looked at why there are not more eucalypt plantations in New Zealand and suggested a number of reasons including (Eldridge pers. Com 1996):

- insufficient continuity of funds and staff for research
- dominance and success of radiata pine, and its ease of production across a wide range of sites, which has made eucalypts (and other species) of minor importance to the NZ forest industry
- the reluctance of NZ forest managers to recognise that eucalypts might be at least as profitable as radiata
- site/species matching and site preparation, considered generally much more important with eucalypts than with radiata pine. Eldridge was not impressed by what he saw in New Zealand
- pests and diseases – part of the problem is that eucalypt species planted have not been not well adapted to planting sites and are therefore more vulnerable to pest and disease attacks. Eldridge considered integrated pest management as essential.

In summary, numerous eucalypt species have been tested in New Zealand for solid wood production, but until the NZDFI initiative, there was never a long-term, properly planned and funded tree improvement programme to enable the full potential of the genus to be explored. Proseed and the NZDFI recognised the potential for further species and provenance testing, and this has driven the NZDFI programme forward since its inception in 2008.

4. SELECTION OF SPECIES AND SEED COLLECTION

In Marlborough, between 2003 and 2006, over 80 small research trials of 25 durable eucalypt species were established in an early research joint venture between Vineyard Timbers, the Marlborough District Council, Proseed NZ Ltd and several private local landowners.

When species were being selected for trial work, the following fundamental criteria were identified:

- high natural durability (Australian Standard Class 1 or 2)
- fast growth, straight stems
- early heartwood formation and good colour
- drought and frost tolerant
- pest tolerant
- vigorous coppice
- good nectar/pollen production for native biodiversity and bees.

Table 1 lists the species planted in the first of NZDFI's trials, all of which were located in Marlborough, the heart of New Zealand's wine industry*:*

Table 1. Durable eucalypt species first trialled by the NZDFI

Symphomyrtus	Monocalypts
Eucalyptus bosistoana	*Eucalyptus agglomerata*
Eucalyptus camaldulensis	*Eucalyptus blaxandii*
Eucalyptus cladocalyx	*Eucalyptus cameronii*
Eucalyptus maidenii	*Eucalyptus eugenoides*
Eucalyptus melliodora	*Eucalyptus fastigata*
Eucalyptus microcarpa	*Eucalyptus globoidea*
Eucalyptus moluccana	*Eucalyptus laevopinea*
Eucalyptus quadrangulata	*Eucalyptus longifolia*
Eucalyptus saligna	*Eucalyptus macrorhyncha*
Eucalyptus tereticornis	*Eucalyptus microcorys*
Eucalyptus wandoo	*Eucalyptus muelleriana*
	Eucalyptus obliqua
	Eucalyptus pilularis
	Eucalyptus youmanii

From these initial trials, and other research and knowledge of existing eucalypt stands in New Zealand, three key species were selected as the focus for tree improvement work:

- *E. bosistoana,*
- *E. globoidea,*
- *E. quadrangulata.*

Two additional species were added to the breeding programme in 2011. A small number of selections of *E. argophloia* and *E. tricarpa* established in progeny tests because of their potential to hybridise with *E. bosistoana* to introduce red timber colouring, and pest tolerance. All these species are grown in the NZDFI's network of breeding trials. In addition, a further six species have been identified as being of interest:

- *E. camaldulensis*
- *E. cladocalyx*
- *E. eugenioides*
- *E. longifolia*
- *E. macrorhyncha*
- *E. notabilis.*

These species are planted together with those mentioned above in smaller demonstration trials scattered around drier and warmer areas of New Zealand. The trials are regularly monitored to obtain information on their performance on a range of different sites.

4.1. Seed collection

The three main species selected by the NZDFI for genetic improvement have never undergone any formal domestication. Furthermore, there is very little genetic material available in New Zealand. Therefore individual family seedlots were purchased from seed providers in Australia where available; however these were very limited. Proseed contracted extensive seed collections to provide broad-based genotypes of *E. bosistoana*, *E. quadrangulata* and *E. globoidea* from across the natural range of these species. As of 2017 NZDFI has deployed ~ 180 *E. bosistoana*, ~ 150 *E. globoidea* and ~ 100 *E. quadrangulata* families in multiple breeding trials, making the programme one of the largest breeding programmes for durable timber internationally. As additional seed becomes available it will be included into the breeding programme. For example, 25 new *E. bosistoana* families were purchased in 2016, and another 30-50 families will be collected in early 2017.

E. argophloia and *E. tricarpa* have small breeding programmes in Australia and family seedlots were obtained from DPI Queensland and Forests NSW.

5. KEYS TO A SUCCESSFUL BREEDING PROGRAMME

Henson (2011) identified a number of keys to a successful breeding programme (Table 2). We believe the NZDFI breeding programme is well on the way to achieving success, based on Henson's criteria.

Table 2. Keys to success in tree breeding

Keys to breeding programme success (Henson 2011)	How achieved by the NZDFI
Focus on the client's needs – as opposed to your 15 minutes of fame	The establishment of the NZDFI has been driven by market demand and therefore focused on end products; ground-durable posts for the vineyard industry and high-stiffness veneers for LVL. NZDFI's partners represent the whole wood chain from seed producers through forest growers to wood processing and end-users. A central focus of the research is on wood properties. This will ensure that the programme will produce quality timber that meets industry specifications, an aspect often ignored in tree breeding programmes (Li & Altaner 2017, Sharma & Altaner 2017).
It is a game of numbers!	NZDFI has probably established the largest breeding populations for ground-durable timbers internationally; significantly larger than any other former NZ programme.
Take opportunities	NZDFI has made use of improved seed where this was available (e.g. *E. cladocalyx*). But for most species of interest no improved seed was available, so targeted collections from the entire natural range of the species were made. If possible seed was also purchased from seed stores and collected from the best trees already established in New Zealand. If new seed becomes available it is continually incorporated into the breeding population.
Always think of how you are going to deploy the material at the start of any tree improvement programme	From the beginning, propagation has been a core element of the NZDFI, thanks to the involvement of Proseed and other nurseries. NZDFI is pursuing several options to mass propagate improved material (Schroeder 2017) ranging from seed to clones and tissue culture (Leung 2017).
Manage the risk	NZDFI is aware of the many health risks to eucalypt plantations. Tree health is a central feature of the NZDFI research programme (Murray & Li 2017). A pest management strategy is being developed as well as screening for increased pest tolerance. The wide range of NZDFI partners and supporters ensures the programme will not falter if one player changes interest.
Always have a back-up plan – or be quick and clever enough to respond to failure	While focussing on the development of one species (*E. bosistoana*) NZDFI has another two species in breeding trials and is monitoring the potential of another six. This provides back-up options in terms of changes in product demand, tree health or growing conditions. NZDFI is also looking to develop more product options to provide a diverse market.

6. NZDFI: ACHIEVING SUCCESS BY COLLABORATION

6.1. NZDFI partners

NZDFI's success has been built on collaboration with four main partners (Table 3), who have all been active in bringing together an integrated research programme.

Table 3. NZDFI partners and areas of activity

Partner	Area of activity
Marlborough Research Centre Trust	Trial management, trial assessments and outreach programme
Proseed NZ Ltd	Seed collection, propagation, seed orchard management
New Zealand School of Forestry (University of Canterbury)	Manage a comprehensive research programme including: site-species matching; growth and yield modelling; tree health; breeding (growth, health, wood quality); wood processing.
Vineyard Timbers Ltd	Vineyard Timbers Ltd is the company of NZDFI project manager, Paul Millen

The partnership has benefitted from having a well-defined long-term strategy, innovative contributions by all key players, and consistent management since its inception by the project manager, Paul Millen.

6.2. NZDFI supporters

NZDFI benefits from having many financial supporters and landowners who host trials and contribute in other ways to the project, listed in Table 4 below:

Table 4. NZDFI supporters

AgMardt	Ministry for Business, Innovation and Employment
Callaghan Innovation	(MBIE)
Ernslaw One	Ministry for Primary Industries (MPI)
Forest Growers Levy Trust	Nelson Pine Industries Ltd
Juken NZ Ltd	NZ Farm Forestry Association
Kaingaroa Timberlands	Regional Councils
Marlborough Lines	Sumitomo
Marlborough Gold Honey	Specialty Wood Products Partnership
	30 landowners hosting trials

7. PROSEED'S INTEREST

Proseed NZ Ltd have held a long interest in the potential for eucalypts to diversify New Zealand's forestry estate. Initially, Proseed's interest went beyond the species selected by the former NZ Forest Service for their special purpose species programme, launched in the late 1970s. Rather, the company wanted to evaluate if there were other eucalypt species that had already been proven by farm foresters to be well-adapted to New Zealand conditions. In addition to managing all the seed collection for the NZDFI programme and supporting the programme in other ways, Proseed has recently invested in a new propagation facility at their Amberley site, North Canterbury. This facility has enabled a start on eucalypt propagation including grafting, clonal production research, and experimentation with hydroponics (Schroeder 2017).

8. CURRENT STATUS OF NZDFI

Amongst the NZDFI's achievements since its inception in 2008, we have some major milestones.

- Establishment of breeding trials: 150,000-plus individual trees from five species in 23 breeding trials at 10 properties in four regions (Marlborough, Wairarapa, Hawkes Bay, Gisborne).
- Establishment of demonstration trials: 40,000 trees with up to 11 species in demonstration trials on 25 sites in seven regions.
- First seed from *E. globoidea* Waikakaho seed stand available 2014.
- First selections of *E. bosistoana* for growth and form grafted for clonal seed orchard (2014). Seedling seed orchards of other species.
- Propagation facility built at Amberley (2014).

8.1. Planting durable eucalypts is increasing

The interest in planting durable eucalypts is increasing with some forest growers having already planted commercial blocks so as to establish a forest resource for processing as soon as possible. The most accurate way to gauge the uptake of durable eucalypts is to analyse nursery sales by species (Figure 1). In 2015 the estimated total durable eucalypt seedlings sold by nurseries was over 500,000, and in 2016, over 680,000 - a significant increase from earlier years.

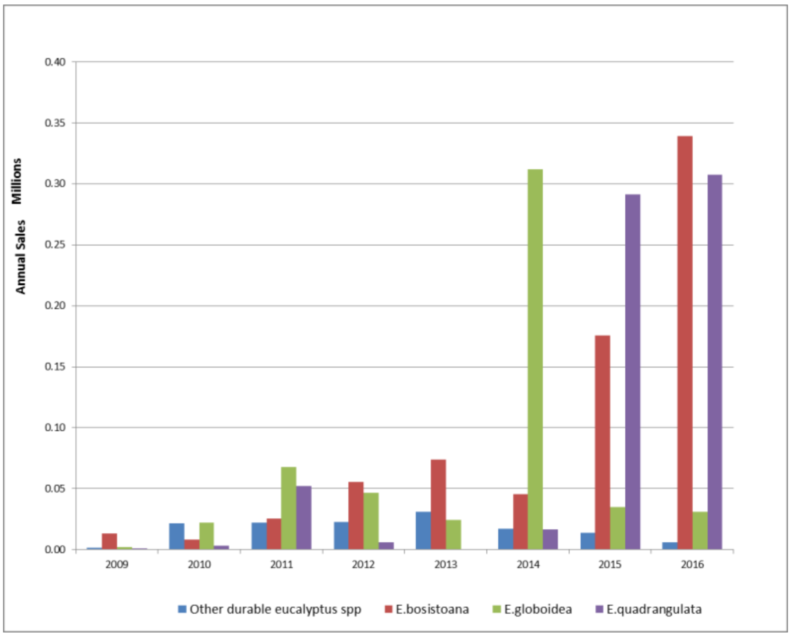

Figure 1. Annual nursery sales of durable eucalyptus seedlings by species.

9. BRANDING NZDFI GERMPLASM

NZDFI's partners have developed a strategy that could make it possible for branding the quality of germplasm so that there is the opportunity of traceability in future markets. To this end the XyloGene trademark (Figure 2) has been registered with the International Property Office of New Zealand.

Figure 2. The XyloGene brand.

This trademark will likely be used for more than seed and seedlings. The forests where our trees are planted can be certified allowing the brand to be tracked from the forest to the timber produced, and used to identify and differentiate all products including posts, poles and sawn timber.

10. HEALTH RISKS

On a final note, pest and disease for eucalypts have come more into public view with the recent arrival of myrtle rust (*Austropuccinia psidii*) and a new defoliating beetle (*Paropsisterna varicollis*) in New Zealand. Eucalypt growers in New Zealand have to accept that there are numerous pests and diseases, either already present in the country, or at risk of arriving from overseas, which could affect their crop because of the lack of natural predators. This is not unique to eucalypts and applies to almost all agricultural crops. Eucalyptus pests and diseases need to managed, and have been successfully managed in the past (Wardlaw 2017).

Eucalyptus Variegated Beetle (*P. varicollis)* is a serious potential threat to eucalypts in New Zealand (Lin et al., In press). Research on the impacts of this beetle is underway as part of the NZDFI research programme. However, the current experience does not suggest that the threat is worse than that of another eucalyptus defoliator *Paropsis charybdis* (Eucalyptus Tortoise Beetle) which has been in New Zealand for a century.

Myrtle rust has recently arrived from Australia. Experience from Australia with this disease suggests that it can be successfully managed. It is restricted to certain climatic conditions and it has been shown that more resistant genotypes within eucalyptus families exist (Potts et al., 2016).

The implications of these diseases are not yet known, but NZDFI and Proseed will be keeping a close eye on their reported spread. Work to establish an integrated pest management programme has begun, as has the search for more pest tolerant genotypes (Murray & Lin 2017).

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12. AFFILIATIONS

Shaf van Ballekom is Managing Director, Proseed NZ Ltd, Canterbury, New Zealand. Shaf is also Chairman of the NZDFI. Paul Millen is Project Manager of the NZDFI and co-owner of Vineyard Timbers Ltd.

S. SALEKIN, J. MORGENROTH AND E. MASON

SITE CHARACTERISATION AND GROWTH MODELLING FOR DURABLE EUCALYPTS

A case study in Marlborough, New Zealand

Abstract Effective site-species matching for eucalypts requires a greater understanding of the effects of environmental micro-site variation on growth. This case study demonstrates the high levels of topographic, climatic, and edaphic variability that exist within a single study site. Differences in height growth for five year old *Eucalyptus globoidea* are described by a juvenile mensurational height model. The model has a better fit at the plot scale, rather than the study site scale, implying that environmental micro-site variability is influencing growth within the study site. Future work will augment the mensurational model with topographic, climatic, and edaphic independent variables, to better understand the drivers of growth at the micro-site scale.

1. SITE VARIABILITY AND NEW ZEALAND'S PLANTED FORESTS

New Zealand's planted forests are generally grown on land that is unsuitable for pastoral agriculture (Millner, 2006). Much of this low value land is found in hill country which, because of its heterogeneity, results in variable production within the stand (Apiolaza et al., 2011; Millner & Kemp, 2012). Hill country comprises a mosaic of microsites with varying topographic, climatic and edaphic factors including aspect and slope (topographic), temperature and precipitation (climatic), and soil depth and water holding capacity (edaphic) (see, Gillingham & During, 1973; Lambert & Roberts, 1976, 1978; Radcliffe & Lefever, 1981). Such heterogeneity has resulted in variable growth and survival of juvenile trees in New Zealand (Bathgate et al., 1993) and overseas (Ares & Marlats, 1995; Larson et al., 2008), but this response is species-specific.

Radiata pine (*Pinus radiata* D. Don) is widely planted throughout NZ and is not generally affected by environmental variability at microsite scale. Exceptions to this exist, whereby reductions in growth have been reported under extreme conditions, such as high altitude or low rainfall zones (Kirschbaum et al., 2011). Where radiata pine productivity is limited by environmental conditions, other species may be more suitable. For example, *Eucalyptus globoidea*, the subject of this paper, is better suited to dry environments. But, the growth of this species has been observed to vary widely within a site, due to environmental heterogeneity (Figure 1). Though eucalypts are not currently widely planted in New Zealand (Apiolaza et al., 2011), there is potential for the stocked area to increase with a greater understanding of their growth potential and survival on a variety of sites.

Figure 1. Variation in the growth of Eucalyptus globoidea *at the study site. Tree height was modelled as a function of micro-site environmental conditions to better understand the drivers of growth. Photo: Serajis Salekin.*

2. SITE-SPECIES MATCHING

Though eucalypts have the potential to thrive in dryland sites, it is critical to match individual species to appropriate sites in order to maximise productivity and other desirable traits (e.g. wood quality) and minimise risk. Site-species matching provides direct benefits, including successful forest establishment, improved tree health and optimal productivity, as well as, indirect ecological benefits such as increasing species diversity.

A first step in site-species matching with eucalypts has been undertaken, with siting maps available for 16 different *Eucalyptus* species (Gordon, 2013). These maps provide an understanding of potential *Eucalyptus* spp. suitability at a regional scale. Unfortunately, the resolution of these maps is limited by coarse input data resolution, which prevents their use in an operational setting. Given the sensitivity of some eucalypts to micro-site variation (Figure 1), it is unlikely that a coarse-scale approach will provide growers with the knowledge necessary to plant eucalypts with confidence.

2.1 Environmental data availability

Past efforts to optimise site-species matching have been hampered by poor data availability and, where data is available, both spatially and temporally coarse data resolution. Soil descriptions are available nationwide from the Fundamental Soil Layers (FSL), which map 16 soil properties at a coarse 1:50,000 scale. This corresponds to a raster with a spatial resolution of 25 m (Tobler, 1988) and a minimum mapping unit of 0.0625 hectares. The FSL is progressively being replaced by S-map, which is purported to provide more reliable soil descriptions. However, current coverage is very limited outside of historically productive agricultural areas, where most forest plantations are established. Climate data are similarly limiting. The best climate data available nationally is NIWA's Virtual Climate Station Network (VCSN), which has a temporal resolution of 1 day, but a spatial resolution of only 5 km, and a minimum mapping unit of 2,500 hectares. The accuracy of VCSN estimates has been found to vary across different climatic factors, with temperature estimates being better than precipitation and relative humidity (Mason et al. 2017). Nationally available topographic data is limited to the 1:50,000 contours (NZTopo50 series) and the 25 m resolution digital elevation model (DEM) derived by Landcare Research, or the peer-reviewed 15 m resolution digital elevation model (Columbus et al., 2011). Even the 15 m resolution DEM results in a minimum mapping unit of 0.0225 hectares, which assumes no changes in topography within that area. Such coarse scale environmental data is best used in regional or national scale site-species mapping and cannot be used to meet stakeholder objectives of fine-scale site-species matching.

3. RESEARCH OBJECTIVES

This paper describes a part of a research programme aimed at matching durable eucalypts to dryland sites in NZ. The research endeavours to incorporate micro-site description into site-species matching to better understand the drivers of *Eucalyptus* growth on a variety of sites. In so doing, the research will optimise eucalypt productivity, while minimising risk. This paper presents a case study to demonstrate the potential benefits of micro-site characterisation for site-species matching.

4. METHODS

4.1 Study site

The study site covers an area of 6.3 ha and is located in Marlborough, NZ (1693300 E, 5378850 N New Zealand Transverse Mercator projection). It comprises 289 plots planted in 2011 with 36 *Eucalyptus globoidea* seedlings of known genetics on a grid with 1.8 m between rows and 2.4 m between columns (Figure 2).

4.2 Data collection

4.2.1 Topographic data

A digital elevation model (DEM) for the site was produced using a survey grade global navigation satellite system (GNSS). GNSS points were established on an approximately regular 5 m grid across the study site and were subsequently interpolated into a DEM. Different interpolation method and resolutions were tested to optimise the DEM accuracy (Figure 3). The focal statistics tool was applied over the candidate DEMs to remove interpolation artefacts, thereby rendering a smoother surface.

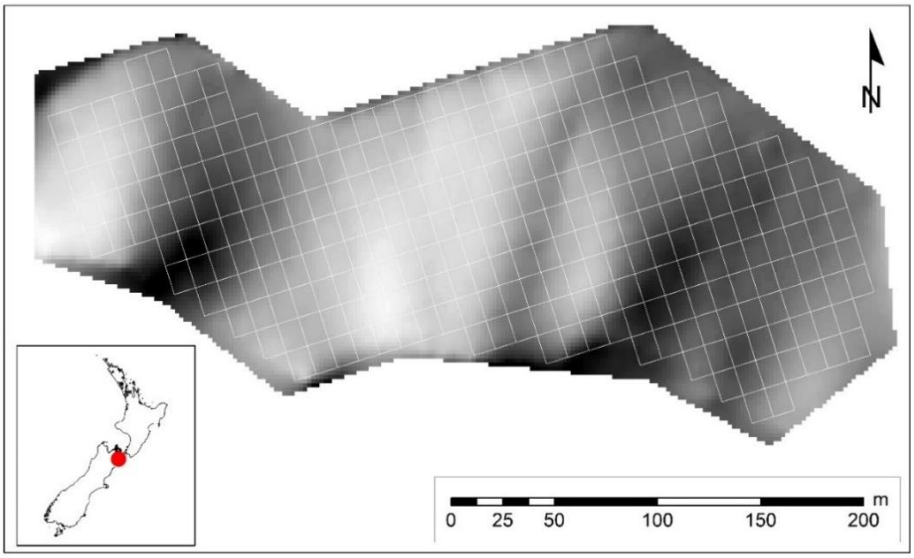

Figure 2. A hillshade model of the study site. Inset map shows approximate location of the study site within New Zealand. White boundaries show plot boundaries within study site.

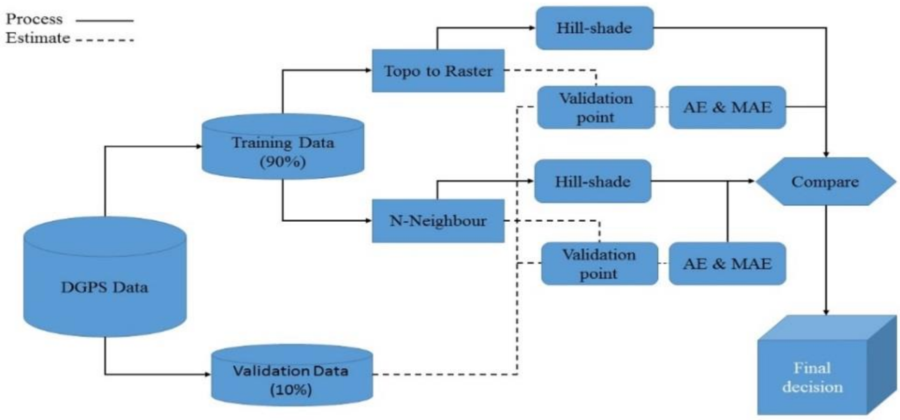

Figure 3. Example workflow for producing a candidate DEM. N-Neighbour: natural neighbour; AE Absolute error; MAE: Mean absolute error.

Absolute error (AE) (Eq 1), Sum of absolute error (SAE) (Eq 2) and Mean absolute error (MAE) (Eq 3) were calculated for candidate DEMs with differing spatial resolutions.

$$AE = X_{interpolated} - X_{measured} \tag{1}$$
$$SAE = \sum_{i=1}^{n} AE \tag{2}$$
$$MAE = \frac{1}{n}\sum_{i=1}^{n} |X_i - X| \tag{3}$$

Where, X = Elevation and n = Number of observations.

The accuracy of candidate DEMs was tested using a leave-one-out cross-validation technique, whereby 90% of GNSS points were used to interpolate the DEM and 10% of GNSS points were used to validate the DEM. The best combination of interpolation method and resolution yielded a DEM with minimal quantitative and qualitative error.

Next, various surfaces were derived from the DEM. These surfaces included slope, aspect, curvature, wetness index, topographic exposure and roughness. Roughness was calculated by following Jenness (2004). All other topographic analyses and calculations were realised using existing tools in ArcGIS (ESRI, 2012) or System for Automated Geoscientific Analysis (SAGA) (Conrad et al., 2015).

4.2.2 Soil data

The study site was stratified by aspect and slope. A total of 12 soil pit locations were distributed throughout the aspect/slope strata. Soil pits were excavated with a small digger and soil samples were collected from each pit. The physical properties of soil samples and pits were described according to Gradwell (1972). In addition, soil profile depth, rooting depth, and soil permeability were measured for each pit. Moreover, samples from these pits were tested at Lincoln University soil physics lab to assess the moisture retention characteristics of the soil at different horizon depths, which further extended to calculate the root available water (RAW) (Allen, Pereira, Raes, & Smith, 1998). Soil moisture was also recorded with HOBO soil moisture logging systems (Onset Computer Corporation, Bourne, MA, USA) within each strata. Each of the loggers is equipped with three sensors installed at 20 cm soil depth and set at recording intervals of 30 minutes for data logging.

In addition to physical analysis, the top 10 cm of soil was sampled at each pit location for chemical analysis. Chemical analysis included Calcium (Ca), Magnesium (Mg), Sodium (Na), Potassium (K), Cation exchange capacity (CEC), pH, Total Carbon (C), Total Phosphate (P), Total Nitrogen (N), Potentially Available Nitrogen (N), Carbon and Nitrogen ratio (C/N). The chemical analyses were undertaken by Hill Laboratories (Hamilton, New Zealand) following their standard procedures.

4.2.3 Climatic data

Climatic data for the study come from a variety of sources. An independent meteorological station was established at the study site. The station was equipped with radiation, temperature, and moisture loggers, as well as wind and rain sensors. Moreover, the study site was equipped with an additional 10 temperature sensors and 12 soil moisture sensors to measure variation across all aspects and slopes. All data were collected at 30-minute intervals. In addition to this site-specific data, climate data were obtained from the virtual climatic station network (VCSN, New Zealand National Institute of Water and Atmospheric Research). The VCSN estimates daily rainfall, potential evapotranspiration, air and vapour pressure, maximum and minimum air temperature, soil temperature, relative humidity, solar radiation, wind speed and soil moisture on a regular (~ 5 km) grid covering the whole of New Zealand. The estimates are produced daily, based on the spatial interpolation of actual data observations made at climate stations located around the country (NIWA, 2015).

4.2.4 Tree data

There were 10,404 *E. globoidea* planted at the study site. Height (h), diameter at breast height (DBH), and tree status (dead or alive) was assessed for each tree. All trees were measured in each of the following measurement periods: February 2012, January 2016, and December 2016.

5. DATA ANALYSIS

5.1 Data preparation

Mean heights of trees were calculated for each plot at each measurement age, and these means were used for all modelling. Prior to averaging graphical operations were undertaken to check tree growth data for normality and outliers. Trees noted as damaged or abnormal were excluded from the modelling dataset.

5.2 Height yield model

Modelling was undertaken to understand the relationship between tree growth and micro-site conditions. Since Curtis (1972), stand-level and individual tree growth and yield models have been well explored (Clutter & Allison, 1974; Ek, 1974; Garcia, 1984; Monserud, 1984). Generally, growth and yield models are developed for mature stands, which means the competition among trees is well defined (Zhang et al., 1996). Juvenile tree yield has not been modelled and reported in as much depth (Avila, 1993; Mason & Whyte, 1997). Growth and yield models exploit the fact that starting stand dimensions (e.g., height, diameter, volume of trees etc.) indicate site quality; modelling juvenile yield is more complex, because starting stand dimensions do not reflect site quality (Mason & Whyte, 1997; Zhang et al., 1996). However, juvenile stand yield has been found to have an exponential relationship with time (Eq 4). This is a widely used model for juvenile stands (Belli & Ek, 1988; Mason & Whyte, 1997). Moreover, as shown by Mason & Whyte (1997) the coefficients can be extended as linear functions (Eq 5 & 6) to include several independent variables and their interactions. The study described here examines the simple fits of the model described in Eq. 4 to overall data and also to individual plots within the study site.

$$H_T = H_0 + \alpha T^{\beta} \quad (4)$$
$$\alpha = \alpha_0 + \alpha_1 V_1 + \cdots + \alpha_n V_n \quad (5)$$
$$\beta = \beta_0 + \beta_1 V_1 + \cdots + \beta_n V_n \quad (6)$$

Where, H_T = Height at given age, H_0 = Initial height, T = Age, α & β = Coefficients and $V_1 \ldots V_n$ = Independent variables.

6. RESULTS AND DISCUSSION

6.1 Topographic description

A large number of candidate DEMs were produced using a range of interpolation methods and resolutions (Figure 3). The optimal DEM was interpolated using a natural neighbour interpolation with a 0.5 m spatial resolution. Though finer spatial resolutions yielded lower absolute error and mean absolute error upon validation (Table 1), the resulting DEMs were deemed inappropriate based on evidence of interpolation artefacts during visual assessment. The resolution of 0.5 m was both quantitatively and qualitatively satisfactory.

Table 1. Comparison between two methods of interpolation at different resolutions. SAE: Sum of absolute error; MAE: Mean absolute error.

RESOLUTION	**TOPO-RASTER**		**NATURAL NEIGHBOUR**	
(m)	**SAE**	**MAE**	**SAE**	**MAE**
0.1	55.038	0.195	38.168	0.138
0.2	56.075	0.199	38.780	0.140
0.3	55.140	0.196	39.026	0.142
0.4	57.498	0.204	39.026	0.142
0.5	**55.721**	**0.198**	**40.366**	**0.146**
0.6	60.015	0.213	44.688	0.162
0.7	58.796	0.208	43.728	0.158
0.8	61.045	0.216	44.688	0.162

The DEM was used to produce a variety of other surfaces representing slope, aspect, landscape curvature and roughness, exposure, and soil wetness (Figure 4). Values extracted from these surfaces were used as candidate explanatory factors when modelling growth as a function of micro-site variation.

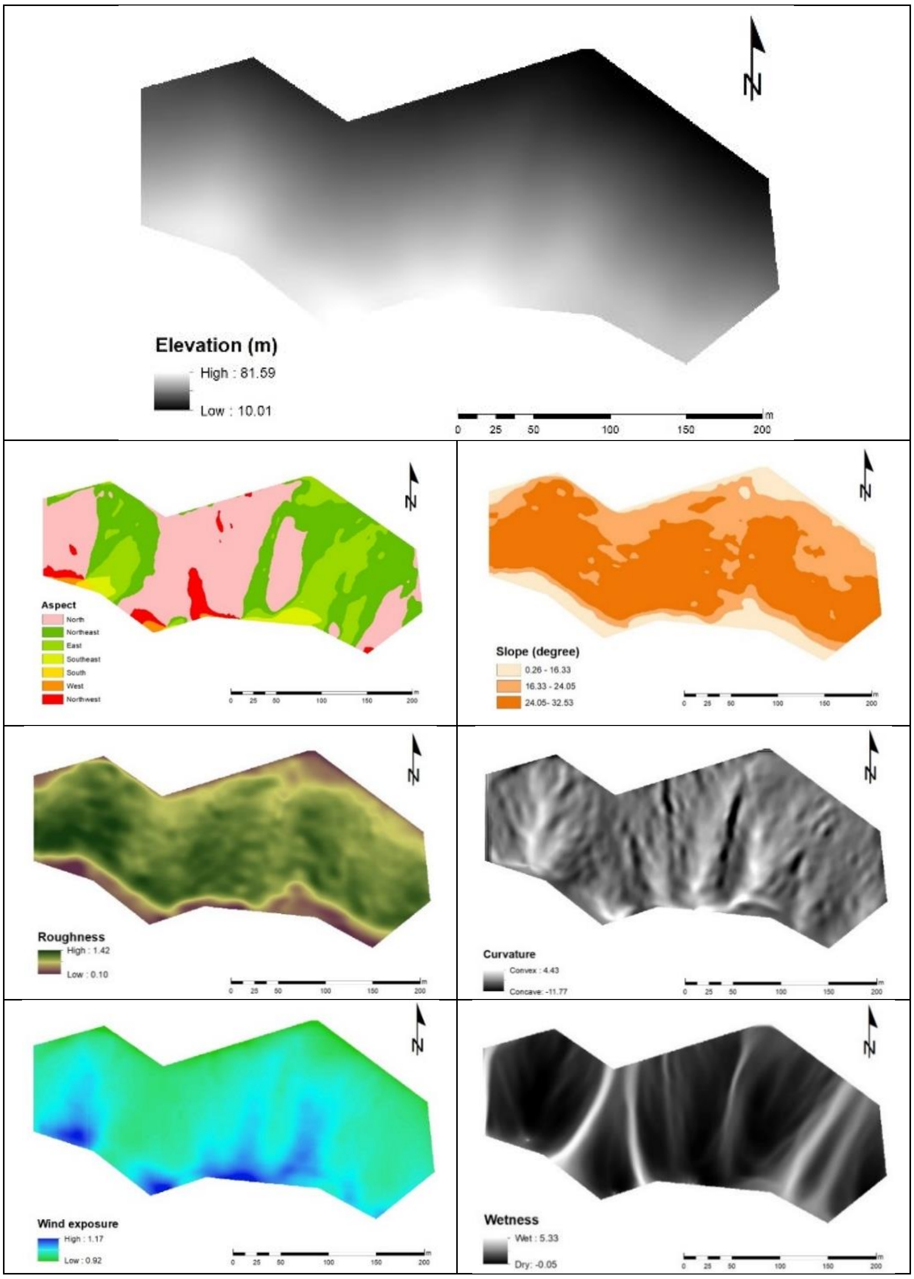

Figure 4. The optimised DEM (top) was used to derive various other surfaces, including aspect, slope, roughness, curvature, wind exposure, and wetness.

6.2 Climatic description

Climatic variables are highly variable between sites in New Zealand, but variation also exists at local scales within a site. At the study site, air temperature was measured at 10 locations and summarised in Table 2. Mean maximum monthly temperature ranged from 19.51 to 23.29 °C, while mean minimum monthly temperature ranged from 7.2 to 8.78 °C.

Table 2. Mean monthly temperature within the study site.

Logger	**Temperature**	**Statistics (Monthly)**				
		Obs. No.	*Max* °C	*Min* °C	*Mean* °C	*St. Dev* °C
1	Maximum	35,422	37.00	6.50	21.60	5.98
	Minimum	35,422	20.00	-4.00	7.20	4.93
2	Maximum	35,422	36.50	6.50	21.06	5.64
	Minimum	35,422	22.00	-2.00	8.23	4.38
3	Maximum	35,423	39.00	7.50	23.29	5.81
	Minimum	35,423	20.00	-3.00	7.53	4.69
4	Maximum	35,423	37.00	7.00	22.71	5.98
	Minimum	35,423	20.00	-3.50	7.49	4.75
5	Maximum	35,422	36.50	8.00	22.93	5.40
	Minimum	35,422	20.00	-2.00	7.93	4.56
6	Maximum	35,422	38.00	7.00	22.47	5.74
	Minimum	35,422	20.00	-3.50	7.33	4.79
7	Maximum	35,421	37.00	8.00	22.24	5.50
	Minimum	35,421	20.00	-1.50	8.23	4.42
8	Maximum	35,421	34.50	7.00	21.17	5.11
	Minimum	35,421	20.50	-2.00	8.27	4.35
9	Maximum	35,421	37.50	7.50	22.14	5.34
	Minimum	35,421	20.00	-1.50	8.14	4.42
10	Maximum	35,420	34.50	5.00	19.51	5.63
	Minimum	35,420	20.00	-1.00	8.78	4.23

6.3 Soil description

As with climatic variables, soil variables were highly variable within the study site (Table 3). Three soil textures were recorded: silt loam, clay loam, and clay. Rooting depth ranged from 49 cm to more than 100 cm. The bulk density and porosity of the soil differed within the site and also with soil depth. The maximum bulk density was 2.09 g cm^{-3}, while the minimum was 1.32 g cm^{-3}. Porosity ranged from a low of 11% to a high of 63%.

Table 3. Soil physical characteristics within the study site.

Pit No.	Horizon	Horizon Thickness (cm)	Texture	Rooting depth (cm)	B. Density (g cm^{-3})		Porosity (%)	
					Mean Bd	*St.Dev*	*Mean Pr*	*St.Dev*
1	A	20	Silt loam	90	1.78	0.03	24	1
	B1	12	Clay loam		2.09	0.43	11	18
	B2	13	Clay		1.72	0.34	27	14
	B3	45	Clay		1.84	0.25	22	11
2	A	25	Silt loam	59	1.46	0.03	38	1
	B1	15	Clay loam		1.68	0.08	28	3
	B2	19	Clay		1.32	0.10	44	4
	B3	27	Clay		1.78	0.00	24	0
3	A	10	Clay loam	86	1.52	0.00	35	0
	B1	11	Clay loam		1.51	0.04	35	1
	B2	30	Clay		1.74	0.02	26	1
	B3	35	Clay		1.51	0.06	35	2
4	A	21.5	Silt loam	100	1.63	0.03	30	1
	B1	13.5	Clay loam		1.76	0.02	25	1
	B2	17	Clay		1.76	0.05	25	2
	B3	48	Clay		1.59	0.40	34	17
5	A	20	Clay loam	52	1.64	0.04	30	1
	B1	32	Clay		1.83	0.03	22	1
	B2	48	Clay		1.85	0.02	21	1
6	A	28	Silt loam	89	1.44	0.04	38	2
	B1	28	Clay loam		1.71	0.02	27	1
	B2	33	Clay		1.83	0.01	22	0
	B3	11	Clay		1.86	0.01	20	0
7	A	35.5	Clay loam	67	1.36	0.12	41	5
	B1	31.5	Clay loam		1.53	0.29	35	12
	B2	17.5	Clay		1.68	0.00	28	0
	B3	15.5	Clay		1.69	0.03	28	1
8	A	31	Silt loam	80	1.60	0.02	32	1
	B1	14	Clay loam		1.66	0.02	29	1
	B2	22	Clay		1.67	0.08	28	3
	B3	33	Clay		1.83	0.01	22	0
9	A	28	Clay loam	85	1.50	0.06	63	2
	B1	23	Clay loam		1.72	0.03	27	1
	B2	34	Clay		1.82	0.02	22	1
	B3	15	Clay		1.74	0.13	26	5
10	A	24	Clay loam	80	1.52	0.19	35	8
	B1	29	Clay loam		1.70	0.07	28	3
	B2	27	Clay		-	-	-	-
	B3	20	Clay		1.77	0.02	25	1
11	A	29.5	Clay loam	49	1.65	0.04	29	2
	B1	19.5	Clay		1.77	0.01	24	0
	B2	29	Clay		1.78	0.02	24	1
	B3	22	Clay		1.82	0.04	22	2
12	A	19	Clay loam	83	1.38	0.09	41	4
	B1	29	Clay		1.69	0.04	28	1
	B2	35	Clay		-	-	-	-
	B3	17	Clay		1.82	0.02	22	1

6.4 Tree height over time

Figure 5 shows a trajectory of the height of *E. globoidea* over time at different plots within the study site. As trees age, the variation in tree height increases. Plot-level mean height ranges from less than 0.5 m to more than 3 m at age 5 years.

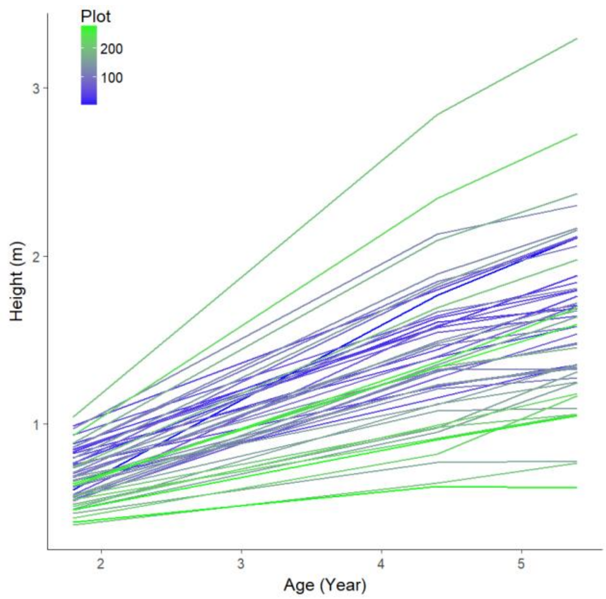

Figure 5. E. globoidea *height over time for different plots within the study site.*

6.5 Mensurational height yield model

The mensurational model (Eq. 4) for height was fitted for *E. globoidea* at the study site. A residual analysis of the model including all site data indicated that the error ranged from approximately -1 – 2 m (Figure 6). However, at the plot level, the model prediction is better than the overall fit, with residuals ranging from approximately -0.2 – 0.3 m (Figure 6). This implies that the mensurational model predicts height more accurately at the plot level, rather than at the site level.

The mensurational model developed here (Eq. 4) represents the mathematical relationship between tree height and time. The mensurational models do not yield information about the underlying processes leading to variation in growth. However, it is evident that there are external factors which are playing a vital role in the growth of the trees at the early stages (Figure 5). It is necessary to identify and model those variables for precise prediction. An example of the impact of micro-site variables on growth can be seen in Figure 7, where height is modelled as a function of local topographic curvature. Evidently, height growth is suppressed in micro-sites with convex local topography. Future work will augment the mensurational model with topographic, climatic, and edaphic independent variables, to better understand the drivers of growth within a site.

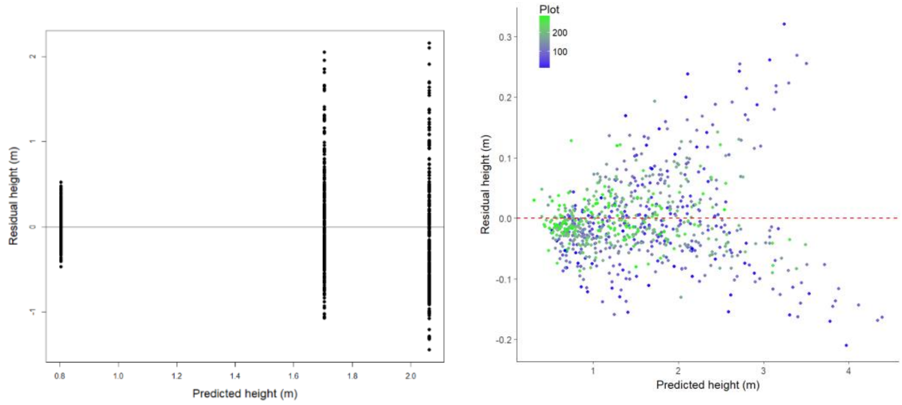

Figure 6. Residual plots from mensurational model for E. globoidea *at the study site. Overall residuals (left) and plot level residuals (right) are shown.*

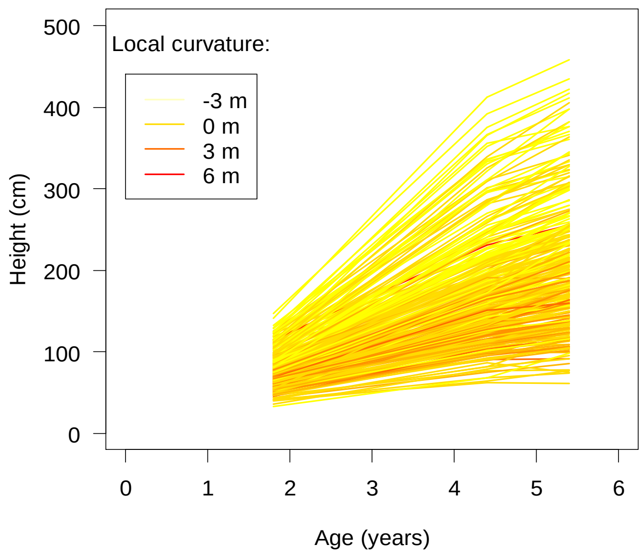

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Figure 7. Height growth of E. globoidea *as a function of time and topographic curvature. Positive curvature represents convex topography, negative curvature represents concave topography. Height growth appears to be greater on concave topography.*

7. CONCLUSION

The environmental variability present throughout New Zealand influences the growth and survival of trees. The regional suitability of sites for growing some eucalypts has previously been demonstrated (Gordon, 2013). Microsite research takes the next step by exploring the effects of local environmental variability on eucalypt growth and survival; this is a necessary step in effective site-species matching. This case study has demonstrated the environmental variability that exists within a single study site. Topographic, climatic, and edaphic characteristics varied substantially within the study site. The height growth data, which ranged from 0.5 m to more than 3 m at age 5 years, highlights the local environmental influence on growth. The mensurational height growth model had a better fit at the plot level than at the site level, further supporting an environmental micro-site effect on growth. Future work will augment the mensurational model with topographic, climatic, and edaphic independent variables, to explain the drivers of growth within a site.

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MANAGING THE HEALTH OF PLANTATION EUCALYPTS IN TASMANIA

Abstract Tasmania's eucalypt plantation estate of 240,000 ha of *Eucalyptus nitens* and *E. globulus* has matured and is progressively transitioning into its second rotation. The main established (mostly native) pest and disease threats to the plantation estate are well known and the threat profile is stable. Importantly, all stages of plantation development through the first rotation have been exposed to these pest and disease threats. Pest-specific integrated pest management is used to protect plantations from the two most prevalent and damaging pest groups – native marsupial browsers and Chrysomelid leaf beetles. Pest-specific management is not used for the less prevalent pests and diseases. However, periodically damaging outbreaks / epidemics of these less prevalent pests and diseases when they occur, are either managed reactively upon detection (for example autumn gum moth), or their impacts are tolerated (for example fungal leaf diseases). Current practices for the management of these pest and disease threats are reviewed and the outcomes of management are evaluated.

1. INTRODUCTION

Tasmania's *Eucalyptus* plantation estate of approximately 240,000 ha was largely established over the past two decades (Downham and Gavran, 2017). The great majority of that estate (approximately 170,000 ha) is privately owned, mainly by major industrial growers, and is currently managed with minimum silvicultural intervention on relatively short (15 to 20-year) rotations for fibre production. This portion of the estate is progressively transitioning into second rotation. A smaller area (about 25,000), primarily on public forest land, is managed for solid wood production on a 25 to 35-year rotation with more intensive silvicultural intervention involving pruning (to 6 metres) and mid-rotation thinning done in one or two stages. This portion of the estate will start transitioning into second rotation in the next few years.

Eucalyptus nitens and *E. globulus* are the dominant species grown in the Tasmanian estate, with the former species predominating (> 80% of the estate). The primary reasons *E. nitens* is favoured are because of its greater cold-tolerance (Volker et al., 1994) and resistance to Mycosphaerella (= Teratosphaeria) leaf disease (Mohammed et al., 2003) caused by a suite of *Teratosphaeria* species, particularly *T. pseudonubilosa* (Pérez et al., 2013). The main current pest and disease threats to the plantation estate have been characterised (de Little et al., 2008; Wardlaw, 2010). That threat profile is relatively stable (Grimbacher et al., 2011) but may evolve with the establishment of exotic pests, notably myrtle rust (Carnegie et al., 2010), or with climate change (Pinkard et al., (in review)).

The approach to managing the main pest and disease threats of plantations on public forest lands is based on their prevalence. Management of less common, but sometimes damaging pests, relies on their detection during annual forest health surveillance triggering, where appropriate, event-specific responses. Pest-specific management programs are used for those pests and pathogens that are most prevalent and threaten large areas of the plantation estate (Wardlaw, 2008). Pest-specific management is currently used to control the two most prevalent pests; Chrysomelid leaf beetles and native marsupial browsers (brush-tail possum, Bennett's wallaby and Tasmanian pademelon) (Figure 1). For both groups of pests, strategies based on integrated pest management (IPM) have been developed and are well-established operationally. This paper documents the IPM strategies for chrysomelids and browsing mammals that have been developed and adopted by Forestry Tasmania, and briefly details management issues relating to other, less prevalent, pest and pathogen threats.

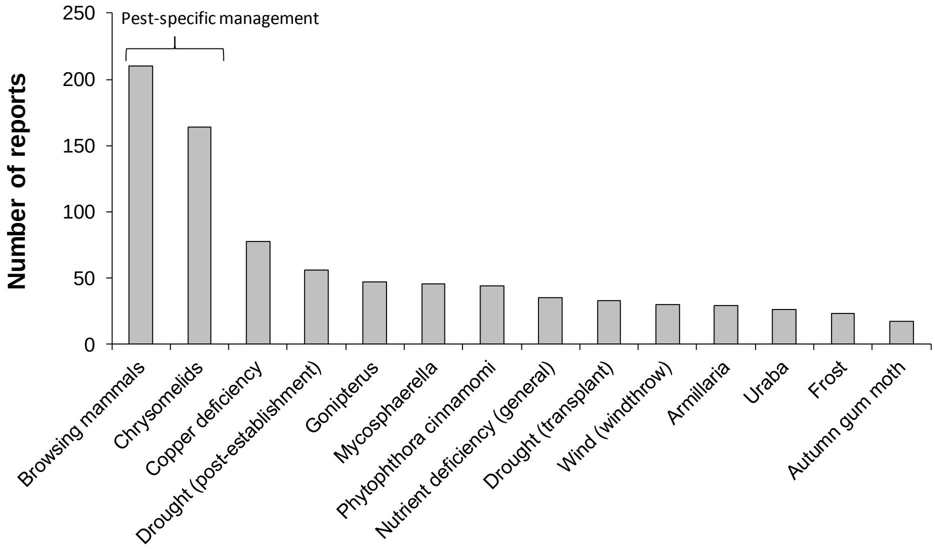

Figure 1. Prevalence of health problems detected in eucalypt plantations on public forest land in Tasmania. Data from Forestry Tasmania's forest health surveillance records 1998-2009.

2. MAMMAL BROWSING IPM

Browsing by native marsupial herbivores threaten young plantations during the first 1-2 years after planting. Severe damage can destroy the plantation to the extent that replanting is required (Walsh and Wardlaw, 2011), while moderate levels of browsing damage depresses growth and causes multiple stems (Borzak et al., 2015; Bulinski and McArthur, 1999). Historically, plantations were protected from severe browsing damage using the poison 1080. The use of 1080 to control browsing mammals in plantations on public forest land in Tasmania ceased after 2005 (Walsh and Wardlaw, 2011), while use in privately-owned plantations was greatly reduced following tightening of conditions under which permits to use 1080 would be issued. In response, shooting, and to a lesser extent trapping, have replaced the use of 1080 as the primary tool used by plantation owners to protect young plantations from damage by browsing mammals in the past decade.

Reducing browsing pressure by shooting and trapping can be expensive, particularly in situations where trees are slower to establish and grow to a "safe" height (about 1 m) that puts them out of reach of the browsers. It is also socially controversial given the target pest species are all native species. Because of this there has been much research to evaluate non-lethal controls to reduce reliance on culling. The three most-tested non-lethal options are seedling repellents (Miller et al., 2008), seedling stockings (Miller et al., 2009) and less palatable seedlings, either through selecting genotypes with higher levels of secondary metabolites in the foliage (O'Reilly-Wapstra et al., 2004) or through manipulation of fertiliser regimes (O'Reilly-Wapstra et al., 2005) in the nursery to harden seedlings. Of these non-lethal tactics, seedling stockings (Figure 2) show the most promise for protecting seedlings from browsing during the initial 12-month period after planting (Miller et al., 2009) and have been widely adopted operationally by plantation growers.

Figure 2. Seedling stockings used to protect seedlings from damage by browsing mammals during the initial post-planting period.

The combination of lethal (shooting and trapping) and non-lethal (seedling stockings) tactics for browsing management is the current approach to integrated pest management used by the eucalypt plantation owners in Tasmania. Regular monitoring of browsing damage and seedling growth is routinely conducted to guide the intensity and duration of culling done in the period after planting and through until the seedlings have reached the safe height of 1 metre (Figure 3).

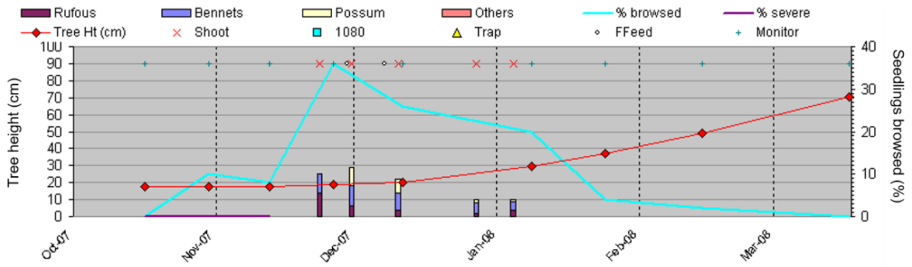

Figure 3. Screen-capture of the graphical output from the Browsing Management Database used by Forestry Tasmania (now Sustainable Timber Tasmania) to monitor seedling growth (red line), browsing damage (blue line) and coordinate culling events (red crosses).

An evaluation of this mammal browsing IPM done on publicly-owned plantations in 2007-08 found that the combination of seedling stockings with shooting / trapping reduced the duration and intensity of post-planting culling (and therefore cost) in low-altitude plantations that rapidly reached safe height within the first growing season. However, in plantations at higher altitude that establish more slowly, a higher browsing risk was assumed and seedling stockings were used to provide additional protection rather than to reduce the intensity of post-plant culling (Tim Wardlaw, unpublished data). This conservative approach to assessing browsing risk on slower-to-establish sites was used because attempts to more objectively assess site browsing-risk as a means of guiding culling intensity have thus far failed (Walsh and Wardlaw, 2011). While the current browsing IPM is effective in protecting young eucalypt plantations from unacceptable browsing damage it is perceived to be very costly. A recent meeting of plantation managers identified a pressing need to do a further evaluation of the IPM to better understand how the tactics are being used and identify the most cost-effective approaches.

3. CHRYSOMELID LEAF BEETLE IPM

The need to manage Chrysomelid leaf beetles in Tasmania, particularly *Paropsisterna bimaculata*, was recognised nearly two decades before the major period of eucalypt plantation establishment commenced (Carnegie et al., 2017). Elliott et al. (1992) described the initial leaf beetle IPM that was adopted by Forestry Tasmania. A similar IPM was used by the other major eucalypt plantation owner at the time, Associated Pulp and Paper Mills (de Little, 1989). The key elements of these early IPMs were: (i) knowledge of the life history of *P. bimaculata* (de Little, 1983) and its natural enemies (de Little, 1982; de Little et al., 1990; Elliott and de Little, 1980); (ii) knowledge of the relationship between egg and larval populations of *P. bimaculata* and the severity of defoliation (Elliott et al., 1992); (iii) knowledge of the impact of defoliation on tree growth (Candy et al., 1992); and, (iv) evidence of the effectiveness of insecticide application in reducing larval populations of *P. bimaculata* (Elliott et al., 1992).

Operationally, this knowledge translated to an IPM that involved regular monitoring of plantations to coincide with the key life history stages of *P. bimaculata* (Figure 4). This IPM was used in young (2-6 years old) plantations where trees were still sufficiently small to sample for leaf beetle egg populations. Monitoring commences in late-spring, when the beetles start laying eggs after emerging from overwintering, and concludes in late-summer, when there is no further egg-laying by that generation of beetles – *P. bimaculata* generally only has one generation per season (de Little, 1983). Plantations are re-monitored fortnightly during this period. This is sufficient time for eggs detected in the previous monitoring period to hatch and the larvae progress no further than their second instar of development (de Little et al., 1990). Those first two instars cause little defoliation compared with the later larval instars (Baker et al., 2002; Greaves, 1966) but are at the part of their life cycle where most predation by natural enemies occurs (de Little et al., 1990). Thus, there is a sufficient window of time between monitoring visits to commence planning for a spray operation but only proceed with spraying if the second monitoring finds the initial egg population has not been reduced sufficiently by natural controls, such as predation or weather events such as strong winds or heavy rain that dislodge the larvae. Typically, natural reduction of leaf beetles provides sufficient control in 10-20% of the plantation area with above-threshold populations each year (Forestry Tasmania, 2014).

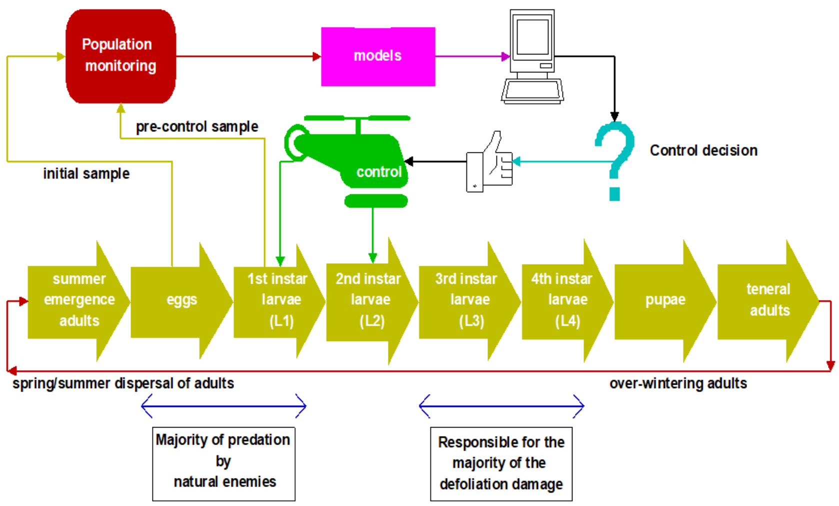

Figure 4. Schema showing the linkages between operational activities (monitoring and spraying) and the biology of the leaf beetle and its natural enemies and captured in the leaf beetle IPM used by Forestry Tasmania (now Sustainable Timber Tasmania).

There have been two major refinements to Forestry Tasmania's leaf beetle IPM since its introduction in 1992. The first, in the early 2000s, involved: (i) the introduction of the more cost-effective monitoring method - "occupied-leaves-per-shoot" - for assessing leaf beetle populations (Candy, 2002); (ii) the introduction of an economic injury threshold for the size of leaf beetle populations above which it is more economic to spray than to not spray (Candy, 1999). The second refinement was in 2011. This refinement was made in response to an evaluation of the effectiveness of the existing IPM (Wardlaw et al., 2011) and from finding a progressive increase in the area of, predominantly older (≥10 years), plantations suffering moderate or severe defoliation by leaf beetles (Wardlaw et al., 2011). The refinement involved changing from the age-based targeting to a risk-based targeting of plantations to include in the IPM. Plantations between 4-12 years-old that were predicted to have a medium or high risk of above-threshold leaf beetle populations were included in the IPM. The prediction of risk of above-threshold populations was based on the findings of Edgar (2011). Two risk criteria identified: (i) plantations being situated above 550 m altitude; (ii) plantations within 10 km of native grassland. For high risk sites both criteria were satisfied; for medium risk sites one of the criteria was satisfied; for low risk sites neither criteria were satisfied.

An evaluation of the effectiveness of the leaf beetle IPM in 2009-10 season found that it provided an overall net financial benefit (Wardlaw et al., 2010). A more comprehensive evaluation of the overall costs and benefits, including the costs of conducting the research to develop the IPM, found that applying the IPM provided considerable financial benefit and the overall project (including research) provided a positive return after the first rotation of the plantation estate on Tasmania's public forests (Carnegie et al., 2017).

A vulnerability of the current leaf beetle IPM is the reliance on the broad-spectrum insecticide α-cypermethrin. This insecticide is rated as highly hazardous by the Forest Stewardship Council (Forest Stewardship Council, 2015) and may only be used under temporary derogation. Forestry Tasmania has done extensive evaluation of more environmentally-friendly insecticides, notably *Bacillus thuringiensis* var. *tenebrionis* (*Btt*) and spinetoram. Both are toxic to young leaf beetle larvae (Elek et al., 2004; Elek and Beveridge, 1999) and relatively non-toxic to natural enemies of leaf beetles (Beveridge and Elek, 1999; Elek et al., 2004; Elek, 1997). Evaluation of *Btt* was discontinued after poor results in operational spraying trials (Elek, 1997). Operational spray trials using spinetoram (Spinosad) showed more promise and were sufficiently effective (Elek and Ramsden, 2001, 2002) to proceed with registration by the Agricultural Pesticides and Veterinary Medicines Authority for use in controlling leaf beetles in eucalypt plantations under the product name Success®. However, use of Success® by Forestry Tasmania was eventually discontinued in 2010-11 because of its high costs and operational complexity. The discontinuance of Success® prompted a comprehensive review of options for manging leaf beetles (Elek and Wardlaw, 2013). An "attract and kill" approach was ranked highly against environmental, economic and social criteria and was evaluated using a "lethal trap-tree" study as proof-of-concept. Results from this study were not sufficiently promising to proceed with further development (Elek et al., 2011). This marked the end of research into softer alternatives to α-cypermethrin by Forestry Tasmania but alternatives will still need to be found if Forest Stewardship Certification is to be maintained in the future.

4. MANAGEMENT OF PESTS AND PATHOGENS THAT MAY BE PERIODICALLY DAMAGING

Pests and pathogens that are only damaging periodically, or not amenable to reactive management, are unlikely to justify the investment in developing pest-specific management programs like the two IPM strategies described above. As shown in Figure 1, there is a long list of such pests and pathogens in Tasmanian eucalypt plantations. The two most notable of this category are autumn gum moth (*Mnesampela privata*) and a suite of fungi causing leaf diseases. Outbreaks / epidemics of each cause severe damage to plantations (Figure 5) with potentially long-lasting impacts on productivity (Rapley et al., 2009).

Figure 5. Mortality in E. nitens *plantations following an outbreak of autumn gum moth (left) and Kirramyces leaf disease* (Teratosphaeria eucalypti) *(right).*

5. AUTUMN GUM MOTH

Autumn gum moth is an outbreaking native species in eucalypt plantations. Damaging outbreaks build up over several seasons in non-heteroblastic *Eucalyptus* species (Steinbauer et al., 2001), but are limited to the duration of the juvenile foliage phase in heteroblastic species such as *E. nitens* and *E. globulus*. Developing outbreaks of autumn gum moth are readily controlled by insecticides using either the broad-spectrum synthetic pyrethroid α-cypermethrin (Rapley et al., 2009) or the biological insecticide Mimic® (Elek et al., 2003). However, such outbreaks are infrequent and localised, making detection a challenge. Routine annual health surveillance of plantations on public land in Tasmania has detected developing outbreaks of autumn gum moth in sufficient time to allow control operations (Wardlaw, 2008). However, static trap monitoring to determine the presence of autumn gum moth in an area might be a more reliable option for detecting pre-outbreak populations (Östrand et al., 2007).

Pheromone-baited traps based on bio-active compounds produced by autumn gum moth females were effective in detecting low populations of autumn gum moth (Walker et al., 2009). The incorporation of autumn gum moth pheromones into an automated monitoring system (Trapview® http://www.trapview.com) shows some promise but the technology requires refinement for reliable monitoring under operational conditions (Jim Wilson, Forico, pers. comm.).

6. FUNGAL LEAF DISEASES

Damaging epidemics of foliar leaf diseases occur when there is the coincidence of long periods of leaf wetness and an abundance of soft young foliage produced during active shoot growth (Park, 1988). For most parts of Tasmania these conditions occur infrequently because active shoot growth is restricted to the warmer months when rainfall is generally insufficient for these diseases. For these areas, epidemics only occur during years of abnormally high summer rainfall. Over the past 50 years there have been three such abnormally wet summers (1972, 1989 and 2011) across northern Tasmania where eucalypt plantations are concentrated.

Unlike outbreaks of defoliating insects, it is not feasible to reactively protect plantations from severe damage by fungal leaf diseases using fungicides when epidemic conditions occur. Thus, during epidemics, extensive areas of severe defoliation can be expected in eucalypt plantations. The 2011 epidemic, for example, caused moderate (25-50%) or severe (>50%) defoliation of 2,000 ha of eucalypt plantations on public land (Wotherspoon et al., 2012), and a large, but unquantified, area of privately-owned plantations. The consequence of severe defoliation from such epidemics may vary. A young (1-2 years-old) *E. globulus* plantation that suffered severe defoliation from Teratosphaeria leaf disease (*T. pseudonubilosa*) showed growth recovering to be comparable with that of an adjacent undamaged plantation in the season following the epidemic (Smith et al., 2017). The 2011 Kirramyces epidemic (*T. eucalypti*) resulted in high levels of mortality in some privately-owned, mid-rotation *E. nitens* plantations (Figure 5). However, most plantations showed crown recovery within 1-2 years following the epidemic (Forestry Tasmania, 2012), although growth impacts were not measured. The reasons for the contrasting responses following the 2011 epidemic have not been examined.

Genetic selection for disease resistance is the most commonly adopted approach for managing leaf diseases that are difficult to manage reactively during epidemics. There is strong heritability for resistance to Mycosphaerella (=Teratosphaeria) leaf disease in *E. globulus* (Milgate et al., 2006), which is relatively stable across sites (Hamilton et al., 2013). Heritability is lower in *E. nitens* (Dungey et al., 1997) but that is based on limited testing and not in trials exposed to epidemics of the most damaging pathogen, *T. eucalypti* (syn. *Kirramyces eucalypti*). Despite the high heritability for resistance to Mycosphaerella leaf disease in *E. globulus*, this trait has not been incorporated into breeding populations because we do not currently have information on the financial benefit (if any) of increasing the level of resistance (Dean Williams, pers. comm.).

The recent establishment of myrtle rust (*Austropuccinia psidii*) in Australia (Carnegie et al., 2010) poses a new threat to eucalypt plantations and native plant communities more widely. The pathogen has now become established in all the eastern states, including Tasmania. In the two southern-most states, disease is restricted to nurseries and amenity plantings of highly-susceptible, non-native Myrtaceae, such as *Lophomyrtus*: it has not yet spread into native plant communities or eucalypt plantations. Under the current climate, most of Tasmania is predicted to be sub-optimal for significant disease by this pathogen: only the coastal strip along northern Tasmania is predicted to be climatically suitable (Kriticos et al., 2013). This coastal strip does, however, coincide with about 40,000 ha of the state's eucalypt plantations. A warmer and wetter future climate is predicted for Tasmania, particularly the northeastern corner of the state (Grose et al., 2010). Some indication of the threat myrtle rust might pose to the eucalypt plantations in these areas under a warmer and wetter climate can be gained from examining the impact of the disease in regions with current climates similar to the predicted future climate in northern Tasmania. Southern Uruguay, which occurs at a similar latitude to the south coast of NSW is a useful comparison. This region of Uruguay has extensive plantations of *E. globulus*; it has the rust pathogen, although probably not the same biotype as the pandemic strain of *A. psidii* that has established in Australia; and, the damaging Teratosphaeria leaf disease pathogen, *T. nubilosa*, recently became established (Pérez et al., 2009). Balmelli et al. (2012) reported that in this region that is climatically more conducive to the rust disease than Tasmania, Teratosphaeria leaf disease caused greater damage in young *E. globulus* plantations where both pathogens were present. From this we can conclude that the threat to Tasmanian eucalypt plantations posed by myrtle rust is likely to be less than the threat currently posed by leaf disease from native pathogens in Tasmania.

The threat posed by myrtle rust to native Myrtaceae in Tasmania under a predicted future warmer and wetter climate will depend, in part, on the level of resistance to the pathogen. Glasshouse screening of the levels of resistance and susceptibility to *A. psidii* in all native Tasmanian *Eucalyptus* species found many species had a higher proportion of plants showing susceptible responses than *E. globulus* (Potts et al., 2016). That study found species within the subgenus *Symphyomyrtus* had higher levels of resistance to *A. psidii* than did species within the subgenus *Eucalyptus*.

7. CONCLUSION

The Tasmanian eucalypt plantation estate has matured and is transitioning into second rotation. Thus, all development stages of the plantation estate have been exposed to the threats posed by pests and pathogens that are currently established in the state. Management strategies based on integrated pest management have been developed for the two most prevalent and damaging threats – native marsupial browsers and Chrysomelid leaf beetles. Current practices are largely effective in protecting plantations from unacceptable damage by these two pest groups as determined by ongoing monitoring (e.g. forest health surveillance). However, vulnerabilities remain. The leaf beetle IPM is reliant on an insecticide that is non-FSC-compliant and may only be used under temporary derogation for those growers seeking to achieve or maintain FSC certification. The mammal browsing IPM is perceived to be expensive and would benefit from a detailed review of approaches used by different growers and pest-management contractors to identify and implement best-practice across the industry.

Less prevalent, but sometimes damaging pests and diseases pose a different set of challenges. Management systems for such pests and diseases are generally less refined and have weaknesses such as reliable methods for population detection in the case of autumn gum moth, or an incomplete understanding of impacts (particularly the reasons for differential responses) in the case fungal leaf diseases.

Finally, the pests and disease threats, while currently stable, will change as new threats become established (e.g. myrtle rust), the climate changes, or the choice of species planted in the estate changes. For these reasons, ongoing vigilance will be needed and technical expertise to respond to changing threats maintained.

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MANAGING INSECT PEST RISKS FOR DURABLE EUCALYPTS IN NEW ZEALAND: OPTIMISED MONITORING AND SELECTION FOR TOLERANCE

Abstract Plantation eucalypts, like other forestry species, face a range of health issues. The New Zealand forestry industry has a long history of proactive biosecurity which focuses on mitigating risks by exclusion where ever possible. Despite all efforts, eucalypt pests have made their way to New Zealand by natural and human assisted pathways and will, most likely, continue to do so in the future. Of around 34 eucalypt specialists that have established, the paropsine beetles are the most damaging, and incursions continue to occur. To effectively manage ongoing risks associated with insect pests in the face of an expanding, more diversified eucalypt industry, multiple approaches are required. A key element is to select for general pest tolerance in breeding programmes, such as the New Zealand Dryland Forests Initiative that is focused on improving a new suite of eucalypt species to produce sustainably-grown, naturally durable, timber products. Field trials are underway to assess eucalypt tolerance to a range of pests at the species and family level. In addition, growers require information on managing established pests, including a scientific basis on which to make decisions as to if and when pest populations require management to prevent production loss, while maintaining environmentally sustainable practices. This requires improved methods for pest monitoring and a robust understanding of the links between pest abundance, damage, and subsequent growth impacts. Herein we look at the risks to eucalypt forestry in New Zealand and discuss the requirements for an Integrated Pest Management (IPM) approach to managing these risks for durable eucalypts.

1. INTRODUCTION

The New Zealand Dryland Forests Initiative (NZDFI) aims to establish an industry based on *Eucalyptus* (Myrtaceae) grown in dryland regions, that will produce naturally ground-durable timber for specific end-uses (Millen, 2009). Initial species selection was undertaken for growth and wood properties; particularly drought and frost tolerance, and the ability to produce class 1 or 2 (Australian Standard, AS5606-2005) ground-durable timber. For the industry to succeed and produce high quality products in an economically and environmental sustainable manner, the elite breeds selected must be able to thrive in the presence of current and future biological threats.

1.1 Threats to plantation eucalypt health in New Zealand

Plantation eucalypt health is strongly influenced by multiple factors which, separately or in combination, may limit productivity, reduce wood quantity and quality, or even cause mortality. In New Zealand, abiotic factors such as frost and drought tolerance are particularly important, but understanding the contributions of other abiotic variables is also essential. As such, detailed site-species matching is a key component of plantation management to optimise productivity and minimise risk (Salekin et al., 2017). Abiotic factors also strongly influence the impact of biotic threats. Fast growing vigorous trees are generally less prone to pest and pathogen attack (Gadgil and Bain, 1999), and are likely to recover more quickly if damaged. Consequently, although we focus here on biotic threats, their interactions with abiotic environmental conditions are integral to tree health, and should always be considered.

For plantation eucalypts in New Zealand pest and pathogen attack is an inevitability, however, debilitating impacts on growth do not have to follow. It has been estimated there are 15,000-20,000 phytophagous eucalypt-feeding insects (Majer et al., 1997), and wherever plantation eucalypts are grown around the world, a suite of these have established and become pests (Paine et al., 2011). Approximately 34 eucalypt-specific Australian insect species have become established in New Zealand since 1955 (Forest Health Database, Scion), particularly herbivorous Coleoptera, Lepidoptera and Hymenoptera, and sap sucking psyllids. Most cause minor to moderate damage, but some occasionally exhibit severe local outbreaks, and around one third require some control (Withers, 2001).

In the past two decades, incursions of the outbreak moth species *Uraba lugens* Walker and the bronze bug, *Thaumastocoris peregrinus*, have raised concerns (Sopow et al., 2012) but have resulted in only limited damage to date, possibly because insecticides are regularly used where they occur and they have not yet established in the most intensive eucalypt growing regions. There have also been several paropsine beetle incursions (see below) and increasing numbers of eucalypt psyllid detections, the impacts of which are yet to be well documented. Pathogens, such as *Teratosphaeria cryptica* (Cooke) Crous & U. Braun., *T. eucalypti* (Cooke & Massee) Crous and several novel *Phytophthora* species have also caused problems, primarily in wetter regions when eucalypt species have been poorly matched to growing conditions (Nicholas and Hay, 1990, Hood et al., 2002).

New and unknown insect pests and pathogens are expected to continue to arrive from Australia. The proximity and position of New Zealand downwind to Australia (the native range of *Eucalyptus*), the ever-increasing travel and trade between the two countries, and their similarity in seasonal and environmental conditions, are long recognised factors providing opportunity for Australian insects and pathogens to arrive, establish and become pests on New Zealand grown eucalypts (Withers, 2001, Ridley et al., 2000). Most recently (May 2017) myrtle rust (*Austropuccinia psidii* (G. Winter) Beenken) was detected for the first time on the New Zealand mainland, most likely having arrived on wind currents from Australia.

1.2 The paropsine threat to plantation eucalypts

The most destructive insect pests for plantation eucalypts are the Chrysomelid or ‘paropsine ‘leaf beetles (Chrysomelidae: Chrysomelinae: Paropsina) (Paine et al., 2011, Elek and Wardlaw, 2013). Out of ~450 described paropsine species (Selman, 1994, Kelly and Reid, 1999), at least 12 are regarded as pests in Australia (Simmul and de Little, 1999), primarily where eucalypt species are grown in plantations outside their native range. On *E. nitens* (H. Deane and Maiden) Maiden in Tasmania, for example, *Paropsisterna bimaculata* (Olivier) and *Pst. agricola* (Chapuis) are chronic pests (Elek and Wardlaw, 2013), while *Pst. selmani* (de Little) has emerged as a sporadic pest (Elek and Patel, 2016). In 2007, significant defoliation by *Pst. selmani* was detected in cut-foliage plantations in south-west Ireland (Fanning and Baars, 2014, Horgan, 2011), and the beetle has since been detected in Southern England (Reid and De Little, 2013). *Trachymela tincticollis* (Blackburn) has been a plantation pest in South Africa since 1982 (Tribe and Chillie, 1997), while *T. sloanei* Blackburn established in California in 1998, where it damages ornamental and commercial eucalypts in conjunction with *Pst. m-fuscum* (Boheman) (estb. in 2003) and several Australian psyllid species (Paine et al. 2000). Since then, *T. sloanei* has spread into Mexico (2014), been detected damaging *E. camaldulensis* Dehnh in Cádiz province, Spain (Sanchez et al., 2015), and appeared in Taiwan (2016) (unpub. data).

In New Zealand (Table 1), five eucalypt- and two acacia-specific paropsine species are currently established. Since 1955, at least 11 other paropsines have been intercepted at the border, and one eradicated post-border. A further 19 unidentified Chrysomelids have reportedly been intercepted at the border from Australia between 1955 and 1982 (Mason and Ward, 1968, Richardson, 1979, Keal, 1981). *Paropsis charybdis* Stål (Figure 1) has been the main historic biotic impediment to commercial eucalypt forestry here, particularly with respect to *E. nitens*, *E. viminalis* Labill., and *E. globulus* Labill. (Nicholas and Hay, 1990). The beetle continues to be regarded as the country's worst eucalypt pest, occasionally causing severe defoliation in plantations (Withers et al., 2015, Withers and Peters, 2017). *Trachymela sloanei* and *T. catenata* (Chapuis) are less problematic, although *T. sloanei* is locally abundant in the dry Gisborne and Hawke's Bay regions (Author, pers. ob.) and its pest status may be underestimated due to its nocturnal feeding habit. The impacts of the most recent arrivals, *Paropsisterna beata* (Newman) and *Pst. variicollis* Chapuis are yet to be determined. *Paropsisterna beata* was thought to have been successfully eradicated in 2013 (Yamoah et al., 2016) but was re-detected in 2016 (MPI, 2016), while *Pst. variicollis* (Figure 1) was detected in 2016 and is currently being assessed (Lin et al., 2017).

Figure 1. Left: Paropsis charybdis*, New Zealand's first introduced paropsine beetle and most destructive eucalypt pest, established since 1916. Right:* Paropsisterna variicollis*, the most recently established paropsine, detected in Hawke's Bay, March 2016.*

1.3 Sustainable forestry in the presence of pests

How does the New Zealand eucalypt industry expand in the face of such high biosecurity risks posed by the vast number of potential eucalypt pests present in

Australia, and the increasing frequency with which they are becoming established internationally (see Paine et al., 2011)? Firstly, it is important to recognise that the impacts of invasive eucalypt insects have been highly variable. Some have caused significant damage, yet others have been relatively benign. Generally, the most important pest species for Australia, such as autumn gum moth and *Pst. bimaculata*, (Wardlaw, 2017), have as yet, failed to arrive. Several species have arrived with, or later accumulated, natural enemies (Withers, 2001) which may account for their limited pest impact, and others have had natural enemies imported through biological control programmes.

Table 1. Paropsine beetles (Chrysomelidae: Chrysomelinae: subtribe Paropsina) established in New Zealand or intercepted by border services since 1955.

	Year first recorded	**Region first recorded**	**Host genus**
Established			
Paropsis charybdis	1916	Canterbury	*Eucalyptus*
Trachymela sloanei	1976	Auckland	*Eucalyptus*
Peltoschema sp.	1990	Auckland	*Acacia*
Trachymela catenata	1992	Gisborne	*Eucalyptus*
Dicranosterna semipunctata	1996	Auckland	*Acacia*
‡*Paropsisterna beata*	2012	Upper Hutt	*Eucalyptus*
Paropsisterna variicollis	2016	Gisborne	*Eucalyptus*
Eradicated post-border			
Peltoschema suturalis	2000	Wellington	*Acacia*
Intercepted at border	**Year intercepted**	**Origin**	**Found on**
**Paropsis sp.*	1955-65	Australia	Triticum seed
**Paropsis sp.*	1973-78	Australia	Tent
**Paropsisterna intertincta*	1973-78	Australia	Flowers
**Trachymela punctipennis*	1973-78	Australia	Tent
**Paropsis ? sp.*	1979-82	Australia	Fruit
**Paropsis sp.*	1979-82	Australia	Tent
†*Paropsis sp.*	1996	Australia	Not recorded
†*Chrysophtharta sp.*	2006	Australia	Personal effects
†*Dicranosterna sp.*	2010	Australia	Distillers grain
†*Paropsis delittlei*	2014	Australia	Tent
†*Peltoschema orphana*	2016	Australia	Tent

‡Thought to have been successfully eradicated but subsequently rediscovered at another location
* Data collated by border services in; Mason and Ward (1968), Richardson (1979) and Keal (1981)
† Data from MPI Diagnostics Centre, Plant Health and Environment Laboratory, Christchurch, July 2017

Although the historic and ongoing incursions are important, they should not be cause to abandon the prospect of a successful eucalypt industry. All commercial plantation species are subject to pest and pathogen attack to some degree, but if appropriately managed, impacts can be reduced below economically damaging thresholds. This has been demonstrated with *Pinus radiata* D. Don, New Zealand's main plantation species. Over 600 pests and pathogens have been recorded on *P. radiata* globally (Brockerhoff and Bulman, 2014). This includes 450 insect and mite species, of which 140 are known to feed on *P. radiata* in New Zealand (J. Bain pers. comm.). Given its apparent susceptibility to pests and pathogens (but see Bain, 1981) biologists J.J. de Gryse (1955) commented, in a report on New Zealand's forest health programme in the 1950s, that growing monocultures of *P. radiata* in New Zealand was "tantamount to challenging the laws of nature". However, the majority of biotic threats to *P. radiata* have, to date, been successfully mitigated, particularly by strong border biosecurity.

New Zealand has one of the strictest biosecurity systems in the world (Eschen et al., 2015). The forestry industry has played a significant role in the initial development and ongoing improvement at all stages of the system (Bulman, 2008, Brockerhoff and Bulman, 2014) including; (1) identifying and closing pathways by which forest pests arrive to New Zealand, (2) implementing and improving effective post-border surveillance to enhance early pest detection which facilitates eradication (Bulman, 2008), and (3) research that aids in the detection, identification and management of forest pests and disease (Bulman and Gadgil, 2014). For *P. radiata*, the impacts of established biotic threats have been further moderated through onsite pest monitoring, intensive stand management, and breeding for resistance (Bain, 1981, Gadgil and Bain, 1999). An example of this is seen in the management of the European wood wasp, *Sirex noctilio* F. In the 1950s, the pest caused significant mortality in some Central North Island stands where trees were suppressed by drought and overstocking. Now, *S. noctilio* is maintained below economically damaging thresholds, following improved site matching, silviculture practices that reduce plant stress, and the importation of effective biological control agents (Bain et al., 2012).

As *P. radiata* has shown, the existence of potential threats elsewhere does not guarantee they will all arrive or have significant impacts if they do. For plantation eucalypts in New Zealand, however, the proximity of Australia with its complement of potential pests, requires that biological risk mitigation be a key consideration in future-proofing industry expansion. While continuing to implement effective border biosecurity is fundamental to reducing biological *risk* (chance of arrival), a proactive approach is required to reduce the *threats* (potential impacts) posed by established pests. The NZDFI aims to achieve this by diversifying the eucalypt species resource and taking a three-fold approach to improve forest health as part of their breeding programme; (1) optimise tree vigour with appropriate site-species matching and genetic selection for elite growth properties, (2) select for pest tolerance (reduced susceptibility and rapid recovery), (3) develop monitoring methods to detect defoliation that will exceed economically damaging thresholds to facilitate effective, sustainable management. Approaches 2 and 3 are discussed below with a particular focus on paropsine pests.

2. PEST MANAGEMENT APPROACH

The most effective means of limiting pest impacts is to prevent establishment via pre-border and border biosecurity measures. However, once pests become established, management may be required to prevent impacts. The NZDFI approach to limiting pest impacts aims to minimise the economic and environmental costs of any management undertaken (see Figure 2). The first step, is to reduce the risk that planted eucalypts will be severely damaged by the established pests. This can be done by selecting pest tolerant species or genotypes in breeding programmes, combined with site-species matching and silvicultural practices that optimise tree vigour. The second step is to determine thresholds above which pest management is required to prevent economic loss (Elliot et al., 1992) and develop monitoring tools growers can use to inform when any management actions should be implemented. These actions must be effective, feasible, environmentally sensitive and socially acceptable.

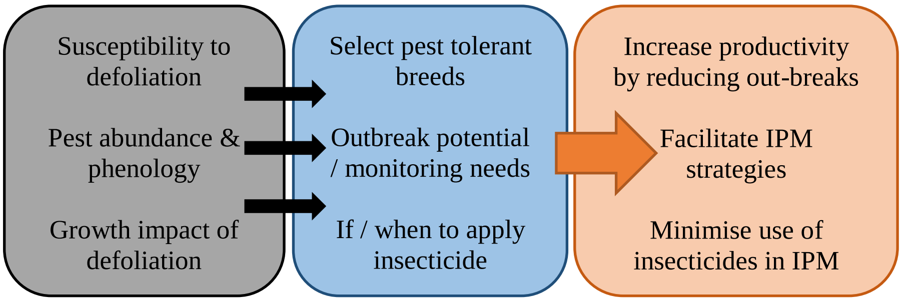

Figure 2. Assessments to be made (grey), information gained (blue) and intended outcomes of the durable eucalypt pest management programme.

3. SELECTING FOR PEST TOLERANCE

Elek and Wardlaw (2013) proposed that, to manage plantation pests in Tasmania, the best approach was to use multiple socially and environmentally acceptable methods with a minimal chemical footprint. They concluded that developing plantation stock more resistant to, or tolerant of, leaf beetle attack was the highest pest management priority for Australian eucalypt plantations. The eucalypt health issues in New Zealand are not dissimilar to those faced in Tasmanian plantations, in which eucalypt species are grown beyond their natural range. In both countries the key pests are there to stay, being either native (Tasmania only) or too well establish to eradicate. There is also ongoing opportunity for new pest problems to emerge given the proximity of pest sources. Consequently, New Zealand would benefit from taking a similar proactive approach to pest management.

Pest resistance is generally not a key selection criteria in the initial improvement of commercial forestry species, but may be incorporated (e.g. *P. taeda* and *P. elliottii* for resistance to fusiform rust, *Eucalyptus* spp. against eucalypt canker in Brazil

(Gadgil and Bain, 1999)) once other key characteristics have been achieved. The importance of pest resistance was recognised in early New Zealand eucalypt breeding programmes, particularly for *E. nitens* against *P. charybdis* (Wilcox, 1980). The current *E. nitens* breeding programme, under the Specialty Wood Products partnership, continues to explore the genetic basis for natural resistance. Given the even larger set of established pests today, the NZDFI durable eucalypt breeding programme considers it a priority to identify pest tolerance. Within the selections for elite growth, form, and wood properties, the programme aims to 'weed out' highly pest susceptible individuals or provenances, and maintain the most tolerant.

3.1 The basis for selection

Within *Eucalyptus* there is an enormous degree of variability in insect tolerance, both within and between species. This can result from complex variations in nutritional, physical and chemical characteristics (Henery et al., 2008, Ohmart and Edwards, 1991, Li, 1994) driving insect herbivore's oviposition and feeding preferences, survival, and productivity. Insects limited by physical factors, such as waxes inhibiting oviposition behaviour, or sclerophylly inhibiting larval feeding (Ohmart and Edwards, 1991, Steinbauer et al., 1998, Steinbauer et al., 2004, Horgan, 2011), may be specific to either juvenile or adult foliage, or to expanding vs. mature leaves. Preferences driven by foliar chemistry or 'plant secondary metabolites' (e.g. essential oils, phenols (such as tannins) and terpenes) are complex, and may interact with nutritional factors (such as nitrogen levels) as well as the physical and phenological limitations noted above. Variation in secondary chemistry can include differences in the presence, quality and relative quantities or ratios of numerous compounds, and few individual compounds have been definitively linked to insect tolerance (Li, 1994, Stone and Bacon, 1994, Andrew et al., 2007). The mix of host plant species available can also influence oviposition and feeding choices. For example, following the incursion of *Pst. selmani* into Ireland, *E. pulverulenta* Sims was found to be highly resistant in most situations, but notable damage was observed in one particular site where the beetle population was very high and moved on to *E. pulverulenta* after depleting other preferred species (Horgan, 2011).

3.2 Symphyomyrtus *vs.* Eucalyptus

Eucalyptus species in the subgenus *Symphyomyrtus* are often regarded as more susceptible to pests than those in the subgenus *Eucalyptus* (previously informal subgenus *Monocalyptus*) (see Noble 1989 for review). Some argue they should not, therefore, be considered when selecting new plantation species. Despite this, the majority of commercial plantation eucalypts are symphyomyrts, due to their relatively rapid early growth rates, wide environmental tolerance and highly desirable wood properties. This is true in New Zealand, where *P. charybdis* has caused significant defoliation to symphyomyrts such as *E. nitens*, *E. globulus* and *E. viminalis*. However, *P. charybdis* has an extensive host range (~51 species, Forest Health Database, Scion) including species in the subgenus *Eucalyptus*, and complex variations in preferences and levels of attack within and between species have been observed in the past 100 years (E.g. Steven, 1973). By alleviating pest pressure with pesticides, Stone et al., (1998) tested the hypothesis that symphyomyrts are more susceptible to pest attack in Australia. They found symphyomyrts generally outperformed the subgenus *Eucalyptus* when defoliation was reduced. This suggests symphyomyrts suffer greater insect suppression, but selecting and breeding those genotypes with high natural pest resistance could potentially produce breeds that are even more productive than the subgenus *Eucalyptus* in plantations. Correlations between pest susceptibility and tree size (Rapley et al., 2004) and tree growth rate (Raymond, 1995) also occur. As such, the rapid growth expressed by many symphyomyrts may itself confer some resistance. Furthermore, it has been observed that although fewer eucalypt generalists tend to attack the subgenus *Eucalyptus*, they do have their own potentially damaging specialists (see Li, 1994 for review). Finally, susceptibility to insects also needs to be balanced against susceptibility to pathogens, such as myrtle rust. Although substantial variation in eucalypt susceptibility to myrtle rust has been reported, screening of the 30 native Tasmanian species indicates subgenus *Symphyomyrtus* may be more susceptible than subgenus *Eucalyptus* (Potts et al., 2016). Consequently, generalisations about pest or pathogen resistance of a species should not be made based on its subgenus alone.

3.3 Within-species tolerance to paropsine pests

Many eucalypt-specific insect herbivores, including paropsine beetles, express significant differences in oviposition and defoliation preferences between eucalypt species, provenances, and genotypes. Raymond (1995) assessed open-pollinated families of *E. regnans* F. Muell. and *E. nitens* in Tasmania and, for both, found significant difference in defoliation by *Pst. bimaculata* between families. In an open-pollinated trial of *E. globulus*, also in Tasmania, Rapley et al., (2004) found significant variation between families in susceptibility to oviposition (and subsequent egg and larval abundance) and damage by *Pst. agricola*. Similarly, Henery et al., (2008) observed heritable variation in crown damage index (a measure of defoliation) by *P. atomaria* Olivier on open-pollinated *E. grandis* Hill ex Maiden families. Although the response could not be linked to the foliar secondary metabolites assessed, or to foliar nitrogen, near infra-red reflectance (NIR) did indicate a chemical difference between families suffering low vs. high defoliation (Henery et al., 2008).

Given the species in the NZ durable eucalypt breeding programme have rarely, if ever, been grown commercially, little is known about their specific susceptibility to pests in a plantation environment. One, *E. argophloia* Blakely, has been shown to be a poor host for *P. atomaria*, a plantation pest in NSW and QLD (Fox and Macauley, 1977, Nahrung et al., 2008). Another, *E. tricarpa*, was shown in open-pollinated breeding trials in Australia to have heritable variation in concentrations of sideroxylonals (Andrew et al., 2007). Mounting evidence indicates that this group of secondary chemicals may confer resistance to both insects and mammals (e.g. Lawler et al., 2000, Andrew et al., 2010) and it has been suggest they may provide a good basis on which to select for general herbivore tolerance. For *E. tricarpa*, concentrations were significantly correlated to Christmas beetle damage, with beetles preferring trees with lower foliar concentrations (Andrew et al., 2007).

3.4 Selection process

Regardless of subgenus, species, or provenance, it is clear there is a significant degree of variation at an individual tree level in foliar characteristics, chemistry and consequent insect damage experienced by eucalypts. We aim to detect and reduce this variability within trees selected for desirable wood and growth properties, in order to retain only the most insect tolerant genotypes in the breeding programme. Given the likelihood of complex environmental interactions, the focus is on identifying heritable pest tolerance in field trials, rather than specifically identifying the cause, such as a chemical profile, although the latter may be useful in developing screening tools. To select for pest tolerance, breeding trials are being assessed as follows;

1) Develop a suitable screening method and test it on unimproved genotypes of one species at a young age
2) Roll out genotype screening across species in as many sites as practical
3) Screen improved selections to confirm characteristics have been retained
4) Repeat screening of unimproved material, late rotation, to determine the ability of early assessment to predict health and growth throughout the rotation period

The first step has seen 14 open-pollinated families of *E. bosistoana* F. Muell. screened for tolerance to four well established herbivore pests. These include the two most damaging chewing pests, *P. charybdis* and *Opodipthera eucalypti* Scott (gum emperor moth), and two other species chosen to represent different feeding patterns; *Phylacteophaga froggatti* Riek, a leaf mining wasp that primarily affects leaves in the lower canopy, and *Strepsicrates macropetana* (Meyrick) a leaf-rolling lepidoptera most prevalent on the growing tips. Initial field trial results show nine *E. bosistoana* families to be significantly more tolerant to the combined defoliation from these four pest than the remaining five families (H. Lin, unpublished data). A second trial assessed damage inflicted by *Pst. variicollis* in its first year of establishment. Although the assessment was made at only one point in time and will need to be repeated, results showed considerable variation (Figure 3) in damage suffered both between and within the eleven eucalypt species assessed (Lin et al., 2017). Damage also varied between the three trial sites, reiterating the importance of environmental interactions on pest impact. Results from both trials indicate there is substantial phenotypic variation in pest tolerance being expressed within trees in the breeding programme. If heritable, these traits will provide a basis for future selection.

4. DEFINING INTERVENTION THRESHOLDS

Increasing pest resistance and/or pest tolerance can reduce the frequency with which pest populations reach high enough densities to cause economic harm. However, occasional pest outbreaks are still likely to occur in response to environmental stress, the arrival of new pests, or changes in interactions between pests and their natural enemies. Although considerable variation has been reported, some studies have found eucalypts can tolerate relatively high levels of defoliation before growth loss occurs

(Rapley et al., 2009, Candy et al., 1992). If so, it may be unnecessary to use pest management tactics such as broad spectrum insecticides in many cases (Withers et al., 2015). Determining economically damaging defoliation levels, and implementing reactive management only when monitoring indicates pest abundance will exceeded these thresholds, is known as Integrated Pest Management (IPM).

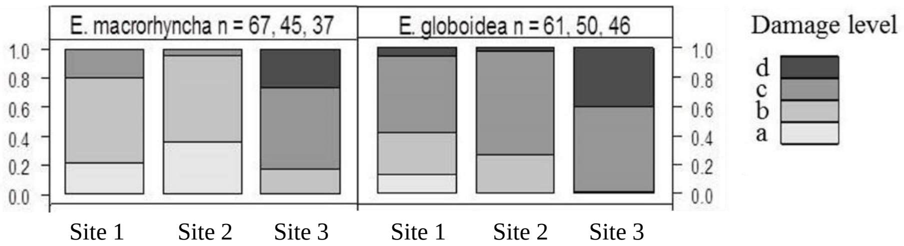

Figure 3. Proportion of trees (n = number of trees assessed per site) suffering negligible (a = <5%) to moderately severe (d = 51-60%) damage from Pst. variicollis *during a single assessment at three sites in Hawkes Bay (adapted from Lin et al., 2017).*

4.1 Adapting Tasmanian IPM to dryland New Zealand

Paropsine beetles have been the focus of an IPM programme in Tasmanian eucalypt plantations since 1992 (Elliot et al., 1992), which has been refined over time (Wardlaw, 2017). The success of the Paropsine IPM is attributed to a robust scientific knowledge of pest biology, life-cycle dynamics, and interactions with natural enemies. Briefly, regular monitoring using an 'occupied leaves per shoot' method, is used to asses plantations included in the programme based on tree age and defoliation risk criteria. Monitoring is repeated fortnightly so eggs present in one session have sufficient time to hatch and develop to the 2nd instar, but not enough time to develop to the damaging 3rd and 4th instars. By understanding how to connect larval abundance to subsequent damage and determine if this will exceed an economic injury threshold, a decision to apply pesticides is only required if natural enemies have failed sufficiently suppress the pest population.

A similar approach could be successful in New Zealand. The monitoring method requires adjustment to account for differences in the behaviour of *P. charybdis*, which often lay eggs high in the canopy. Also, as durable eucalypts are being prioritised for dryland regions where plantation eucalypts have not previously been grown, the regionally-specific lifecycle dynamics of the established pests and their natural enemies, and the impacts of defoliation severity and seasonality required to calculate economic damage thresholds, are unknown. To this end, field trials with *E. bosistoana* have been established to assess insect pest phenology, seasonal life-stage abundance, and subsequent levels of defoliation by the same four pests noted in Section 3.

It is also noteworthy that, relative to Tasmania, there are few natural enemies to regulate paropsine outbreaks in New Zealand. Some control of *P. charybdis* is achieved by introduced natural enemies from Australia, including two egg parasitoids (Pteromalidae) and a predatory coccinelid beetle (Murray et al., 2008), although the former are not well suited to the New Zealand climate. A new larval parasitoid, *Eadya sp.* (Braconidae) is currently being assessed to increase control in the future (Withers et al., 2015). It is not yet know how effective these biological control agents will be against *Pst. variicollis* and *Pst. beata*. If an IPM approach similar to that used in Tasmania were applied in New Zealand, pesticide use could be minimised to allow these natural enemies to control pest populations if possible, but the low diversity and ecological limitations of the current enemies means research is required to understand their potential to impact pest abundance between fortnightly monitoring events.

In addition to studying pest dynamics on *E. bosistoana*, artificial defoliation trials have begun to determine growth impacts of different defoliation severities and of early or late season, or repeated defoliation (Figure 4). Measurements to date indicate that tree growth is not significantly reduced by moderate defoliation (~50%) if it occurs only in early spring, but is reduced if it is repeated in late summer (Lin, unpublished). Severe (~90%) defoliation appears to reduce growth regardless of timing, but no more so than repeated moderate defoliation. Similar results have been seen in the limited number of related studies. Elek and Baker (2017) reported that *E. nitens* subject to late-season defoliation for two consecutive years had a 21% lower mean annual increment and ≥ 17% smaller DBH 13 years later, and concluded trees would require three to four more years to obtain the same harvest volume as undefoliated trees.

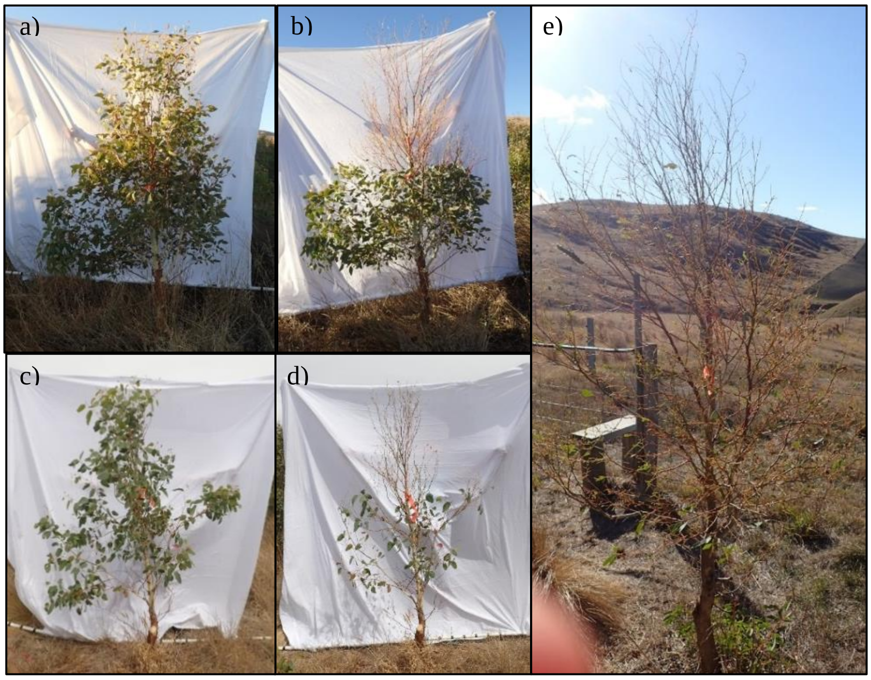

Figure 4. Artificial defoliation of young E. bosistoana *to assess grown impacts of defoliation severity and timing. A) Before and B) after moderate (~50%) defoliation. C) Before and D) after severe (~90%) defoliation. E) Natural defoliation by gum emperor moth at the same site.*

Studies such as those described above, are invaluable to inform decisions on how to deliver effective IPM to minimises both long term growth impacts and pesticide use. Effective pest population modelling is essential to work out when interventions are truly needed in order to protect the productivity of plantations over a whole rotation and achieve the desired outcomes at harvest, while minimising economic and environmental costs. For example, is it best to control spring generation recruitment, or to target control only on late season defoliation? In addition to solving these problems, improved technologies to effectively deliver pesticides into infested tree crowns are sorely needed.

5. CONCLUSIONS

New Zealand eucalypt plantations have suffered from a long history of incursions of specialist eucalypt-feeding insects from Australia. These pests will remain, and new incursions will occur. This should not detract from the expansion of the eucalypt plantation industry, rather it should encourage diversification. Substantial variation is observed in the susceptibility of individual eucalypts to pests, and this provides a basis on which to select for highly tolerant genotypes that can be used to reduce future pest risks. To protect against the remaining risks associated with occasional pest outbreaks, or new pest interactions, economically and environmentally sustainable IPM methods must be developed for plantation eucalypts wherever they are grown in New Zealand. This will require sound, regionally-specific knowledge of pest phenology to optimise monitoring, and an ability to predict defoliation impacts based on pest abundance, that can be compared to regional economic damage thresholds to inform intervention decisions. This integrated, adaptable approach, should provide an effective working toolkit to future-proof the eucalypt industry against biological threats.

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NEW ZEALAND GROWN EUCALYPTS FOR ROTARY PEELED VENEER PRODUCTION

Abstract Eucalypts offer the opportunity to reduce fibre costs of engineered structural wood products like LVL. Additionally they would also be capable of improving the mechanical properties of LVL to meet the ever-increasing demands posed by large-scale timber construction. From a New Zealand perspective, only a few eucalypt species have the necessary resource backing needed to establish a viable industry-scale forestry resource. Properties of eucalypts relevant in the New Zealand context are listed and discussed. Eucalypts differ significantly in their properties and therefore their suitability for different products has to be carefully considered. Eucalypts producing very stiff timber are typically also of very high density, which is not acceptable for all products. Like softwoods, eucalypts also feature lower stiffness and density juvenile corewood, which needs to be considered when utilising spindle-less lathe technology to convert corewood into veneer. Not all eucalypts are naturally durable, however in some markets natural durability is a sought after wood property. Eucalypts typically suffer from high growth-strains, which negatively affect veneer recovery.

1. INTRODUCTION

Laminated Veneer Lumber (LVL) producers in New Zealand are looking for an alternative fibre supply to radiata pine (*Pinus radiata*). Production of LVL from radiata pine is currently commercially viable. However, it does not allow the production of high stiffness products. In recent times the size of timber buildings has increased dramatically (Kolb, 2008, Kakitani, 2017). Such construction places high demands on the stiffness of the utilised timber products. Super-stiff timber products (> 16 GPa) cannot be manufactured from radiata pine as this species is not able to form wood with such properties.

Furthermore, radiata pine contains a considerable amount of low-stiffness corewood. This restricts the part of the stem from which veneers of structural grade can be produced to the outerwood. The corewood is rejected in larger diameter (9 cm) peeler cores and used for lower value products such as medium density fibreboard (MDF) or firewood. The need for outerwood a) requires the supply of larger diameter logs from older trees and b) decreases recovery of structural veneer from these logs. Both effects increase fibre cost.

Peeling technology does not constrain the conversion of a larger stem volume to veneer. Spindle-less lathes achieve peeler cores of ~ 2 cm. Spindle-less lathe technology is now extensively used in China and Brazil (Arnold et al., 2013; de Carvalho et al., 2004). Also Australian plywood manufactures have replaced conventional lathes with spindle-less technology. The constraining factor is the stiffness of the available wood resource if structural products are targeted.

Eucalypts achieve growth rates which can exceed those of radiata pine while producing much stiffer wood (Walker, 2006). Additionally the wood of some eucalypts can be naturally durable. Therefore, eucalypts are well suited to supply wood for structural timber products such as LVL or plywood. This has been recognised in several countries with eucalypt resources like Australia (McGavin, 2016; Ozarska, 1999), China (Arnold et al., 2013), Brazil (de Carvalho et al., 2004) and Europe (Konnerth et al., 2016).

Two different strategies can be pursued when utilising an eucalyptus resource for the production of structural engineered wood products. First, it is possible to target the production of higher value structural products (> 16 GPa). These require exceptionally stiff veneers in reasonable quantities. Only a few eucalyptus species form such wood (Bootle, 2005) and it has to be recognised that not all parts of the stem are of equally high stiffness. Second, fibre costs could be reduced by utilising trees grown in shorter rotations and achieving higher veneer yields when considering standard LVL products (8 to 13 GPa), which are currently manufactured from radiata pine. Green veneer recoveries of ~ 75% were reported for several < 15-year old plantation grown eucalyptus species (McGavin et al., 2014). Higher veneer yields from younger trees implies the utilisation of less stiff juvenile corewood. Again eucalypt species of exceptional stiffness are more likely to achieve structural grade veneer stiffness at young age (McGavin et al., 2015).

A further factor to consider is that radiata pine timber is not resistant to biological degradation. Thus preservative treatment is essential to make the radiata products decay and termite resistant. Preservative treated products are perceived negatively in some export markets and can pose a significant waste disposal problem (Townsend and Solo-Gabriele, 2006). Some eucalypts on the other hand have highly naturally-durable heartwood (Bootle, 2005). This would allow the production of structural engineered wood products, which are highly resistant to biodegradation without the application of toxic chemicals.

Experience with peeling eucalypts on both research and commercial scales demonstrated that it is possible to obtain good quality veneer from plantation-grown eucalypts e.g. (McGavin, 2016). The work also identified challenges. First, yields of rotary peeled veneer from logs sourced from younger plantation-grown eucalypts are considerably reduced by end-checking (Yang and Waugh, 2001). End-checking is caused by excessive growth-stresses. Growth-stresses are formed inside tree stems by the developing wood cells. The developing cells on the outside of the stem tend to contract in axial direction during cell wall formation (Gardiner et al., 2014). Therefore, the outside of the stem is under axial tension. The centre of the stems counters these forces and, as a consequence, is under axial compression (Archer, 1987). These forces are released when a log is cut lengthwise causing the axial expansion of the side closer to the centre and contraction of the side closer to the bark of the separated piece. The consequence is the distortion or even fracture (end-splitting) of the separated wood piece if the stresses exceed the strength of the wood.

Secondly, problems have been encountered with gluing eucalypt veneers (Ozarska, 1999). Explanations including high wood density or the presence of extractives have been put forward to explain this problem (Konnerth et al., 2016). High density timbers (> 800 kg/m^3) have only small cell lumens into which adhesive resin can penetrate and harden. This would limit mechanical connections between the adhesive and the wood. Some eucalypts can have high amounts of extractives (> 15%)

in the heartwood. Heartwood extractives can interfere with the chemical reactions involved in polymerising the adhesive resin or its chemical bonding to the wood (Rowe, 1989). It also should be considered that these timbers are exceptionally strong, therefore the glue itself needs to have a better performance to satisfy the bonding test criteria according to AS/NZS 2098.2. In any case gluing eucalypt veneers requires attention, but it seems possible to achieve strong bonds.

2. METHODS

2.1. Wood properties

Eucalyptus bosistoana samples were taken from 180 four year old trees from 50 families grown at two sites in Marlborough, New Zealand. *Eucalyptus quadrangulata* samples were taken from 264 two year old trees from 22 families grown at one site in Marlborough, New Zealand. Branch-free, straight 50 cm long stem section were cut from near the top (*E. bosistoana*) or near the bottom (*E. quadrangulata*) at a stem diameter above bark of approximately 4 cm. Average tree height of the sampled *E. bosistoana* trees at age 4 was ~ 4.5 m. *E. argophloia* samples came from 40 two year old trees grown in Canterbury, New Zealand.

The samples were debarked and split lengthwise through the pith in the green state to assess growth-strain by measuring distortion (Chauhan and Entwistle, 2010; Entwistle et al., 2014). From the split end, two ~ 12 cm long samples were cut. After determining their green mass and volume (by immersion weighing) they were dried in an oven at 103 ºC. After measuring the acoustic velocity of the dry samples by resonance (WoodSpec) their mass and volume was determined. This allowed calculation of densities, the dynamic Modulus of Elasticity (MoE) and volumetric shrinkage (Chauhan et al., 2013). 196 *Pinus radiata* trees were grown in Canterbury, New Zealand and processed as above without measuring growth-strain.

2.2. Discs

Nine ~ 5 cm thick discs of *E. bosistoana* and *E. globoidea* each were obtained from the stem base. The trees were harvested during a thinning operation of New Zealand Dryland Forests Initiative (NZDFI) breeding trials. Acoustic velocity was measured 5, 15 and 25 mm away from the pith at 8 positions around the circumference by time-of-flight (Tree Disk Machine) (Knopp and Hayes, 2010).

3. RESULTS

A wide range of several hundred eucalyptus species exist (Brooker, 2000). These vary greatly in their wood properties as well as their ability to grow under New Zealand conditions. Table 1 lists the eucalypt species, which have been introduced to New Zealand with a genetic breadth that can support a tree breeding programme needed for a viable wood processing export industry. The data listed in Table 1 refers to the Australian old-growth resource and properties can be expected to differ for younger trees grown in New Zealand plantations. All eucalypts produce stiffer wood than radiata pine. The advantage, however, ranges from a 40% to an 130% increase in MoE. Not all species are suitable to produce super-stiff (> 16 GPa) engineered wood products. Standard structural engineered wood products require MoE between 8 and 13 GPa. All listed eucalypts have the potential to be used for such products. Although the higher the stiffness the more likely it is to obtain structural veneers from juvenile corewood, i.e. small-diameter logs of young fast-grown trees (see 3.1).

Another important difference is the natural durability of these timbers. Natural durability is not required for all products, but if durability is necessary then some species have a clear advantage.

*Table 1. Properties of eucalypts relevant in the New Zealand context. Data from Australian old-growth trees (Bootle, 2005). ND: no data available; *(Anonymous, 2013; Cookson et al., 2009)*

Species	MoE (GPa) old growth	Air-dry density (12% MC) (kg/m^3)	In-ground life expectancy (years)	Lyctid susceptibility of sapwood	Termite resistance
E. nitens	*13*	*700*	*0 - 5*	*Susceptible*	*Not resistant*
E. fastigata	*14*	*750*	*0 - 5*	*Susceptible*	*Not resistant*
E. regnans	*13*	*680*	*0 - 5*	*Depending on origin*	*Not resistant*
E. bosistoana	*21*	*1100*	*>25*	*Susceptible*	*Resistant*
*E. argophloia**	*14 (age 13)*	*1055*	*>25*	*Susceptible*	*Not resistant*
E. tricarpa / E. sideroxylon	*17*	*1130*	*>25*	*Susceptible*	*Resistant*
E. quadrangulata	*18*	*1030*	*15 - 25*	*Not susceptible*	*Resistant*
E. globoidea	*17*	*880*	*15 - 25*	*Not susceptible*	*ND*
E. cladocalyx	*17*	*1090*	*>25*	*Susceptible*	*Resistant*
Pinus radiata	*9*	*480*	*0 - 5*	*Not susceptible*	*Not resistant*

3.1. Stiffness

Like for softwoods, in eucalypts the stiffness of the wood increases with distance from the pith and with height in the lower stem section (butt log) (Ozarska, 2009). As a consequence, if high stiffness veneers (> 16 GPa) and/or small peeler cores (i.e. high conversion rates) are envisaged, it is important to consider the stiffness potential of each species. *E. bosistoana* and *E. quadrangulata* appear to be best suited to achieve these goals. Species like *E. nitens* or *E. fastigata* could still out-perform radiata pine in terms of fibre cost as corewood does not need to be removed to that extent with a large peeler core. But these species might not be suitable to significantly increase the performance of the engineered wood products (> 16 GPa).

The available information on wood properties of young New Zealand-grown eucalypts is limited. It is important to have information on corewood properties to evaluate the potential of spindle-less lathe technology for the production of structural veneers. Spindle-less lathes allow the recovery of veneer 1-2 cm from the pith, essentially the 2nd annual growth ring of fast-growing plantation trees. Over the last few years the New Zealand School of Forestry has conducted scoping studies on some eucalypts at young age to a) develop methodologies to assess wood properties efficiently to screen large populations and b) to gauge the potential of some species for high stiffness timber. This data is summarised in Table 2.

*Table 2. Mean values of wood properties of eucalypts at young age. Coefficient of variation in parentheses. *12% MC, **0% MC, ***5% MC.*

Species	Age (a)	Diameter (mm)	Growth-strain (µstrain)	Dry dynamic MoE (GPa)	Dry density (kg/m^3)	Volumetric shrinkage (%)
E. nitens[a]	*2*	*34.0 (17.5)*	*681 (41.6)*	*6.4 (10.5)* *	*591 (6.4)* *	*14.1 (16.5)*
E. bosistoana	*1*[a]	*21.6 (18.8)*	*1007 (44.3)*	*9.7 (15.3)* **	*802 (5.1)* **	*28.3 (11.3)*
	4 (top)	*34.6 (10.1)*	*949 (30.7)*	*17.5 (11.7)* **	*875 (5.2)* **	*24.5 (9.6)*
E. argophloia	*2*	*27.0 (12.9)*	*501 (66.2)*	*9.0 (19.5)* **	*825 (5.8)* **	*22.3 (9.4)*
E. quadrangulata	*2*	*33.0 (9.8)*	*1289 (25.4)*	*13.9 (9.1)* **	*691 (5.4)* **	*23.0 (11.5)*
Pinus radiata	*2*	*34.6 (11.4)*	-	*3.5 (12.3)* ***	*364 (5.2)* ***	*10.0 (21.4)*

[a](Sharma et al., 2017)

The ranking of the species for MoE at a young age mimicked that of the old resource (Table 1), but at a lower level. Radiata pine showed the largest decrease in MoE for juvenile corewood compared to mature wood. It is also important to note that the well described trend of MoE of the corewood being lower in the lower part of the stem, i.e. juvenile corewood (Burdon et al., 2004), was confirmed with this data. *E. bosistoana* corewood stem sections were comprised of approximately 2 year rings when cut from the tops of 4-year old trees with an average height of ~ 4.5 m. These samples had a MoE of 17 GPa which was ~ 100% stiffer than those sampled at the base of the stem at age 1. These values are encouraging considering spindle-less lathe technology for veneer production as no low-stiffness wood needs to be rejected in a larger peeler core even for the products with the highest specifications. This statement also applies to *E. quadrangulata*, which had a MoE of ~ 14 GPa at age 2.

Very little information on the stiffness of juvenile corewood of *E. globoidea* is available. *E. globoidea* is a species of interest in the New Zealand context as it has good growth characteristics and probably the largest existing resource of the durable eucalypts. For the latter reason, NZ-grown *E. globoidea* has also been subject to sawing (Jones et al., 2010) and peeling studies. These have repeatedly shown that the stiffness of the wood from these less than 30-year old trees was with 12-13 GPa significantly lower than that reported for the old-growth Australian resource (17 GPa). The underlying reason appears to be a relatively high microfibril angle in the juvenile corewood as can be seen from Figure 1. The acoustic velocity is a good measure of the microfibril angle and together with density determines the stiffness of wood. However, a better way to interpret the data in Figure 1 is that *E. bosistoana* has an exceptionally small microfibril angle and therefore high stiffness in the juvenile corewood. *E. globoidea* is still outperforming softwoods such as radiata pine, which achieves such high acoustic velocities only in outerwood after > 20 years of growth (Toulmin and Raymond, 2007).

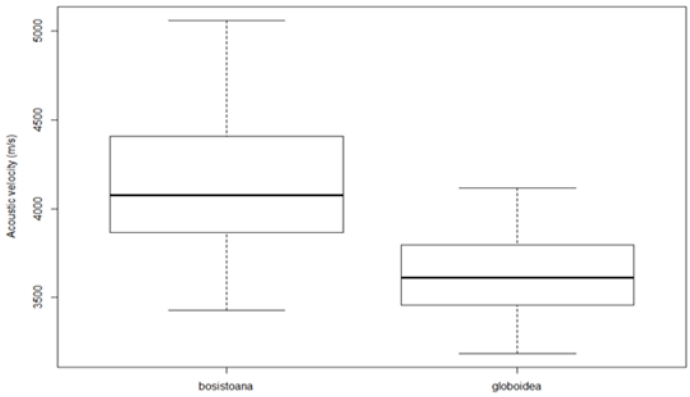

Figure 1. Acoustic velocity of nine E. bosistoana *and nine* E. globoidea *trees in juvenile corewood (within 2.5 cm of the pith at the base of the stem).*

The data also highlights that the large differences in stiffness between the eucalyptus species (Table 1, Table 2) are not primarily differences in density but caused by diverse microfibril angles (Figure 1). Therefore, the specific MoE, i.e. the MoE normalised for density, appears to be worth considering as high densities make building materials unnecessarily heavy and might contribute to gluing issues.

A further fact to consider is the variation of the properties within species. The genetic gains in a breeding programme are directly influenced by the variation. In corewood, density generally has a much lower coefficient of variation than microfibril angle (Table 2). Therefore, any selection for stiffness should preliminarily be based on microfibril angle rather than density as both traits are of similar heritability.

3.2. Density

The density of the timber also contributes to the stiffness. However, in corewood, where the microfibril angle is high, its influence is small (Walker, 2006). Exceptionally stiff timber, never the less, is characterised by both, a low microfibril angle and a high density. On the contrary, building materials should not be unnecessarily heavy, favouring lower density species (Ozarska, 1999). Processing has also been claimed to be easier for species with moderate density. Considering the eucalypts with relevance in a NZ context, the non-durable species *E. fastigata*, *E. nitens* and *E. regnans* and, to a lesser degree, *E. globoidea* fulfil the criterion of moderate density (Table 1). However, they do not provide the stiffest timber.

Typically the density also changes within trees, with juvenile corewood being less dense (McGavin et al., 2015). This could be an advantage when considering the production of rotary peeled veneers from a young resource of high density species with spindle-less lathes. For example the dry density of mature *E. bosistoana* is 1100 kg/m^3, considerably higher than at age 4 (875 kg/m^3) (Table 1, Table 2). This radial variation in stiffness within a tree is larger than that between trees. The former can be exploited by harvesting young trees. The latter could be influenced by breeding. However, although the heritability of density is typically high, the variation in density is low (Table 2) making large gains unrealistic (Apiolaza, 2012). Therefore, the density of a eucalyptus resource appears to be controlled best by species choice. It might be possible to change the density of a eucalypt resource by creating hybrids between high and low density species.

3.3. Growth-stress

Growth-stresses have been identified as a major factor reducing veneer yields. Whichever species is chosen, growth-strain significantly reduces veneer yield and quality due to end-splitting. Technological remedies such as stress release by long heat treatments have not proven to be economically viable and are an ongoing cost.

We have shown that it is possible to reduce growth-strain through genetic selection (Davies et al., 2015). This would remove growth-stresses from the resource making costly technical remedies obsolete. Four species are currently screened for growth-strain (under the SFF programme 407602). It is possible within 2-3 years to cull the breeding resource of high growth-strain material using the ‘splitting’ test at age 2 (Chauhan and Entwistle, 2010). More expensive assessments (strain gauges / peeling) using older trees are also possible. What still needs to be determined is the acceptable level of growth-stress in a log. This threshold would provide a target for lowering growth-stress by genetic selection. The threshold could be established in a peeling trial with logs of predetermined growth-stress.

Alternatively, logs of an unimproved resource could be segregated by growth-strain. This would require a quick and cheap assessment of growth-strain which, at this point, does not exist. Preliminary, lab-based experiments indicate that it might be possible to measure the growth-strain in solid wood by infrared spectroscopy. However, it remains to be seen if these measurements can be transferred into an industrial environment.

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NON-DESTRUCTIVE ASSESSMENT OF NATURAL DURABILITY: A U.S. PERSPECTIVE

Abstract Naturally durable heartwoods produced by some wood species remain commercially important in the United States, but there are few standard methods for classifying durability. Changes in the characteristics of second growth timber and increasing imports of species with durable reputations suggest the need for a non-destructive method for rapidly assessing durability. The potential for using Fourier Transform Infrared Spectroscopy (FT-IR) was explored on Alaska yellow cedar (*Callitropsis nootkatensis*) heartwood. FT-IR was capable of detecting carvacrol, a major extractive constituent of this species and further work is underway to refine the process.

1. INTRODUCTION

The presence of high levels of lignin makes wood one of the most durable cellulosic materials (Zabel and Morrell, 1992). Lignin is an extremely recalcitrant polymer as evidence by its resistance to degradation in the humic acid fraction of soil. At the same time, lignin does not render wood immune to decay; wood is still a biological material that is susceptible to degradation when used under adverse environmental conditions. While dead sapwood is nearly universally susceptible to degradation, some wood species have evolved to produce heartwoods containing chemicals that are exceptionally resistant to biological degradation (Scheffer and Cowling, 1966; Taylor et al., 2002). In principal, more durable heartwood should allow a tree to stand for a longer period of time, thereby increasing the probability that it will continue to reproduce longer than its competitors. Humans have long taken advantage of this durability for house and marine construction and this preference for durable timbers has even driven deforestation in some parts of the world, notably the Levant where the famous Cedars of Lebanon were nearly wiped out by over-harvesting (Graham, 1973).

Durable woods also found widespread use in the United States as the population expanded across the continent. The American chestnut (*Castanea dentata*) was widely used in buildings in the eastern part of the country until it was nearly wiped out by the chestnut blight. Farmers in the centre of the country used naturally durable black locust (*Robinia pseudoacacia*) for fence posts, southerners used bald cypress (*Taxodium distichum*) in buildings, and when settlers finally reached the Pacific Coast they found vast quantities of naturally durable western red cedar (*Thuja plicata*) and coast redwood (*Sequioa sempervirens*). Until the late 1800s, naturally durable woods were the only practical option for prolonging the useful life of a structure. The nearly simultaneous development of synthetic wood preservatives and the methods for effective wood treatment ushered in a period of substitution of naturally durable woods with synthetically protected materials (Graham, 1973). These developments coincided with a rapid growth in infrastructure that created an unprecedented demand for materials that could not be met by naturally durable wood alone.

Despite the emergence of preservative treatments, naturally durable woods still enjoy a sizable regional market. Public concerns about the use of chemicals of all types have encouraged a resurgence in interest in the use of naturally durable heartwoods.

As a biological material, heartwood durability can vary widely within a given tree and between trees (Hillis, 2012; Scheffer and Cowling, 1966). This variability is problematic, but most countries have dealt with this issue by creating durability classification systems. For example, the European Union and the Australian/New Zealand standards both divide materials into classes based upon combinations of field and laboratory studies (CEN, 1994a, 1994b; Standards Australia, 2005). The inherent variability of heartwood makes these classifications difficult, but they provide consumers with some idea about performance expectations. There is no comparable system for classifying natural durability in the United States although there are a number of field test sites and voluminous laboratory data on a variety of domestic and imported species (Morrell et al., 1999; Woodward et al., 2011).

The approach taken by wood users in the U.S. is much less formal. Initially, many universities, along with the U.S. Forest Products Laboratory, established field trials of posts of commercially important wood species. Data from these tests, along with practical field experience with actual commodities, shaped the durability reputations of the various wood species. Only a limited number of these sites remain active. There is no systematic assessment of any changes in durability, nor are there consistent assessments of species imported into the U.S. Instead, many users of naturally durable wood species will assess durability using the laboratory soil block test described in American Wood Protection Association Standard E10 (AWPA, 2016). This test exposes small cubes of the test wood to various brown and white rot fungi for 12 to 16 weeks and uses mass loss as the measure of decay resistance. The results can then be used to characterise durability; however, this standard provides no guidance concerning durability categories. Many researchers use a scale described in ASTM Standard D2017 (Table 1) which is also a soil block test used for assessing natural durability for categorising various decay resistance classes as follows (ASTM, 2005):

Table 1. Durability classes according to ASTM D2107 (2005)

Mass loss (%)	Durability rating
0-10	*Highly resistant*
11-24	*Resistant*
25-44	*Moderately resistant*
>45	*Slightly or non-resistant*

This scale is often used to classify materials; however, there are no specific rules or regulations in the U.S. around making durability claims. More importantly, ASTM Standards must be reaffirmed every five years or they are removed. This Standard was not reaffirmed and is therefore not valid.

Durability is also evaluated in various field sites using either small stakes, dimension lumber or full-scale posts (AWPA, 2016). There are also standards for assessing durability using these materials; however, there are no criteria for classifying durability.

The lack of credible standards for classifying durability would, by itself, not be a problem if the market for these materials was stable with only a limited number of species and a consistent resource. However, that is not the current situation.

One aspect of natural durability that is changing is the resource. The perceived durability of most wood species used in the U.S. originated from field trials performed in the early part of the 20th century using materials obtained from natural forests, often including materials cut from old-growth timbers. There is increasing recognition that wood originating from more intensively managed forests can have very different properties. Trees in managed forests typically grow more quickly which can result in higher percentages of juvenile wood. There is also increasing evidence that the heartwood cut from rapidly growing second growth trees is less durable than that cut from older trees. In the U.S., second growth coastal redwood, bald cypress and Port Orford cedar have also shown evidence of reduced heartwood durability (Ajuong et al., 2014; Clark and Scheffer, 1983; Jones et al., 2014). It is important to note that this trend is not evident in all species as reported for western red cedar (Freitag and Morrell, 2001). Other studies suggest that heartwood extractives contents are lower in second growth materials (Haupt et al., 2003).

The second change in the use of naturally durable species is increasing substitution with so-called secondary species. This is less of an issue in native species, but a number of naturally durable species are imported into the U.S., especially from Asia and South America. Declining supplies of these species have encouraged a search for alternative durable species. The potential durability of these species is typically based upon prior experience in the country of origin coupled with assessments using AWPA E10 soil block tests on a limited amount of material. This test is reasonably aggressive, but applying the results can be problematic because the wood is often obtained from within a limited geographic area that may not be representative of the overall species.

The changing quality of the existing supply of the naturally durable heartwood resource coupled with the need to classify the durability of secondary species has created a need for a method to rapidly assess durability. Laboratory decay tests take months to complete and are only useful if the sample size is representative of the population. Extractive content is generally correlated with durability; however, developing these data is time consuming and requires a considerable amount of effort. Both soil block and extractives content assessments are also destructive. The changing nature of the durable heartwood resource will make it increasingly important to identify rapid, non-destructive methods for assessing the relative durability of these materials. While there are a wide array of non-destructive tools for assessing other aspects of wood quality, durability assessment requires some ability to detect the levels of extractives in the wood. Two approaches that have merit for this approach are Near Infra-Red Spectroscopy (NIR) and Fourier Transform Infrared Spectroscopy (FT-IR) (Leinonen et al., 2008; Taylor et al., 2008; Gierlinger et al., 2003).

Near infrared examines the spectra between 700 and 2500 nm. This region produces a complex spectra for wood that, taken alone, would be difficult to use to delineate wood properties; however, principal components analysis can be used to examine patterns within the spectra and these patterns can then be used to infer differences in properties. NIR has been used to estimate density, mechanical properties, and a range of other properties. It has been examined for assessing heartwood decay resistance with mixed results. While there appears to be some relationship between NIR and decay resistance, a substantial amount of data will be required to develop acceptable predictive models.

FT-IR is more precise and provides more basic information on the chemistry of specific wood components. Infrared radiation activates/excites the sample molecules to determine the presence of fundamental molecular vibrations that are characteristic of a chemical compound or class of compounds. The resulting spectra are extremely complex, but the use of Fourier transformation makes the spectra more meaningful. FT-IR spectroscopy, also known as the mid infrared, detects functional groups of compounds at the mid infrared region of 4000 cm^{-1} to 400 cm^{-1} (Stuart 2004). Compared to other infrared techniques such as Raman and near-infrared spectroscopy, FT-IR spectroscopy is more readily available in many analytical laboratories. Several applications, combined with multivariate data analysis, have been explored for qualitative and quantitative determination of wood properties including lignin content, as well as chemical changes during and after treatment (Ajuong and Breese 1998, Pandey and Pitman 2003, Rodrigues et al. 2005, Rana et al. 2010, Fabiyi et al. 2011, Shangguan et al. 2014).

FT-IR is commonly used to assess changes in wood under-going ultra-violet light degradation; it has been used to examine reactions between wood and various additives and a range of other applications (Schauwecker et al., 2013). The advantage of FT-IR is that it can be used to identify more specific changes in wood chemistry. The disadvantage is that the data processing is much more complex and not yet suitable for routine analysis. However, data processing capabilities continue to improve and further refinements in instrumentation could make FT-IR or NIR feasible for routine evaluation of durability.

In practice, these techniques would be applied to lumber being produced at mills. A board would pass under a scanner that would capture the IR spectra and then process this signal to determine if the board could be classified as durable. This system could be used to identify boards with low extractive contents so that they could be removed from the product mix. This would reduce the risk of poorly performing materials diminishing the reputation of a given species. Alternatively, the system could be used to identify high extractives content boards that would be expected to provide exceptional performance. In either case, the system would not need to be especially precise since it would be selecting materials from the far ends of the extractives spectrum and rejected boards could still have a market.

Before either of these techniques is applied to wood, a considerable amount of work will be required to calibrate the system for a given species. The goal of our work is to explore the potential for using FT-IR for assessing the durability of Alaska yellow cedar (*Callitropsis nootkatensis*). Alaska yellow cedar is native to western North America along the coasts of southeast Alaska and British Columbia extending as far south as northern California (Sturrock 2010). The high strength and excellent durability of the wood of this species makes it suitable for a variety of exterior applications (Grace and Yamamoto 1994, De Groot et al. 2000, Hennon et al. 2000). Alaska yellow cedar uses include decks, play structures, poles, furniture and totem poles for indigenous peoples of coastal North America. This species is also a popular choice in Japan for building temples and teahouses due to its termite resistance.

The durability of Alaska yellow cedar heartwood is related to its extractives content (Barton 1976, Taylor et al. 2006). Alaska yellow cedar contains large amounts of tropolones, including nootkatin, as well as carvacrol, a terpenoid (Kelsey et al. 2005, Manter et al. 2007). Carvacrol has been found to be an effective control for arthropod pests including mosquitoes and fleas (Anderson and Coats 2012).

2. MATERIALS AND METHODS

2.1. Sample collection and preparation

Fifteen Alaska yellow cedar (*Callitropsis nootkatensis* (D. Don) Oerst. Ex D.P. Little) (YC) boards measuring 80 x 130 x 200 mm (3-3/4” x 5-3/4” x 8’) were provided by a sawmill in British Columbia, Canada. No obvious colour differences were observed between the heartwood and sapwood. One board was selected randomly for this study, while the rest were used for a separate durability study. The lumber was cut to smaller strips along the radial face (15 x 90 x 140 mm, r x t x l). These strips were further divided into five subsamples (15 x 15 x 140 mm) that were conditioned for one month at ~20°C and 65% relative humidity before being cut into 15 mm cubes.

2.2. Extractives-free wood blocks

Thirty selected cubes were used to prepare extractives-free wood using the soxhlet extraction method following ASTM Standard D 1105-96 (ASTM, 2013) as modified by Kirker et al. (2012). Blocks were conditioned at room temperature (20-23°C and 30% relative humidity) for a week before obtaining the initial weight. Six blocks from each radial strip were retained as the unextracted control samples. The remaining 18 blocks were extracted in 320 mL of 95% ethanol–toluene (2:1 v/v) in a soxhlet for 6 h at 60°C for removal of waxes, fats, some resins, and wood gums. The samples were then rinsed with 95% ethanol and air-dried overnight. Once dried, blocks were extracted again with 320 mL of 95% ethanol for 6 h at 60°C. The samples were then drained, washed with 95% ethanol and air-dried overnight. The blocks were boiled in a hot water bath for 8 h at 100°C for removal of tannins, gums, sugars, starches and colouring matter (ASTM, 2013). Blocks were then washed with hot distilled water and air-dried overnight. Extracted blocks were conditioned at room temperature for one week and weighed to determine mass loss due to extractive removal. Six blocks representing each radial face were ground to pass a 60 mesh screen and then sealed inside air-tight bags that were stored in the dark at 5°C until used. The remaining wood blocks were used for a separate durability study.

2.3. Carvacrol preparation

Carvacrol (Sigma-Aldrich, 99%) was diluted in ethanol (Sigma-Aldrich, ≥99.5%) to produce concentrations of 0%, 1%, 3%, 5%, 10%, 25%, 50%, and 100% (wt/wt basis). All samples were placed into 4 ml glass vials that were stored in the dark at 5°C until used.

2.4. Collection of IR spectra

FT-IR spectra of the powdered samples of extracted and non-extracted Alaska yellow cedar were measured by direct transmittance using the KBr pellet technique on a Nicolet iS50 spectrometer (Thermo Scientific, USA). One to two drops of a given concentration of carvacrol was applied to the wood powders. These powders were allowed to dry for 1 to 2 h at room temperature prior to FT-IR analysis. Powders were then mixed with potassium bromide (KBr) to approximately 0.5-1.0 % wood and then compressed at about 16 Mpa to form pellets. A background spectrum was acquired prior to wood analysis using only potassium bromide to exclude signals that were not relevant to the sample. Each sample was scanned 32 times at a resolution of 4 cm^{-1}. The pellets were made, then broken up, mixed and recast/compressed three times. The resulting spectra were averaged to produce a composite spectrum representing the entire sub-sample.

2.5. Data processing and analysis

Spectral analysis was performed using OMNIC software version 9.2 (Thermo Fisher Scientific Inc.). A baseline was constructed by connecting the lowest data points on either side of the peak and then smoothing the curve. A vertical line from the top of the peak to the baseline gave peak height, and these values for extractives and carvacrol associated bands were divided by the carbohydrate reference peaks to provide relative changes in the composition of the extractives and carvacrol components relative to each other. Bands on the FTIR spectra were assigned to structural components on the basis of previous studies (Table 2).

3. RESULTS AND DISCUSSION

3.1. Unextracted and extracted samples

Changes in the spectra between extracted and unextracted samples were observed in several bands with prominent differences at the fingerprint region (1800 to 600 cm-1) (Figure 1). Strong hydrogen bond (O-H) stretching absorption at 3417 cm^{-1} was observed in both extracted and non-extracted samples in the functional group region (4000-1800 cm^{-1}) (Figure 1a). This band is characteristic of lignocellulosic materials (He et al., 2007). Another prominent band around 2918 cm^{-1} was associated with C-H stretching absorption.

Table 2: FT-IR bands related to wood extractives found in the Alaska yellow cedar heartwood.

Peak (cm^{-1})	**Reference peak (cm^{-1})**	**Description**	**Associated wood compounds**	**References**
1734	1730	C=O stretching vibrations produced by ester carbonyl	Fat, wax or esterified resin acids	Zhou et al. 2015
1650-1600 (broad shoulder)	1600	C=C stretching or aromatic ring deformation	Aromatic compounds, phenolic group	Zhou et al. 2015, Pandey & Pitman 2003
1633	1633	Olefinic double bond	-	Zhou et al. 2015
1510	1510	Deformation vibration within benzene rings	Aromatic compounds	Zhou et al. 2015
1266	1271	Carbon single bonded oxygen	-	Zhou et al. 2015
808	811	Out-of-plane CH wagging vibrations	Carvacrol	Schulz et al. 20015

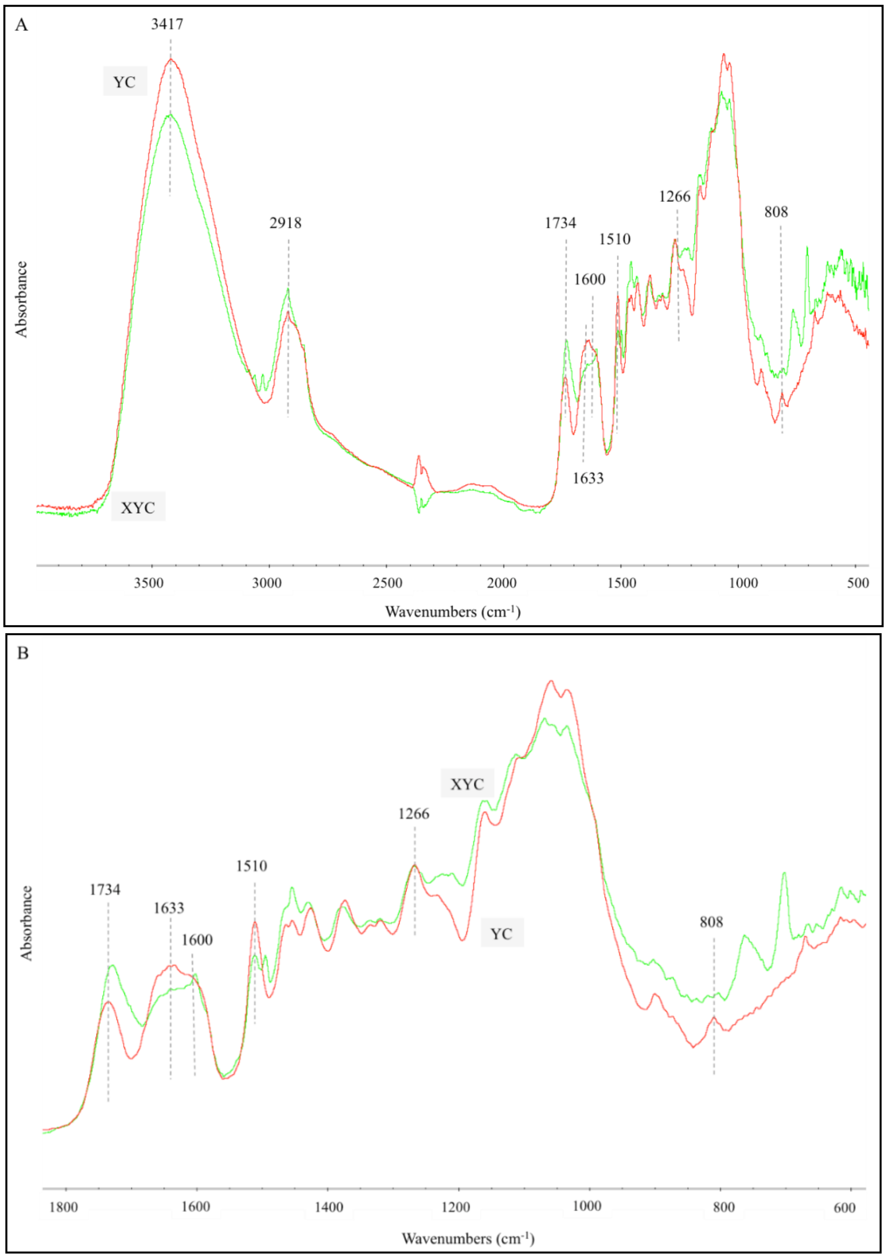

Figure 1. Comparison between FT-IR spectra of non-extracted (YC) (red) and extracted (XYC) Alaska yellow cedar (green).

The 1800 to 600 cm^{-1} region showed the greatest evidence of unique characteristics or 'fingerprints' that might be used to differentiate between materials (Figure 1b). A strong peak was observed at 1734 cm^{-1} that corresponded to C=O bonds typical of non-conjugated ketones and conjugated carboxylic acids in hemicellulose and lignin. Similar findings have been reported previously with Alaska yellow cedar (Moore and Owen 2001).

Previous researchers suggested that bands related to wood extractives occurred at 1730 cm^{-1}, 1633 cm^{-1}, 1600 cm^{-1}, 1510 cm^{-1} and 1271 cm^{-1} (Table 2) (Pandey and Pitman 2003, Nuopponen et al. 2003, Colom and Carrillo 2005, Schauwecker et al. 2013, Mattos et al. 2014, Zhou et al. 2015). These peaks, with slight shifts in wavenumber position, were all observed in our samples except the 1600 cm^{-1} peak that was present as a broad shoulder (1650 to 1600 cm^{-1}). There was a strong peak at 1510 cm^{-1} on the unextracted sample, but this peak was cleaved in the extracted samples. This band corresponds to deformation vibration within benzene rings that are found in aromatic compounds such as those present in phenolic groups of extractives. These results suggest the loss of some phenolic extractives after extraction.

3.2. Carvacrol treatment

Adding carvacrol to the extracted Alaska yellow cedar produced several notable differences in FT-IR spectra, especially on the related extractives bands (Figure 2). Peak intensity increased in the bands at 808 cm^{-1}, 1510 cm^{-1} and 1617 cm^{-1} with higher carvacrol concentrations, except for samples treated with 10% or 25% carvacrol, which appeared to have lower intensities than the other treatments (Figure 3). The reasons for these variations are unclear and these tests are being repeated.

Carvacrol contains both phenolic OH and aromatic rings. The presence of these groups was supported by the presence of two strong peaks around 1600 cm^{-1} and 1630 cm^{-1} on samples treated with 50% or pure carvacrol (Figure 2). The band at 808 cm^{-1} corresponds to out-of-plane CH wagging vibrations. Schultz et al. (2005) reported similar results on carvacrol using ATR FT-IR analysis. Our samples showed strong peaks with increasing carvacrol concentrations, suggesting that the relationship between peak height and carvacrol concentration could serve as an indirect measure of durability (Figure 2).

Extractives generally exist at levels ranging from 1-5% of the total wood mass (Hillis 1987). The sensitivity of FT-IR allows differences to be detected using the peak location and intensity. The sensitivity is illustrated by the ability to detect as little as 1% carvacrol in our samples (Figures 2 and 3). An alternative approach to durability prediction might be to compare possible extractives bands with bands from more stable wood components that are always present such as cellulose or hemicellulose.

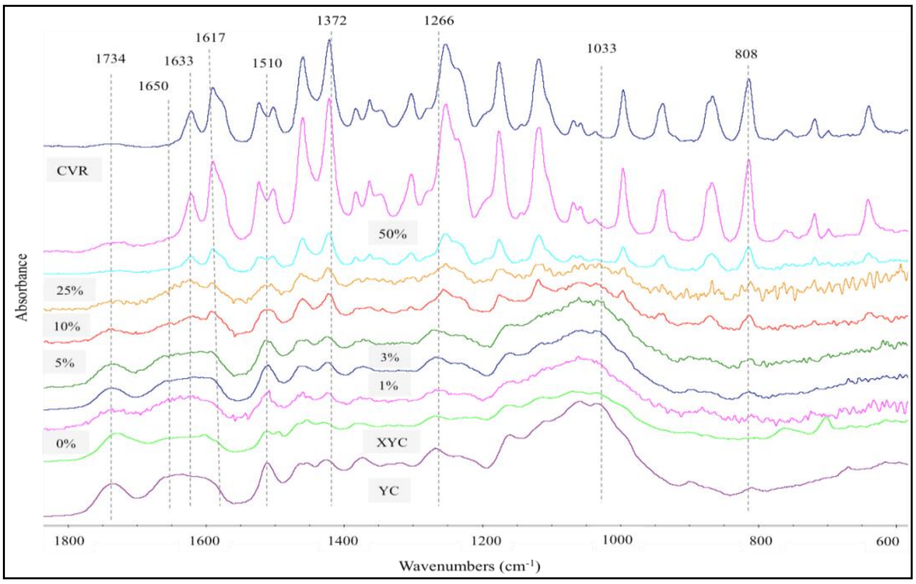

Figure 2. FT-IR spectra of non-extracted (YC) and extracted (XYC) Alaska yellow cedar and non-extracted treated with 1 to 50% carvacrol (CVR) in ethanol at the 1800 – 600 cm^{-1}.

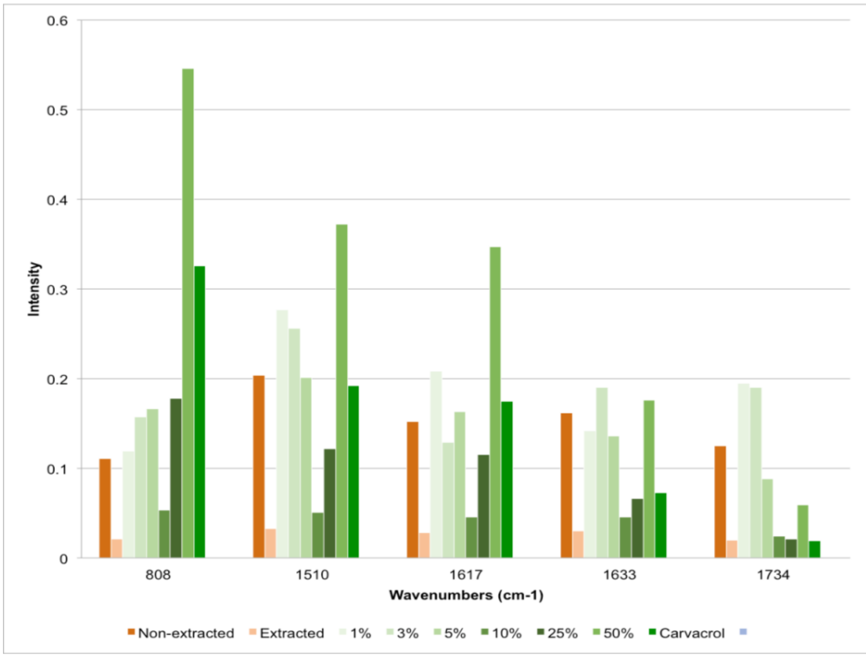

Figure 3. Intensity of unextracted, extracted, and extracted Alaska yellow cedar treated with various concentrations of carvacrol at bands related to extractives.

The bands related to extractives and carvacrol were compared against a band at 1372 cm^{-1} corresponding to C-H deformation in cellulose and hemicellulose (Xu et al. 2013) (Figure 4). The 808 cm^{-1}/1372 cm^{-1} (A808/A1372) ratio increased with increased carvacrol concentration, although no differences were observed between ratios for non-extracted and extracted samples. The peak ratios at 808 cm^{-1}/1372cm^{-1} (A808/A1372) had strong associations with carvacrol and cellulose, respectively (Schulz et al. 2005). Ratios were less than 0.5 in almost all the samples except those with more than 5% carvacrol. Interestingly, samples with 10% carvacrol had ratios approaching 2. In contrast, no meaningful trends were detected for ratios of bands at 1617 cm^{-1} (A1617/A1372), 1633 cm^{-1} (A1633/A1372) and the aromatic 1510 cm^{-1} (A1510/A1372), suggesting that further analysis may be needed through pretreatment of data using derivatives or deconvolution to determine if there are relative differences between peaks at different carvacrol levels. These pretreatments allow separation between overlapping peaks and help distinguish between functional groups with different structural features.

Comparisons were also made using the ratios of aliphatic to aromatic peaks at wavenumbers 2918 cm^{-1} and 1510 cm^{-1} (A2918/A1510) to determine if extractives values differed between treatments. The ratios for non-treated and extracted samples treated with ethanol (0% carvacrol) approached 0 indicating that no aromatic and aliphatic compounds were present after extraction. Overall, the ratio increased with increased carvacrol concentrations, except for the 10% carvacrol (Figure 4). Associations between peak ratios and carvacrol content may represent another approach for using FT-IR to qualitatively assess carvacrol content and, indirectly, wood durability.

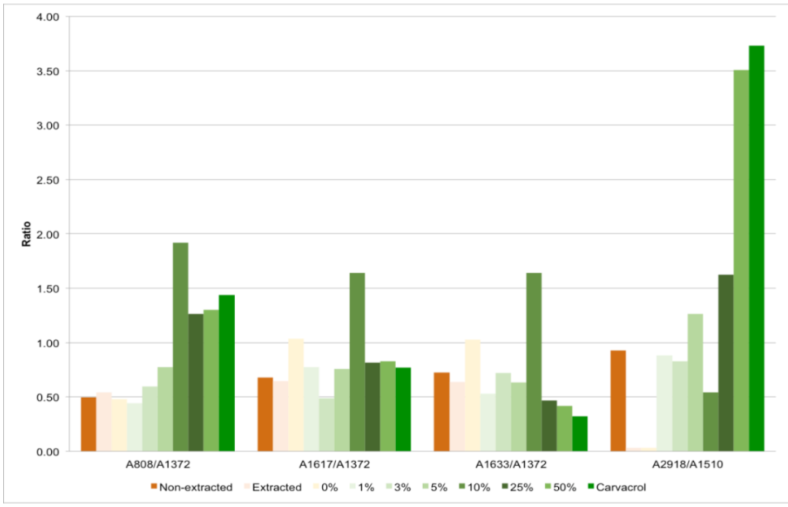

Figure 4. Ratio of CH wagging vibrations to cellulose and hemicellulose peaks (A_{808}/A_{1372}), carvacrol related bands to cellulose and hemicellulose (A_{1617}/A_{1372}) and (A_{1633}/A_{1372}), and aliphatic to aromatic (A_{2918}/A_{1510}).

4. CONCLUSIONS

Changes in the naturally durable heartwood resource and the use of new species suggest the need for a non-destructive method for assessing durability. Preliminary trials suggest that FT-IR has the potential to sort durable materials based upon specific heartwood extractives levels. Further trials are planned using both FT-IR and NIR.

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DETERMINING THE NATURAL DURABILITY OF EUCALYPTS IN AUSTRALIA

Abstract There is wide variation in heartwood natural durability between eucalypt species, which is mostly governed by polyphenol composition. Polyphenols can degrade (polymerise) with age in the inner heartwood of trees which reduces natural durability. In young eucalypt trees, timber density can be a useful predictor of natural durability within a species, but it is less useful when trees are at least 30-50 years old. The development of standards for natural durability is discussed, along with the trials that influenced the assignment of durability classes for each timber species when exposed in-ground, above-ground, and against lyctine beetles, termites and marine borers. Accelerated test methods for determining natural durability are also discussed.

1. EXTRACTIVES

The natural durability of eucalypts is caused by extractives, and a wide range of compounds are involved (Da Costa et al., 1962; Da Costa, 1975). Back in the 1950-60s, Rudman published numerous papers to show that the majority of the compounds responsible for decay resistance in eucalypts were polyphenols (tannins). These compounds were soluble in methanol, often aided by weak alkali conditions. In contrast, the compounds responsible for termite resistance were ether soluble (Rudman, 1964).

Many of the important extractives are coloured, so that in some non-eucalypt species a deeper colour equates to increasing natural durability (Gierlinger et al., 2004; Bhat et al., 2005; Kokutse et al., 2006). Within the eucalypts there is also a trend between species where pale coloured eucalypts such as the generic 'Victorian ash' or 'Tasmanian oak' (*Eucalyptus regnans*, *E. delegatensis* and *E. obliqua*) have low durability while the red and deep brown coloured eucalypts (e.g. *E. tricarpa*, *E. bosistoana*) have high natural durability. However, Rudman (1964) found that within a species such as *E. marginata* and *E. diversicolor* there were too many exceptions for colour to be a useful indicator of natural durability. The problem appeared to be that while increasing polymerisation of polyphenols could give a deeper colour, that polymerisation also made those extractives less fungitoxic (Rudman, 1964).

2. SAPWOOD

The sapwood of all species is non-durable, and in pale coloured eucalypts it can be difficult to delineate the sapwood/heartwood boundary. The pH of heartwood is lower than sapwood, so its location can be determined using an indicator such as methyl orange (dissolve 0.1g methyl orange in 100 ml of 80% ethanol, lasts for years. Brush on fresh surface in the sapwood to heartwood direction) (Zosars and Kennedy, 1994). In larger trees, the sapwood of some eucalypts such as *Corymbia maculata* is thick, at 25-35 mm, while for others such as *E. pilularis* it is thin at 7-15 mm. While the heartwoods of both have similar natural durability, the same diameter post of *C. maculata* will obviously not last as long as *E. pilularis* if untreated simply because of the difference in sapwood thickness. The untreated sapwood of many eucalypts is also susceptible to lyctine beetles (powder post beetles) which can turn the sapwood into powder usually within 5-10 years. Lyctine susceptibilities are provided in AS 5604: 2005, with some further information for a few species provided by Cookson et al. (2009).

The sapwood of most timber species can be treated, and while a thick sapwood band is preferable from a treatment perspective (and radiata pine is a favourite of the treatment industry), some eucalypt sapwoods treat better than others. So for example, spotted gum and blackbutt poles and piles are usually treated in the same charge, and in a marine trial treated blackbutt poles performed better against marine borers than spotted gum piles, even though they had much thinner sapwood bands (Cookson, 2007).

If eucalypts are being grown for vineyard post production, then as well as natural durability, the propensity for splitting should be examined. Eucalypts posts would usually be air dried (not kiln dried) under hessian to slow drying rates and reduce splitting, and in a recent study species with excessive splitting under such a regime were *E. globulus, E. pilularis*, and *E. dunnii*, while those with low levels of splitting were *E. grandis, E. cladocalyx* and *C. 78aculate* (McCarthy et al., 2005; Mollah et al., 2006). Splitting could be another factor to look at in tree breeding. Also, the propensity to split can change as trees get older, so that for example *E. grandis* poles have an increased tendency to split compared to posts.

Due to the high proportion of sapwood, and the immaturity of the heartwood, vineyard posts of even naturally durable species need to be treated to ensure long term durability. An example of what can go wrong was with Australian native cypress pine (*Callitris glaucophylla*), which has durable heartwood (Johnson et al., 2006). Young trees were cut to produce vineyard posts, and because the sapwood is unusual in that it is difficult to treat, they were sold untreated. There were many court cases involving vineyard owners and post suppliers when the posts fell down after only 4-6 years of service. An alternative would be to grow older trees that can then have the sapwood removed, as long as there is still enough timber to make a post. Also, the remaining heartwood should have natural durability more similar to that found in mature trees, which is where tree breeding and selection can help.

3. HEARTWOOD

The most durable region in eucalypts is the outer heartwood of butt logs. Inner heartwood is usually less durable, and Rudman (1964) described the inner heartwood as being the inner one-third of the whole of the heartwood. There are two reasons for the lower durability. One is that eucalypts typically produce juvenile heartwood during their first 8-12 years at least (Nelson and Heather, 1972; Wilkes, 1984), and in this heartwood lower amounts of extractives are formed (Rudman, 1964). This inner core, or pith, is often degraded in older trees leading to ‘piping’ after it has been decayed and eaten by termites. They often become important hollows for native animals as well (Adkins, 2006). The second reason for lower durability of inner heartwood is that the polyphenols produced in mature heartwood gradually alter, which, due to age, shows up first in the inner heartwood. One theory by Rudman (1964) was that oxidation of polyphenols released acetic acid which then increased polymerisation of the remainder of the polyphenols, making them less durable.

Wood density tends to give a good indication of natural durability, especially when comparing between hardwood species (Chafe, 1989). Within eucalypt species, a correlation between density and durability appears to apply for trees of less than around 25 years of age (Cookson and McCarthy, 2013), but for older trees clear evidence of a correlation is lacking (Rudman, 1964; Johnson et al., 1996; Cookson and McCarthy, 2013). Bush et al. (2011) found good correlation for eight year old *E. cladocalyx* trees where those with higher basic density and higher methanol extractive contents were less susceptible to decay.

Producing durable heartwood has a number of advantages, such as being a natural material that is less likely to cause environmental problems. Another advantage from a preservative treatment perspective is that most heartwood cannot be properly treated, unlike sapwood. If the heartwood is non-durable then the percentage of heartwood in a treated piece of timber needs to be restricted, especially under the Australian standard specifications, although this is not policed adequately. Therefore, if the heartwood is already durable, more of it can be included within treated products. For example, slash pine has an advantage over radiata pine in meeting H2 treatment requirements in Australia, as its heartwood is termite resistant so does not require penetration, only the sapwood. Whereas radiata pine does require heartwood penetration, which is almost impossible to achieve in most cases, so that treatments either do not meet specification (other than for the newer H2F treatments) or the percentage of heartwood must be limited.

A long term exposure trial that ran for over 33 years has shown that properly CCA-treated (perfectly treated) radiata pine sapwood performs better than all naturally durable timbers of similar size (Cookson, 2004). However, a problem for treated timber as mentioned above can be the impenetrability of heartwood, so that in practice CCA-treated pine sleepers in Australia can contain more than half of their section as heartwood, and may therefore fail after 5-15 years. New, naturally durable eucalypt sleepers last longer.

4. STANDARDS

Before 2003 in Australia, only in-ground natural durability ratings were provided, along with lyctine borer sapwood susceptibilities. AS 5604:2003 was a new standard, where all information for natural durability was assembled into the one document. It also introduced information on termite resistance under H2 conditions (house framing) and above ground decay durability, while the 2005 revision added marine borer ratings as well. During the 1950s, the in-ground ratings were based upon the experience of foresters, lab testing and a limited amount of field testing. In 1968-69 an in-ground trial of 77 timber species was installed at five sites around Australia to verify these ratings (Thornton et al., 1983). The stakes were 450 x 50 x 50 mm outer heartwood specimens, and at each site there were 10 replicates with two obtained from each of five different trees. The trees were sourced from several regions where the species grew naturally. The last and final inspection was after 33-36 years (Cookson, 2004), and most of the ratings already in place were validated, with only a few changes needed in the 2005 revision.

For the above-ground decay ratings, most information came from Queensland Forest Service where 39 timber species were tested, mostly Queensland species (Cause, 1993; Francis and Norton, 2005). The test specimens were L-joints placed at 11 different sites, and even though the specimens were 35 x 35 mm square it was the tenon which was 11 mm thick that was inspected and rated. It is generally known that timbers above-ground will last much longer than in-ground, often at least twice as long. Much of this information was synthesised into the TimberLife Educational Software Program, which can be found at the Wood Solutions website[1]. More recently, a nine-year flat panel test of six eucalypt species was conducted and some adjustments to ratings made (Cookson and McCarthy, 2013), although these have yet to be incorporated into a revision of the standard. The H3 decay field test is the slowest wood durability test, and recently a series of H3 methods were compared in Australia and New Zealand, and tests faster than the two mentioned above include the ground proximity test, deck test, and the embedded test (Cookson et al., 2014).

For H2 termite resistance, most of that information came from experience, coupled with a few rules such as Class 1 timbers (in-ground) would also be termite resistant, while Class 4 timbers would be non-resistant. There were some field tests as well, such as for pine species (Kennedy et al., 1996; Peters and Fitzgerald, 2004). The tests needed are usually of only 6-12 months duration. A more recent trial showed that termite resistance in eucalypts applies mainly to areas where the termite species *Mastotermes darwiniensis* is lacking, as after one year in an H2 field test five out of six 'resistant' timbers were virtually destroyed (82-97% wood volume lost), with river red gum being the only exception. In comparison, in a trial of the same timber species against *Coptotermes acinaciformis* the mass losses were restricted to 9-29% wood volume (McCarthy et al., 2009). Although not examined, the results would probably be influenced by how much baitwood is included in the test, as it does for boron-

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[1] Wood Solutions TimberLife program, https://www.woodsolutions.com.au/Articles/Resources/TimberLife-Educational-Software-Program

treated wood (Peters and Fitzgerald, 2006). New Zealand does not have any native economically important termite species, although there have been some introductions from Australia of *C. acinaciformis* over the years in imported sleepers and poles (Pearson and Bennett, 2008).

The marine borer durability ratings produced in the AS 5604: 2005 revision arose mainly from a sea trial of 25 timbers at three ports (Cookson and Scown, 2008), an aquaria trial (Cookson, 1996) and experience. Also, any timber not tested but listed Class 4 in-ground, as well as Class 3 timbers also non-resistant to termites, were assumed to be non-durable against marine borers.

5. ACCELERATED TESTING

When testing new timbers for natural durability, it is important to include the mature heartwood of a range of yardstick timbers with known ratings, so that the novel timber species or breeding stock can be placed into proper context. In Australia where there is reduced support for wood durability research, the different yardstick 'trees' could be obtained by buying timber from different timber yards or from different timber packs within the same timber yard. The trials needed to prove natural durability would mostly be similar to those listed for wood preservatives in the AWPC protocols available on the TPAA website.

Still to be resolved, is whether naturally durable timbers placed in laboratory decay tests or termite H2 field tests should first be artificially weathered (leaching, vacuum oven drying) as is done for preservative treated wood. Some preservatives are dissolved in organic solvents, which need to be removed before testing within enclosed containers, while naturally durable timbers are less likely to be detrimental to the testing organisms involved. Conversely, weathering would be a way of obtaining accelerated results, or better comparative results, as the naturally durable timbers will have lost fractions that would be easily lost in service in any case. It can be difficult to separate Class 1-3 timbers in short term fungal bioassays, if not artificially weathered. Table 1 shows the results from a recent soil-block fungal bioassay after 12 weeks incubation, where several mature and naturally durable heartwood timbers had decay above the 3% threshold used to indicate significant decay. Whereas, in an agar tray bioassay of fencing components where there was no artificial weathering, there was no decay of untreated messmate heartwood after 16 weeks incubation (Cookson et al., 2002), suggesting that comparisons in durability bioassays would be even more difficult without weathering. Note however, that agar bioassays are also usually less severe than soil substrate bioassays (need to do a direct comparison of weathered and unweathered blocks).

In tree breeding research, the initial priority is to select those trees that show the best traits for natural durability. The 'formal' tests needed for proving natural durability in comparison to species with established ratings should occur at later stages in the forestry breeding program, after genotypes have already been selected and trees are grown with sufficient mature heartwood for testing. For timber samples produced by core-boring into young trees, often with hundreds of individual trees involved, a bioassay similar to that shown in Table 1 could be considered. Perhaps, the artificial weathering step is not needed, especially if the heartwood is juvenile. Another option would be an in-ground or in-soil 'AFS' test (e.g. Cookson et al., 2000), where the heartwood cores are tested as mini-stakes. Such tests should give results in 6-18 months if conducted in the wet tropics, or within bins of fresh soil housed within an incubation room at 25-28°C. Normally, in-ground stakes are inspected by removing each one, and probing them with a knife to determine the depths of decay. Another option would be simply to 'nudge' each stake without removing it from the ground, and seeing if it breaks under a constant force. Some post trials are inspected by a moderate push against post tops (Lebow et al., 2014), or a 50lb 'pull test' against the tops of the posts (Freeman et al., 2005).

Table 1. Percentage mean mass losses (standard deviations) of six replicate blocks 20 x 20 x 10 mm and H3 weathered (leached then vacuum oven dried) after 12 weeks of exposure to decay fungi.

Timber	Fungus				
	Brown rots				White rot
	Fomitopsis lilacinogilva	*Coniophora olivacea*	*Gloeophyllum abietinum*	*Oligoporus placenta*	*Perenniporia tephropora*
Radiata pine sap	52.9 (8.8)	45.1 (7.7)	61.5 (6.9)	59.5 (10.9)	36.5 (7.3)
Messmate heart	38.0 (2.7)	33.4 (5.1)	33.3 (7.4)	1.8 (2.8)	49.6 (4.5)
Merbau heart	1.4 (0.9)	0.4 (0.1)	0.9 (0.7)	0.3 (0.1)	18.5 (8.9)
Spotted gum heart	12.8 (10.2)	12.4 (14.1)	5.7 (7.7)	1.4 (2.0)	17.4 (20.9)
Jarrah heart	10.8 (3.4)	10.3 (4.2)	1.9 (1.6)	0.4 (0.5)	7.5 (5.1)
H3 CCA P. radiata pine 0.41% m/m TAE	0.6 (0.2)	0.2 (0.1)	0.3 (0.2)	6.2 (4.4)	0.6 (0.3)

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IMPROVING HEARTWOOD QUALITY OF DURABLE EUCALYPTS

Abstract The New Zealand Dryland Forests Initiative (NZDFI) aims to establish a new hardwood forest industry based on naturally durable eucalypts. As a key product, NZDFI has identified sustainably-grown naturally durable posts and poles for the agricultural industry as an alternative to CCA treated pine (Millen 2009). For these products natural durability is essential, but natural durability is also a highly variable trait. To ensure a quality product the variability can be reduced by genetic selection. NZDFI's wood quality research programme addresses the variable performance of the timber through a breeding programme. However, incorporating heartwood quality into a breeding programme is not straight forward and requires a novel approach which is able to cope with the necessary large sample numbers. NZDFI has developed a novel sampling system as well as heartwood quality assessment. This will facilitate a viable hardwood forest industry based on naturally durable eucalypts.

1. INTRODUCTION

Wood is biodegradable. Being biodegradable is a positive attribute when considering the disposal at the end of a product's life. However, susceptibility of wood to biological decay can result in premature product failure. Biodegradation of wood is particularly rapid in moist conditions with ground contact – e.g. for wooden poles. The environment in which wood is used is described by Hazard Classes (NZS3640:2003 2003). The natural resistance of timbers against biodegradation is highly variable. While some timbers decay quickly, others can withstand moist in-ground conditions for a considerable time (Scheffer and Morell 1998, Bootle 2005). This property is referred to as (natural) durability and assessed by various national standards (EN350-1 1994, ASTM 2005, AWPC 2007). Unfortunately, high natural durability is uncommon among tree species and those which are utilised are mostly rare and/or harvested unsustainably (UNEP 2012). As an alternative, the resistance to biological decay of non-durable timber can be improved by modifying the chemical structure of the wood (Hill 2006) or by impregnation with one of the many available preservatives (Eaton and Hale 1993, Richardson 1993, Goodell, Nicholas et al. 2003). The former has only recently been used on an industrial scale and achieves either only lower durability (thermal modification) or is costly (acetylation). The latter has been used extensively for decades but converts the bio-degradable wood into a toxic waste for which often no acceptable disposal option exists (Read 2003, Townsend and Solo-Gabriele 2006, Graham 2009).

Biodegradation of wood is caused by fungi, bacteria, insects and marine organisms.

- Fungal decay (Schmidt 2006)
  Numerous fungi are able to enzymatically decompose the chemical constituents (hemicelluloses, cellulose and lignin) from which wood is made. These fungi use the wood constituents as their energy source. Different types of fungal decay have been described (white-rot, brown-rot, or soft-rot). These differ in appearance and in the type of enzymes that decompose the wood. In all cases the result is a complete loss of structural integrity, i.e. strength. Prerequisites for fungal decay are the presence of free water and oxygen. This implies that all wood in air-dry and anaerobic water-logged conditions is safe from fungal decay. Fungal decay is an important consideration when wood is used in ground contact, for example as posts and poles.

- Sap stain (Zabel and Morrell 1992)
  Some wood-colonising fungi do not have the enzymes required to break down the structural wood cell wall components but can feed on reserve materials (mostly starch) present in sapwood. Therefore, heartwood is not affected by sap stain. These fungi do not compromise the structural properties of wood but do pose a hygienic issue and discolour the wood.

- Bacteria (Greaves 1971, Clausen 1996)
  Bacteria have also been reported to enzymatically break-down wood components. This can occur in oxygen deficient environments. However, the process is slow and does not pose a significant threat to timber.

- Wood-degrading beetles (Peters, Creffield et al. 2002)
  Some beetles, like lyctids or anobiids (e.g. house borer) destroy wood mechanically by chewing. They are not able to feed directly on the cell wall components like wood-decaying fungi. They usually digest the tree’s starch reserves which are present in sapwood only. Some (e.g. ambrosia beetles) rely on symbiotic fungi to break down wood components. As insects do not require the presence of free water sapwood can be prone to attack even when used inside buildings in air-dry conditions. Some ants and other insects can cause similar damage.

- Termites (Shelton and Grace 2003, Ahmed, French et al. 2004)
  Termites also destroy wood mechanically. They, however, can also use wood cell walls as an energy source with the help of symbiotic gut bacteria. Termites usually colonise wood in soil contact but some species can build tunnels to reach wooden structures above ground. Termites are most problematic in tropical/subtropical regions and termite-resistant woods are in high demand for construction in these parts of the world.

- Wood-degrading marine organisms (Eaton, Ampong et al. 1989, Cragg, Pitman et al. 1999, Nishimoto, Haga et al. 2015)

Some molluscs (e.g. Teredinidae - shipworms) and crustaceans (e.g. Limnoriidae - wood lice) use wood as habitat and food. These species need to be considered when wood is to be used in marine constructions like piers. Only few timbers last a significant time in marine conditions.

The natural durability according to the Australian standard "Timber – Natural durability ratings" (AS5604 2005) for NZDFI species is listed in Table 1. These ratings have been determined from timber harvested from old-growth natural forests in Australia, and timber of the same species from other sources, especially short-rotation plantations, can compare unfavourably.

Table 1. Natural durability ratings of NZDFI species according to (AS5604 2005) and heartwood colour (Bootle 2005)

Species	Lyctid suscept. of sapwood	Termite resistance of heartwood	In-ground life expect. (years)	Above-ground life expect. (years)	Life expect. in southern waters (years)	Colour
Eucalyptus bosistoana	*Suscept.*	*Resistant*	*>25*[a]	*>40*	*21 to 40*	*Pinkish pale brown*
Eucalyptus argophloia	*Suscept.*[b]	*ND*	*ND*	*ND*	*ND*	*Orange -brown to deep red-brown*[c]
Eucalyptus quadrangulata	*Not suscept.*	*Resistant*	*15 to 25*	*15 to 40*	*ND*	*Pale yellow*
Eucalyptus sideroxylon	*Suscept.*	*Resistant*	*>25*	*>40*	*41 to 60*	*Dark red*
Eucalyptus globoidea	*Not suscept.*	*ND*	*15 to 25*	*ND*	*21 to 40*	*Pinkish pale brown*

[a] See (Cookson 2004)
[b] See (Cookson, Carr et al. 2009)
[c] See (AWPC 2007)

1.1. Basis for natural durability

The large differences in resistance to fungal decay between timber species is predominately caused by its chemical composition, i.e. the secondary metabolites deposited in heartwood (Hawley, Fleck et al. 1924, Rudman 1963, Schultz, Harms et al. 1995). The effect of wood density on fungal decay is less clear as higher density wood often coincides with a higher concentration of secondary metabolites, known as the ‘extractive content’. It has been reported that density has a positive effect on decay resistance (Wong, Wilkes et al. 1983, Edlund 1998, Yu, Yang et al. 2003, Sehlstedt-Persson and Karlsson 2010, Bush 2011, Cookson and McCarthy 2013, Plaschkies, Jacobs et al. 2014). Increased density has been shown to significantly reduce mechanical damage by insects and marine organisms (Peters, Bailleres et al. 2014). However, these results were based on comparisons between timber species and such large variation is not necessarily present within a species (Cragg, Danjon et al. 2007). Other factors contribute to the natural resistance of wood to biological decay, for example pore size (Peters, Creffield et al. 2002) or permeability (Bush 2011).

In most trees the wood in a stem changes from sapwood to heartwood some years after formation (Beakbane, Mishra et al. 1971, Hillis 1987, Rowe 1989, Taylor, Gartner et al. 2002). The first year rings, closest to the bark, are young and contain some living cells, called parenchyma. This wood is defined as sapwood and contains reserve materials like starch. After a species-specific period of years the reserve materials are removed from the older parenchyma and the parenchyma cells die. Following this transition the tissue is called heartwood and it starts forming at the centre of the stem, while new sapwood continues to be formed closest to the bark. During heartwood formation some species synthesise numerous smaller organic compounds, which are deposited into the wood. These compounds are called heartwood extractives. Heartwood extractives are not a structural part of the wood cell walls, but some of the compounds are coloured or have bioactive properties, which can result in an attractive timber colour and high resistance against biodegradation. Sapwood is never regarded as naturally durable (AS5604 2005) nor is it coloured other than the typical pale brown (Kohl 2012).

Another important change in the wood properties with time is a decrease in permeability. The transport function of the tissue is removed to reduce the risk of embolism by pit aspiration, tylosis or deposition of extractives. This can precede heartwood formation (Ziegler 1968) and is thought to reduce the susceptibility for wood to biodegradation.

1.2. Variability and control of heartwood traits

Within a species variability in wood properties has economic consequences as timber products and wood processing benefit from consistent and adequate properties (Walker 2006). Some of the variation in wood properties is under genetic control, enabling the selection of superior trees, i.e. healthy trees which produce larger quantities of good quality timber. Like other factors, heartwood properties vary between individuals, but variation of heartwood extractives and natural durability within a stem has also been reported. Within-stem variation exists as characteristic spatial pattern as well as random local variations. Environmental parameters have been found to influence this variation, highlighting the need to address heartwood in site-species matching and growth and yield modelling (Sharma, McLaughlin et al. 2014).

1.2.1. Within tree variability of heartwood features

The natural durability of heartwood decreases towards the pith (Sherrard and Kurth 1933, Taylor, Gartner et al. 2002). This is recognised in relevant standards, for example it is stated in AS5604 that:

> "… the inner heartwood (the first few growth rings around the pith), generally, has a lower natural durability than the rest of the heartwood."

The typical radial pattern of heartwood durability is mirrored by the amount of extractives in the stem (Sherrard and Kurth 1933, Taylor, Gartner et al. 2002). Additionally slight increases in heartwood durability were reported with stem height. This is in analogy to wood 'quality' of juvenile pine corewood (Burdon, Kibblewhite et al. 2004), which generally has unfavourable properties for most applications.

Heartwood extractives can also vary considerably in their abundance on a micro scale. For a durable product a homogeneous distribution within cell walls, between cell types (e.g. fibres, parenchyma) and within year rings is desirable (Taylor, Gartner et al. 2002). Conversely a variable extractive content can be the defining feature in the appearance of timbers like *Microberlinia brazzavillensis* (Kohl 2012) or *Dacrydium cupressinum*.

Preliminary results on the distribution of extractives in *E. bosistoana* confirm these general statements for the macroscopic (within stems) and microscopic (within year rings) distribution of extractives.

1.2.2. Genetic control of heartwood features

Previous studies have reported on the variability and the degree of genetic control of heartwood features in various tree species e.g. (dos Santos, Geraldi et al. 2004, Poke, Potts et al. 2006, Bush, McCarthy et al. 2011, Stackpole, Vaillancourt et al. 2011, Denis, Favreau et al. 2013, Miranda, Gominho et al. 2014). The research on within tree variation is limited, however, substantial within species variation in durability has been demonstrated. Although the durability of heartwood from young trees is generally lower than that of old trees, individuals having class 1 durable heartwood at young age have been reported (Palanti, Susco et al. 2010, Bush 2011). Therefore the production of ground-durable posts from young, short-rotation plantations should be possible by selecting a genetically superior resource.

A wide range of extractive contents have been observed in heartwood samples of *E. bosistoana*. Ethanol soluble extractives varied between 1.5% to 15% (wt/wt basis) at age 4½ (McLaughlin 2013, Sharma, McLaughlin et al. 2014), indicating that trees of good durability at a young age can be found.

A recent study on the variability in heartwood traits of hybrid larches reported heritabilities of >0.65 for heartwood diameter and extractive content (total phenolics) (Paques and Charpentier 2015). Genetic gains of 10% in heartwood diameter and phenolics content were achievable. Furthermore, it was reported that the influence of female (European larch) and male (Japanese larch) parents differed between the traits. A good prospect for genetic improvement of *E. cladocalyx* heartwood quantity (%), methanol extractive content and durability was reported (Bush 2011). The data did not indicate unfavourable genetic correlations between growth and durability. Similar results were found for other species.

Another heartwood feature determining the value of the timber is its colour. The genetic control of heartwood colour has been studied for several species (Rink and McBride 1993, Mosedale, Charrier et al. 1996, Gierlinger, Schwanninger et al. 2004, Moya, Marin et al. 2013).

1.3. Chemistry of heartwood extractives

Little is known about the identity of the chemical compounds in heartwood of eucalypts included in NZDFI's breeding programme (*E. bosistoana*, *E. argophloia*, *E. tricarpa*, *E. quadrangulata* and *E. globoidea*). Research on the chemical heartwood compounds of other durable eucalypts has been conducted in the past (Hillis 1991). In recent times the research focus has been on non-durable eucalypts species grown for pulp and paper, for which low extractive contents are desirable (Swan and Akerblom 1967). Chemotaxonomy of eucalypts by heartwood (Hathway 1962) and leaf (Hillis 1966, Hillis and Inoue 1967, Padovan and Manzan 2014) compounds has been explored and bark and root extractives of eucalypts have also been studied (Dayal 1987, Cadahia, Conde et al. 1997, Cadahia, Conde et al. 1997, da Seca and Domingues 2006).

The heartwood compounds within a species are numerous (Rowe and Conner 1979, Hillis 1987), with each molecule having different properties influencing, for example bioactivity (Ohtani, Noguchi et al. 2009, Morris and Stirling 2012), colour (Zavarin and Smith 1962, Balogh and Anderson 1965, Takahashi and Mori 2006) or interaction with glues (Wang 1992). Furthermore the relative proportions of the individual compounds vary within species (Daniels and Russell 2007, Niamke, Amusant et al. 2014), therefore it is important to understand how both the absolute amount of extractives and the extractive composition affect wood properties like durability and colour. As the biosynthesis of the individual compounds is also partly under genetic control (Fries, Ericsson et al. 2000) the possibility exists to further improve wood quality by breeding. A requirement is the identification of the key compounds in the heartwood for the NZDFI species.

Individual extractives from heartwood or other tree tissues can also be of value themselves. Numerous reports are published on natural compounds to be used as natural wood preservatives (Singh and Singh 2012), in medicine or for other applications. For example a compound isolated from *E. globoidea* buds (Globoidnan A) has been found to be an inhibitor of HIV integrase (Ovenden, Yu et al. 2004) Recently the variability in the essential oils extracted from *E. bosistoana* leaves has been reported (Bouzabata, Bighelli et al. 2014). Tannins from eucalypts are other compounds of interest (Cadahia, Conde et al. 1997).

1.4. Measuring heartwood volume

The relative amounts of sapwood and heartwood in a tree can have a marked impact on its value. For naturally durable NZDFI species, high heartwood content is desirable. However, sapwood is desired for pulp production and other wood manufacturing processes as heartwood can drastically increase processing costs (Morais and Pereira 2007). Sapwood width is also a key factor for understanding water balances of forest plantations (Kumagai, Aoki et al. 2005), which are increasingly in the spotlight with climate change and intensified agriculture. Therefore measuring the sapwood width in standing trees is not only of interest for research purposes but also for quality control in production forestry in a variety of settings. Unfortunately assessing sapwood depth in standing trees is not trivial.

It is possible to detect heartwood and sapwood on extracted cores, but this can be difficult for species, which do not have marked colour or moisture content differences between sapwood and corewood. For these cases colour stains may be available to highlight heartwood or sapwood (Hillis 1987). Alternatively microscopy, X-ray tomography or NIR (near infrared spectroscopy) have been used to detect the heartwood sapwood boundary in cores (Pfautsch, Macfarlane et al. 2012).

Non-destructive methods have been developed in recent years. A transportable magnetic resonance imaging system has been developed, which can measure sap flow in standing trees (Jones, Aptaker et al. 2012), but in its current form the equipment size and weight as well as the limitations to stem diameter (~10 cm) prevent this tool from being used more widely.

Electrical resistivity tomography has also been used to detect sapwood in standing trees (Wang, Guan et al. 2016), but the reported accuracy of the method has been questioned for eucalypts (Pfautsch, Macfarlane et al. 2016) and the need for multiple sensors limits its use for fast assessment of many trees for quality control of plantations or breeding trials.

1.5. Measuring durability

The standard methodology to assess the durability of timber is to measure the mass loss of a sample after exposure to wood degrading organisms either in field or under laboratory conditions. The details differ significantly depending on the hazard class tested for (AWPC 2007). These tests require numerous (>6) reasonable sized (>20 mm) samples and may run for a considerable time (>12 weeks) (AWPC 2007). The effort of measuring natural durability by mass loss has been recognised as prohibitive in large scale screening programmes (Bush, McCarthy et al. 2011, Paques and Charpentier 2015).

Experimental alternatives to accelerate durability assessments have been proposed. The required exposure time can be shortened by creating more favourable environmental conditions that accelerate the decay (Cookson and McCarthy 2013). Furthermore it is possible to use more sensitive techniques to assess decay in the early stages, before significant mass loss occurs. In the early stage of decay remarkable changes in the physical properties and the chemical composition of the wood can be observed. Acoustics, which are associated with the stiffness of a material, have been found useful to detect decay early (Machek, Militz et al. 2001). Several studies report that NIR can be used to predict the severity of decay in wood, based on changes in the chemical composition of the woody cell walls, removing the need to measure mass loss (Fackler and Schwanninger 2012). However, these methods are still difficult to realise in a sizable breeding programme due to their resource demands.

As outlined above (1.1) the durability of wood is related to the extractive content in heartwood. Again, the resources needed for the conventional test method to determine the extractive content by solvent extraction of milled wood (TAPPI 2007) are prohibitive for use in a screening programme (Takashima, Tamura et al. 2015). Harju and Venäläinen (2006) proposed to use a more efficient Folin-Ciocalteu assay for total phenolics to more rapidly assess durability in *Pinus sylvestris*. Alternatively, NIR is a technique able to obtain information on the chemical composition of a material (Osborne, Fearn et al. 1993) and is used for this purpose for agricultural products. Several studies have found NIR is able to accurately assess the extractive content of heartwood (e.g. Poke, Wright et al. 2004, Giordanengo, Charpentier et al. 2008, Bush, McCarthy et al. 2011, Stackpole, Vaillancourt et al. 2011, Alves, Simoes et al. 2012). However, the prediction of mass loss by decay fungi was not always reported to be accurate enough to support a breeding programme e.g. (Gierlinger, Jacques et al. 2003, Bush, McCarthy et al. 2011).

Wounding was suggested as an early testing method to breed for heartwood (Harju, Venalainen et al. 2009). The wound reaction in stems after injury is not identical but somewhat related to heartwood formation (Blanchette, Wilmering et al. 1992).

1.6. NZDFI's approach for assessing heartwood in breeding populations

NZDFI has established numerous breeding trials since 2009. The resources necessary to test natural durability in a breeding programme are prohibitive. Additionally sample size (one 14 mm diameter increment core of each individual) is limited. Therefore a potentially more durable resource is selected through the proxy of high heartwood extractive content. The trees with high extractive content are more likely to produce more naturally durable timber. As the trees age and start to form heartwood families will be assessed on a) the amount of heartwood in the stem and b) the extractive content in the heartwood. Having characterised the genetic resource it will be possible to select trees with abundant heartwood rich in extractives for propagation.

The actual natural durability rating of this selected resource needs to be determined according to standards by independent organisations at a later stage when trees reach harvest age. As this is only done for the selected trees the resources required are reduced significantly compared to assessing the entire breeding population. Standards also vary depending on the envisaged export market.

For the breeding population the extractive content in the heartwood will be assessed by NIR spectroscopy on cores with a fibre optics probe as milling and subsequent extraction is resource demanding. In order to assess the extractive content in heartwood in this way the system needs to be calibrated for each NZDFI species.

2. METHODS

2.1. Tree corer

The assessment of heartwood requires a heartwood sample. As it is not desirable to fell trees in a breeding population a non-destructive method is required to extract a wood core from a standing tree for analysis. This is not a trivial task. The NZDFI species are of very high density making the use of the conventional hand corers impossible, especially for the extraction of larger diameter cores for further measurements. CSIRO in Australia had designed a tree corer (TRECOR) in the 1990's (Downes, Hudson et al. 1997) to extract 12 mm diameter cores from eucalypts leaving a 22 mm hole, but its manufacturing had stopped in the 2000s and no comparable corer was available internationally when NZDFI embarked on its wood quality programme. Only recently a version of TRECOR was made available again by Forest Quality (Australia). In designing a new tree corer, it was desirable to avoid the petrol-driven engine used for TRECOR to reduce weight and address concerns regarding fire safety raised by land owners.

In collaboration with Callaghan Innovation, the NZ School of Forestry has developed a battery-powered, light-weight tree corer which allows the easy and quick extraction of 14 mm diameter cores from a 21 mm hole, ideal for young small diameter trees (Figure 1). Extraction of cores is quick, taking only ~30 s for a 15 cm diameter tree. A battery pack lasts for 20-40 cores depending on tree diameter. A team of two was able to core >1000 trees in less than two weeks including the measurement of heartwood quantity. The corer can be made available through the New Zealand School of Forestry, University of Canterbury.

2.2. Calibration of NIR for extractive content in E. argophloia

In order to quickly predict the extractive content in heartwood, NIR needs to be calibrated with samples of known extractive content. Discs, form the base of stems, were collected from 37 *E. argophloia* trees aged 7-years. Samples were air-dried and subsequently equilibrated at 20 ℃ and 65% relative humidity resulting in an equilibrium moisture content of ~9%.

2.2.1. NIR spectroscopy

NIR spectra were taken from the sanded cross-section of the discs using a fibre optics probe (Bruker) at wavelengths from 9000 to 4000 cm^{-1} at 4 cm^{-1} intervals (average of 32 scans). For each disc, NIR spectra were collected every 5 mm from one side of the heartwood-sapwood boundary to the other across the pith and weight-averaged to represent the cross-sectional area according to their radial position.

Figure 1. Extracting a core from an E. bosistoana *tree using the light-weight, battery-powered tree corer developed by Callaghan Innovation and the New Zealand School of Forestry.*

2.2.2. Extractive content (EC)

Heartwood from each disc was isolated by drilling into the cross-section with a 12 mm drill. The drill frass was milled into a finer powder with a Wiley mill fitted with a 2 mm screen. The powder was extracted with ethanol using an Accelerated Solvent Extractor (ASE – Thermo Fisher) using the following extraction conditions: static time 15 min, temperature 70°C, 100% rinse volume and 2 extraction cycles. Extractive content was calculated from the known oven-dry wood powder mass and the oven-dry extractive content determined after evaporation of the solvent.

2.2.3. NIR spectra processing

Data was analysed in R (Team 2014). The prospectr package (Stevens and Ramirez–Lopez 2014) was used for spectra pre-processing. The first and second derivatives were calculated using the Savitzky-Golay algorithm with 2^{nd} order polynomial and a window size of 15 data points. Significant Multivariate Correlation (sMC) was achieved using the plsVarSel package (Mehmood, Liland et al. 2012). Calibration models were developed using the pls package (Mevik, Wehrens et al. 2015) with leave-one-out cross-validation after dividing the samples randomly into a calibration (n = 30) and validation (n = 7) data set.

3. RESULTS

To achieve a good calibration it is necessary to cover the full range of extractive contents (EC) in the resource. The available *E. argophloia* heartwood samples had a wide range of extractive content varying between 4.64% and 18.85% (Table 2), similar to what was reported for *E. bosistoana* (Sharma, McLaughlin et al. 2014). NIR calibrations benefit from large sample size and more than the available 37 *E. argophloia* samples would have been desirable.

Table 2. Summary of E. argophloia *heartwood ethanol extracts used for NIR calibration*

	Mean Extractive content (%)	Min Extractive content (%)	Max Extractive content (%)	CV
Calibration n=30	*10.76*	*4.64*	*15.80*	*0.25*
Validation n=7	*11.24*	*7.85*	*18.85*	*0.35*
All n=37	*10.59*	*4.64*	*18.85*	*0.27*

3.1. Pre-processing methods

Various spectra manipulations were tested for their influence on the quality of PLS regression models for the amount of ethanol soluble heartwood extractives in *E. argophloia* (Table 3). Regardless of the pre-processing method the PLS models were of reasonable accuracy, with residual mean square errors (RSME) of ~2% when considering that the extractive content varied between 4.6% and 18.9%. However, models based on the 1st derivative of the raw spectra yielded the best results with $RMSE_C$ = 1.91% and $RMSE_V$ = 1.11%. The 1st derivative of the spectra were used in the subsequent analysis.

3.2. Variable selection

Not all signals in NIR spectra are correlated to the investigated property. Elimination of unimportant wavenumbers often results in more reliable and robust models. Significant Multivariate Correlation (sMC) was chosen for variable selection (Tran, Afanador et al. 2014). Numerous significant signals were identified by the sMC algorithm (Figure 2). Signals which explain most of the variance in extractive content were located between 6000 cm^{-1} to 4000 cm^{-1} with two additional peaks at 8330 cm^{-1} and 6880 cm^{-1}. The bands near 6000 cm^{-1} and 4680 cm^{-1} have been assigned to the 1st overtone of C-H stretching vibrations of methyl, methylene and ethylene groups (Schimleck, Michell et al. 1996, Schwanninger, Rodrigues et al. 2011) in extractives. The band around 5793 cm^{-1} is the stretching vibration of CH bands that correlated to lignin. Two strong and board signals in the average 1st derivative spectra of *E. argophloia* heartwood at ~7070 cm^{-1} and ~5100 cm^{-1} assigned to adsorbed water were effectively rejected by the model.

Table 3. PLS regression models for calibration and validation of EC with and without pre-treatment methods. (SNV: Standard Normal Variate; RMSE: Residual Mean Square Error)

	Calibration			Validation	
Pre-treatment	R^2_C	$RMSE_C$ (%)	Number of components	R^2_V	$RMSE_V$ (%)
Raw spectra	*0.51*	*2.14*	*5*	*0.73*	*1.31*
SNV	*0.52*	*2.13*	*6*	*0.67*	*1.46*
1st derivative	*0.61*	*1.91*	*5*	*0.81*	*1.11*
2nd derivative	*0.65*	*1.82*	*6*	*0.40*	*1.98*
SNV + 1st derivative	*0.59*	*1.96*	*7*	*0.75*	*1.27*
SNV + 2nd derivative	*0.68*	*1.72*	*6*	*0.21*	*2.27*

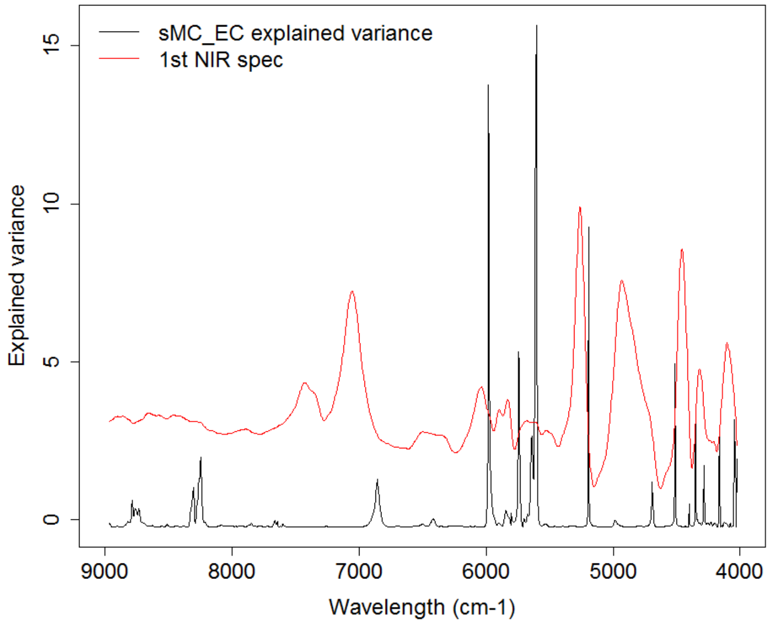

Figure 2. Average 1st derivative NIR spectra for E. argophloia *heartwood (red) and the explained variance in EC for each wavenumber (black).*

The 173 wavenumbers (~15% of the total) of the NIR spectra identified by the sMC algorithm (significance level = 0.05) were chosen to build an improved PLS model. This improved the accuracy of the model, reducing the $RMSE_v$ from 1.11% to 0.92% (Table 4).

Table 4. PLS regression models for calibration and validation of EC with selected variables on 1st derivative NIR spectra of E. argophloia

	Calibration			Validation	
Variables used	R^2_C	$RMSE_C$ (%)	Number of components	R^2_V	$RMSE_V$ (%)
173 selected by sMC	*0.81*	*1.33*	*6*	*0.91*	*0.92*
1296 (all)	*0.61*	*1.91*	*5*	*0.81*	*1.11*

3.3. Cross species calibration of NIR for EC

As the available number of *E. argophloia* samples was at the lower limit of what is usually required for robust NIR calibrations, the possibility of building a cross-species calibration was investigated. Previously a NIR calibration for heartwood EC of *E. bosistoana* based on 126 samples was created. *E. bosistoana* is a species closely related to *E. argophloia* (Brooker 2000). The *E. bosistoana* model gave reasonable predictions of the EC in the *E. argophloia* data. The RMSE of 1.43% was still small compared to the variation in the sample (Table 2). No obvious bias between the measured and predicted EC values was observed (Figure 3). This indicted that it could be feasible to build a multiple eucalypt species NIR calibration for EC.

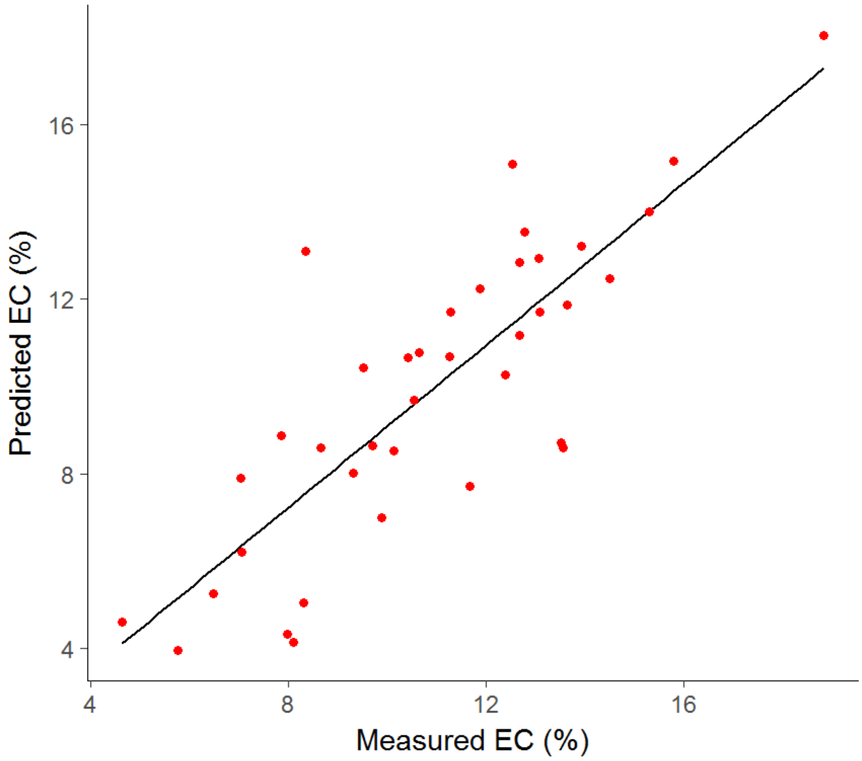

Figure 3. Correlation of measured and predicted EC from NIR spectra of discs of E. argophloia using a calibration for E. bosistoana.

4. CONCLUSION

A tree corer has been developed to quickly extract 14 mm cores from high density trees, as such a tool was not commercially available. From reviewing the literature on naturally durable wood it appears necessary and possible to ensure consistent high quality timber through a breeding programme. Directly assessing natural durability is resource consuming and impractical to apply in a breeding programme due to the high sample numbers required. It has been shown that it was possible to predict ethanol soluble extracts in heartwood of *E. argophloia* quickly by NIR. This required the development of a PLS regression model from solid wood samples. Using the sMC algorithm a robust model was obtained to predict the ethanol soluble extracts in heartwood of *E. argophloia*. To compensate for the rather small number of samples used for calibration, a model for *E. bosistoana* was also tested for *E. argophloia*. This also gave good predictions, indicating that a cross-species calibration could be feasible.

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P.F. SCHROEDER

PROPAGATION OF EUCALYPTS

Abstract Propagation plays an important role in tree breeding programmes, both for deployment of genetic gain and to help facilitate future breeding cycles. Genetically improved material can be deployed as a) seed from orchards of selected trees, b) rooted cuttings from selected trees and/or c) plants raised from tissue cultures of selected trees. The following is a resume of propagation work undertaken by Proseed to support New Zealand Dryland Forests Initiative (NZDFI) breeding programmes, which involves both grafting of field trial selections for seed orchard establishment and rooted cuttings taken from young (~2 year old) stool plants.

1. INTRODUCTION

Propagation plays an important role in tree breeding programmes, both for deployment of genetic gain and to help facilitate future breeding cycles. Selections that, for whatever reason, cannot be propagated are of little practical use. Genetically improved material can be deployed as a) seed from orchards of selected trees, b) rooted cuttings from selected trees and/or c) plants raised from tissue cultures of selected trees.

The most common way of propagating forest trees is by seed. The main advantages are a price competitive product, and in a breeding context, the possibility to advance breeding populations by crossing individuals with desired characteristics. The main disadvantages include slightly lower gains compared to clonal programs due to the genetic variation of the off-spring and, in the context of a breeding programme, a time delay before selected plants produce seed. Clonal forestry is typically based on propagation of rooted cuttings. This approach is more costly compared to propagation from seed but can achieve large genetic gains soon after selecting superior individuals. Propagation by rooted cuttings is used for commercial propagation of eucalypts (Cliffe, 2011). However, clonal propagation cannot advance a breeding programme. That typically requires sexual reproduction.

Propagation from tissue culture is the newest and most challenging technique and therefore the least often method used for multiplying trees. The time from selection to commercial scale deployment can be shorter than that for rooted cuttings. Propagation from tissue culture offers the opportunity to ‘rescue’ desired clones which are difficult to propagate otherwise and with technical advances might become cost effective.

The following is a resume of work undertaken by Proseed to support New Zealand Dryland Forests Initiative (NZDFI) breeding programmes, which involves propagation by grafting for seed orchard establishment and rooted cuttings.

2. PROPAGATION BY SEED

Generally, interbreeding of superior individuals in a seed orchard further improves genetic gain in the seed produced, especially when, as with several NZDFI species, outcrossing occurs: when parents originate from spatially distant populations which have had no opportunity to interbreed. A disadvantage of deploying genetic gain through seed is that deployment of genetic gain is slow, since trees need to be both old enough to flower and big enough to produce useful quantities of seed. Assuming selections are already sexually mature (some trees can take a decade or more to reach sexual maturity) this could be several years.

2.1. Grafting

Grafting is not an economic method for producing bulk planting stock but, since physiologically old material is frequently difficult to propagate from cuttings, grafting is commonly used to produce plants for seed orchard establishment. If grafted planting stock is used then another disadvantage can be graft incompatibility: when the scion and rootstock tissues reject each other causing the graft union to fail and the plant to die. This phenomenon can manifest soon after grafting or it may be delayed for several years in which case there may still be opportunity to take some benefit.

2.2. Seed orchard establishment

Proseed has established orchards of two NZDFI species and an archive of one other. These trees have been selected for good growth and form. In a next step, selections will also include wood quality traits such as good heartwood and low growth-strain.

- *E bosistoana:* Around 170 ramets from 16 clones were planted spring 2015. About half of the available orchard positions are still vacant and will be filled with ramets from the next round of NZDFI selections.

- *E. globoidea:* This species has proved more difficult to graft than others resulting in insufficient plants to establish an orchard having all clones evenly distributed throughout. Around 130 ramets of 30 clones were planted spring 2016 into a more intensively managed archive area for further multiplication.

- *E. quadrangulata:* Three hundred ramets from 28 clones were planted as an orchard in spring 2016 (Figure 1).

Figure 1. E. quadrangulata *orchard planted in Proseed's Amberley seed orchard.*

A possibility for the NZDFI programme to accelerate sexual reproduction and to advance the breeding programme and potentially produce considerable amounts of seed would be to convert the established breeding trials into seed orchards by rouging unwanted individuals. The trials have been established from 2009 onwards and trees are starting to flower. An alternative possibility to produce more seed would be collection from individual trees from which the breeding programme was established.

3. PROPAGATION FROM CUTTINGS

Propagation from cuttings is well suited to rapid multiplication and deployment of superior selections from breeding programmes. Sometimes, such as with willow and poplar, it is easy and very successful while at other times, especially with physiologically old material, it can be technically difficult. Unfortunately, eucalypts fall into the latter category. Never-the-less, vegetative propagation of some eucalypt species is successfully used on a commercial scale (Cliffe, 2011).

3.1. Narromine nursery

Narromine Transplants (New South Wales, Australia) has developed a high level of expertise with propagation of eucalypts from cuttings, with three million rooted cuttings being produced in one six month period. David Cliffe, owner of Narromine Transplants, was very forthcoming with help developing vegetative propagation for NZDFI eucalypts and has contributed to NZDFI workshops (Cliffe, 2011). In November 2015 Proseed took up an invitation from David Cliffe and Paul Schroeder and Maree Creswell viewed Narromine Nursery's work propagating eucalypts from cuttings, mainly the hybrid *E. grandis* x *E. camaldulensis*.

Mass propagation from rooted cuttings requires sufficient stool plants to harvest plant material. Good nutrition of stool plants plays an important role in successfully striking eucalypt cuttings. At Narromine a hydroponic system of stools growing in coir filled grow bags in a large greenhouse was destroyed when strong winds tore the plastic greenhouse cover away. New stools have been established on the same, now exposed benches that remained, but growing instead in a peat based media in individual plastic pots while still using the same run-to-waste hydroponic system as before. Stools were trimmed to keep them small and as juvenile as possible.

Short 'mini' cuttings (~5 cm, 2-3 nodes) from semi-hardened shoot sections are treated with hormone, set into cell trays filled with perlite-peat media and placed on heated benches (22°C) under mist. In mid-summer rooting commences as soon as 12 days after setting. Hardening of the plants commences after 20 days. Strike rates of 70-90% have been achieved.

3.2. First Proseed settings

Proseed proceeded to replicate what had been seen at Narromine Transplants in its Amberley greenhouse facility. During the summer of 2015/2016 around 750 rooted cuttings were produced from *E. bosistoana* material taken from seedlings grown for growth-strain trials by School of Forestry at Harewood, Christchurch. These pilot settings at Proseed ran from November through to March and indicated that, similar to Australia, settings made in December and January had highest survival rates. Monitoring of growth on coppice trials conducted that same season showed development of suitably sized shoots took around 8 weeks in Canterbury.

3.3. Stool bed establishment

A hydroponic batch system was constructed in a greenhouse. In mid-June two hundred and fifty rooted *E. bosistoana* cuttings (representing 18 clones) plus seedlings of *E. bosistoana*, *E. globoidea*, *E. quadrangulata* and *E. tricarpa* were planted into coir filled grow bags. Growth was spectacular as can be seen from Figure 2. However, nutrient deficiencies were noted and new growth was soft and not the best quality for taking cuttings. Edema (wart like growths on foliage resulting from intensive irrigation and high humidity causing abnormal water retention) was also an issue. Solution analyses showed the eucalypts to be voracious feeders with a large portion of available nutrients being stripped away in just one pass of solution through the roots. Even though the system was changed from recirculating to run-to-waste, trace element deficiencies persisted. It is expected that, in future, custom nutrient solutions will be required instead of 'off-the-shelf' formulations intended for horticultural crops.

Figure 2. Hydroponic E. bosistoana *stools; newly planted (left) and 14 weeks after planting (right).*

A new batch system has been constructed outdoors, modelled on one seen used for growing roses (Figure 3). This system will be evaluated in summer 2017/2018 with the aim of improving plant nutrition and hardening the shoots to make them more suitable for collection of good quality cutting material.

Stool beds are required for timely mass propagation of improved plant material. However, in a breeding programme archiving plant material is often important. A plant archive does not need many individuals. Previously, NZDFI and Proseed explored the possibility of lifting *E. bosistoana* root stocks of ~2-year-old trees from breeding trials and transplanting them into containers either until sufficient coppice was available for propagation, or to be transplanted into a plant archive (Schroeder and Altaner, 2016). While the transport of containerised root stools is less logistically challenging than fresh cuttings, severe damage to plant roots during lifting induced high mortality. However, the method of lifting root stools for archiving could be improved.

Figure 3. Outdoor hydroponic gully system constructed at Proseed's Amberley seed orchard for Eucalyptus *stool establishment.*

3.4. Establishing a new breeding population

Under the Sustainable Farming Fund programme SFF 407602 "Minimising growth-strain in eucalypts to transform processing" Proseed is tasked to produce 5 rooted cuttings from 2000 *E. bosistoana*/*E. argophloia* selections. These trees are selected for early growth and low growth-strain with the objective of maintaining broad genetic diversity. In summer of 2016/2017 the first of two *E. bosistoana* growth-strain trials located at Murray's Nursery in Woodville was assessed and superior individuals earmarked for propagation. The general strategy is that stems of ~2-year-old seedlings are cut and taken for growth-strain testing and then the seedlings propagated later from cutting material collected from coppice growth produced on the remaining stumps.

Proseed constructed two new propagation tables in their Amberley greenhouse for this purpose (Figure 4). The tables are heated with a bank of Nu-Klear Ag Pads and provided with mist triggered from both solar integral and timer functions in the greenhouse controller.

Material was collected in two expeditions: one late February and one late March. Selected ortets had already been labelled on site. Collected material was placed into plastic bags, sprayed with systemic fungicide, packed into polystyrene fish boxes and chilled. Boxes were transported from Woodville to Amberley overnight in a refrigerated truck. All material was set within 4 to 5 days of collection at Woodville. This was deemed a satisfactory time frame, based on experience with grafting eucalypt scions. Generous assistance from Murray's Nursery is gratefully acknowledged. In total 11,342 cuttings were set from 693 selections. Not all stools of the 1,000 selections had produced enough sufficiently developed coppice material for collection before close of the seasonal window. From a propagation perspective cutting source seedlings down in September/October would be better than the November/December schedule used in the season just passed.

Figure 4. A propagation table (left) with its geotextile cover rolled back to show Nu-Klear Ag Pads underneath and Woodville settings (right) (February and March).

As far as Proseed is aware this is the first attempt at commercial scale production of *E. bosistoana* from cuttings. So far results have been very encouraging. For the 2017/2018 summer season tasks will be to make good the shortfall on last season's targets and then set material from additional selections from the second *E. bosistoana* growth-strain trial.

Figure 5. Rooted cuttings from Woodville February collection already potted on 11 weeks after setting.

4. ACKNOWLEDGEMENTS

Propagation of *E. bosistoana* from cuttings is part of the MPI co-funded SFF 407602 project "Minimising growth-strain in eucalypts to transform processing".

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D.W.M. LEUNG

TISSUE CULTURE OF EUCALYPTS

Micropropagation of Eucalyptus bosistoana

Abstract A well-established way to mass-multiply genetically superior eucalypts is vegetative propagation. This will result in clones. Micropropagation is a plant tissue culture approach to mass propagate plants in a laboratory. There is no prior study of micropropagation of dryland eucalyptus species of interest to NZ forest industry. Bud break was successfully induced in shoot cuttings of *Eucalyptus. bosistoana*.

1. INTRODUCTION

It is necessary to have technology in place to ensure that the emerging durable eucalypts NZ dryland forests industry can mass propagate trees with superior growth, health and wood quality (Henson, 2011). From a tree breeding programme, typically only a few individual trees are selected which have the desirable attributes. Nurseries can mass-multiply selected individuals by vegetative propagation for a number of practical objectives including the establishment of genetically superior clonal seed orchards (Schroeder, 2017).

Plant tissue culture is a group of biotechnological techniques that has been developed for diverse practical reasons. The purpose of the most well-known application of plant tissue culture, micropropagation, is the same as vegetative propagation in nurseries. The key differences between these two vegetative propagation approaches lie in the technical details involved (Figure 1). Micropropagation requires all the handling steps involving plant propagules under sterile and controllable environmental conditions, typically only achievable in a plant biotechnology laboratory. At the University of Canterbury, a plant biotechnology laboratory has been set up for micropropagation and other plant tissue culture applications since 1986.

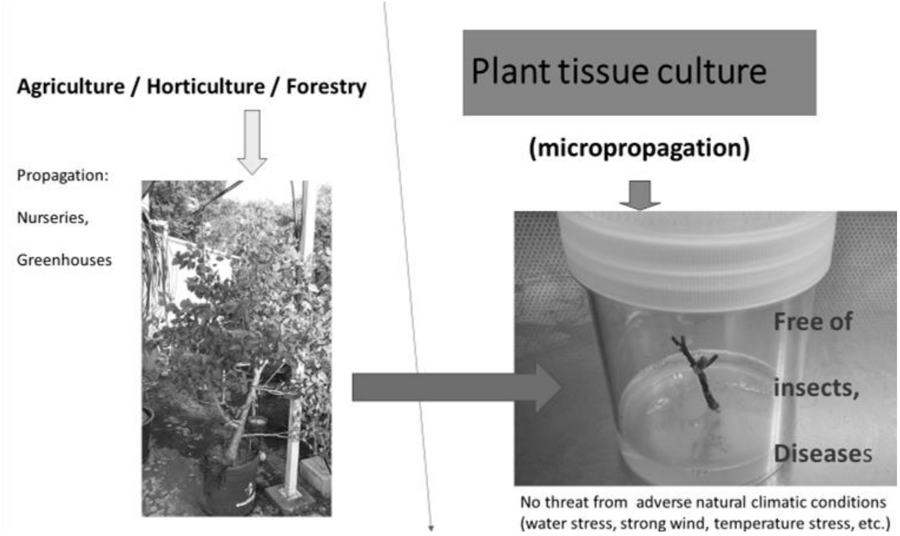

Figure 1. Contrasting features of vegetative propagation in nurseries and micropropagation in a plant biotechnology laboratory

Myrtle rust (*Austropuccinia psidii*) has been found in New Zealand in March 2017. This fungus poses a serious threat to eucalypts and some iconic New Zealand native plants. The risk of the myrtle rust fungus could be better controlled in the highly controlled environment of a plant biotechnology laboratory, therefore helping to future-proof and protect the values of the industry. Although beyond the scope of this manuscript, plant tissue culture may also be useful to assist the development of *Eucalyptus* plants that exhibit resistance to myrtle rust. Consequently an investment in the deployment of micropropagation alongside vegetative propagation in nurseries is of interest to the NZDFI.

Eucalyptus bosistoana is a species of interest to the NZDFI. Although there are many reports of tissue culture or micropropagation studies of eucalypts species in the literature (e.g. Jones and van Staden, 1994; McComb et al., 1996; Ma et al., 2011; Aggarwal et al., 2012; Nakhooda and Jain, 2016) there is no report of successful tissue culturing *E. bosistoana*. An unsuccessful attempt has been previously published (Menzies et al., 2012). The objectives of this report were: (1) to give a general, basic description of the major steps involved in the micropropagation, and (2) to show as a proof-of-concept study that micropropagation of eucalypts of interest to NZDFI is feasible locally.

2. METHODS

Two-year-old *E. bosistoana* plants were obtained from NZDFI. Shoot tip cuttings (about 2-3 cm long) were taken randomly throughout the plants in the summer (February-March) of 2016. The cuttings were brought back to the Plant Biotechnology

Lab, School of Biological Sciences, University of Canterbury (Christchurch, NZ). The cuttings were washed with a bleach solution to rid them of microorganisms including fungi that might adhere to their surfaces. Then the cuttings were placed on the surface of agar containing a nutrient medium made up of minerals, vitamins, sugar and plant hormones. The composition of the tissue culture medium had to be specifically designed to keep the cuttings alive and induce bud break. The new shoots that emerged from the buds were physically excised and placed separately on a medium tailor-made to promote rooting of the micropropagated shoots. Full detailed technical descriptions will be disclosed after further validation and signing of an intellectual property arrangement.

3. RESULTS

The nutrients supplied in the plant tissue culture medium can also be used by microorganisms. Therefore, to obtain, multiply and maintain a healthy plant propagule in culture, disinfection is important. The surface of the initial shoot cuttings, which is placed in direct contact with the medium, needs to be free of microorganisms. Disinfection is difficult as the plant propagule is a living organism which needs to survive the treatment. Experiments were conducted to find a surface disinfection treatment that removed the microorganisms from *E. bosistoana* shoot cuttings without injuring them. This was claimed to be challenging for this species (Menzies et al., 2012). An important result in the present study was that healthy propagules free of microorganisms can be produced. There was no sign of any contaminating microorganisms in the culture of the *E. bosistoana* cuttings. Moreover, after 10-14 days from surface disinfection and start of culture, bud break (development of new shoots) was observed (Figure 2a) in a majority of the cuttings put into culture. This has never been reported before. Furthermore, evidence was also obtained showing that it was possible to induce bud break in multiple locations along the shoot cuttings (Figure 2b). A closer look at each bud break position revealed that there were multiple shoots emerging.

The location at which the bud break occurred was where the bud meristems are normally located in the plants. Meristematic cells (an analogy to the stem cells in animals and humans) are found in a bud meristem. The meristematic cells have the natural ability to form a new shoot but those found in bud meristems located away from the growing tips of the plant body are normally inactive or dormant. Once the shoot cuttings are excised from the plant body (away from the influence of the growing tips), then plant biotechnologists can design the nutrients and plant hormones required to activate the dormant bud meristem to produce new shoots. Rooting trials of the shoot clusters at each bud are underway.

Figure 2. Bud break in shoot cuttings of Eucalyptus bosistoana *during micropropagation: at a single location after 10-14 days (left), and multiple leafy shoots developed at multiple locations (right).*

4. DISCUSSION

A plant propagation workshop was organised by the NZ Dryland Forests Initiative (NZDFI) in August of 2015 held at the University of Canterbury. Vegetative propagation starting from coppice shoots of selected *E. bosistoana* trees for rooting in the nurseries was deemed the most promising route to establish a new breeding generation for the assessed trees (Schroeder, 2017). Plant tissue culture of this eucalypt was tried in New Zealand without success (Menzies et al., 2012). A survey of plant tissue culture studies on eucalypts overseas has also revealed a lack of information on micropropagation of *E. bosistoana*. Promising results on micropropagation of this eucalypt have been obtained in the present study. The knowledge gained is useful for development / refinement of micropropagation of this and other eucalypts of interest to the NZDFI. The future of the industry will be better ensured with more than one vegetative propagation technology. Micropropagation complements vegetative propagation in nurseries (Schroeder, 2017) for both, capturing genetic gain in breeding programs as well as mass deployment of improved material to the forest industry.

Interestingly, the rate of shoot multiplication in the micropropagation protocol developed here, was substantially higher than vegetative propagation in the nurseries. This is based on the ability of inducing multiple shoot formation in a bud meristem on a shoot cutting in tissue culture. With the potential threats of myrtle rust and other future biosecurity risks, the risks of taking shoot cuttings from field-grown eucalypts would be better controlled with micropropagation without relying on large-scale application of potentially costly and potential toxic fungicides etc. in the field before taking cuttings. The propagules resulting from micropropagation are from a high-hygiene environment. Consequently, establishment of a clonal seed orchard from this material would reduce the risk of transmitting disease.

The new shoots from micropropagation should be true to type (having the same genetics as the shoot cutting used to initiate tissue culture) as they arise from the bud meristem, which is comprised of genetically stable cells. There are DNA fingerprinting techniques that can be deployed to verify this (Aggarwal et al., 2012). In brief, DNA can be extracted non-destructively for example from a part of a leaf of the propagules. The DNA is then multiplied using the standard molecular biology technique polymerase chain reaction (PCR) and the unique patterns of each plant can be visualised (a concept similar to a bar code on products in a supermarket). If some of the propagules are not true to type, they would exhibit different DNA 'barcodes'. The industry may invest in this technique as an additional quality control or assurance standard.

In conclusion, a knowledge base to enable micropropagation of healthy durable eucalypts for the forest industry has been established. This ongoing research alongside a breeding programme which will enhance and protect the value of the industry.

5. ACKNOWLEDGEMENTS

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T. KAKITANI

THE GLOBAL TIMBERLIZATION MOVEMENT AND THE POTENTIAL FOR DURABLE EUCALYPTS

Downstream opportunities

Abstract Some eucalypts have the potential to satisfy the demand for stiff and naturally durable timber created by recent developments in large timber constructions. Such timber is scarce and predominantly sourced from tropical virgin forests, which are often unsustainably or illegally harvested. The New Zealand Dryland Forests Initiative (NZDFI) works toward establishing a sustainably-grown naturally durable heartwood plantation resource which could substitute these timbers. Heartwood of unimproved *Eucalyptus globoidea* and *Eucalyptus bosistoana* seem to have termite and decay resistance in the Japanese environment. Sapwood was not as durable as heartwood. Further research is needed to determine durability of these eucalypts according to Japanese Standards in more detail.

1. INTRODUCTION

Recently, large scale timber buildings have attracted attention all over the world. For example in Japan, the new National Olympic Stadium in Tokyo for 2020 features timber frames. Worldwide various medium- to large-scale timber building projects are underway and more are planned. A key driver for this trend is that people like timber and timber buildings. Modern timber building and construction technologies now enable attractive and holistic timber projects to become reality. This trend is also called “timberlization of cities”, in which an entire city is aimed to be made of timber including exteriors like wooden decks and cladding.

Concrete and steel are the main competitors for timber as a construction material. Concrete and steel are stiff and durable. This creates a demand for high stiffness and naturally durable timbers. Tree species meeting these requirements are predominantly growing in tropical forests. Unfortunately they are now a scarce resource, often including endangered species which are frequently harvested unsustainably from virgin forests. Nowadays sustainability is essential to business activities and therefore many tropical hardwood species are less likely to be an acceptable choice.

The vision of the New Zealand Dryland Forests Initiative (NZDFI) is to establish a forest industry in New Zealand based on sustainably plantation-grown durable eucalypts. The species considered by NZDFI could provide a sustainable alternative to tropical hardwood for the timber construction industry. However, apart from ensuring that the NZDFI’s species meet the material specifications for engineered wood products, a resource of sufficient scale to supply wood processing facilities needs to be established. An international market for durable and stiff engineered wood products does exist.

Eucalyptus globoidea and *E. bosistoana* are known to be stiff and durable species in Oceania as described in the Australian Standard AS 3660.1 and AS5604 or Scheffer and Morrell (1998). Every region, however, has a different climate as well as different flora and fauna. Durability of these eucalypts is not known yet under Japanese conditions, which are considered one the world's most severe environments for timber usage.

The purpose of this paper is to investigate durability of *E. globoidea* and *E. bosistoana* in the Japanese environment, where threats include Japanese termites and fungi.

2. METHODS

2.1. Fungal cellar test

A fungal cellar test was carried out in accordance with Japanese Standard K 1571 (JIS K 1571, 2010) with a minor modification. This test accelerated decay by placing the wood samples in specially prepared soil with plenty of moisture and nutrients under controlled temperature to enhance the activity of decay fungi. The specimens were cut to smaller dimensions (than the standard) of 20 mm x 20 mm in width and 10 mm in height in order to enhance penetration of hypha into the specimens.

Ten wood blocks for each timber sample were tested. The specimens were soaked in the water at 20^{o}C with stirring for 8 h, then dried for 16 h at 80^{o}C. This procedure was repeated 10 times to simulate outdoor weathering by leaching water-soluble and volatile extractives. Finally the samples of known dry mass were buried in the soil (Figure 1). Appearance and weight were periodically checked every four months.

Figure 1. Wood samples in the fungal cellar test before burying.

Wood species used in this test were heartwood of Red oak (USA), Walnut (USA), Western red cedar (USA), Selangan batu (Indonesia) from commercial sources. *E. globoidea* and *E. bosistoana* (NZ) were obtained from the NZDFI. Samples were cut from the heartwood of an 80-, 20- and 12-year old *E. globoidea* and a 60- and 40-year old *E. bosistoana* tree. *E. globoidea* sapwood samples were cut from the same 12-year old tree and *E. bosistoana* sapwood samples from a 6-year old tree.

2.2. Termite test

Termite resistance was tested in accordance with Japanese Standard K 1571 (JIS K 1571, 2010) with minor modification. The specimens were cut to dimensions of 20 mm x 20 mm in width and 10 mm in height. This is larger than the standard to prevent splitting and loss of the specimens during wash and dry cycles.

Only two blocks for each timber sample were tested due to the limited availability of termites. The specimens were soaked in the water at 20ºC under stirring for 8 h, then dried for 16 h at 80ºC. This procedure was repeated 10 times to simulate outdoor weathering by leaching water-soluble and volatile extractives.

One wood block of known mass, fifteen soldiers and 150 workers of the Formosan subterranean termite (*Coptotermes formosanus*) were put in a cup (Figure 2). Appearance and weight were checked after three weeks.

Species used in this test were Radiata pine (NZ), Western red cedar (USA), Selangan batu (Indonesia), *E. globoidea* and *E. bosistoana* (NZ). The origin of the trees was the same as for the fungal cellar test described above.

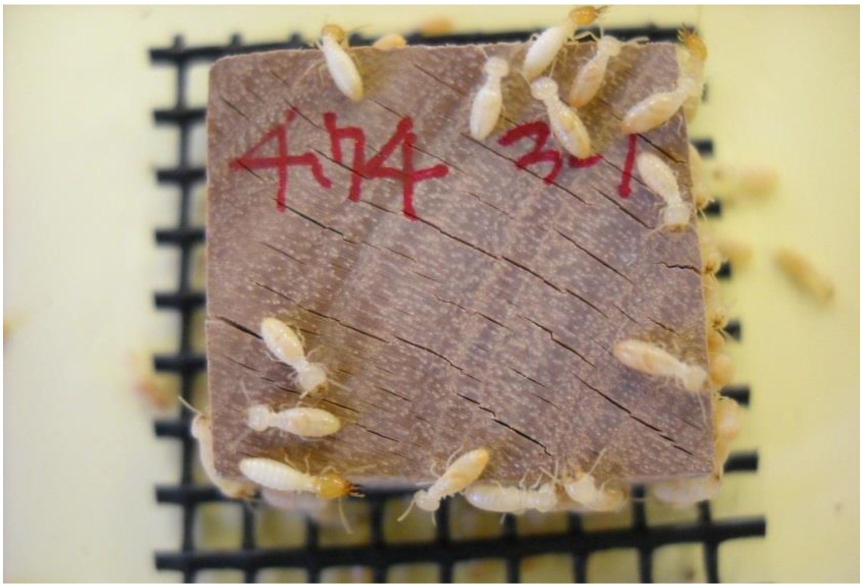

*Figure 2. Wood block exposed to Formosan subterranean termite (*Coptotermes formosanus*).*

3. RESULTS AND DISCUSSION

3.1. Fungal cellar test

As is shown in Table 1, both *E. globoidea* and *E. bosistoana* samples lost less mass compared to Red oak and Walnut. However, mass loss was greater than for Selengan batu or Western red cedar. Not much difference was seen at this stage between the two different eucalypts. With the exception of 12-year old *E. globoidea*, heartwood was more durable than sapwood. This was expected as durability is governed by extractives in heartwood. It is also interesting to note that at this stage that the sapwood of the eucalypts was more durable than the heartwood of Red oak and Walnut. At this stage it is too early to estimate the lifespan of these eucalypt timbers. The measurements will be continued. Also samples from more trees are needed in order to reach a definitive conclusion.

Table 1. Mass loss (%) due to fungal decay determined in a modified JIS K 1571 test. ND: not determined yet; NA: not available.

	Months			
Species	0	4	8	12
Red oak	*100*	*79.3*	*36.5*	*NA*[1]
Walnut	*100*	*92.8*	*64.4*	*58.3*
Western red cedar	*100*	*103.9*	*97.1*	*92.4*
Selangan batu	*100*	*101.4*	*96.1*	*93.3*
E. globoidea (80 yrs old heartwood)	*100*	*90.2*	*86.5*	*ND*
E. globoidea (20 yrs old heartwood)	*100*	*90.0*	*87.2*	*ND*
E. globoidea (12 yrs old heartwood)[2]	*100*	*81.7*	*76.1*	*ND*
E. globoidea (12 yrs old sapwood)	*100*	*85.6*	*77.9*	*ND*
E. bosistoana (60 yrs old heartwood)	*100*	*86.1*	*82.5*	*ND*
E. bosistoana (40 yrs old heartwood)	*100*	*87.7*	*85.3*	*ND*
E. bosistoana (6 yrs old sapwood)	*100*	*83.8*	*75.5*	*ND*

[1]discontinued
[2]may contain sap wood

3.2. Termite test

Results of the termite test are shown in Table 2. Radiata pine and Western red cedar were severely attacked by Japanese termites. On the other hand, *E. globoidea* and *E. bosistoana* samples were less damaged, with heartwood from older trees showing more resistance than Selangan batu. Again heartwood of 12-year-old *E. globoidea* did not outperform sapwood. The *E. bosistoana* sample showed similar mass loss to the radiata pine. While this data might suggest some differences in resistance to termites between the eucalypts it is hard to draw a definitive conclusion due to the small sample size used in this study.

*Table 2. Mass loss (%) after 3 weeks exposure to Formosan subterranean termites (*Coptotermes formosanus*) (modified JIS K 1571).*

Species	Weight reduction (%)
Radiata pine	*11.4*
Western red cedar	*19.0*
Selangan batu	*3.6*
E. globoidea (80 yrs old heart wood)	*0.6*
E. globoidea (20 yrs old heart wood)	*0.3*
E. globoidea (12 yrs old heart wood)[1]	*3.5*
E. globoidea (12 yrs old sap wood)	*3.1*
E. bosistoana (60 yrs old heart wood)	*0.0*
E. bosistoana (40 yrs old heart wood)	*0.0*
E. bosistoana (6 yrs old sap wood)	*12.5*

[1]may contain sap wood

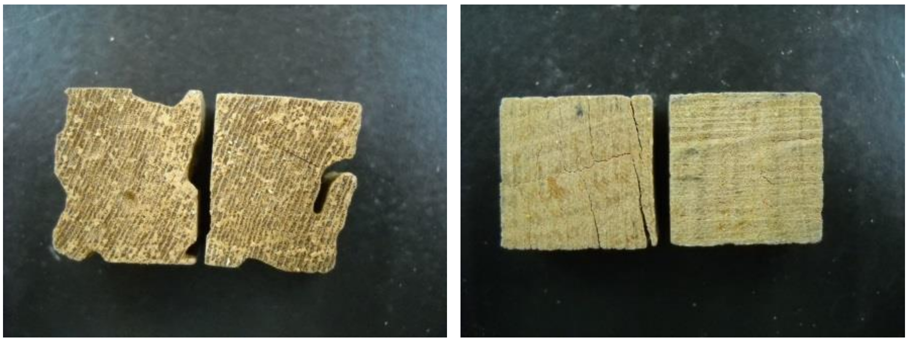

*Figure 3. Wood blocks after 3 weeks exposure to Formosan subterranean termites (*Coptotermes formosanus*); Western red cedar (left),* E. bosistoana *heartwood (right)*

4. CONCLUSIONS AND RECOMMENDATIONS

Conclusions drawn from the current preliminary results:

4.1. Decay resistance

Both *E. globoidea and E. bosistoana* are likely to be durable in Japanese conditions. The few samples were taken randomly from an unimproved eucalypt resource. These eucalypts are currently in a breeding programme which considers heartwood quantity and quality as traits for selection. An improved resource is expected to show less variation and more durability.

4.2. Termite resistance

Both *E. globoidea and E. bosistoana* heartwood are likely to have resistance against Japanese termites. An actual outdoor exposure test will give us further confidence.

4.3. Concerns

Eucalyptus bosistoana samples showed ‘cracking’ when undergoing the tests (Figure 3). The cracks might have caused by the leaching procedure which involve severe wetting and drying cycles. Such ‘cracks’ are not only concern regarding appearance but also the splinters are a safety issue when handling the timber. Cracks can also facilitate the biodegradation of the timber.

5. REFERENCES

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6. AFFILIATIONS

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