Section 2: NZDFI Wood Quality Research Plan

1 Background

NZDFI aims to establish a new hardwood forest industry based on naturally durable eucalypts. NZDFI has identified sustainably-grown naturally durable posts and poles for the agricultural industry as key products as an alternative to CCA treated pine (Millen, 2009). For these products natural durability is essential. The timber of these eucalypt species also has a high Modulus of Elasticity (MoE). A second targeted product is high stiffness LVL. These products can be produced from short-rotation smaller diameter trees. As these timbers also have attractively coloured heartwood, high quality appearance grade solid timber products are also a possibility if trees are grown on a longer rotation to a larger size.

To ensure a quality product the variability in these properties can be reduced by genetic selection. Furthermore the trees must be easy to process, which requires trees with low growth-stresses and a low level of drying defects. NZDFI's wood quality research programme addresses these problems to facilitate a viable hardwood forest industry based on naturally durable eucalypts. Some research work is financed through SWP (MBIE) while other work is funded through SFF (MPI) and other sources.

Wood quality is a key research theme alongside other essential areas such as tree health, tree growth, propagation and forest management.

2 Natural durability

Wood is a bio-material and biodegradable. Biodegradability is a positive attribute when considering the disposal at the end of a product's life. However, susceptibility of wood to decay by organisms 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 (e.g NZS3640:2003). 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 (e.g. Bootle, 2005; EN350-2; Scheffer and Morell, 1998). This property is referred to as (natural) durability and assessed by various national standards (e.g ASTM, 2005; AWPC, 2007; EN350-1). Unfortunately high natural durability is uncommon among tree species and those which are utilised are mostly rare and/or unsustainably harvested (UNEP, 2012).

As an alternative, the resistance to biological decay of non-durable timber can be improved technologically by modifying the chemical structure of the wood (Hill, 2006) or by impregnation with preservative of which there are numerous (e.g. Eaton and Hale, 1993; Goodell et al., 2003; Richardson, 1993). On an industrial scale the former is a more recent approach and achieves either only lower resistance (thermal modification) or is costly (acetylation). The latter is used extensively for decades but converts the bio-degradable wood into a toxic waste for which often no acceptable disposal option has been found (Graham, 2009; Read, 2003; Townsend and Solo-Gabriele, 2006).

Biodegradation of wood can be separated into different types:

Decay

- *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 (whit-rot, brown-rot, or soft-rot). These differ in appearance and in the type of enzymes that decompose wood but in all cases the result is a complete loss of structural integrity, i.e. strength.
  A prerequisite for fungal decay is the presence of free water (and oxygen). This implies that all wood in air-dry (and water logged) conditions is safe from fungal decay. Fungal decay needs to be considered especially 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 walls (i.e. hemicelluloses, cellulose and lignin) 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 (Clausen, 1996; Greaves, 1971)*
  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 by insects

- *Wood-degrading beetles (Peters et al., 2002)*
  Some beetles, like house borer's (e.g. lyctids or anobiids) destroy wood mechanically by chewing. They are not able to feed directly on the cell wall components (lignin, cellulose and hemicelluloses) like wood decaying fungi. They usually digest the tree's reserves (mainly starch) which are present in sapwood only. Some (e.g. ambrosia beetles) rely on symbiotic fungi to break down carbohydrates. Insects do not require the presence of free water and therefore sapwood is prone to attack in dry conditions. As a consequence use of sap wood inside buildings need to consider this threat. Some ants and other insects can cause similar damage.
- *Termites (Ahmed et al., 2004; Shelton and Grace, 2003)*
  Termites also destroy wood mechanically. They, however, can also use wood as an energy source with the help of symbiotic bacteria present inside their body. Termites usually need soil contact but some species can build tunnels to reach above ground wooden structures. Termites

occur in tropical/subtropical regions and termite resistant woods are in high demand for construction in these parts of the world.

Wood-degrading marine organisms (Cragg et al., 1999; Eaton et al., 1989; Nishimoto 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.

2.1.1 Natural durability of NZDFI species

The natural durability according to the Australian standard "Timber – Natural durability ratings" (AS5604) for NZDFI species is listed in Table 1. This refers to timber harvested from old-growth natural forests in Australia, and can differ for timber from other sources including when it has been grown under short-rotation plantations in New Zealand.

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

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

[a] See (Cookson, 2004)

[b] See (Cookson et al., 2009)

[c] See (Anonymous, 2013)

2.2 Basis for natural durability

The large differences in resistance to fugal decay between timber species is predominately caused by its chemical composition, i.e. the secondary metabolites deposited in heartwood (Hawley et al., 1924; Rudman, 1963; Schultz et al., 1995). The effect of wood density on fungal decay is less clear as higher density wood often coincides with a higher extractive content. But it has been reported that density has a positive effect on decay resistance (Bush et al., 2011; Cookson and McCarthy, 2013; Edlund, 1998; Plaschkies et al., 2014; Sehlstedt-Persson and Karlsson, 2010; Wong et al., 1983; Yu et al., 2003). For mechanically caused damage from insects and marine organisms, wood density has been shown to have a significant effect (Peters et al., 2014). However, these results were based on observations between species and such large variation is not necessarily present within a species (Cragg et al., 2007). Other factors contribute to the natural resistance of wood to biological decay, for example pore size (Peters et al., 2002) or permeability (Bush, 2011).

In most trees the wood in a stem changes from sapwood to heartwood some years after formation in the cambium (Hillis, 1987; Mishra et al., 2016; Rowe, 1989; Taylor et al., 2002). The first year rings, closest to the bark, are young and contain some living cells, which are referred to as 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. 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. Therefore, heartwood of some species is of attractive colour and very resistant against biodegradation. Sapwood is never regarded as naturally durable (e.g. AS5604) or is 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 risk of embolism by pit aspiration, tylosis or deposition of extractives. This is not necessarily coinciding with heartwood formation (Ziegler, 1968) but is thought to reduce the susceptibility for wood to biodegradation.

2.3 Variability and control of heartwood traits

Wood properties, including heartwood associated features, are variable within a species. This is of economic importance 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. trees which produce larger quantities of good quality timber. On top of variability between individuals, variation of heartwood extractives and natural durability within a stem was reported; with variation existing in both as characteristic spatial pattern as well as random local variations. Environmental parameters affect heartwood features. This is topic of a separate research plan around site-species matching and growth and yield modelling of NZDFI eucalypts.

2.3.1 Within tree variability of heartwood features

The natural durability of heartwood decreases towards the pith (Sherrard and Kurth, 1933; Taylor et al., 2002). This is recognised in relevant standards, for example (AS5604) stating 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 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 et al., 2004), which generally has unfavourable properties for most applications.

Additionally heartwood extractives can vary considerably in their abundance on a micro scale. For a durable product a homogeneous distribution within cells walls, between cell types (e.g. fibres, parenchyma) and within year rings is desirable (Taylor et al., 2002). On the other hand 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 (Li and Altaner, 2015).

2.3.2 Genetic variability of heartwood features

Previous studies have reported on the variability and the degree of genetic control of heartwood features in various tree species (Table 2, Table 3,

Table 4). The research on within tree variation is limited. However, substantial within species variation in durability has been recently reported. 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 (Bush, 2011; Palanti et al., 2010). Therefore the production of ground-durable posts from young, short-rotation plantations should be possible by selecting a genetically superior resource.

Preliminary results have found a wide range of extractive contents in heartwood samples of *E. bosistoana*. Extractive content varied between 1.5% to 15% (wt/wt basis) at age 4½ (McLaughlin, 2013; Sharma et al., 2014), indicating that trees of good durability at a young age could 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 predicted. 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 et al., 2011). The data did not indicate unfavourable genetic correlations between growth and durability. Similar results were found for other species (Table 2).

Another heartwood feature determining the value of the timber is its colour. The genetic control of heartwood colour has been studied for several species (e.g. Gierlinger et al., 2004; Mosedale et al., 1996; Moya et al., 2013; Rink, 1987).

Table 2: Studies on heritability of heartwood abundance

Species	Heritability	Reference
Eucalyptus cladocalyx	0.38	(Bush et al., 2011)
Spotted gum (*Corymbia* spp.)	significant	(Bush, 2011)
Eucalyptus grandis	0.39	(dos Santos et al., 2004)
Pinus sylvestris	0.18 / 0.3 – 0.54	(Ericsson and Fries, 1999; Fries and Ericsson, 1998; Fries et al., 2000; Harju et al., 2001)
Larix x *eurolepis*	0.42 – 0.67	(Paques, 2004; Paques and Charpentier, 2015)
Pinus radiata	0.22 / 0.98	(Kennedy et al., 2013; Kennedy et al., 2014; Nicholls, 1965; Nyakuengama et al., 2000)
Eucalyptis obliqua		(Nicholls and Matheson, 1980)
Cunninghamia lanceolata	0.35 – 0.43	(Duan et al., 2016)
Sequoia sempervirens	0.4 – 0.5	(Meason et al., 2016)
Eucalyptus globulus	0.3	(Miranda et al., 2014)
Tectona grandis	0.02 / 0.70 – 0.77	(Moya et al., 2013; Narayanan et al., 2009; Solorzano Naranjo et al., 2012)
Juglans nigra	0.4	(Woeste, 2002)
Larix sibirica	0.22 – 0.39	(Venalainen et al., 2001)
Pinus banksiana	0.23	(Magnussen and Keith, 1990)
Eucalyptus globulus	0.23 – 0.31	(Miranda et al., 2014)
Juglans nigra	0.56	(Rink, 1987)

Table 3: Studies on heritability of heartwood extractives

Species	Heritability	Reference
Eucalyptus globulus	0.35	(Poke et al., 2006; Stackpole et al., 2011)
Eucalyptus cladocalyx	0.25	(Bush et al., 2011)
Larix x *eurolepis*	0.12 – 0.56	(Paques and Charpentier, 2015)
Pinus pinaster	0.35	(Lepoittevin et al., 2011; Perez et al., 2007; Pot et al., 2002)
Pinus sylvestris	0.3 – 0.9	(Partanen et al., 2011)
Cryptomeria japonica		(Tamura et al., 2005)
Abies sachalinensis		(Takashima et al., 2015)
Pinus sylvestris	0.57	(Fries et al., 2000)
Eucalyptus urophylla	0.28	(Denis et al., 2013)
Pinus roxburghii	0.58	(Raj et al., 2010)
Populus deltoides	0.99	(Klasnja et al., 2003)
Pinus taeda	0.22	(Schmidtling and Amburgey, 1982)
Quercus petrea, Quercus robur	strong	(Mosedale et al., 1996)

Table 4: Studies on heritability of natural durability

Species	Heritability	Reference
Eucalyptus globulus	0.5 – 0.6	(Poke et al., 2006)
Eucalyptus cladocalyx	0.13	(Bush et al., 2011)
Picea glauca	0.21 – 0.27	(Yu et al., 2003)
Tectona grandis	0.05	(Moya et al., 2013)
Abies sachalinensis		(Takashima et al., 2015)
Pinus sylvestris	0.02 / 0.37	(Harju and Venalainen, 2002; Harju et al., 2001)
Larix sibirica	0.39	(Venalainen et al., 2001)

2.3.3 Environmental influences on heartwood features

Contradictory data on the influence of site quality in general as well as water availability or humidity have been published (Hillis, 1987; Taylor et al., 2002). Larger *Eucalyptus globulus* trees contained more heartwood independent of spacing (Miranda et al., 2009). Injury to and poor health of trees has been often associated with increased heartwood content in trees, however, the contrary has also been reported (Hillis, 1987; Taylor et al., 2002).

Preliminary results indicate there are site effects on the amount of heartwood formed by *E. bosistoana* (Li and Altaner, 2016b).

2.3.4 Heartwood extractives

Little to nothing is known about the identity of the chemical compounds in heartwood of NZDFI's eucalypts (*E. bosistoana*, *E. argophloia*, *E. tricarpa*, *E. quadrangulata* and *E. globoidea*). In former decades research on the chemical heartwood compounds of some durable eucalypts has been conducted (Hillis, 1991). In more recent times the research in this area focused on non-durable eucalypts, the species grown for pulp and paper, where low extractive contents are desirable (Swan and Akerblom, 1967). Table 5 gives an overview of heartwood extractive compounds identified in some durable eucalypts. Chemotaxonomy of eucalypts by heartwood (Hathway, 1962) and leaf (Hillis, 1966, 1967; Padovan et al., 2014) compounds has been explored. Bark and root extractives of eucalypts were also studied (e.g. Cadahia et al., 1997a; Dayal, 1982; Domingues et al., 2011).

Table 5: Extractives present in some durable eucalyptus species

Species	Compounds	Tissue	Reference
Eucalyptus wandoo	• 3,5,4'-trihydroxystilbene • 3,5,4'-trihydroxystilbene-3β-D-glucoside	Heartwood	(Hathway and Seakins, 1959)
Eucalyptus microcorys	• cycloeucalenol	Heartwood	(Da Costa and Rudman, 1958)
Eucalyptus sideroxylon / Eucalyptus	• 3,5,4'-trihydroxystilbene (resveratrol) (and cis isomer) • 3,5,4'-trihydroxystilbene-3β	Heartwood	(Hart and Hillis, 1974; Hillis et al., 1974; Hillis and Isoi, 1965)

tricapa	D glucoside (and cis isomer) • 3,3’-di-o-methylegallic acid • 3,3’-di-o-methylegallic acid glucoside • 3,3’,4-tri-o-methylegallic acid • 3,3’,4-tri-o-methylegallic acid glucoside • gallic acid • catechin • egallic acid • polymerised leucocyanidin		
Eucalyptus marginata	• leucoanthocyanins	Heartwood	(Hillis, 1956)
Eucalyptus citridora	• *trans*-calamenene • T-muurolol • α-cadinol • β-hydroxy-a-cadinol • 4-hydroxy-3,5-dimethoxybenzaldehyde • 4-hydroxy-3,5-dimethoxybenzoic acid • linoleic acid • squalene • α-tocopherol • erythrodiol • morolic acid • betulonic acid • cycloeucalenol • cycloeucalenol vernolitate • β-sitosterol • β-sitosteryl-β-D-glucopyranoside • β-sitostenone • yangambin • sesamin	Heartwood	(Lee and Chang, 2000)
Eucalyptus astrigens	• catechin • gallic acid • 3,5,4'-trihydroxystilbene (resveratrol) • 3,5,4'-trihydroxystilbene (resveratrol) glucoside • chlorogenic acid • polymerised ellagitannins • ellagic acid	Heartwood	(Hillis and Carle, 1962)
Eucalyptus camaldulensis	• gallic acid • vanillin	Branch, mostly sapwood	(Cadahia et al., 1997b; Conde et al., 1995)

	• syringaldehyde sinapaldehyde • ellagic acid • naringenin • proanthocyanidin		

The heartwood compounds in a species are numerous (Hillis, 1987; Rowe and Conner, 1979), each molecule having different properties e.g. in bioactivity (Morris and Stirling, 2012; Ohtani et al., 2009), colour (Balogh and Anderson, 1965; Takahashi and Mori, 2006; Zavarin and Smith, 1962) or interaction with glues (Wang, 1992). Furthermore the relative proportion of the individual compounds varies within a species (Daniels and Russell, 2007; Niamke et al., 2014). Therefore not only the absolute amount of extractives but also the extractive composition is important in respect to wood properties like durability and colour. As the biosynthesis of the individual compounds is also partly under genetic control (Fries et al., 2000) there are possibilities 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 preservative (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 et al., 2004). Recently the variability in the essential oils extracted from *E. bosistoana* leaves has been reported (Bouzabata et al., 2014). Tannins from eucalypts are other compounds of interest (Conde et al., 1997).

Leaf chemistry (extractives as well as reserve carbohydrates) is linked to the susceptibility of trees to leaf defoliators. Managing and improving pest tolerance is essential for a successful establishment of a eucalyptus plantation estate. NZDFI's work in this area is described in more detail in an associated research plan.

2.4 Measuring heartwood /sapwood

The amount of sapwood and heartwood in a tree can have a marked impact on its value. In the case of naturally durable NZDFI species high heartwood content is desirable. However, sapwood is the desired part of the stem for pulp production and other wood manufacturing processes as heartwood can drastically increases processing costs (Pereira et al., 2003). Sapwood width is also a key factor for understanding water balances of forest plantations (Kumagai et al., 2005), increasingly under the focus in a changing climate 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. This can be difficult for some species which do not have marked colour or moisture content differences between sapwood and corewood. Colour stains are 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 et al., 2012).

A transportable magnetic resonance imaging system has been developed, which can measure sap flow in trees non-destructively (Jones et al., 2012). In its current form portability (size and weight of the equipment) and the limitations to stem diameter (<20 cm) prevent this tool to be used more widely.

Recently electrical resistivity tomography has been found useful to detect sapwood in standing trees non-destructively (Wang et al., 2016). The reported accuracy of the method has been questioned for eucalypts (Pfautsch and Macfarlane, 2016) and the need of multiple sensors limits its usefulness for fast assessment of many trees for quality control of plantations or breeding trials.

2.5 Measuring durability

The methodology set by standards to assess the durability of timber is by measuring the mass loss of the samples after exposure to wood degrading organisms either in field or under laboratory conditions, with the details differing significantly depending on the hazard class tested for (AWPC, 2007). These require numerous (>6) reasonable sized (>20 mm) samples and testing for a considerable time frame (>12 weeks) (AWPC, 2007). The effort of measuring natural durability by mass loss was recognised as prohibitive for inclusion in large scale screening programmes (Bush et al., 2011; Paques and Charpentier, 2015).

Experimental alternatives to accelerate durability assessments have been proposed. The required exposure time can be shortened by accelerating the decay by creating more favourable environmental conditions (Cookson et al., 2014). 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 et al., 2001). Several studies report that NIR was useful 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 are still difficult to realise in a sizable lean breeding programme.

As outlined above (2.2) 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) is prohibitive to be useful in a screening programme (Takashima 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 et al., 1993) and is used for this purpose for agricultural products. Several studies have found NIR being able to accurately assess the extractive content of heartwood (Table 6). However, the prediction of mass loss by decay fungi was not always reported to be accurate enough to support a breeding programme (Table 7).

Wounding was suggested as an early testing method to breed for heartwood (Harju et al., 2009). The wound reaction in stems after injury is related to heartwood formation (Blanchette and Biggs, 1992).

Table 6: Studies quantifying the extractive content of heartwood by NIR

Species	**Model accuracy (R^2)**	**Residual mean square error**	**Reference**
Eucalyptus cladocalyx	0.93	0.009	(Bush et al., 2011)
Eucalyptus globulus	0.82 – 0.94	1.37	(Alves et al., 2012; Poke et al., 2004; Stackpole et al., 2011)
Larix sp.	0.86 – 0.98	0.21 – 0.86	(Gierlinger et al., 2002)
Thuja plicata	0.71	2.2	(Stirling et al., 2015)
Tectona grandis	>0.8	2.36	(Niamke et al., 2014)
Astronium graveolens	0.75	1.42	(Taylor et al., 2008b)
Quercus alba	0.85	1.52	(Taylor et al., 2011)
Pinus sylvestris	0.84	0.33	(Holmgren et al., 1999; Leinonen et al., 2008)
Quercus petraea, *Quercus robur*	0.93	0.57	(Zahri et al., 2008)
Pinus pinaster	0.92 – 0.97	0.28	(Lepoittevin et al., 2011; Perez et al., 2007)
Pinus brutia	0.91	0.09	(Uner et al., 2011)
Eucalyptus urophylla × E. grandis	0.77	0.87	(Giordanengo et al., 2008)
Swietenia macrophylla	0.68	0.02	(Taylor et al., 2008a)
Betula pendula, *Betula pubescens*	0.92	0.77	(Toivanen and Alen, 2007)

Table 7: Studied quantifying the natural durability of wood by NIR

Species	**Decay predictability**	**Reference**
Eucalyptus cladocalyx	Unsuccessful	(Bush et al., 2011)
Larix decidua, L. kaempferi	Successful	(Gierlinger et al., 2003)
Larix sibirica, L. decidua	Successful	(Sykacek et al., 2006)
Thuja plicata	Unsuccessful	(Stirling et al., 2015)
Sequoia sempervirens	Partially successful	(Jones et al., 2011)
Cupressus lusitanica, C. macrocarpa, Cuprocyparis leylandii x C. ovensii	Partially successful	(Jones et al., 2013)
Astronium graveolens	Unsuccessful	(Taylor et al., 2008b)
Pinus sylvestris	Successful	(Flaete and Haartveit, 2004; Leinonen et al., 2008)

2.6 Research on heartwood

2.6.1 Genetic selection

NZDFI has established numerous breeding trials since 2009. Details of the breeding trials can be found in the NZDFI Breeding plan. As the trees age and start to form heartwood we will assess our families on a) the amount of heartwood in the stem and b) the extractive content in the heartwood.

Having characterised our genetic resource we will be able to select trees with abundant heartwood rich in extractives for propagation.

We have recently developed a battery-powered, light-weight tree corer which allows the easy and quick extraction of 12 mm diameter cores (Li and Altaner, 2016b). On these cores the abundance of heartwood will be assessed using a colour indicator (methyl orange) to highlight the heartwood. Additionally the extractive content in the heartwood will be assessed by NIR spectroscopy as milling and subsequent extraction is resource demanding. In order to assess the extractive content in heartwood by NIR spectroscopy we will calibrate the system for each NZDFI species. This has already been achieved for the *E. bosistoana* (Li and Altaner, 2016a).

The trees with high extractive content are more likely to produce more naturally durable timber. Natural durability will be directly tested according to standards for the trees which have a high extractive content.

2.6.2 Identifying key heartwood compounds

The identity of the key compounds in heartwood of the NZDFI species is unknown. Knowing the key heartwood compounds will enable further improvement of the natural durability of the resource by selecting the trees with the most favourable extractive composition among those with high extractive content. A similar approach is taken for *Thuja plicata* (Morris and Stirling, 2012). Knowing the key compounds would also facilitate the identification of target genes. A better understanding could also contribute to processing of the timbers (e.g. colour stability, drying or gluing). Last but not least it could be possible to find high value applications for individual extractives.

Extracts will be analysed by standard analytical chemistry methods. The School of Forestry has a gas chromatograph and access to the facilities in UC’s Chemistry department. We are collaborating with Dr. Odermatt (University of Hamburg), whose expertise is on the analysis of wood extractives. Furthermore we will conduct experiments to identify bioactive compounds in the extract.

2.6.3 Certifying durability

The resources necessary to test natural durability in a breeding programme are prohibitive. Additionally samples size (one 12 mm diameter core of each individual) is limited. Therefore a potentially more durable resource is selected through the proxy of high heartwood extractive content. The natural durability rating of the selected resource needs to be determined according to standards by independent organisations. Standards vary depending on the envisaged export marked. Some of NZDFI’s industry partners expressed their intent to lead this work. Additionally we are in contact with international institutions regarding the testing of our samples.

2.6.4 Detecting heartwood in standing trees

Heartwood has a dramatic influence on the value of a tree. However, there are no tools available for the quick assessment of sapwood depth in standing trees. Measuring sapwood depth quickly is, however, necessary in an industrial context to efficiently produce forest inventories for quality control. In a research context this data is needed to investigate the environmental influences on heartwood formation in order to add heartwood into growth and yield models. A portable tool to measure quickly the sapwood depth in standing trees will be developed. Concepts have been developed based on the different electrical properties of heartwood and sapwood.

2.6.5 Colour

No research into colour of NZDFI species is planned at the current stage. However, the fact that some of the chosen species, which are closely related, have differently coloured heartwood opens the possibility to screen hybrids for colour.

3 Growth-strain

Growth-strain has often been identified as the reason why plantation grown eucalypts are not used for solid wood products in significant amounts (Cown, 2016; Poole et al., 2014). Board distortion after sawing, end splitting and other wood defects have been associated with growth-strain, restricting plantation-grown eucalypts to the low-value pulp chip market. Technical solutions to mitigate growth-strain during processing have been investigated but come with considerable costs. On the other hand growth-strain has been shown to be partly under genetic control (Chauhan and Aggarwal, 2011; Davies et al., 2015; Murphy et al., 2005; Solorzano Naranjo et al., 2012). NZDFI's primary approach to resolve the problem of high growth-strain is through a breeding programme. The reason why tree breeding programmes have rarely included growth-strain as a trait are the difficult and labour intensive measurements. NZDFI makes use of a newly developed method to assess growth-strain quickly in young trees (Chauhan and Entwistle, 2010; Entwistle et al., 2014). This allows effective screening of NZDFI's entire breeding populations for low growth-strain. This work is financed for *E. bosistoana* and *E. argophloia* through the associated independent MPI research programme "Minimising growth-strain in eucalypts to transform processing" SFF 407602 running 2015-2018.

To make use of the exiting eucalypt resource for solid wood processing we propose to investigate the possibility of segregating harvested logs for low growth-strain. This requires a tool which can measure growth-strain quickly and non-destructively. Such a tool does currently not exist.

3.1 Research on growth-strain

3.1.1 Breeding

The methodology to screen entire economically breeding populations for growth-strains has been outlined in the MPI programme "Minimising growth-strain in eucalypts to transform processing" SFF 407602" project. This programme is currently running satisfactorily with work on *E. bosistoana* and *E. argophloia*. Further funding will be sought to generate a low growth-strain resource for the other NZDFI species.

3.1.2 Segregation

Work has started to test if it is possible to exploit the effects of mechanical strain on the vibrational behaviour of molecular bonds to determine the strain-level in solid wood. A literature review has been prepared for SWP (Guo and Altaner, 2016) and experimental details can be found in the associated SWP work plan. The current work will establish if it is possible to assess growth-strain in green solid wood by IR spectroscopy under laboratory conditions. If possible, future work will build on that and develop a tool which can be used on logs in an industrial environment.

4 Other wood properties

The eucalyptus species in the NZDFI programme where chosen preliminarily for their natural durability and their potential fast growth under the climatic conditions in the drier parts of New Zealand. However, the timbers of NZDFI species have also excellent physical properties shown in Table 8. Most of the available data considers the Australian old-growth resource with only a small number of species tested in New Zealand using timber from younger plantation-grown trees (Jones et al., 2010) These demonstrate that, the timber from a young plantation resource can still be expected to be of excellent quality.

4.1 *Eucalyptus bosistoana* (grey coast box)

The timber of *E. bosistoana* from the Australian old-growth resources has exceptional properties (Table 8). More properties are listed in the Australian Standard (AS1720.2). Its high density might prevent it from being used for furniture but is ideal for flooring, construction and many other uses. The species was reported to express interlocked grain.

Logs from 43 and 47 year-old *E. bosistoana* grown in South Africa were reported to saw easily apart from splits in the pith containing centre boards and to season without the development of serious drying defects (Poynton, 1979a).

Wood properties, close to those published for the Australian resource, were reported for 42 year-old trees grown in Uruguay from seed sourced in New South Wales, Australia (Mantero et al., 2014).

4.2 *Eucalyptus argophloia* (Queensland white gum)

Little information is available for the wood properties of *E. argophloia* as it is a uncommon and has only recently gained interest as a plantation species (Lee et al., 2011). Basic density was reported between 726 and 861 kg/m^3 for samples ranging between 6 and 32 years of age for a small number of trees (<50) from various sites (Harding et al., 2012). The same report lists MoE values between 8.25 and 14.43 GPa and MoR values of 82 to 150 MPa for these samples. Shrinkage values were also reported.

E. argophloia is an endangered species with a limited genetic base. However, it is closely related to *E. bosistoana* with which it may hybridise. The inclusion of *E. argophloia* into the NZDFI programme was largely driven by the potential to create hybrids with *E. bosistoana* thereby broadening the genetic resource for future selections.

4.3 *Eucalyptus globoidea* (white stringybark)

Properties of *E. globoidea* timber from the Australian old-growth resources are listed in (Table 8). More properties are listed in the Australian Standard (AS1720.2). *E. globoidea* timber does not reach the exceptional properties of *E. bosistoana*. Its lower density is not necessarily a disadvantage. The species expresses interlocked grain and a very narrow sapwood band.

Sawing of 25 year-old *E. globoidea* grown in NZ was reported to yield good amounts of higher visual grades (Jones et al., 2010). The average physical properties of this timber were with a kiln-dry density of 655 kg/m^3, a MoE 12 GPa and a Janka hardness of 5.5 kN markedly lower than those reported for the Australian old-growth resource (Table 8).

Sawing studies were conducted on *E. globoidea* logs sourced from 10 to 44 year-old stands from various regions throughout South Africa (Poynton, 1979b). The material sawed readily with the centre flitches often badly splitting. Boards from young trees expressed notable honeycombing and collapse during seasoning. Seasoning defects were only moderately expressed in boards from older trees.

A description of the wood anatomy of *E. globoidea* can be found in study of stringy barks (Ilic, 2002). This study reports a basic density of ~620 kg/m^3 for this species.

4.4 *Eucalyptus quadrangulata* (white-topped box)

Properties of *E. quadrangulata* timber from the Australian old-growth resources are close to those of *E. bosistoana* (Table 8). The species is not listed in the Australian Standard (AS1720.2). *E. quadrangulata* sometimes expresses interlocked grain.

Logs grown in South Africa sourced from a 35 and a 41 year-old stand did saw easily with the centre flitches tending to split (Poynton, 1979c). During seasoning the timber showed only mild tendency to cup or check and sometimes collapse near the pith. The most serious defect was a high incidence of kino rings. Timber cut from logs sourced from a 9 year-old stand did not season well with a good deal of end-splitting, cupping and collapse. The latter could not be remediated by kiln reconditioning.

4.5 *Eucalyptus sideroxylon (tricarpa)* (red ironbark)

Properties of *E. sideroxylon* timber from the Australian old-growth resources are similar to that of *E. quadrangulata* (Table 8, AS1720.2). The species expresses interlocked grain.

Logs from 39 and 47 year-old South African stands were reported to saw easily with some splitting of the central flitch (Poynton, 1979d). Overall the timber seasoned well with some splits occurring near knots and a tendency to collapse for wood close to the pith.

The taxonomic difference between *E. sideroxylon* and *E. tricarpa* are debatable. Chemotaxonomic investigations on the difference between *E. sideroxylon* and *E. tricarpa* were published (Hillis and Isoi, 1965). The species is related to *E. bosistoana* with which it may hybridise and therefore has the potential to increase the genetic resource of the NZDFI breeding programme.

Table 8: Some wood properties reported for NZDFI species and radiata pine according to (Bootle, 2005).

Species	Dry MoE (GPa)	Density at 12% MC (kg/m^3)	Dry MoR (MPa)	Dry Hardness (Janka) (kN)
*Eucalyptus bosistoana**	21	1100	163	13
*Eucalyptus quadrangulata**	18	1030	163	14
*Eucalyptus sideroxylon (tricarpa)**	17	1130	133	13
*Eucalyptus globoidea**	17	880	133	8.8
*Eucalyptus argophloia***	14	862-1005	-	7-14
Pinus radiata (NZ)	9.1	480	76	2.8

*Note: this is data considering the Australian old-growth resource

** (Anonymous, 2013); age 13

4.6 Research on other wood properties

The NZDFI species are characterised by high density, strength and stiffness (Table 8). The available information also indicates that they saw and dry without too many difficulties. At present we do not intend to select the NZDFI species for stiffness, collapse, density, grain or colour. However, during the assessment of growth-strain we obtain as a by-product data on density, stiffness and collapse. These good wood properties are monitored to ensure they are not compromised when selecting for tree growth, form, health, heartwood and growth-strain. These traits can be selected for if needed, as the data is pedigreed.

The assessment of heartwood properties is achieved by taking 12 mm diameter core samples that can be analysed further. If deemed necessary and resources allow, these cores can be analysed for colour, grain and other wood properties.

4.6.1 Stiffness

In conjunction with the assessment of growth-stress (Chauhan and Entwistle, 2010; Entwistle et al., 2014) the dynamic MoE is measured (Chauhan et al., 2013). These assessments are performed on young trees less than 2-years old. The relationship between stiffness and the level of growth-strain is unclear as for eucalypts positive, negative and no correlations have been reported (Chauhan and Aggarwal, 2011; Chauhan and Walker, 2011). The correlation between growth-stain and stiffness will be monitored for the NZDFI species to ensure no significant unintended loss in the selected trees. It is further possible, if deemed necessary, to assess the cores obtained for heartwood assessments at age 7 with a purpose build acoustic velocity scanner for stiffness available to NZDFI (Hayes and Pink, 2012). Measurements of acoustic velocity of standing trees and destructive sampling are further options available later in the programme when the trees have reached an older age. Such measurements are routinely conducted by NZDFI partners, which have the necessary equipment available.

4.6.2 Density breeding

The NZDFI species are of high to extreme density (Table 8). No selection for wood density is planned, however, excessively high density is not an advantage and it might be of interest to select for lower density. As for stiffness, density data is generated during the assessment of growth-strain when trees are ~2-years old. The genetic resource will be characterised. Furthermore cores samples from heartwood studies at age 7 will be available, allowing evaluation of radial patterns in density.

4.6.3 Collapse

Collapse is excessive volumetric shrinkage. Volumetric shrinkage data is generated during the growth-strain assessments at age ~2-years. For most NZDFI species collapse during seasoning has not been reported to be problematic. We will monitor collapse in the data and select to eliminate this if necessary. Collapse is also apparent on the cores for the heartwood assessment at age 7. Preliminary data confirms that *E. bosistoana* does not collapse when drying.

4.6.4 (Interlocked) grain

The NZDFI species express interlocked grain. Regular interlocked grain can be a desirable feature for appearance grade timber products (Harris, 1989; Kohl, 2012). Spiral grain on the other hand can lead to twist in sawn timber or distortion of veneer sheets. At present grain patterns are not a breeding trait, however, they have been reported to be under strong genetic control in *E. dunnii* eucalypts (Thinley et al., 2005) and twist associated with spiral grain has been reported for 20-year old *E. cladocalyx* and other species (Wessels et al., 2016). If the cores which are obtained for heartwood assessments are assessed for stiffness with the available purpose build acoustic scanner (Hayes and Pink, 2012), a by-product of the data is the radial grain pattern. The intention is to use this data to characterise the NZDFI species if resources can be found.

5 Validation of early selections

NZDFI pursues early selection to ensure early deployment of improved material and to minimise the costs of the breeding programme (Altaner, 2015). The School of Forestry has developed early selection methods for wood quality over the last decades and successfully applied to radiata pine (Apiolaza, 2009; Apiolaza et al., 2011; Chauhan et al., 2013; Entwistle et al., 2007; Sharma, 2013).

5.1 Research

In due course the NZDFI breeding trials require a 2nd thinning (around age ~10). This can yield some logs big enough to verify the early selection for heartwood and growth-strain on a family basis. Growth-strain is intended to be measured on the logs classically with strain gauges and additionally the splitting test using a portable sawmill. Wooden stakes can be sawn from trees with heartwood that can be tested in fungal cellars. This work allows the confirmation of genetic gain and will reassure growers that planting genetically improved seedlings will yield higher quality timber.

6 Processing

Processing is dictated by the targeted products. In the first instance NZDFI targets naturally durable posts and high stiffness veneers for LVL. At a later stage the trees will also yield durable and coloured sawn timber. The sawing of eucalypts has been reviewed for SWP (Cown, 2016). In general the processing of smaller diameter eucalyptus logs is hampered by excessive growth-strain and for many species difficult drying. NZDFI’s primary approach to remediate growth-strain is by breeding. The NZDFI species have been reported to saw easily and dry without too much problems. Some products such as posts are used green. It should be noted that early pruning is essential to obtain posts and quality sawn timber from young plantations (Nolan et al., 2005).

The domestic LVL production is based on radiata pine, which does not yield structural grade material in the core. Therefore, peeling technology is based on conventional spindled-lathes producing a large peeler core (>8 cm) requiring large diameter trees. However spindle-less lathes have been developed which are able to obtain veneer from low-quality small-diameter logs. This technology is now widely used in China for plywood production (Arnold et al., 2013). Current research of spindle-less lathe technology has shown great potential for processing small-diameter logs from Australian eucalypt plantations (Hamilton et al., 2015; McGavin, 2016; McGavin et al., 2015a; McGavin et al., 2015b; McGavin et al., 2014a; McGavin et al., 2014b). Opportunities and hurdles of NZ grown eucalypts for LVL productions have been reviewed for SWP (Riley, 2016).

Research on processing NZDFI eucalypts is restricted by the availability of trees. Larger breeding populations have been planted from 2009 onwards with a few stands planted in the early 2000s. Therefor no larger diameter logs are accessible. However, trees are growing well and smaller diameter logs will could be sourced from thinning operation at age ~10 years towards the end of the SWP programme.

6.1 Research on posts

Production of posts is simple and does not need extensive research. NZDFI is targeting small scale farm forestry growers for the durable post market. For these small scale plantations on-site processing is an attractive option. A proposed sawing pattern is to cut 4 square posts from the heartwood by squaring and quartering the log with a mobile horizontal band saw.

In due course the NZDFI breeding trials require a 2nd thinning (around age ~10). This can yield some logs big enough to trial processing of posts. Yields could be estimated.

6.2 Research on LVL

The feasibility of spindle-less lathe technology to produce veneers from small diameter logs obtained from thinning NZDFI breeding trials will be explored. Grade recovery, physical veneer properties and processing costs are parameters to be determined.

Currently, using spindle-less lathes is also the only way to obtain veneers to investigate LVL from NZDFI species as no larger diameter logs are available. Preliminary results have indicated challenges with gluing the high density veneers, indicating the need for research. NZDFI industry partners have emphasised the role of adhesive manufactures in this area. The mechanical properties of the envisaged high spec-LVL need to be verified.

As small-scale farm forestry growers are a major interest group of NZDFI we will explore the possibility to make the spindle-less lathe technology mobile for on-site veneer production in analogy to / as an alternative post production by sawing.

6.3 Research on sawn timber

At present no research on processing large logs of NZDFI eucalypts for sawn timber is planned. Research in this area requires access to logs >30 cm in diameter, which are not yet available from the NZDFI programme. Grade recovery and drying are areas to be considered at a future time.

7 Silviculture

Silvicultural regimes for durable eucalypt plantations depend on the envisaged end-product. Early pruning appears to be essential for most targeted products. The importance of pruning plantation eucalypts intended to be used for solid wood products has been highlighted recently (Nolan et al., 2005). Some thinning schedules for growing durable eucalypts for saw logs or transmission poles in South Africa have been summarised by (Poynton, 1979e).

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