Understanding drying defects and improving the drying quality of Eucalyptus

Research Proposal

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1 Introduction

Wood has been one of the oldest building materials used by mankind. Due to global awareness on environmental issues, greater emphasis is being given on the use of wood in construction in recent times. However, the supply of timber from natural forests is dwindling. In order to meet the increasing demand of the growing population, a large part of wood is sourced from short-rotation plantation forests. Most of the wood procured from short-rotation plantation forests suffer from various limitations such as dimensional stability, drying quality and durability due to a greater portion of juvenile wood.

Eucalyptus plantations have been estimated to cover more than 20 million ha in 2009, mainly distributed in Australia, India, Brazil, China and Africa (Iglesias & Wilstermann, 2009). However, plantation grown eucalyptus is largely restricted to low-value pulpwood as milling and drying the timber without defects is challenging. Most plantation eucalyptus are prone to drying defects such as collapse and honeycomb caused by its low permeability (Resende et al., 2018; Zen et al., 2019). Drying most hardwoods is generally slow due to the low permeability and moisture transport coefficients compared with softwoods. For instance, the transverse green permeability of *Eucalyptus delegatensis* wood is in the order of 4.6×10^{-18} m^2, whereas the permeability of green *Pinus radiata* wood is 263 to 410×10^{-18} m^2 (Langrish & Walker, 1993).

"Fundamentally, the collapse is largely an inherent property of the timber" (Blakemore & Northway, 2009) although processing parameters are still key elements, which may be modified to reduce the loss. A major reason of economic loss is checking in wood caused by collapse shrinkage. Currently, processing most plantation eucalypt wood without collapse is un-economical. In the longer term, "genetic improvement is the only approach that is likely to eliminate the problem" (Blakemore & Northway, 2009).

The New Zealand Dryland Forest Initiative (NZDFI) has established a breeding program for *E. globoidea* as a high value timber resource. Instead of just focusing on high growth rate and improved form, favorable wood properties are key objectives in the breeding program to produce high-value timber (Millen et al., 2018). However, even if this is achieved, it would take a full rotation of 20-40 years before it would be available for processing. In the mean-time, the solid wood industry will have to use the existing plantation-grown resource, requiring suitable drying practices.

1.1 Background information on wood drying

1.1.1 Wood structure

Wood is defined as the secondary xylem in the stems of trees (Hickey & King, 2001). In a living tree it performs a support function, enabling woody plants to grow tall. It is a plant tissue, made up of cells having an outer covering, the cell wall, surrounding an inner material which is living called cytoplasm. Most of the sapwood and the entire heartwood is composed of dead cells i.e. cell walls with empty cell lumens because the cytoplasm is quickly lost during development. However, as all life processes take place in an aqueous environment, so wood, as the skeletal remnant of these processes, retains large amounts of water. The cell wall is divided into three layers: the middle lamella, the primary wall, and the secondary wall (Figure 1). The middle lamella and primary wall are thin compared to the secondary cell wall and control cell development. The primary wall contains three main components: cellulose, hemicellulose, and pectin. The secondary cell wall is made up of cellulose, lignin and hemicellulose and divided into three layers, the outer (S1), middle (S2) and inner (S3) layers, which have different microfibril angle with respect to the fiber axis.

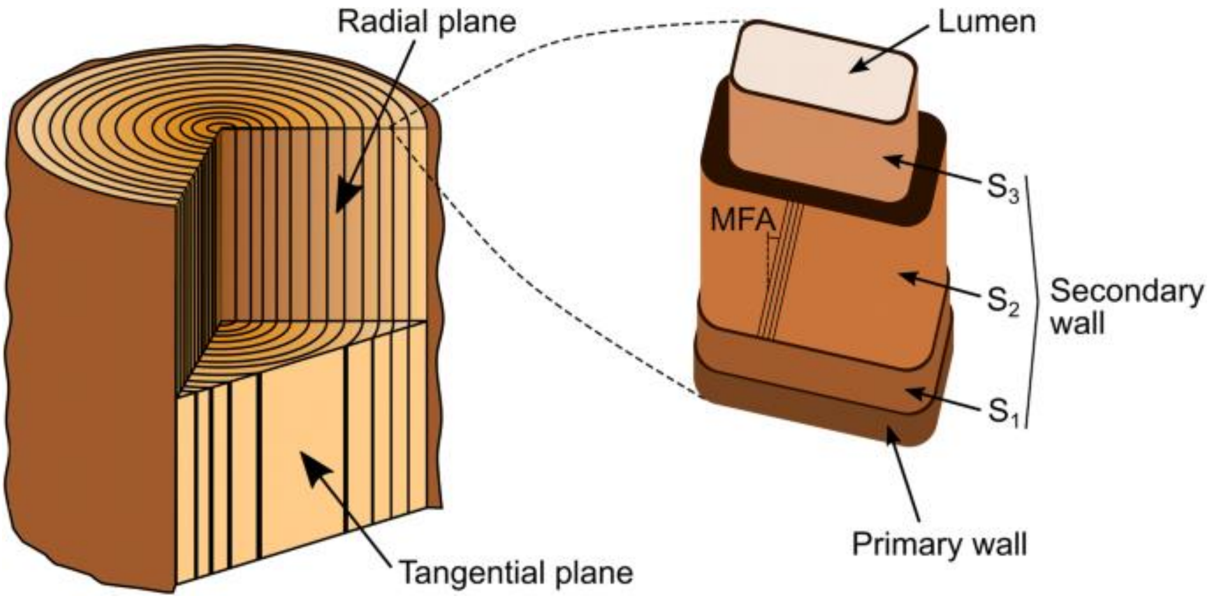


Figure 1. Simplified model of wood structure showing the cutting planes and cell wall layering, with the microfibril angle (MFA) illustrated in the S_2-layer (Penttilä et al., 2020)

The structure of hardwoods

The processing of hardwoods is often more complex than softwoods because of their diversity in species as well as structure (Figure 2a). There are generally three kinds of cells present in hardwoods; namely, vessels (conduction of sap), fibres (strength and mechanical support) and parenchyma (storage) including ray cells as well as tracheids and epithelial cells. Vessels comprise many individual cells or vessel elements joined end to end to form long conducting channels (Figure 2b). The vessels are about 0.2 to 0.5 mm in length and 20 to 400 µm in diameter (Desch and Dinwoodie, 1996). These vessels are sometimes blocked by tyloses. Tyloses are formed as a part of the transformation of sapwood to heartwood in some trees. Tyloses also retard the flow of sap due to physiological reasons (during drought or low water contents in the vessel), mechanical injury, or as a result of a viral or fungal infection (Panshin and de Zeeuw, 1970). The fibres are axially elongated, thick-walled, with small lumens and ends that taper into pointed tips. The proportion of fibres present in wood largely determine the density of hardwoods. In low-density wood, the vessels occupy a significant proportion of the volume of wood, while the denser woods have a larger proportion of thick-walled fibres. The secondary walls of fibres are typically sparsely pitted and at functional maturity, the cells lack cell contents (Walker, 2006).

Softwood processing technologies (including drying) are considered relatively easy, well established and implemented by many timber companies around the world due to the uniformity of softwood resources and a large amount of research on softwood processing, and are also very advanced in New Zealand and Australia due to the availability of large areas of softwood plantation resources, predominantly of *P. radiata.*

Pits: structure and function

There are pits, openings between vessels or fibres in the cell walls. The pits in hardwood vessels are often bordered and are formed by an overarching of the pit membrane by the cell walls of the two adjacent elements, leaving an elongated opening (generally 5-12 µm in diameter) (Figure 2). This opening is called the pit aperture, but is lacking a torus, which is typical of softwood bordered pits. The pits are much less frequent in the walls of fibres, and these pits are mainly simple pits, i.e. without any border (Desch and Dinwoodie, 1996). Hardwood vessel pit membranes are homogeneous structures consisting of a tight web of microfibrils of cellulose (Figure 2c) (Walker, 2006). The mesoporous (5-50 nm) mesh of pit membranes appears to be essential for preventing the spread of embolism and maintaining the integrity of the xylem sap transport system. However, the small pore constrictions of pit membranes also add hydraulic resistance to the xylem pathway. The exact function of pit membranes in sap flow is still debated (Kaack et al., 2019).

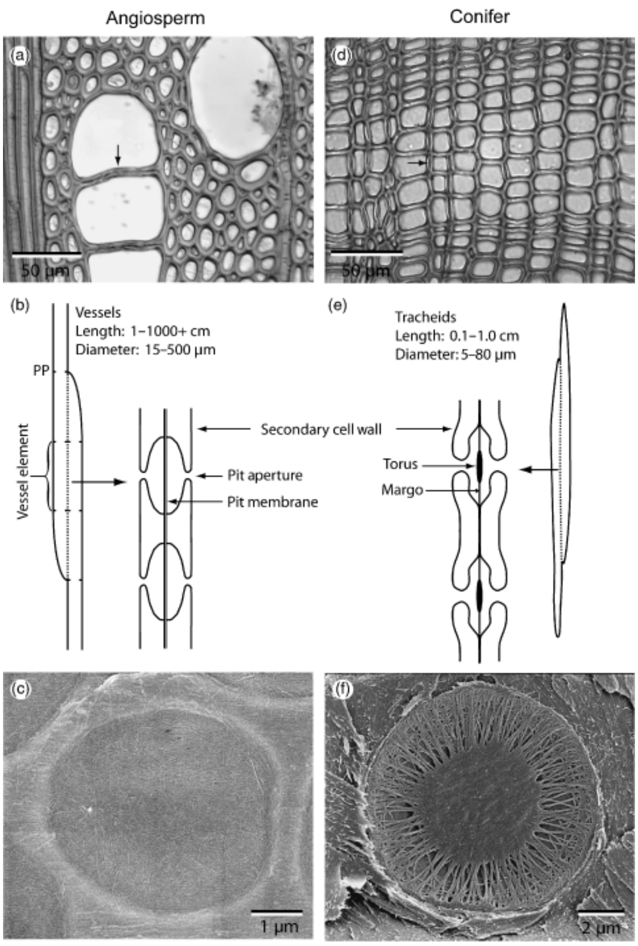


Figure 2. Structure of xylem and inter-conduit pits in hardwoods and softwoods. (a) Transverse section (TS) of angiosperm xylem tissue (b) Each vessel is made up of multiple vessel elements joined end-on-end through a perforation plate (c) SEM showing 'homogeneous' pit membrane of angiosperms (d) TS of typical conifer xylem tissue made up of tracheids with bordered pits located in radial walls. (e) Tracheids consist of a single tracheary element (f) SEM of a typical gymnosperm pit membrane with a torus (Choat et al., 2008)

Sapwood and heartwood

Three distinct zones can be identified in tree stems; sapwood, heartwood and transition zone. The parenchyma cells are alive in the sapwood and are active in transport (between symplast and apoplast). The sapwood of eucalyptus is comparatively permeable and the drying of the sapwood material usually proceeds with little difficulty. The sapwood is the prime conduit of water movement within the tree and confined to a relatively narrow band near the stem periphery. The transition zone is the boundary between the sapwood and the heartwood. This is usually a narrow, often pale-colored zone around the heartwood containing living cells that are normally devoid of starch, impermeable to liquids and with a moisture content lower than sapwood (Hillis, 1987; Taylor et al., 2002). Heartwood is the inner part of the stem, devoid of living cells, water conduction, and in which reserve materials have been removed. The heartwood that contributes most to the overall volume of the stem, is impermeable. The heartwood is formed by the death of parenchyma (thin-walled transport and storage cells), the deposition and formation of a variety of substances collectively called extractives, and the frequent development of tyloses in the vessels. Extractives and tyloses endow the heartwood with its high impermeability. Extractives play an important role in the reduction of the cell wall capillaries (Chafe et al., 1992).

1.1.2 Wood-moisture relationships

Wood, like many natural materials, is hygroscopic; it absorbs moisture from the surrounding environment. The moisture exchange between wood and air relies on the relative humidity and temperature of the air and the current amount of water in the wood. Some of the difficulties of using wood as an engineering material arise from changes in moisture content. Many of the wood's physical and mechanical properties depend upon the moisture content of the wood. Water in wood can exists in two forms: bound water, within the cell wall and free water, in the large voids, such as lumens of tracheid cells (Telkki et al., 2013). Green wood is often defined as freshly sawn wood in which the cell walls are completely saturated with water and additional water may be found in the lumina. The moisture content of green wood can range from around 30% to more than 200%. The moisture content at which only the cell walls are fully saturated (all bound water) but no water exists in cell lumina is called the fibre saturation point. Operationally, the fiber saturation point is known as the moisture content above which, as a function of the moisture content, the physical and mechanical properties of wood do not change. The fiber saturation point of wood averages about 30% moisture content, but it can differ from that value by several percentage points in the individual species and individual pieces of wood.

According to Siau (1984), the transport process in wood may be classified according to two basic physical mechanisms: bulk flow of fluids (sap) through the interconnected voids of wood under the influence of a pressure gradient, and diffusion which can be split into inter-gas (within cell lumens) and bound water diffusion (within cell walls). Flow in wood may be laminar, turbulent, from the slip type or non-linear (Siau, 1984). Laminar flow is assumed in Darcy's law, which states that linear velocity and volumetric flow rate are directly proportional to the applied pressure difference. The physical mechanisms behind the sap transport are of interest for both understanding xylem functionality and from a wood material and processing perspective.

Sap flow in xylem

Xylem transports water and nutrients from the roots to the leaves under negative pressure. This negative pressure is generated by the surface tension of capillary menisci in the nano-pores of fibrous, cellulosic cell walls, driven by strong, solar-powered humidity gradients (Figure 3). Capillary action induces the flow of free water through the cell cavities and pits. The cell walls are hydraulically connected to the rest of the plant's hydraulic system. The voids present in secondary xylem, macrovoids (cell lumina between 10 and 400 micrometer in diameter), micro-voids (pointed ends of lumens, pit membrane voids diameter between 10 and 5 micrometer in diameter) and nano-voids (pores in the cell wall < 10 nm in diameter), are responsible for water movement. Capillary force reaches a maximum when the curvature of the meniscus equals the radius of the largest opening.

Laplace equation $(p_1 - p_2) = 2\,\gamma / r$

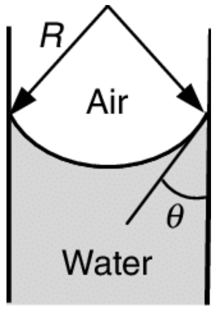


Figure 3. Negative water pressure generated by meniscus concave on the air side (Tarantino, 2013)

Sap flowing through vessels in hardwood passes through pores or perforations in the end walls of each cell from one vessel element to another. Sideways movement of the sap between adjacent vessels takes place through the inter-vessel pits. The differences between a pit and a perforation is the absence of the separating pit membrane in the perforation and the size. The small size of the pores in these membranes permits lateral water flow between adjacent vessels, but it is likely that air embolism will not spread to adjacent, sap-conducting vessels (Walker, 2006). Under normal circumstances the necessary negative pressures would cause the water column to break and a water vapour embolism to occur. Kaack et al. (2019) explore the hypothesis that “pit membranes enable water transport under negative pressure by producing stable, surfactant coated nanobubbles while preventing the entry of large bubbles that would cause embolism”. Where the water column is broken, the adjacent intertracheary bordered pit membranes are pulled towards their pit borders and seal the pit apertures so isolating a small number of wood cells that are affected by the air/vapour embolism. This process is called pit aspiration. It occurs during the drying of timber (Walker, 2006). Xylem sap is saturated with atmospheric gas or even supersaturated with it and may contain molecules that are surface-active that can reduce surface tension. The possibility of bubble nucleation (Weathersby et al., 1982; Lubetkin, 2003), particularly on rough hydrophobic surfaces, is greatly increased by gas super saturation (Ryan and Hemmingsen, 1998).

Bound-water diffusion

Differences in moisture content induce bound water to move through the cell walls by diffusion, moving water from high to low moisture content areas. The moisture movement in wood below the fibre saturation point is governed by two different mechanisms: one is water-vapour diffusion in the cell lumen and pit openings (inter-gas diffusion), and the other is bound-water diffusion in the cell wall with the latter having a lower diffusion coefficient. The total flow rate in the transverse direction is controlled by the latter due to frequent cell wall obstacles. In the axial direction, the resistance of the lumen may be predominant (Siau, 1995). Longitudinal diffusion is approximately 10 to 15 times faster than lateral (radial or tangential) diffusion. The bound-water diffusion controls the total rate of water movement in wood in the transverse direction which is mainly the way wood dries in conventional kilns. Bound-water molecules are attached to the sorption sites within the wood by hydrogen bonds. The water molecules, even though fixed with respect to each other, have considerable vibrational energy, and there is a random distribution of energy among the molecules and components. The vibrational velocities, the square root of kinetic energy, of the sorbed molecules follow a Gaussian distribution. When a water molecule receives enough energy to break its bond, it becomes "activated" and it is able to migrate to another sorption site, if it is available in the neighbour-hood. The energy required for the molecule to become "activated" is called activation energy, E_b, measured in kJ per mol and is a function of the moisture content of wood (Bramhall 1976, Siau, 1995).

Normal shrinkage

Free water is lost until the wood reaches the fibre saturation point (FSP) of about 25-30% moisture content (Jackson & Day, 1989). When wood loses MC below FSP it begins to shrink. Conversely, as water is absorbed, it appears to swell. Tensile stress is produced if the normal shrinkage of wood is restrained. In a structure, tensile and compressive stresses need to be balanced as a material such as wood becomes distorted when stressed (McMillen, 1958). The development and effect of drying stresses are governed by differences in MC between two adjacent parts of wood below FSP (Lazarescu & Avramidis, 2008).

1.1.3 Wood permeability

Permeability is a measure of ease with which fluids flow through a porous solid under pressure gradient (Siau, 1995). Since drying involves the movement of fluids in wood, permeability is often used as an indicator of drying rates. Due to the wood structure, permeability is anisotropic and also changes with moisture content. The flow of fluids in the longitudinal direction is primarily regulated by the size and number of vessels that are unclogged by tyloses and other obstructions (Wardrop & Davies, 1961). Polar and non-polar liquids may move through pits from the vessels to adjacent parenchyma, vasicentric tracheids or fibres (Rudman, 1965; Wardrop & Davies, 1961). The pit structure of wood is the most important factor regulating permeability at laminar flow level (Rudman 1966). For diffusion, the combined path of vapour movement through the cell lumens in series with bound water movement in cross walls are of primary importance for both transverse and longitudinal movement (Choong, 1965).

Moreover, pit membrane permeability plays an important role in hydraulic flow in xylem. Many researchers have studied the hydraulic resistance of the pit membrane. The hydraulic resistance of pit membrane is about 58% of the total xylem resistance for water (Choat et al., 2008). However, it is unclear to what extent the estimated pit membrane resistance values represent differences in pit membrane thickness or sizes of pore constrictions (Kaack et al., 2019).

The hydraulic resistance of xylem was reported to decrease due to the concentration of ions (Zwieniecki et al., 2001). Increasing concentrations of ions flowing through the plant xylem results in significant, rapid and reversible decline in hydraulic resistance. Changes in hydraulic resistance in response to concentration of solution ions, pH, and nonpolar solvents are consistent with hydrogels mediating this process (Zwieniecki et al., 2001). The impact is localized to inter-vessel bordered pits, suggesting that micro-channels in the pit membranes are altered by the swelling and shrinking of pectins, which are known as hydrogels (Zwieniecki et al., 2001). However, Choat et al. (2008) concluded that there is no direct evidence that pectins are present in mature pit membranes of most angiosperm species. This conclusion still holds today.

Green wood permeability

The ease with which water moves through a porous material refers to hydraulic conductivity. Permeability, on the other hand, refers primarily to the inherent properties of the porous material itself, excluding the peculiar effects of the fluid type. Permeability is the property of the porous medium itself, while hydraulic conductivity is the property of the whole system, including the porous medium and the flowing fluid. Hence, it can be assumed that the permeability is like the electrical conductivity of the material i.e. the ability of the material to allow fluid to pass through. Hydraulic conductivity is generally measured in m/s and permeability is m^2. Hydraulic conductivity depends on the intrinsic permeability of the material, the degree of saturation, and on the density and viscosity of the fluid. Water potential is the potential energy of water in a system compared to pure water, when both temperature and pressure are kept the same. It can also be described as a measure of how freely water molecules can move in a particular environment or system.

In the field of wood-permeability, the term hydraulic conductivity is used exclusively to refer to the longitudinal permeability of green (unseasoned) xylem (Booker, 1977). The hydraulic conductivity of green timber can be measured as:

$$\text{Hydraulic conductivity (K)} = (Q\ L/A\ \Delta\Psi)\ \eta$$

Where, Q is volumetric flow, L is the length of sample, A is cross-section area of flow, $\Delta\Psi$ is difference in water potential and η is dynamic fluid viscosity (Reid et al., 2005).

Volumetric flow (Q) can be calculated as:

$$Q = \Delta m/\Delta t$$

Where, Δm is the volume that flowed during a given time interval Δt.

Measurement of wood permeability

The use of liquids, particularly water, as permeating fluid complicates the permeability measurements. Entrapped air in wood could block pit openings, and high pressures are required to move through the menisci of liquid-air through these openings (Kelso Jr et al., 1963). Measurement of water permeability requires full saturation of the specimens. Full saturation of balsam fir is difficult to achieve even under vacuum pressure cycles due to pit membrane aspiration. For these reasons, gas is more often preferred to liquid for wood permeability determinations.

Liquid and gas permeability of core samples or sawn timber could be determined using rotameter and methods suggested by Comstock (1965, 1967) and Markstrom and Hann (1972). The general equipment and procedures used to measure gas and liquid permeability have been previously described (Comstock, 1965). Green permeability can be measured within 1 to 2 weeks with four permeability test plugs: outer sapwood, inner sapwood, outer heartwood and inner heartwood, each around 6.35 mm in diameter and 8.89 mm in the fibre direction are recommended. A rubber stopper, drilled out in the center, holding the specimen, is placed in a chamber tapered at the sides. A tube of plexiglass providing a maximum hydrostatic head of approximately 80 centimeters of water is used to maintain flow through the wood permeability plugs. Then the flow rate is measured on a rotameter, flowmeter or a graduated pipette after the liquid passed through the test cell. Pressure will be applied to the water in the system with nitrogen regulated by a standard pressure regulator. Dry permeability can be measured with gas. The apparatus consists of a nitrogen tank, a pressure measuring and regulating system, the specimen holder, and a series of rotameters. Gas-permeability is measured at atmospheric pressure on the downstream side, while maintaining a pressure drop through the specimen of approximately 40 cm of mercury (0.53 bar) (Comstock, 1965).

Another method for measuring transverse permeability is using a dyeing liquor. The end faces of the specimens are sealed using an epoxy resin, allowing the dyeing liquor to enter in the wood only along with the transverse direction. All the faces except the longitudinal, are sealed for axial permeability assessment. After the resin has cured, specimens can be placed in a chamber at a constant temperature (20 °C) and humidity (65%). Specimens can be weighed immediately after the equilibrium treatment. In the impregnation experiment, specimens can be placed into a dyeing liquor under atmospheric pressure and weighed every 1 h, 2 h or 4 h.

1.1.4 How wood dries

The Australian and New Zealand Standard (AS/NZS 4787: 2001) defines wood drying, also known as seasoning, as the process of evaporation or extraction of moisture from green or partially dried timber. Seasoned timber has improved dimensional stability and is protected from decay. In wood manufacturing processes, drying is an essential and critical part. While a multitude of wood seasoning methods exists, the most conventional methods are kiln, high temperature and vacuum drying.

Drying process

The drying process can be divided into two stages: the transfer of water from the interior to the wood surface, and removal of water from the surface. When green wood begins to dry, the evaporation of water from the surface cells creates capillary forces, which exert a pull on the free water in the zones of wood beneath the surface, and a flow results. This is analogous to the flow of water in a wick. Much free water in sapwood moves in this way. The capillary movement is fast compared to diffusion. There is faster radial diffusion, perpendicular to the growth rings, than tangential diffusion, parallel to the rings. This explains why flat-sawn lumber dries more quickly than quarter-sawn lumber. Permeable species dries faster than the impermeable ones, and the rate of diffusion decreases as the specific gravity increases. Since moisture passes more easily in sapwood than in heartwood, both by diffusion and by capillary movement, sapwood usually dries faster than heartwood under the same drying conditions. However, heartwood of many species is lower in moisture content than sapwood, and may reach final moisture content more quickly (Simpson, 1991). In heartwood, moisture moves more slowly to the surface than in sapwood, mainly because extractives plug the heartwood pits and due to low permeability of the heartwood. In the drying process, the surface fibers of the heartwood of most species achieve moisture equilibrium with the surrounding air soon after drying begins. This is the beginning of the development of a typical moisture gradient, a difference in moisture content between the inner and outer portions of a board. The surface fibers of sapwood also tend to achieve moisture equilibrium with the surrounding air if the air circulation is fast enough to evaporate water from the surface as fast as it comes to the surface.

Water moves as liquid or vapor through wood through several passageways. These are the cavities of fibers and vessels, pit chambers and their pit membrane openings, ray cells, resin ducts, other intercellular spaces, and transitory cell wall passageways (Panshin & Zeeuw, 1980). Most of the water lost during the drying process passes through cell cavities and pits.

When wood is drying, a number of forces may act simultaneously to move water (Siau, 1984): 1. Capillary action induces the flow of free water through the cell cavities and pits. 2. Differences in relative humidity allow water vapor to pass through the cell cavities by diffusion, which moves water from high to low relative humidity areas. The source of water vapor is cell walls; that is, water evaporates from the cell walls into the cell cavities. 3. Differences in moisture content induce bound water to move through the cell walls by diffusion, which moves water from high to low moisture content areas. Water can evaporate into a cell cavity from a cell wall, move through the cell cavity, be re-adsorbed on the opposite cell wall, move through the cell wall by diffusion, and so on until it reaches the board surface.

Defects develop during the drying process mostly are warping, checking, splits, honeycomb, collapse and case hardening. Warping can be differentiated into cupping, bowing, spring or twist. Checking and honeycomb is caused by excessive drying stresses.

1.2 The phenomenon of collapse

In a timber piece, shrinkage can not only be induced by normal shrinkage. The normal shrinkage in timber is due to the loss of moisture from the cell walls below the FSP. Recoverable collapse shrinkage occurs in the early stages of the drying process when most cell lumens are still saturated. It occurs in many eucalypts and leads to severe checking problems (Blakemore & Northway, 2009). A third type of shrinkage in wood is non-recoverable collapse shrinkage that may occur when the wood contains large amounts of tension wood, which is formed to control the spatial orientation of the stem. Tension wood has high density and low lignin leading to excessive shrinkage below FSP resembling recoverable collapse in timber. Collapse in tension wood is not recoverable by reconditioning (Chafe et al., 1992). All forms of shrinkage are anisotropic in nature (Blakemore & Northway, 2009).

Recoverable collapse

Collapse is due to the physical collapse of fiber cells. It occurs above the FSP, when water is contained within the lumens, and it is manifested by cell wall bucking and flattening of the cell lumens when the water is removed. It is usually a very local phenomenon that generally occurs in one or more discrete early wood bands, often for the full length of the board. Collapse is frequently seen as a corrugation, or "wash-boarding" of the board surface. Tiemann (1915) first provided a detailed description of cell collapse, and also coined the term 'collapse'. He proposed the liquid tension theory to describe its formation. Essentially, the liquid tension theory of collapse formation relies on two fundamental equations from mechanics and thermodynamics.

$\triangle p = 2\sigma/a$ (Laplace, 1806)……………………………………………………………(1)

and $\triangle p = -\rho RT \ln rh$ Kelvin's equation; (Thomson, 1872)………………………………. (2)

The pressure difference across a meniscus $\triangle p$ (Pa), is the tensile stress in a cell lumen saturated with water, σ is the surface tension of water (N/m), a is the radius (m) of the curvature of the meniscus and, effectively, the radius of the opening (capillary) through which water must pass; ρ is the density of liquid water (g/cm^{-3}), R is the gas constant for water, rh is the relative humidity (%), T is the temperature (Kelvin) and ln is the natural logarithm. From Eq. 1, it is possible to see that the smaller the capillary, the greater the tension in the water in the cell lumen ($\triangle p$). Equation 2 illustrates how $\triangle p$ is correlated with temperature and relative humidity in the immediate vicinity of the meniscus.

During the drying process, above the FSP, the free water in the cell cavities is withdrawn through interstitial opening in the cell walls. A meniscus formed in one of these openings at the air-water interface will induce liquid tension (negative pressure) in the water behind its convex face. If this tension exceeds the compressive strength of the cell wall, the cell collapses. In permeable wood species, the pathways connecting cells (open pits in the cell wall or pores in the pit membrane) are large enough to allow the movement of water to proceed at low negative pressure during the drying process. However, when the pathways are narrow i.e. when pit membranes are densely packed or micro-pores in the pit membrane are occluded with cytoplasmic debris or other extraneous materials (i.e. in low permeable species), the first condition for collapse formation is satisfied (Chafe et al., 1992). In addition to impermeability, two other requirements are mandatory for collapse, water saturation of the cell lumen and comparatively thin/weak cell walls. If the cell lumen contains air/vapour, negative pressure cannot build up and it would be highly unlikely to collapse the cell during drying regardless of the level of permeability and cell wall strength. If an air bubble was present in the lumen, any tension in the water would be relieved by the expansion of the air bubble (Hayashi, 1974), thus mitigating the potential for collapse of the cell. If the cell walls are thick, i.e. high wood density, the collapse is less likely to occur because the timber is stronger. This is the main reason why collapse and internal checking are greater in lower density wood than higher density wood from the same species.

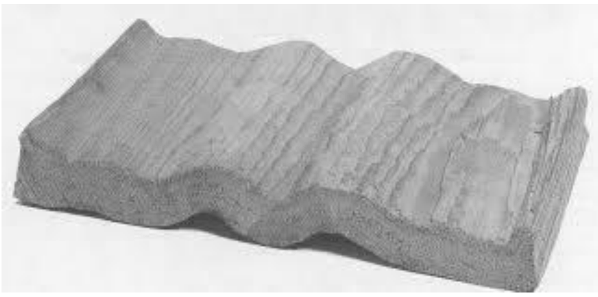


Figure 4. Severe collapse in western red cedar (Simpson, 1991)

2 Review of literature on collapse

The first study concerning "excessive shrinkage" had been undertaken in Australia (Cunningham, 1827). Warren (1892) later published data showing the high shrinkage of Australian timbers. Dunlap (1906) first captured photographs of collapsed wood in America through images of case hardening. Harry D. Tiemann, an American researcher, was the first to examine in detail the excessive shrinkage in eucalyptus and point out its distinction from normal shrinkage (Tiemann, 1915). He gave the term "Collapse" to the phenomenon and also published the liquid tension theory for collapse.

As early as 1917, James Grant and George Grant independently discovered that "steam could be used to recover collapse in Australian eucalyptus" (Greenhill, 1938). The excessive loss in volumes could be largely recovered by steam treatment and has since become known as "reconditioning" (Anonymous, 1953). In steam reconditioning, collapsed wood is placed in a chamber with saturated steam for several hours, depending on the board thickness and species (Blakemore & Northway, 2009). Greenhill (1938) executed various reconditioning trials on *E. regnans* and *E. delegatensis* samples, recommending a steaming temperature around 100°C. Various industrial methods have been in use for many decades in Australia, based mainly on the experiments conducted by Greenhill (1938). Unfortunately, the samples used in his research were prepared from only one or two planks, and the size of the samples was also small, rendering the results somewhat questionable (Blakemore & Northway, 2009).

The study of microscopic structure of collapsed wood is difficult as preparing microscopic sections from the collapsed wood is challenging without softening and embedding procedures due to the very dense nature of the collapsed material. However, the normal methods of softening and embedding samples involve swelling agents that likely change the configuration of collapsed cells due to swelling. Tiemann (1941) was able to prepare a smooth transverse surface of collapsed wood for microscopic observation using vertical illumination (Figure 5 andFigure 6). Micrographs provided by Tiemann show the basic general outline of collapse in wood but little detailed information at the cellular level (Tiemann, 1941).

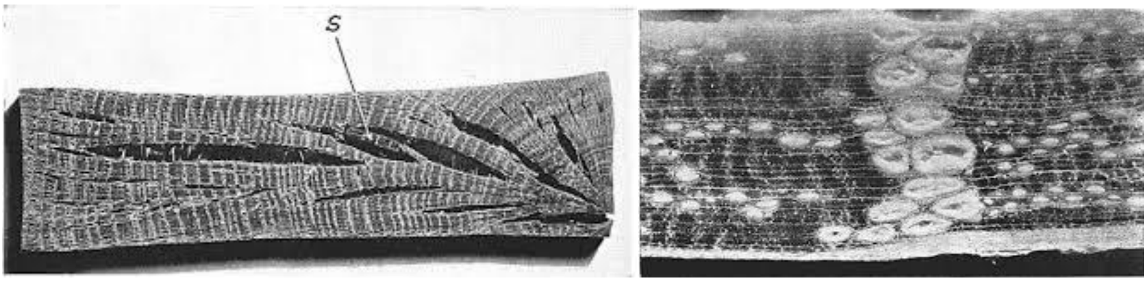


Figure 5. Cross section of an oak board which collapsed in drying, causing honeycombing (s), Photo-micrographs of collapsed oak timber (Tiemann, 1941)

Figure 6. Western red cedar which has collapsed in drying (Tiemann, 1941)

2.1 Causes of collapse/ Theories of collapse

Liquid-tension theory

The liquid tension theory proposed by Tiemann (1915) is the most accepted theory for collapse. W. G. Kauman provided a good detailed discussion and thorough development of the liquid tension theory and collapse (Kauman, 1964). The theory has been detailed in section 1.2.

The liquid tension theory has important assumptions. The first is that collapse can only occur in cells that are fully saturated. The liquid tension forces will principally act on the meniscus of largest radii. The second assumption is that the sap has adequate cohesive strength to transmit the liquid tension. And, if this were not the case, cavitation would occur before cell collapse. In addition to the magnitude of the liquid tensions developed, the other main determinant of collapse occurring is the strength of the cell walls. Unfortunately, the mechanical properties of individual cell walls, or of the various cell wall layers are nearly impossible to measure directly. Therefore, as a first approximation, the average compressive strength in the perpendicular cross-section of small test samples is often used as an approximate value for cell wall strength (Blakemore & Northway, 2009). Chafe et al. (1992) quote a transverse compressive strength of 4.0 MPa for *E. regnans* (Bolza & Kloot, 1963) implying that collapse was likely to occur in case the liquid tension force was exceeding this value.

In the saturated cell lumens, the stresses that develop in the water depend on the diameter of the capillaries with smaller capillaries developing larger tension forces. This relates to wood permeability i.e. the smaller these capillaries are, the lower will be the permeability of the wood (Blakemore & Northway, 2009). Therefore, inherently slow drying and low permeability are intrinsic properties of collapse prone wood.

The interstitial openings in the fiber to ray parenchyma or fibre to fibre pits should be in the range of 60–100 nm in the cells that are collapse prone (Kauman, 1964). Therefore, the collapsing cells have the magnitude of the liquid-tension forces of at least 1.46–2.43 MPa. The size of the interstitial capillaries is important and affected by extraneous material i.e. extractives and cell debris (Blakemore & Northway, 2009). The risk of collapse increases significantly, if the extraneous materials reduce the size of the capillaries.

Classical boiling theory

It is well understood in the theory of boiling that a certain size of vapour bubble can grow against surface tension forces. To overcome the tension field at the interface, the pressure inside a vapour bubble must be greater than the pressure outside the bubble. Since surface tension forces increase with reducing bubble radius, a critical bubble radius exists at which the system will be metastable. If a vapour bubble is formed at a smaller radius than this critical value, it will shrink and disappear (Volmer, 1939) as quoted by Gerum et al. (1977).

Contraction theory

R. E. Booker (1994) assumed that contraction of fibres filled with water under tension causes differential stresses which lead to internal checking. Collapse of the cells would occur after release of restraint which is caused by checking i.e. the internal checking comes first followed by collapse due to the differential stresses. Booker (1994) also reported that the near square tracheids in *Pinus radiata* may contract more however, buckling of the cell walls appears likely to occur at a similar order of magnitude to the round fibres. Square tracheids would have to maintain their shape to maintain the integrity of the wood but should be more prone to buckling.

Shrinkage stress-induced collapse

It has been reported by some researchers (Clarke, 1927; Stamm & Loughborough, 1942) that collapse may be caused by compressive stresses resulting from drying of the wood. Theories focused solely on the collapse caused by shrinkage stress do not comprise any effect of negative pressure in the fibre lumens. Keylwerth (1951) states that in the later stages of drying, when the center of the wood is exposed to tensile stresses because of tensile set at the board surfaces, internal cracking may happen. Collapse can be caused by high temperatures early in the drying process. This in general questions the theory of stress prompted collapse, as in the early period of drying compressive stresses have not developed because normal shrinkage has not occurred since most parts of the board are above FSP.

2.2 Wood anatomy and variability

Various studies have been undertaken in relation to the variability and anatomical aspects of collapse prone wood. Chafe et al. (1992) reported that "wood collapse varies within trees, between trees and also between species". Such variation originates from variation in properties such as density, cell wall strength, lumen saturation and permeability. Despite the differences between drying methods, some logs produced boards that consistently had low or high levels of degrade, even in the severe or mild drying methods. Cuevas (1969) reported wide variability in only three trees of *E. viminalis* and Barnacle et al. (1967) showed that for eight trees of the same species taken from one small geographic area maximum tangential collapse varied from 2.6 to 17.7 %. Within trees, a decrease in collapse with height has been reported by Kaumann

(1960), Pankevicius (1961) and Chafe (1985). The anatomical review of collapse prone wood suggests that the wood cells that most clearly show collapse are the fibres (Tiemann, 1941), which are elongate cells that make up the bulk of the wood tissue and provide mechanical support to the tree. The collapse of fibres occurs primarily in radially oriented zones (Wilkes & Wilkins, 1987) and Hart (1984) has suggested that ray cells play an important role in collapse occurring. Ilic and Hillis (1984) reported that collapse was related to the proportions of fibres with a specific cell wall thickness. When 90% of the fibres had a lumen diameter of less than twice the thickness of the cell wall, no collapse occurred. This is in agreement with the negative relationship between collapse and basic density detailed by Chafe (1985).

Chafe (1985) reported a relationship of collapse, volumetric shrinkage, green moisture content and density in *E. regnans.* He found that collapse and volumetric shrinkage each were significantly related to green moisture content (positively), basic density (negatively), and to the derived values i.e. per cent of theoretical saturation and per cent of cell cavity volume containing water (positively).

Samples containing sapwood showed significantly lower collapse values than heartwood samples. This was reflected by a positive relationship between collapse and distance from the periphery when every material was considered, but a negative relationship when sapwood-containing samples were neglected. Collapse increased with distance from the periphery to around 85% of the radius where it started a sharp decline towards the pith; total volumetric shrinkage increased to about 45% of the radius, gradually declined to 85% of radius where it starts a rapid decline towards pith; moisture content increased to about 75% radius and suddenly declined at 85-90%; basic density declined with distance from the periphery to about 75% radius, at a point indicated a slight increment towards the pith; per cent saturation remained relatively constant from the periphery to about 90% of the radius, then abruptly declined (Figure 7Figure 8) (Chafe, 1986).

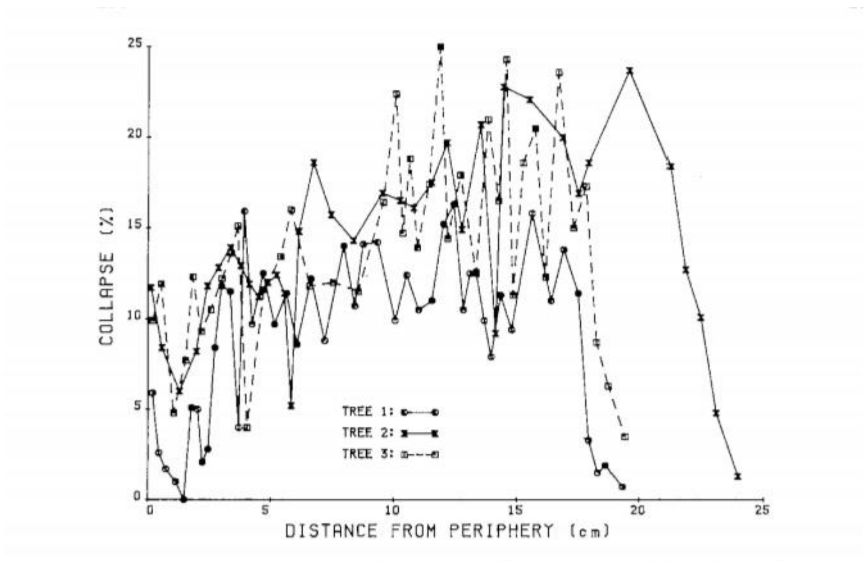


Figure 7. Collapse data by trees over distance from periphery in centimeters (Chafe, 1986)

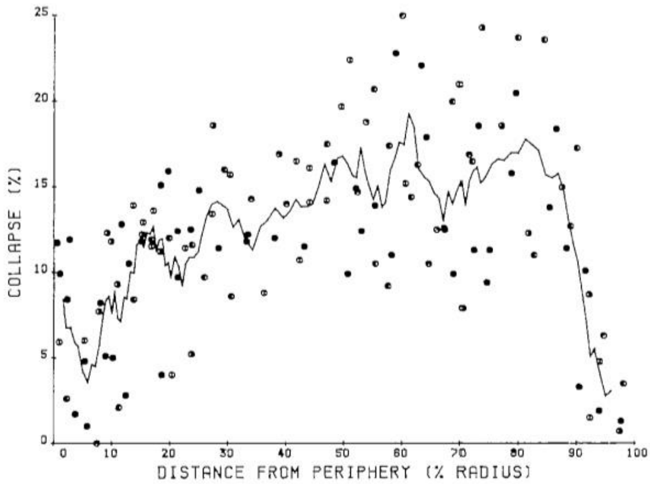


Figure 8. Collapse data over distance from periphery in percent radius for individual trees (Chafe, 1986)

Ananias et al. (2014) measured the collapse of eucalypt timber after drying depending on the radial location within the stem. They found that the centre portion of the trees was less susceptible to collapse than the transition zone between the centre and the periphery. On average, collapse was approximately 50% higher in the transition zone than the collapse observed in wood cut from the central zone of the trees. The transversal shrinkage and collapse tended to increase with radial position despite increased densities (Ananias et al., 2009).

Yang et al. (2003) studied the shrinkage and non-recoverable collapse of 10-year-old *E. globulus*. They reported that several shrinkage properties were significantly correlated with microfibril angle and cellulose crystalline width. Microfibril angle, however, had a direct effect (negative) only on tangential shrinkage and cross-sectional shrinkage, and cellulose crystalline width had a direct effect (positive) only on non-recoverable radial collapse. Density, microfibril angle, and cellulose crystalline width, either individually or collectively, accounted for a small to moderate amount of variation in shrinkage and collapse in both the radial and tangential directions. Total tangential shrinkage was found to be the best single predictor for tangential collapse ($r^2 = 0.896$) and for total cross-sectional shrinkage ($r^2 = 0.924$).

2.3 Wood extractives

Many studies have been undertaken in relation to the extractive content of wood, but its association with impermeability and collapse is studied much less. In certain species, dimensional stability has been attributed to high extractives content (Kuo & Arganbright, 1980) because these materials tend to bulk the cell wall filling the spaces where water would be located and therefore preventing normal shrinkage (Chafe, 1987). Despite the fact that extractives in eucalypts are often high in quantity (Hillis, 1962), they effectively have the contrary effect by decreasing permeability. Ilic and Hillis (1984) noticed that eucalypts, in general, have relatively high levels of extractives compared with other genera. However, even within one species, extractive levels could also be significantly variable. Consequently, it has been indicated that recoverable collapse was positively related to extractive content for several eucalypt species (Chafe, 1987) and that decreased collapse after hot water extraction was negatively related to amount of extractives removed in *E. regnans* (Chafe, 1990). It may be assumed that the formation of impermeable heartwood in the eucalypts is beneficial to their survival because these trees periodically have to endure long periods of drought. Retention of water would be facilitated by impermeable heartwood. In the absence of sufficient water during drought conditions, slow movement of water from the heartwood to living tissue may assist in survival under water stress. However, what aids tree survival is not necessarily better for product conversion (Chafe & Ilic, 1987).

2.4 Amelioration and prevention of collapse

Methodologies to control or prevent collapse fit into one of three categories. These are: a) techniques that increase bubble nucleation or decrease surface (liquid) tension, b) methodologies that improve permeability, and c) methods that increase stiffness or compressive strength of the cell wall. Unfortunately, so far none of them has proved to be economically viable.

The influence of pre-treatments

Pre-drying treatments include storage in controlled environments, different wrapping types, pre-surfacing and preheating. Cutting boards radially, rather than tangentially, can likewise be regarded as a form of pre-drying treatment, as well as the application of an end-coating to freshly sawn logs. Some other pre-treatments are steaming, microwave treatment, pre-freezing, and boiling (Ellwood, 1953; Haslett & Kininmonth, 1986; Kong et al., 2018; Lee & Jung, 1985; Vermass & Bariska, 1995; Zhang et al., 2011).

In the 1950s, a number of studies were undertaken in order to reduce collapse, including chemical pre-treatment of wood to enhance the permeability i.e. capillary radius. Zinc chloride (Chudnoff, 1953, 1955) and dilute hydrochloric acid (Pankevicius, 1962) were used to treat wood. Such treatments do show marginal benefits. More concentrated solutions may have a more significant effect on the wood permeability, however, causing a weakening of the cell wall intensifying collapse.

Replacement of the sap with other liquids or impregnation with wetting agents has been tried, to reduce surface tension (Kauman, 1964). However, the low permeability of the eucalypt timber poses a challenge for sap replacement. In case of diffusion-based methods, the treatment times were long and frequently still ineffectual in getting the active chemical into the wood core. Vacuum and pressure techniques were most effective when the entirety of the water was first removed, and on thin material such as veneers. This sort of approach is currently used in experimental techniques; for instance, alcohol drying is used with Silviscan 2 strips to prevent collapse (Evans et al., 2000). Similarly, the introduction of salts and other particulate impurities have been attempted to increase the bubble nucleation sites (Kauman, 1964). Techniques for bubble formation include the impregnation with sodium bicarbonate (Karl & Dedrick, 1950) or carbon dioxide (Kauman, 1964). Some unsuccessful attempts have also been reported by Kauman (1964) to use ultrasonic fields to produce concentrations of local stress and nucleation in the water.

Another method to prevent a gas/liquid phase boundary is super-critical drying. The supercritical point of water is too high (647 K, 22 MPa) (Blakemore & Northway, 2009). Instead, super-critical carbon-dioxide (304 K, 7 MPa) drying has been explored for the treatment and seasoning of *Pinus radiata* (Franich et al., 2008). Lumens are filled at high pressure with liquid water saturated with supercritical CO_2. The CO_2 comes out of solution as the pressure is removed and CO_2 gas bubbles develop, creating a pressure gradient to push the free water out of the wood as the bubbles expand. This technique for removing free water from green wood was shown to reduce collapse in a variety of softwoods and hardwoods (Dawson & Pearson, 2017). The water removal efficiency of the supercritical CO_2 treatment varies according to species (Dawson & Pearson, 2017). Supercritical CO_2 pre-treatment and kiln drying of *E. nitens* wood, reduced the collapse by 75% and washboard depression by 71% (Dawson et al., 2020). However, this technology needs to be up-scaled from the laboratory sized specimens (37 mm × 37 mm × 200 mm) and is likely to increase the drying costs.

Steam pre-treatments and hot water treatments reduce collapse. In such treatments, modification of the extractive content might allow the water flow, most important in and around the pit membranes (Greenhill, 1938); Campbell, 1961). Pre-steaming can reduce wood moisture content and change the permeability in eucalypts (Elaieb et al., 2019).

Microwave pre-treatment can increase the permeability of refractory species. Boiling water inside the wood results in a sharp rise of pressure which damages anatomical structures, such as ray cells, tyloses or pit membranes (Torgovnikov & Vinden, 2010). Applying microwave pre-treatment prior to kiln drying to *E. obliqua* back sawn boards, increased the number of boards without drying defects from 31 to 55% (Harris et al., 2008). Torgovnikov et al. (2013) reduced drying duration by half and the number of boards with defects also by half by pre-treating timber of four *Eucalyptus* species with microwaves before conventional drying. Likewise, microwave treatment of *E. macrorhyncha* timber reduced collapse (20%), surface check length (84%), internal check length (50%) and internal check width (70%) (Balboni et al., 2018).

The effect of drying temperature and schedules

Drying temperature has an influence on collapse development (Ellwood, 1952; Greenhill & Dadswell, 1940). In general, during drying, high temperatures contribute to higher levels of collapse, as the stiffness and strength decreases due to a softening of the cell walls at higher temperatures. In addition, higher temperatures can lead to increased stresses facilitating collapse. Likewise, the relative humidity of the drying medium and the duration of the drying treatment has been considered important in determining collapse intensity. Kauman found that the wood temperature for collapse prone timber must be maintained below 60 ^{o}C during drying until all portions of the boards are below FSP to avoid collapse (Kauman, 1964). Innes (1996a); (1996c) indicated that there might be a temperature threshold below which there would be no collapse, although, Ilic (1999b) questioned the validity of the temperature threshold, while acknowledging the significance of temperature on collapse. Samples stored in refrigerators at around 4°C had still experienced some collapse. Nevertheless, a main objective of the drying schedules is to minimise the dry-bulb temperature above FSP. Furthermore, Yuniarti et al. (2015) reported a threshold temperature for *E. saligna* boards of below 20 °C, which was different from that suggested by Innes (1995, 1996a) for *E. regnans*. Sargent et al. (2017) found that the drying temperature had a significant effect on levels of degrade seen in *E. nitens* boards - boards dried at 50°C had significantly higher levels of degrade (53% boards degraded) compared to boards dried at 20 or 25°C (15% of boards degraded). *E. grandis* poles grown in South Africa are recommend to be dried longer than 8 days at a dry-bulb temperature of less than 80°C to minimise drying defects (Mugabi et al., 2011).

Freeze-drying has been demonstrated to be effective in preventing collapse when drying *E. delegatensis* (Choong, Mackay, & Stewart, 1973) but it is uneconomic and expensive for large scale application. In freeze drying, the liquid is transformed into solid ice and then directly removed as vapour by sublimation at low temperature and pressure (vacuum). Therefore, there is no liquid/vapour interface inducing negative pressure causing collapse. Ilic (1995) explored the potential use of pre-freezing to minimise shrinkage, collapse and drying times. The effects tended to be species dependent. The effect is not completely clear and thought to be a mixture of several effects. First the freezing process moves some water out of the cell wall and into the lumen. Then water expands in volume when freezing. This expansion and loss of cell wall moisture imparts tensile stresses in the cell wall, making the cell wall more rigid and less likely to collapse. The movement of extractives from the lumen into the cell walls can also provide a re-enforcement effect in the cell walls. Pre-freezing of *E. regnans* at -20°C for 72 hours resulted in an average reduction of 36% in collapse, but a similar reduction in internal checking was not apparent (Ilic, 1999a).

Langrish et al. (1992) found that intermittent drying may eliminate internal checking in red beech. Vermaas (2000) stated that with an intermittent drying schedule, good results could be achieved in the drying of *E. grandis* but the consequence is a longer period of drying. Reductions of surface and inner checks of *E. regnans* by using intermittent drying were found by Chafe (1992, 1995), but he could not verify if it had a positive effect on decreasing total shrinkage and collapse. However, boards from *E. nitens* dried with varying temperatures (air drying) had slightly higher degrade than boards dried at a constant temperature (Sargent et al., 2017). Intermittent drying procedures were developed by Wu et al. (2005a); (2004; 2005b) on seven species of young plantation-grown eucalypts from China and they concluded that intermittent drying was likely suitable for collapse-prone eucalypts. The intermittent drying mechanism is thought to be effective by reducing the stress gradient that has been developed in wood with the progressive removal of water and consequent shrinkage that induces stress in the material. Yang et al. (2014) reported that collapse recovery after intermittent drying was more extensive than in continuous drying, with axial parenchyma and ray parenchyma recovering from collapse more than fibres. Phonetip et al. (2019) compared two intermittent drying schedules for timber drying quality. They used identical conditions at 45°C/60% relative humidity (RH) during the heating phase, except for RH during the non-heating phase (80 and 90%). They analysed the quality of the timber during and at the end of the drying process. During the non-heating phase, the different RH did not generate a significant difference in MC at surface of the boards between the two drying schedules.

Vacuum drying

Vacuum kilns allow enhanced drying rates at lower temperatures. Thus, in the case of low-permeable or collapse-prone species, they do offer the potential to minimise collapse and internal checking levels while enhancing drying rates (Blakemore & Northway, 2009). There is little strength loss during vacuum drying and timber is less susceptible to checking and honey-comb, early in the drying process (Denig, 2000). However, even drying at 20°C can lead to a significant collapse, and ideally vacuum kilns operate at a temperature slightly above that (Blakemore & Northway, 2009). The effective industrial use of such kilns is an economic question, if the reduction in checking and drying times is worth the cost of the equipment. Radio-frequency vacuum drying might be an option for drying collapse prone timbers as energy transform is based on radiation rather than convection and conduction, and the higher internal pressure would therefore work better against collapse (Hansmann et al., 2008). Volumetric collapse in *E. nitens* wood decreased about 60% using radio-frequency vacuum drying because of drying temperature and drying stresses are lower than conventional drying (Ananías et al., 2020). Moreover, drying from the inside does not create steep moisture gradients between surface and core of the timber, which might be effective to reduce collapse, and also enhance drying rates due to vacuum. It might be economic if the drying rates are four times faster as compared to kiln drying.

Genetic control of collapse

Tree breeding is another option for improving the quality of wood. In studies evaluating collapse on radial cores, Kube and Raymond (2005) and Hamilton et al. (2008) found that collapse was under strong to moderate genetic control in *E. nitens*. Collapse in *E. nitens* is also not affected by genotype by site interactions (Kube & Raymond, 2005). It has good and favorable genetic correlations with basic density but strong and adverse correlations with diameter growth (Kube & Raymond, 2005). Hamilton et al. (2008) looked further at how the breeding objective for internal checking could be more broadly incorporated into the breeding program, which focuses generally on pulpwood objectives. The biggest challenge was, to establish an economic weight for this objective. Improving the profitability of solid wood plantation has become an increasingly important objective for *E. nitens* growers. Harvest volume, log diameter, timber hardness, timber stability in use, drying degrade (checking and collapse) and strength properties have been identified as potential solid wood objective traits (Hamilton & Potts, 2007; Raymond, 2002).

2.5 Assessing collapse

There is no commonly accepted method of measuring collapse. However, there are generally the following types of collapse measurements that are made for experimental purposes:

1) Assessing dimensional changes: a) maximum volumetric shrinkage b) maximum tangential shrinkage on cores c) depth of collapse on boards

2) Normal shrinkage free collapse: a) Collapse free shrinkage method d) recoverable collapse method

1(a). The maximum volumetric shrinkage

Volumes of wood can be determined by water displacement or measuring the dimensions (l × b × h). The volumetric shrinkage from green to a stable moisture content can be determined using the following equation

$$\text{Maximum vol. shrinkage} = (V_g - V_d) \times 100/V_g$$

Where V_g and V_d are volumes when green and dried, respectively.

1(b). The maximum tangential shrinkage

The narrowest tangential diameter of each core sample can be determined with a Vernier caliper (D_{dry}). The widest tangential diameter can be measured as reference in the green state. The maximum tangential shrinkage in the core can be calculated according to the following equation.

$$\text{Maximal tangential shrinkage } = \frac{D_{green} - D_{dry}}{D_{green}} \times 100\ \%$$

Maximum tangential shrinkage was found to be the best single predictor for tangential collapse (r^2 = 0.896) and for total cross-sectional shrinkage (r^2 = 0.924) (Yang et al., 2003)

1(c). The depth of collapse on boards

Collapse can be quantified by measuring the depth of collapse on a board surface. The depth of collapse for each face can be measured by placing a straightedge across the face of a board, and measuring the depth of collapse using a Vernier caliper (AS/NZS 4787: 2001).

The degree of collapse will be determined using the following equation:

$$\text{Degree of collapse } = \mathrm{D}_a + \mathrm{D}_b$$

Where, D_a and D_b are depth of collapse for face A and B respectively.

2(a). Collapse free shrinkage

When measuring the total shrinkage of a wood sample, the measurement has a component of normal shrinkage and collapse shrinkage in it. Collapse free normal shrinkage can be measured on thin sections (<1 mm along the grain). As the fibres in most eucalypts are longer than 1 mm, there should be almost no intact fibres present in such a thin sample. If there are no intact fibres, the large openings ensure that negative tension in the wood stays low and therefore preventing collapse. By subtracting this measure of normal shrinkage from the total shrinkage that occurs in a matching longer sample, a measure of collapse shrinkage can be obtained with pre-dominantly intact fibres.

Measures of collapse recovery can be similarly obtained.

$$\text{Collapse} = \text{SB} - \text{ST}$$

$$\text{Recovery} = (\text{SB-SA/SB-ST}) \times 100$$

Where, SB = total percentage shrinkage to a given moisture content before reconditioning (based on green dimension)

SA = total percentage shrinkage to a given moisture content after reconditioning (based on green dimension)

SO = total percentage shrinkage to oven-dry moisture content after reconditioning (based on green dimension)

ST = true percentage shrinkage to a given moisture content (based on green dimension) – obtained from thin collapse-free sections.

2(b). Recoverable collapse

Another technique for measuring collapse is to measure recoverable collapse. This typically involves measuring the shrinkage from the green state before and after reconditioning (Chafe, 1985) at a standardised moisture content. This assumes that the reconditioning recovers all collapse after steaming for a period of 2 h at 100 °C, and subsequently equilibration to 12% MC. Volumes can be determined by water displacement in case of laboratory sized specimens. The total shrinkage of boards (in width and thickness) from green to final MC can determined considering the average of dimensions measures in three measuring points located along the specimens (center and both ends). The volumetric shrinkage from green to a stable moisture content can be determined before and after reconditioning with steam using the following equation

$$\text{Vol. Shrinkage} = (V_g - V_d) \times 100/V_g$$

Where Vg and Vd are volumes when green and dried, respectively. The percent difference in the volume of the sample before reconditioning (V_{BR}) and after reconditioning (V_{AR}) with respect to the volume in green condition (V_g) is a measure of the amount of collapse in the samples.

$$\text{Collapse} = (V_{AR} - V_{BR}) \times 100 / V_g$$

Non-destructive assessment for collapse

Hamilton et al. (2004) expanded a study undertaken by Kube and Raymond (2001) aimed at developing a suitable low-cost non-destructive technique to measure collapse severity upon drying. They compared four non-destructive techniques for total shrinkage (i.e. true shrinkage plus collapse): 1) visual scoring of tangential total core shrinkage using a 1 (no observable total shrinkage) to 4 (obvious total shrinkage) scale; 2) calculation of the difference between green core volume and dry-core volume expressed as a percentage of green core volume; 3) averaging the minimum tangential diameter on each side of the pith measured with calipers and 4) estimation of average tangential core diameter using image analysis. They suggested that the measurement of volumetric total core shrinkage appears a most promising method for assessing total shrinkage.

Qualitative assessment

The study of microscopic structure of collapsed wood is difficult as preparing microscopic sections from the collapsed wood is challenging. However, Tiemann (1941) was able to prepare a smooth transverse surface of collapsed wood for microscopic observation using vertical illumination, and provided the basic general outline of collapse in wood but a little detailed information at the cellular level (Tiemann, 1941). The morphology of the samples can be examined by scanning electron microscope (SEM). Slices of a size of 3 to 5 mm with radial and tangential surfaces can be examined in order to analyze their microstructure. The SEM examination can be done for qualitative measurement of collapse and permeability and requires extensive image analysis (Yang et al., 2014).

Couceiro, et al. (2016) used X-ray CT-scanning to assess checking and collapse behaviour of *E. nitens* providing a high level of accuracy of internal cracking and collapse assessments (Couceiro et al., 2016). X-ray CT-scanning is fast and nondestructive, and can yield quantitative data of collapsed cells (Yang et al., 2019).

Non-recoverable collapse assessment

NIR predictions of cellulose content, cellulose crystal width and stiffness (modulus of elasticity, MOE) from spectra obtained from radial longitudinal surface of *Eucalyptus globulus* wood were found to be reliable indicators of zones of non-recoverable collapse associated with the presence of tension wood (Downes et al., 2014). Non-recoverable collapse occurred when cellulose content and MOE exceeded 50% and 25 GPa respectively. With core sampling techniques and radial NIR scanning, these thresholds can be used as a relatively low cost and effective means of identifying zones of excessive non-recoverable shrinkage associated with tension wood occurrence in *E. globulus* (Wentzel-Vietheer et al., 2013).

3 Objectives

The forgoing discussion demonstrates that a great deal of work that has been carried out on eucalyptus and other wood species to understand morphological, anatomical characteristics associated with collapse as well as control measures. However, many problems remain unresolved. The proposed study will focus on three major themes: 1) investigating parameters contributing to collapse development; 2) finding the genetic basis for minimising collapse in future resources and 3) exploring the drying technologies for reducing collapse in current resources.

The proposed study consists of the following three objectives.

3.1 Genetic control of collapse in *E. globoidea* and *E. quadrangulata*

Tree breeding has been recommended as a potential method for managing checking and collapse (Kube & Raymond, 2005). Lausberg et al. (1995) suggested that breeding can potentially improve certain wood characteristics including density, spiral grain, and internal checking severity in eucalyptus. Large variations between trees have been reported (Chafe et al., 1992; Purnell, 1988) including a contribution of genetically controlled variation. Earlier, genetic studies on collapse in eucalypts were restricted to a provenance study for *E. delegatensis* (King et al., 1993), and a small study with 5 seedlots for *E. nitens* (Purnell, 1988). In the 2000s, a more detailed study on the genetic parameters of checking and collapse by Kube and Raymond (2005) suggested that collapse has strong and favorable genetic correlations with basic density. Chauhan and Walker (2004) reported that shrinkage-related properties have some association with the mean growth strain in trees. They suggested that *E. nitens* trees with low growth strains could show a lower level of drying defects such as collapse and checking during processing.

E. globoidea and *E. quadrangulata* are showing promise within the NZDFI trials to produce high value naturally durable timber. To make this product profitable, collapse in this species should be reduced. Within the NZDFI project there are a number of concerns for breeders, such as growth stresses, durability, form and growth rate. Using conventional breeding methods, collapse could be included and minimised within the NZDFI genetics. Therefore, the proposed genetic study will evaluate tree breeding as a tool for managing the collapse of *E. globoidea* and *E. quadrangulata.* There are two parts to this study: 1) verify quick assessment methods suitable for collapse assessment in tree breeding and 2) measure the degree of genetic control for collapse in different breeding trials.

3.2 Improving permeability of eucalypt timber

The second part of this study will investigate technical drying solutions aimed to reduce collapse and improve drying quality. Collapse in wood is caused by liquid tension, which develops in sap-filled cell lumens during drying. It depends upon how smoothly water passes through the capillaries i.e. the permeability of the wood. Permeability refers to the innate properties of the porous material itself, excluding effects of the fluid type. Two pre-treatment methods will be explored to increase the permeability of wood: micro-explosion treatment and pulse pressure waves. Micro-explosion uses air at room temperature as the medium. Air at room temperature is more convenient and secure compared to steam, and the safety risks are significantly reduced. The mechanism of micro-explosion is similar to that of steam explosion. The pressure differential inside and outside the wood is the major factor. An instantaneous release of pressurised air results in fine fractures, improving permeability at the weakest part of cell walls, the pit membrane (Zhang and Cai 2006). Previously, this method was used to improve the drying rate and reduce drying time (Quing et al. 2016).

Pulse pressure waves have the benefit of both raising permeability and facilitating liquid penetration in one process. The pressure waves are generated by hitting a closed-container filled with liquid which is assumed to be continuous from the wave source to the closed tissues in wood. The waves propagates through the liquid into the wood, inducing a kinetic momentum in cell cavities to add the impact on the closed tissues (Tanaka et al., 2019). It is expected that the impact of the momentum will break the closed tissues, consequently improving the permeability.

3.3 Ionic effects on water transport in wood

The third part would help us to understand the parameters contributing to collapse and would enable potential treatments in their modification. There would be two parts to this study: 1)

Study green wood permeability with the aim to replace sap with salts ions and study their influence on hydraulic conductivity and collapse 2) look for electrical effects during this process.

Effect of ion concentration: The natural variability within wood species in terms of their water-stress-induced changes in stem moisture content is large (Malavasi et al., 2016). The variation in xylem sap ions may influence the hydraulic conductivity of wood and woody plants may actively regulate the ion concentration in the xylem sap to modify hydraulic conductivity of xylem. The ion-mediated response in plants is considered a major factor in sap-flow regulation (Ryu et al., 2014), as flow rate of tap water is considered to be faster than distilled water in woody plants (Zimmermann, 1978). Zwieniecki et al. (2001) explored hydraulic conductance upon perfusion of plant stems by salt solutions, and found that the impregnation of salts ions improved water flow in xylem by reducing the hydraulic resistance of the pit membrane. Interestingly, ion-mediated sap flow is a process, which occurs in dead cells (Zwieniecki et al., 2001). This suggests that sap flow in xylem differs from the biological phenomenon that occurs in living cells, and can be studied from a drying point of view. The ion-mediated flow regulation and chemistry of xylem sap are of interest for both understanding xylem functionality and from a wood materials perspective. Previous studies have investigated the effect of ions on sap flow control in plants (Jansen et al., 2011; Nardini et al., 2011; Van Ieperen et al., 2000; Zwieniecki et al., 2001). However, its effect in water transport during timber drying is unclear. Therefore, from a materials standpoint, effects of ion-mediated flow on collapse will increase our understanding of the physicochemical mechanism of water transport in xylem during drying above FSP.

Electro-osmosis: is a transfer of liquid in capillary porous bodies under the action of an external electric field. Electro-osmotic flow is caused by a Coulomb force induced by an electric field on net mobile electric charge in a solution. A chemical equilibrium between a solid surface and an electrolyte solution leads to the interface acquiring a net fixed electric charge (a layer of mobile ions) called an electric double layer. When an electric field is applied to the fluid using electrodes, the net charge in the electric double layer is induced to move by the Coulomb force. The resulting flow is called electro-osmotic flow (Alexandrovna et al., 2017). The heterogeneity of phase charges leads to the displacement of mobile ions in the constant electric field pulling the liquid phase to the corresponding pole. Electro osmotic transport through the capillary-porous body is determined by the electro-kinetic potential and the structure of the double electric layer at the interface. Vice versa the mass transfer in colloidal systems is also accompanied by the generation of an electric field (Nikandrov & Porsev, 2018). It can also be hypothesized that conduction of electrical current in wood is more or less similar to that in an ionic solution i.e. current conduction in wood by means of ions is not restricted by wood structure. However, electrical conductivity of green wood is highly dependent on temperature and grain orientation (Nursultanov et al., 2020). Xylem may play a more active role in the electrical response (Gibert et al., 2006). Electric potential variations in standing trees using electrodes have been reported (Gibert et al., 2006; Gurovich & Hermosilla, 2009; Koppán et al., 2000, 2005; Le Mouël et al., 2010), and suggested that the electrical monitoring of a living tree can reveal new mechanism of charge exchange in xylem conduits (Gurovich & Hermosilla, 2009). Previously, bipolar electro kinetic dehydration of wood by electro-osmosis has also been explored (Alexandrovna et al., 2017; Zhang et al., 2018), and it is considered as a promising technique for drying wood with a minimal energy input (Nikandrov & Porsev, 2018). However, its influence on reducing defects during drying is unclear. The working hypothesis will be based on the assumption that: ion movement in small capillaries directly induces the electric current in wood. If it is the case then electric field can induce water flow and therefore pressure gradient. This process can be switched on or off reversibly and an electric potential is used to control the flow of water in wood.

4 Research methodology

4.1 Genetic control of collapse in *Eucalyptus*

4.1.1 Non-destructive assessment techniques for collapse

Hamilton et al. (2004) compared non-destructive techniques for total shrinkage (true shrinkage plus collapse) and suggested that the measurement of volumetric total core shrinkage appears a most promising method for assessing total shrinkage. The collapse in the NZDFI breeding trials is being assessed by the “maximum tangential shrinkage’ method; however, suitability/accuracy of this method is also to be verified. To verify the quick assessment methods suitable for assessing collapse in tree breeding, two methods will be compared in dried *E. quadrangulata* cores. The genetic parameters will be presented for each method of collapse assessment, DBH, basic density, extractive content etc.

Maximum tangential shrinkage

Dried cores were equilibrated to a stable moisture content at 60% relative humidity and 25°C. The narrowest tangential diameter of each core was determined in the sapwood with a Vernier caliper (D_{dry}) as well as the two narrowest tangential diameters in the heartwood before steam conditioning.

The widest tangential diameter of 204 (*E. quadrangulata*) and 500 (*E. globoidea*) randomly selected cores was measured as reference in the green state and averaged (D_{green}). The maximum tangential shrinkage in the core, separately for heartwood and sapwood, was calculated according to the following equation.

$$\text{Maximal tangential shrinkage} = \frac{\mathrm{D_{green}} - \mathrm{D_{dry}}}{\mathrm{D_{green}}} \times 100\ \%$$

Volumetric shrinkage and recoverable collapse

The green volumes and weight of *E. quadrangulata* samples were measured before drying. After equilibration to ~12% MC, weight and volume of the samples were re-measured. The volumetric shrinkage was calculated using the following formula:

$$\text{Maximal volumetric shrinkage \%} = (V_{green} - V_{dry}) \times 100/(V_{green})$$

Where, V_{green} and V_{dry} are volumes when green and dried, respectively.

The recoverable collapse was calculated after reconditioning. The percent difference in the volume of the sample before reconditioning (V_{dry}) and after reconditioning ($V_{reconditioned}$) with respect to the volume in green condition (V_{green}) was considered to be the amount of true collapse in the samples.

$$\text{Collapse} = (V_{reconditioned} - V_{dry}) \times 100/(V_{green})$$

4.1.2 Degree of genetic control in different breeding trials

Trial establishment and assessment

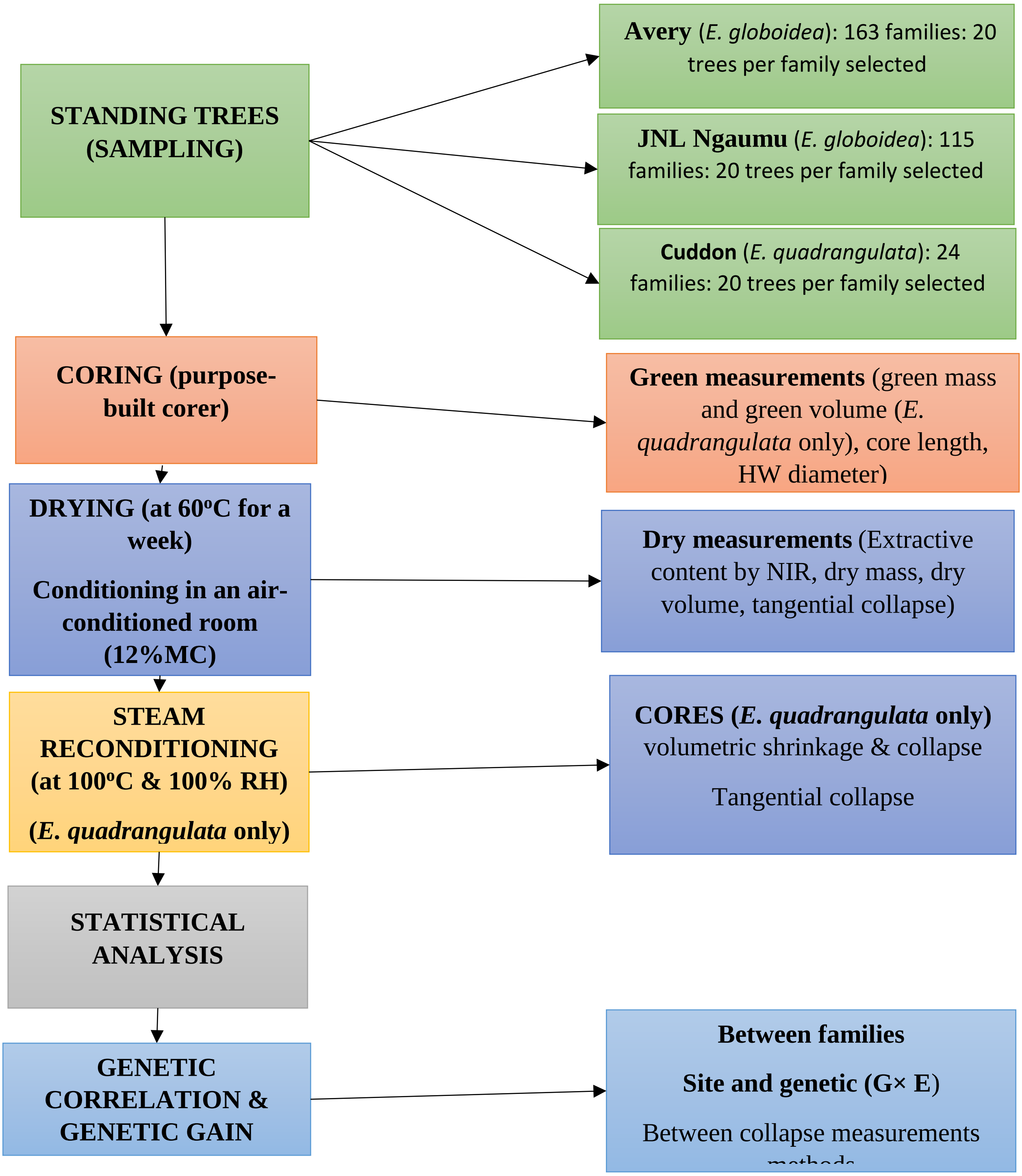
All NZDFI breeding populations are tested as standard open-pollinated families at 3 contrasting sites across the Marlborough, North Canterbury, Wairarapa, and Hawkes Bay.

An open-pollinated progeny trial of 24 *E. quadrangulata* families was established in 2011 at Cuddon, Marlborough, New Zealand. The trial site was located at latitude -41° 53’ 84” S, longitude 173° 87’ 33” E and at an altitude of ~38 m and featured a silt loam and stony alluvium soil. The site experienced an annual rainfall of around 600 to 1000 mm and an annual mean temperature of 14°C, ranging from 10 to 30°C during summer and 4 to 15°C during winter. The annual mean relative humidity was around 70%, ranging from 55 to 75% during summer and 65 to 85% during winter. Single-tree plots were established in 70 blocks with 24 trees in each block and a different number of individuals per family ranging from 30 to 109, totaling 1680 trees. The spacing of the trees was 2.4 m × 1.8 m. The trial was assessed for height at age 1.6 years in April 2013 and again at age 2.3 years in December 2013 for form and DBH. Recently, the trial was measured for DBH, height and form at the age of 8.9 years in August 2020. The trial was previously thinned.

An open-pollinated progeny trial of 163 *E. globoidea* families was established in 2011 at Avery, Marlborough, New Zealand. The trial site was located at latitude -41° 43’ 59” S, longitude 174° 09’ 60” E and experienced an annual rainfall of around 600 to 800 mm. The seed was collected from across the natural range of the species in Australia and from three NZ plantation sites with a known seed lot. Single-tree plots were established in 298 blocks with 36 trees in each block and a different number of individuals per family ranging from 31 to 81, totaling 10,728 trees. The spacing of the trees was 2.4 m × 1.8 m. Due to high mortality, 16 blocks were abandoned and 12 blocks were replanted with *E. tricarpa* in 2013. The trial was assessed for height at age 1.7 years in May 2013 and again at the age of 5.3 years in December 2016 for height, basal diameter and DBH. Recently, the trial was assessed for DBH, height, form, flowering and seed development at the age of 9 years in October 2020. The trial has been marked for the first thinning and was thinned at the age of 9.2 years in December 2020.

The JNL Ngaumu trial was planted in 2011 in a single tree plot design with 115 families of *E. globoidea* in 240 blocks (but three blocks were abandoned) of 30 trees each. The individuals per family varying from 1 to 80. The trial was measured for tree height at age of 1.7 years. DBH and tree form data was collected at age 5.8 years.

Figure 9. Details of sampling strategy and wood property assessment of Eucalyptus



Sampling strategy

Up to 20 trees with a diameter (DBH) above 50 mm were randomly selected from each family for sampling. Not all families had 20 trees with these specification left. This resulted in 455 trees being cored from the Cuddon trial.

Some trees were selected from non-assessed blocks to increase the number of individuals for some families, resulting in 2,752 trees being cored from the Avery trial. The JNL Ngaumu trial will be assessed in the upcoming months, following the same strategy.

Coring

A bark to bark 14 mm diameter core including the pith was extracted using a purpose-built corer from the selected trees in October/November 2020 at ~0.5 m stem height. The cores were labelled and packed into plastic bags to avoid drying during the day.

Traits measurements

Traits measured were core length, heartwood length and core thickness. The green weight and volume were measured from *E. quadrangulata* cores for volumetric collapse assessment. The green moisture content, basic density, extractives content, tangential collapse, volumetric shrinkage and recoverable collapse will be measured soon.

Core length, heartwood diameter

The heartwood diameter in the stem can be assessed by measuring the heartwood length with a ruler on the core samples in the green state at the day of coring. The heartwood can be highlighted by immersing cores into an aqueous 0.1% solution of methyl orange that can change heartwood color to pink while the sapwood remains yellow. Additionally, the length of the core (without bark) can be measured.

Core thickness, green mass and volume

The core thickness can be assessed by averaging the core diameter measurement obtained with a Vernier caliper from three different position in the green state. Green mass can be determined by weighing the fresh samples and green volume can be measured using the water-displacement.

Drying core samples

The core samples will then be oven-dried at 60°C for a week before equilibrating to a stable moisture content at 65% relative humidity and 25°C in a climate controlled room.

Extractive content

Extractive content can be measured using Near Infrared (NIR) spectra. NIR spectra will be taken on the sanded tangential-radial surface of the oven-dried cores using a fibre optics probe every 1 cm along the heartwood. Heartwood extractive content of each NIR measurement will be predicted with a previously developed method (Li & Altaner, 2016).

Collapse

Collapse will be assessed using the above described methods (section 4.1.1).

Basic density, green density, green moisture content

The basic density will be measured using a 12 mm diameter bark to bark core taken at a height of 0.5 m. Core sampling at this height has been shown to be a reliable predictor of whole tree values of basic density (Raymond & Muneri, 2001).

The basic density of the cores will be calculated from dry-wood mass and green volume.

$$\text{Moisture content} = \frac{W_{green} - W_{dry}}{W_{dry}} \times 100$$

$$\text{Basic density} = \frac{W_{dry}}{V_{green}}$$

$$\text{Green density} = \frac{W_{green}}{V_{green}}$$

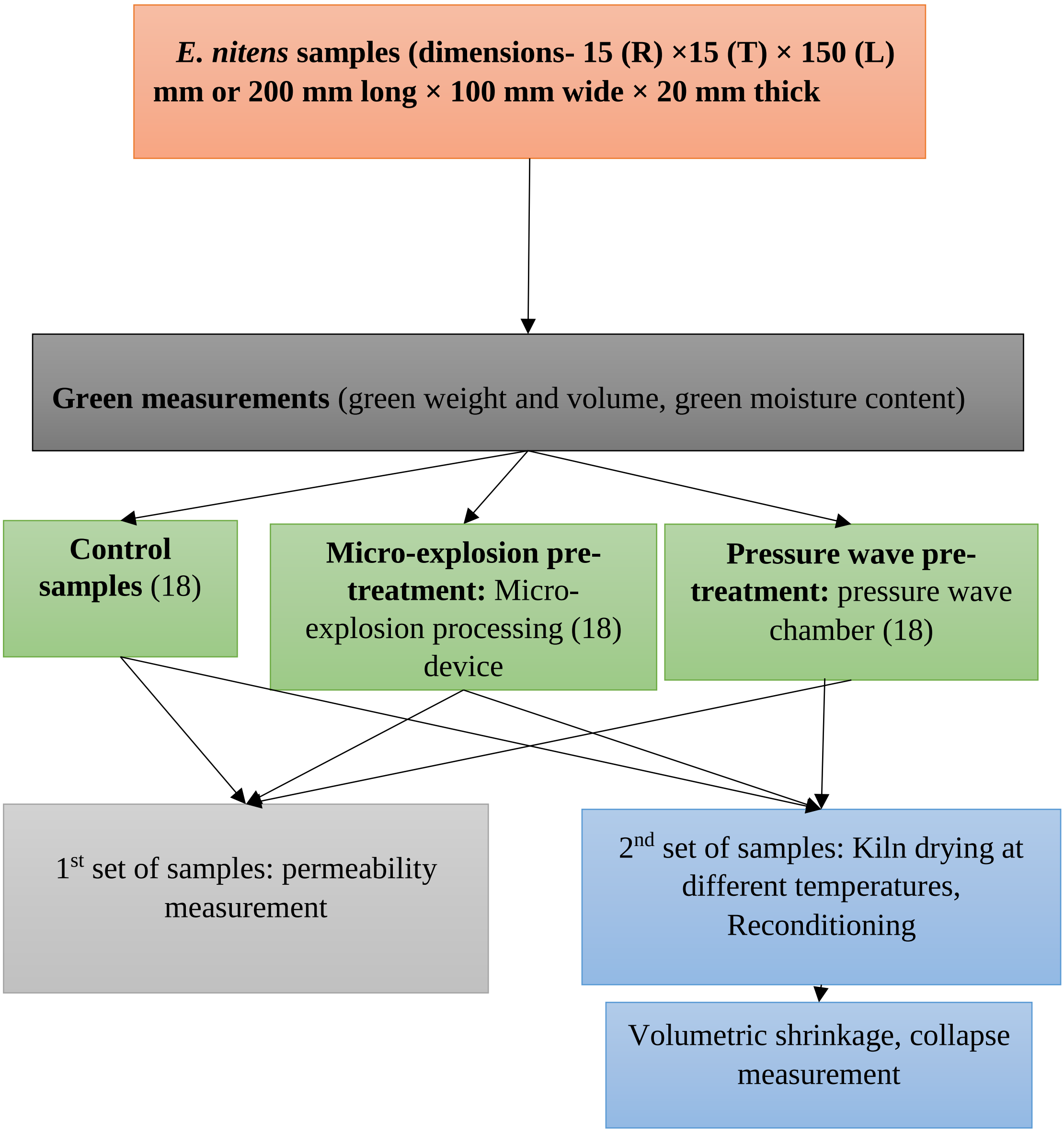
Where,

W = Weight (kg), V = Volume (m^3)

4.2 Improving permeability of eucalypt timber

Two methods are identified to improve the permeability of wood in order to reduce collapse.

Figure 10. Details of the experiments to improve the permeability of wood



Materials: Samples will be cut into uniform blocks 200 mm long by 100 mm wide by 20 mm thick in a tangential direction or 15×15×150 m^3 size samples will be used. The specimens will be weighed and measured before the experiments. Green specimens will be divided into 3 groups: for micro-explosion pre-treatment, for pressure wave pre-treatment, and a control group (without pre-treatment). Each group of specimens will be further divided into 2 subgroups from each pre-treatment method: one for evaluating the pre-treated wood drying characteristics and the other for permeability measurements.

4.2.1 Micro-explosion pre-treatment

The micro-explosion processing device: consists of a pressure chamber and an air compressor linked together by an intake tube (Figure 11). The specimens will be placed in the hermetic chamber. A burst of high pressure air at room temperature will be provided through the inlet valve. In addition, the pressure of the chamber will be monitored with a pressure gauge. After being pressurized for 2 to 3 min, the pressure will immediately be released through the outlet valve, leaving the wood in a state of no pressure. The outlet valve will then be closed, and the treatment cycle will be repeated for a pre-specified number of times (Figure 12) (Ma et al., 2016).

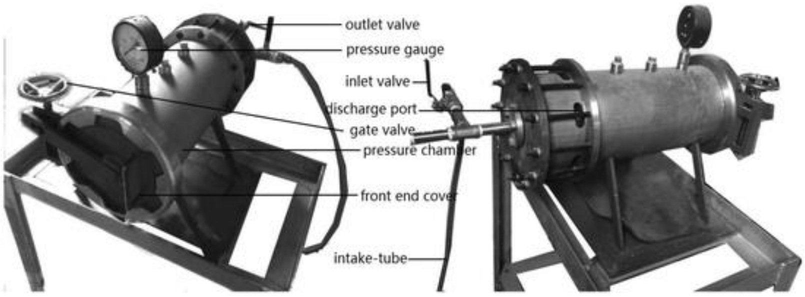


Figure 11. Micro-processing Device (Ma et al., 2016)

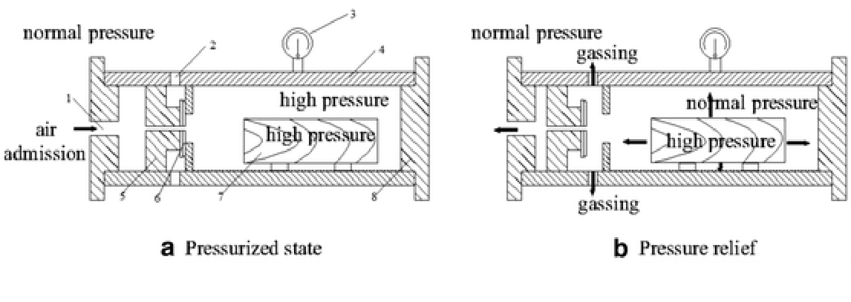


Figure 12. Working states of micro-explosion equipment: 1 inlet port, 2 outlet port, 3 pressure gauge, 4 chamber, 5 piston, 6 rubber gasket, 7 wood, 8 front end cover (Ma et al., 2016)

4.2.2 Pressure wave pre-treatment

An impulsive pressure wave can be generated by dropping a hammer (2 kg) along a guide pole from 80 cm height into a container filled with liquid (water). The waves propagates through the liquid into the wood, inducing a kinetic momentum in cell cavities impacting on the closed tissues (Figure 13). A more detailed description of this technique can be found in the literature (Tanaka et al., 2019).

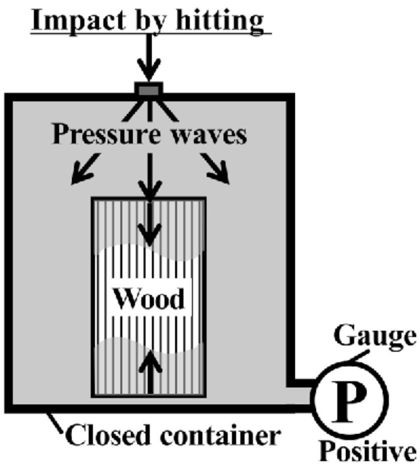


Figure 13. Conceptual diagram for an apparatus with a closed container (Tanaka et al., 2019)

The container is capable of being separated into two pieces at the joint coupler so that the samples is placed on and taken out of the container (Figure 14). A feed pump can be used to supply the liquid to fill up the container. A digital pressure sensor (GM-025, Keyence Co.) connected to the data collecting system (NR-500 and NR-HA08, Keyence Co.) can be used to measure the temporal variability of the hydraulic pressure in the container after impact.

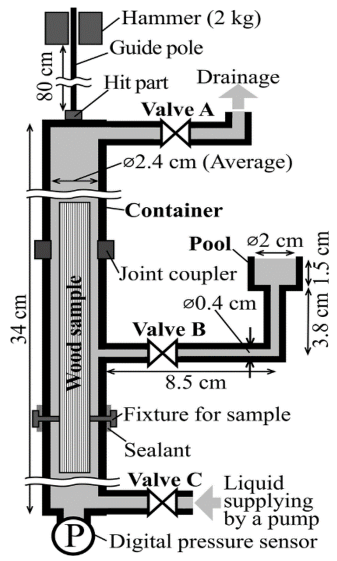


Figure 14. Experimental apparatus (Tanaka et al., 2019)

Permeability measurement: In order to calculate transverse permeability, the end faces of the specimens are sealed using an epoxy resin, allowing the dyeing liquor to enter in the wood only along the transverse direction. All the faces except the longitudinal, are sealed for axial permeability assessment. After the resin has cured, specimens can be placed in a chamber at a constant temperature (20 °C) and humidity (65%). Specimens can be weighed immediately after the equilibrium treatment. In the impregnation experiment, specimens can be placed into a dyeing liquor under atmospheric pressure and weighed every 1 h, 2 h or 4 h.

Drying experiments: The drying experiments will be conducted in a conventional kiln and the test condition will be arranged to 40 ^{o}C with the corresponding humidity of 70%, in an attempt to maintain the EMC of 12%.

Shrinkage and collapse measurement:

Volumetric shrinkage will be determined using volumes of green and dry samples as described previously in section 2.5.

Steam reconditioning will be done for a period of 2 h to recover collapse and subsequently equilibrated to 12 % MC. Weight and volume of the samples can be determined before and after reconditioning.

Recoverable collapse will be measured as described in section 2.5.

4.3 Ionic effects on water transport in wood

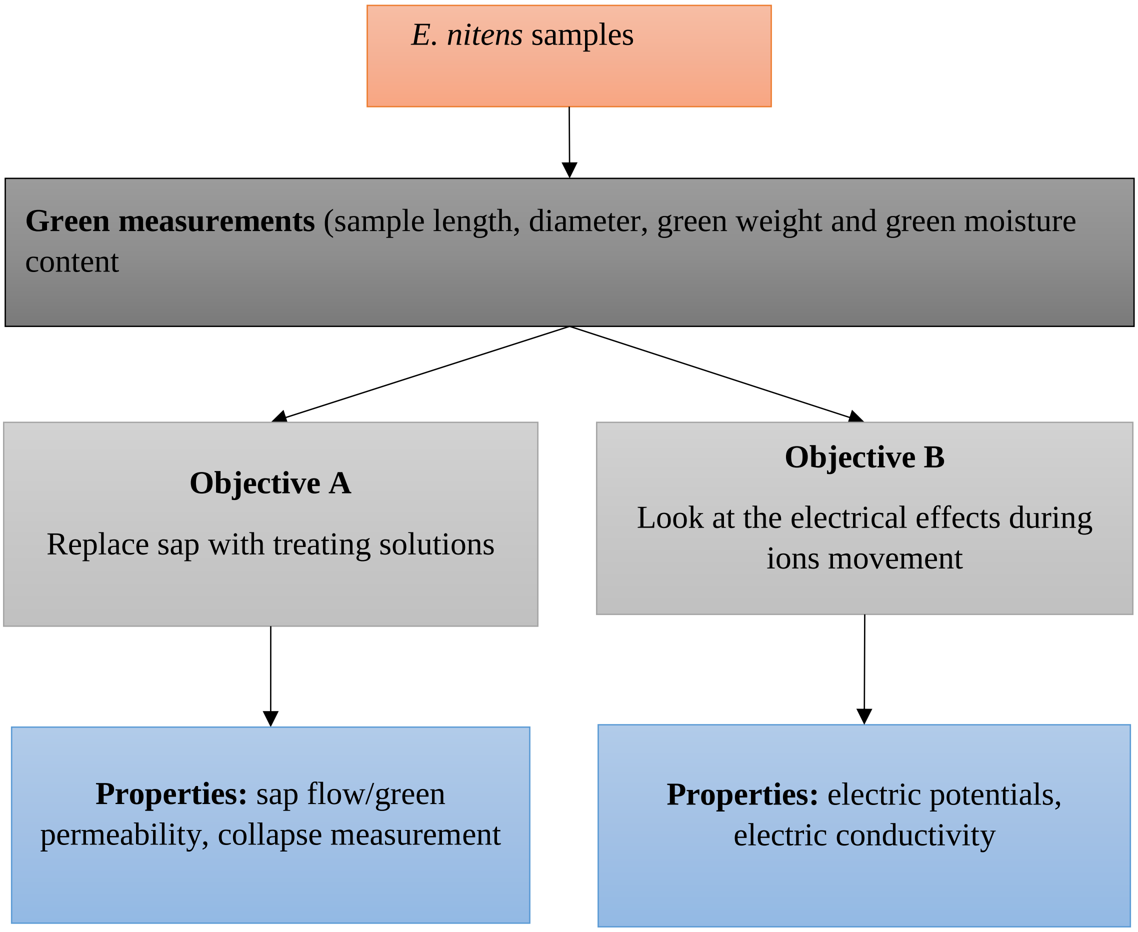
Materials

Log sections of *E. nitens* up to 3 m (not less than 20 cm) in length and ~12 cm basal-end diameter will be cut. All specimens will be chosen for uniform girth. The log ends will be sealed in polythene to avoid drying. The logs will then be processed or stored at 4 ^{o}C to keep them green. Six specimens for each replicate will be tested. A representative sample will be cut from the each log section for measuring moisture content. After the experiment, samples will be prepared from the each log section for assessing collapse and permeability.

Objective A: Influence of ions on hydraulic conductivity and collapse

A water-tight collar will be fitted to the basal end of the sample log and a constant pressure of 10 psi (0.6894 bar) will be applied to force the treating solutions through the stem (Prendergast et al., 2007). The effluent will be collected and weighted at regular intervals to obtain sap flow rate or sap flow meter can be used that comprises a set of probes and associated electronics connected to the data logger (Implexx sap flow sensor, model HPV-06). A number of preliminary experiments were conducted to check the suitability of this technique for sap-displacement and measuring sap flow.

Figure 15. Flow chart of the experiments



Treating solutions

1) 1 M NaCl solution

2) 1 M KCl solution

3) 1 M boric acid solution

4) H_2O dist

5) Carbonised water

6) Sap

Flow rate/ Green wood permeability

Volumetric flow rate and green wood permeability (K) will be calculated as described in section 1.1.3.

Objective B: measuring electric phenomena during sap flow in wood

The concept of electric potential is useful in understanding electrical phenomena during sap flow in wood. Electrical potential can be defined as the amount of charge from a reference point to a specific point against an electric field.

Electric potential and electrical conductivity

Electric potential difference between two points in the log section will be determined using electrodes inserted into the log connected with a voltmeter in parallel series. Electrical conductivity of green wood has been measured by Nursultanov et al. (2020). This method will be adapted for these experiments.

Drying and collapse measurement

The drying experiments will be conducted in a conventional kiln at 40 ^{o}C and 70 % RH. After drying, collapse will be measured using "recoverable collapse" method as described in section 2.5.

5 Importance and contribution of Research

The genetic study will evaluate tree breeding as a tool for managing the collapse of NZDFI *Eucalyptus globoidea* and help improve future breeding trials concerned with drying stresses such as checking and collapse, and hence will increase the quality of the NZDFI breeding stock.

Technological solutions for improving drying quality could provide options to reduce drying defects i.e. collapse and honey comb in the low permeable plantation eucalyptus. This would enable potential drying methods for low permeable species, which can further be implemented at a large scale.

Physiological influence, how the sap ions affect the hydraulic conductivity will provide insight into the physiological mechanisms and parameters related to it contributing to collapse development. Information regarding the mechanisms for collapse development is useful for fundamental understanding of the parameters responsible for collapse occurring and would enable potential treatments in their modification.

6 Proposed thesis chapters/publications

6.1 Introduction and review of literature

6.2 Comparison of non-destructive assessment techniques for collapse in *Eucalyptus*

6.3 Genetic variation in shrinkage and collapse related properties of *E. globoidea* and *E. quadrangulata* juvenile wood

6.4 Effect of pre-drying treatments on permeability and collapse of dried *E. nitens*

6.5 Influence of ion-mediated water flow on hydraulic conductivity and subsequently collapse of *E. nitens*

6.6 Role of electro-osmosis dehydration during the drying of collapse prone wood.

Chapters 3 to 6 might result in content suitable for peer-reviewed publications.

7 Expected outcome

This study is aimed at finding solutions for reducing drying defects in eucalyptus. In order to meet the increasing demand of the growing population, plantation timbers need to be used for high value timber products. This is only be possible if the drying quality of such timbers is appropriate. This study envisages potential methods which would reduce collapse in a future resource and minimize collapse in the current resource.

8 Research plan

Tasks		Sep 2020	Mar 2021	Sep 2021	Mar 2022	Sep 2022	Mar 2023
Literature review and Preliminary experiments							
Objective 1	Assessment of *E. quadrangulata* trial (Cuddon)						
	Assessment of *E. globoidea* trial (Avery)						
	Assessment of *E. globoidea* trial (JNL Ngaumu)						
Objective 2	Micro-explosion and pressure waves treatment						
	Properties assessment						
Objective 3 Part A	Sap-replacement experiment						
	Electro-osmosis dehydration						
Objective 3 Part B	Measurement of permeability and collapse						
	Measurement of electric potential and current						
Writing-up thesis							

9 Draft budget

This research project is financially supported by the New Zealand Dryland Forestry Initiatives (NZDFI), which covers a stipend and research expenses.

Materials: Access to *E. globoidea* and *E. quadrangulata* breeding trials is ensured through NZDFI. *E. nitens* samples are available from Harewood (School of Forestry) and through Solid Timber Solutions sawmill.

Most equipment is available at SoF (NIR, autoclave, kiln and sap-flow meter). A micro-explosion device, pressure waves equipment and an electric conductivity experimental setup needs to be built with SoF and EPEC workshop assistance.

10 Health and safety risk assessment

1) College of Engineering health and safety induction (completed)

2) Wood tech lab health and safety induction (completed)

3) School of Forestry postgraduate induction (completed)

4) Wood science laboratory health and safety induction (completed)

5) Field trip for assessing *E. quadrangulata* breeding trial (completed)

6) Field trip for assessing *E. globoidea* breeding trial (completed)

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