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A forest resource characterisation of Tasmania - stage 1 of 2. Feasibility

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NATIONAL INSTITUTE FOR
FOREST PRODUCTS INNOVATION
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A forest resource characterisation of Tasmania – stage 1 of 2. Feasibility

Prepared for

National Institute for Forest Products Innovation

Launceston

by

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Executive Summary

This study assessed the feasibility of developing models to characterise the wood volume and wood quality of the Tasmanian hardwood estate. Increasing the ability to model the characteristics of the Tasmanian hardwood estate would provide valuable information to the forestry sector for both forest growers, timber producers, and end users.

To determine the feasibility of developing statewide characterisation models we reviewed the current, available data and methods used for collecting information on wood properties and volume. In addition, we assessed the availability of information on key drivers of variation in wood characteristics such as climate and environment. Key gaps in the capacity to create a complete forest characterisation of the Tasmanian hardwood estate and potential projects to address these gaps were determined.

There is large body of evidence available indicating the major drivers of both wood properties and volume. Environmental factors such as water availability, temperature, elevation and soil are all critical drivers and vary substantially across the Tasmanian hardwood estate. The major gap in the capacity to characterise the Tasmanian hardwood estate is a lack of available data on variation in wood property information across the estate. The only current detailed information exists for plantation *Eucalyptus nitens* however this information only exists across a specific area of Tasmania and for a limited environmental range. However, there are numerous techniques and tools available for the assessment of wood properties and therefore, there is capacity to increase data collection of wood property information across the estate.

To collect data across the range of environmental conditions of the Tasmanian hardwood estate, a large sampling project is required. While current projects underway in the Australian Research Council Training Centre for Forest Value, will take a step towards increasing the available data for a state-wide characterisation, more data is required. In addition, variation in wood properties is highly dependent on silvicultural management, age and species. We recommend that initial projects designed to model wood properties across the whole estate focus on a single silvicultural method (plantation or native) and a single species at a set age. Matched with this, there is a wide range of environmental and climatic data available that could be used to inform wood property models.

While a Tasmanian estate wide model of wood volume is not currently available, the data and modelling available within individual forestry companies already provides the information to produce volume characterisation models and predictions, although estate wide modelling will rely on the sharing of such data. With publicly available environmental and estate distribution maps, expanding models beyond individual companies is feasible. On area that does require more focus in the future is the area/volume of timber available from private native forests.

New remote sensing technologies may also provide techniques for estate level assessments of productivity, however current limitations on the automation of collection and data processing means that this technology is not yet applicable over large forest areas.

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Section 1: Introduction

This project aims to assess the available data as well as the feasibility of, and best techniques for, the development of accurate and reliable models to estimate the characteristics of the Tasmanian hardwood timber resource. The creation of forest characteristic models would have numerous benefits for the forest and wood products industry including aligning forest estate data to primary product outcomes. The focus of this project is the Tasmanian hardwood estate (*Eucalyptus* spp.*)* from both private and publicly owned native forest and plantations. The Tasmanian hardwood forest and wood processing industry produces a variety of products based on market demand and the specific wood characteristics of the available forest resource. The inherent wood characteristics are crucial, as they influence how the wood will respond to processing and the quality of the final product. Important characteristics used to assign wood products to different processes include density and modulus of elasticity (MOE). Accurate prediction of the volume of timber available with desired wood characteristics, would improve the ability of processors to optimise resource use and plan for current and future market demands.

Increasing the ability to model the characteristics of the Tasmanian hardwood estate would provide valuable information to the forestry sector for both forest growers, timber producers, and end users. Increased predictability of the resource will improve the sustainability and efficient use of natural resources (Malan 2003, Moore and Cown 2015), as well help industry adapt to changes in product demand (McEwan et al. 2019). In addition, increased capacity to model the spatial variation in wood characteristics could;

- identify high value areas for current and future growers of solid wood;
- allow estate managers to better balance their competing requirements for both attractive growth rates and optimal wood property characteristics;
- help project the potential characteristics profile of logs recovered into the future to aid growers planning to diversify into growing for solid wood products; and
- provide information to processors considering investing in high volume sawing or peeling projects.

The ability to model the key characteristics of a timber estate, such as wood properties and wood volume, relies on knowledge of how those characteristics vary in response to several key factors including; genetics, climate, site characteristics, silvicultural management and age (Zobel and van Buijtenen 1989). The nature and relative importance of these influences is likely to vary between species and geographic regions. Understanding how geographic variation and the associated variation in growing conditions, silvicultural management and genetic factors (Blackburn *et al*. 2010, Blackburn *et al*. 2011) influences these wood properties is central to optimising the use of available resources and improving the competitiveness of forestry industries (Malan 2003, Blackburn *et al*. 2014, Lessard *et al*. 2014, Payn *et al*. 2015).

To fully evaluate forest characteristics for economically viable solid-wood production, quantitative information on both external (e.g. tree volume) and internal tree characteristics (wood properties) is required. However, the high cost and logistic constraints of directly measuring wood properties across forest resources means that predictive models are required to accurately and efficiently predict these properties. In conifers there have been several regional characterisation studies in New Zealand and the south-eastern United States (Jordan *et al*. 2008, Antony *et al*. 2011, Moore *et al*. 2014) as well as in Australia for radiata pine (Drew and Downes 2013) using the ecambium tool (this work is currently ongoing). One of the most comprehensive regional forest characterisation models with several wood properties evaluated was for Canadian conifers (Lessard *et al*. 2014). While some small scale models have been developed in Tasmania for specific regions and species, to date, no models capable of predicting the wood properties of Tasmanian hardwood species across the whole estate are available (Vega 2016). The Tasmanian hardwood estate exists across a wide range of climatic and geographic conditions as well as across many species and management regimes. Therefore, current modelling cannot accurately encompass the whole estate so expanding modelling capabilities is fundamental to optimising wood use and improving competitiveness in the Tasmanian forest industry.

The key objective of this study is to assess the feasibility of developing models that can characterise the variation in the Tasmanian hardwood estate for wood volumes and wood properties. Specifically, we hope to identify a feasible project that could identify key forest, environmental and climatic variables and use these to predict product-critical wood properties. Due to the range of products that are currently sourced from the Tasmanian estate this report will encompass wood properties relevant to the production of wood chip, sawn-board and veneer-based products.

To assess the feasibility of producing a forest resource characterisation model this report will;

1. Review the drivers and methods of assessing variation in wood properties of *Eucalyptus* spp. grown in Tasmania (Section 2)
2. Review the drivers and methods of assessing wood volume variation in *Eucalyptus* spp. grown in Tasmania (Section 3)
3. Determine the range of environmental and climatic conditions over which the Tasmanian hardwood estate sits. (Section 4)
4. Design a project to create a model of variation of wood characteristics across Tasmania and determine the projects feasibility (Section 5) and cost (Section 6).

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Section 2: **Factors affecting wood properties in Tasmanian hardwoods**

Introduction

Wood properties in production forests show large variation between sites, due to differences in management and growth conditions. Unwanted wood property variations lead to reduced yield, increased processing costs and problems with final product quality in the industry. Therefore, characterising and predicting wood properties across the forest estate provides the forest industry with information about the wood properties of the wood supplied, supports efficient operation and optimisation of product quality (Lundqvist and Gardiner 2011) and aids in the optimal allocation of wood to different productions chains, mills and products. Three steps are involved in the development of models to predict regional variation in wood properties. The first step is sampling wood properties from a range of species and growing conditions across the region. This is a critical step in model development and important decisions need to be made about sampling methodology and the technology to be used in data collection as well as the intensity of sampling across the region. The second step is the development of predictive models for the wood properties selected, and the third step is validation of the models against an independent data set.

This section assesses the available information relating to wood properties, its variation with environmental conditions and the methodologies used to assess wood properties. These factors will be examined in the context of the Tasmanian hardwood estate.

Wood properties relevant in the Tasmanian context

Wood properties provide indicators of wood quality that are linked to product potential and performance (e.g. pulp yield, wood density and wood stiffness). The importance of specific wood properties is defined primarily by the forest industry, but ultimately their importance is determined by the end-customers (Chauhan *et al*. 2006). In the Tasmanian context, wood density, MOE, MFA and pulping properties are essential properties used to assign wood to any particular process.

Wood density

Wood density is the most common property used to characterise wood quality because it is closely related to the mechanical, physical and chemical properties of wood (Shmulsky and Jones 2011a). Wood density is defined as weight per unit of volume, usually expressed as kilograms per cubic metre (kg m^{-3}). Wood density is commonly measured as oven-dry weight per unit of green volume, which is denoted as 'basic density' [1]. Green density [2] and air-dry density [3] may also be used (Shmulsky and Jones 2011a).

$$Basic\ density = \frac{Oven\ dry\ mass}{Green\ volume} \quad [1]$$

$$Green\ density = \frac{Green\ mass}{Green\ volume} \quad [2]$$

$$Air\text{-}dry\ density = \frac{Mass\ (at\ any\ given\ moisture\ content)}{Volume\ (at\ any\ given\ moisture\ content)} \quad [3]$$

Although air-dry density is less commonly used than basic density, Hamilton *et al*. (2008) found that the two metrics are very strongly correlated (r=0.997).

Wood density can provide general information about the performance of the timber in end-products. For example, wood with high density indicates the timber or veneer produced will have a better aptitude for structural products, or that the pulp yield per unit volume will be higher. While wood density is a good general indicator of the performance of the wood, its importance varies largely between species and technology used in the industrial process. For example, MacLeod (2007) describes the top ten factors determining kraft pulp yield, where wood species and their chemical composition is the top factor, but wood density was not listed as wood density alone is not enough for determinate potential pulp yields because it depends to many other factors.

Stiffness (MOE)

One of the most significant mechanical properties relevant for structural applications is stiffness which is, in general terms, the resistance to deformation of the wood under load. This mechanical property is measured by Modulus of Elasticity (MOE), which is calculated from the linear portion of the load-deflection curve (Raymond *et al*. 2007), as shown in Figure 2.1.

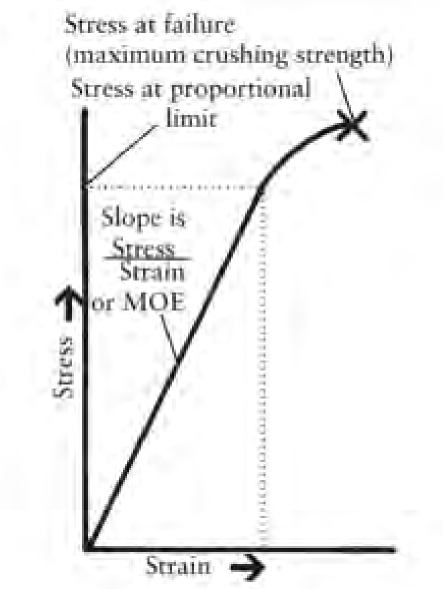


Figure 2.1. The relation between stress and strain in a typical compression parallel-to-grain bending test (Shmulsky and Jones 2011b).

Stiffness can also be measured using non-destructive evaluation (NDE) techniques which use the longitudinal stress wave method. This measurement is referred to as dynamic MOE (MOEd) to distinguish it from the static modulus of elasticity derived from bending tests. In Australia, timber and veneers used for structural purposes can be graded into different stress grades according to AS/NZS2878 (2017). The stress grade is directly related to unit price, with higher stress grades fetching significantly higher prices (Dickson *et al*. 2003). Therefore, stiffness is a highly important characteristic for the management of solid-wood production.

Microfibril Angle (MFA)

Microfibril angle (MFA) is defined as the angle between the direction of crystalline cellulose fibrils in the cell wall and the longitudinal direction of the cell (Barnett and Bonham 2004), depicted in Figure 2.2. It is very well recognised that MFA of the woody cell wall S2 layer has a critical influence on the behaviour of wood, especially on its mechanical and physical properties (Barber and Meylan 1964; Barnett and Bonham 2004). High values of MFA have an adverse effect on stiffness, strength and shrinkage (Fig. 2.3) and so lower values of MFA are better for structural purposes (Barnett and Bonham 2004)

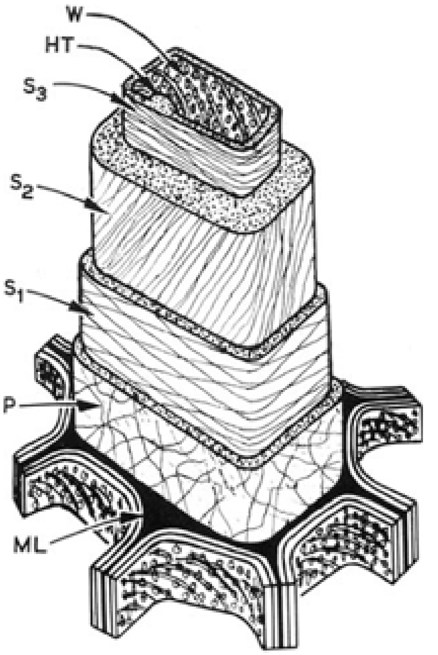


Figure 2.2. A schematic diagram to illustrate the general structure of the cell wall of axially elongated wood elements and the dominant, helical orientation of the cellulose micro fibrils within each wall layer. ML, middle lamella; P, primary wall, S1, outer layer of the secondary wall, S2, middle layer of the secondary wall; S3, innermost layer of the secondary wall; HT, helical thickening; W, warty layer. Microfibril angle is the angle between the direction of crystalline cellulose fibrils in the S2 cell wall and the longitudinal direction of the cell (Butterfield and Meylan 1980).

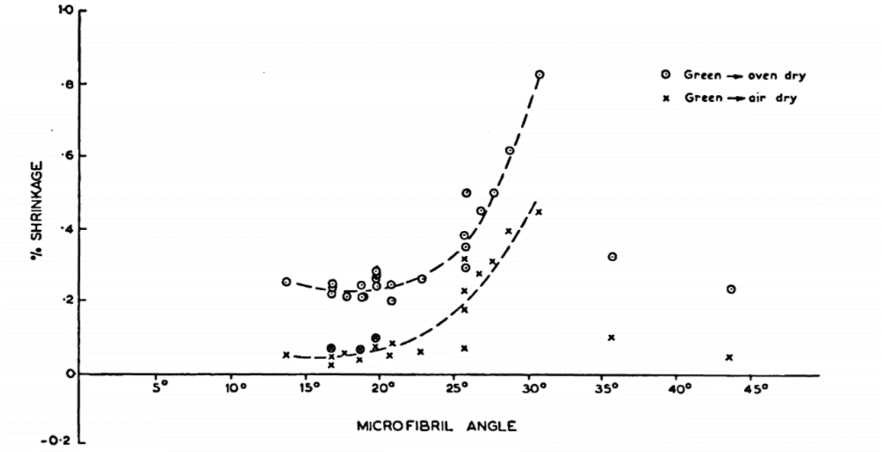


Figure 2.3. Relationship between MFA and shrinkage in conifer wood, (Figure from Barber and Meylan (1964)).

Pulp and chemical properties

Wood is an organic raw material consisting principally of cellulose, hemicelluloses, lignin, and extractives which can be used to produce a range of chemical products. Traditionally, Tasmanian plantations and native forests have been used to produce wood chips for Kraft pulping, which produces fine paper such as tissues. The chips value is associated with the pulp recovery, which is commonly expressed as the percentage, by oven-dry weight, of pulp obtained from the original wood weight.

The forest industry uses wood density as a general predictor of pulp recovery; however, it has been reported that there is a weak to no correlation between Kraft pulp yield (KPY) and wood density in *Eucalyptus* spp. and other species (Santos *et al*. 2012). Specifically, for *E. globulus* Miranda and Pereira (2001) reported that wood density had no influence on pulp yield (Fig. 2.4).

The lack of relationship between wood density and KPY is explained because KPY depends on the interaction of several factors, for example, wood and chip characteristics, pulping chemistry and processing technology (MacLeod 2007). Kraft pulp yield provides a better estimate of the potential of species for pulping than wood density.

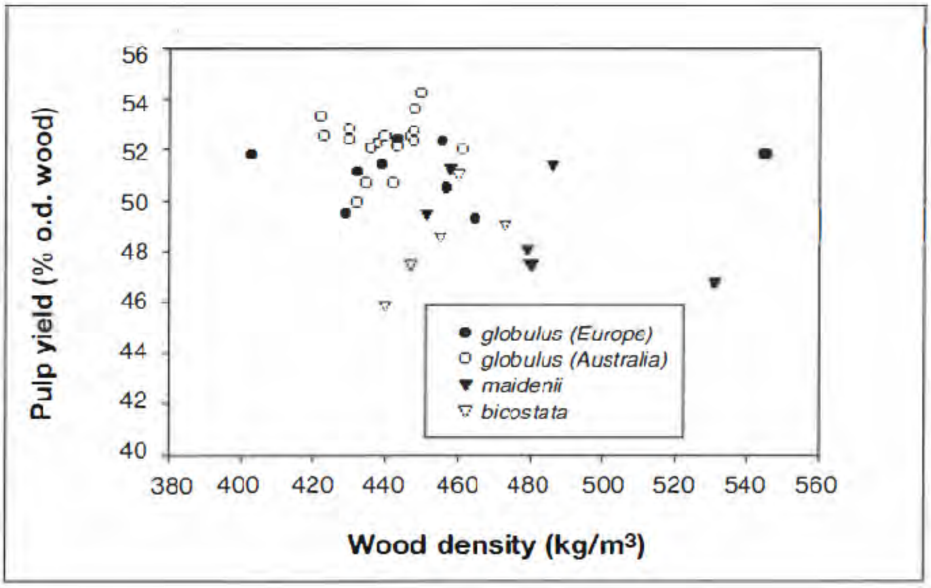


Figure 2.4. Relationship between pulp yield and wood density for provenances of *Eucalyptus globulus.* (Miranda and Pereira 2001).

Conclusions – relevant wood properties

Knowledge of chemical and structural wood properties is crucial to determining the quality of wood chips and structural timber, the traditional products of the Tasmanian forest industry. However, knowledge about other wood properties is required to develop new products requiring specific characteristics to be known. An example is microfibril angle (MFA) which is not commonly assessed but is strongly associated with shrinkage, stiffness and dimensional stability which play a critical role in high-value solid wood products, such as furniture (Walker 2006). Accurate assessment of the spatial variation and prediction of the quantity of wood with desired properties within existing Tasmanian forest resources, would enhance the ability of processors to optimise resource use (Wood *et al*. 2008).

Technology to assess wood properties

A range of technologies and methodologies are currently available to measure wood properties in the forest. Among them, non-destructive evaluation (NDE) methodologies/technologies have recently emerged as a viable alternative to traditional methodologies in the forest and processer sector. NDE is define as “the science of identifying the physical and mechanical properties of a piece of material without altering its end-use capabilities and then using this information to make decisions regarding appropriate applications” (Ross, 2015).

The most significant disadvantages of the traditional methodologies over NDE technologies are that they can be expensive, time-consuming and usually do not allow re-evaluation of the properties in the same sample. For example, according to Downes *et al*. (1997) studies of basic density at tree level using discs are expensive, destructive and very labour intensive in the field and the laboratory and the samples cannot be re-evaluated to check the measurements. While NDE techniques have multiple advantages, it is critical to recognise that any technique has its limitations, and it is essential to select the appropriate technique for a given application.

In this section, we describe methodologies/tools which have been used in the Australasian context. For a better description and comprehension of the tools, they are divided into two categories: i) field-based tools; and ii) lab-based tools. The first group are typically robust, easy to use in the field and provide data almost instantly, while the second group provide highly accurate measurements of specific wood properties in laboratories, that complement data collected by field-based tools.

Field-based techniques

The following list contains a summary of tools commonly used to assess wood properties of trees. It should be noted that some of these tools utilise several different techniques to measure properties.

Acoustics

Acoustic wave velocity (AWV) is a field-based metric used to predict wood stiffness (MOE). The use of AWV as a measure of wood quality in trees and logs has been widely recognised by growers and forest industries. The development of standing acoustic tools has opened the way for assessing wood properties on standing trees before harvest; enabling management, planning, harvesting, and wood processing to be carried out in a way that maximises extracted value from the resource.

AWV has been used to predict dynamic MOE via the following equation:

$$MOE_d = \rho * AWV^2$$

where MOE_d is dynamic MOE, ρ is wood density, and AWV is acoustic velocity.

The wood density term (ρ) in the MOE_d equation is generally assumed to be constant when assessing standing trees and logs, although measuring the actual green density can improve the accuracy of the acoustic velocity models if relating to static properties is of interest (Wang and Chuang 2000). However, measuring the basic density is not a suitable technique for improving the accuracy of the MOE_d equation (Butler *et al*. 2017) because AWV changes with the moisture content of wood (Wang and Chuang 2000). Acoustic Wave Velocity increases rapidly with decreasing moisture content below the fibre saturation point. Above the fibre saturation point AWV will decrease with increasing moisture content but at a slower rate than below the fibre saturation point (Moreno Chan *et al*. 2010).

Acoustic Wave Velocity is used to assess both standing trees and cut logs, however there are differences in the measurement principle. While time of flight (TOF) is typically used for trees, resonance is used for logs. An important limitation of AWV to note is that, in trees, TOF only measures acoustic wave velocity in the outerwood of a trunk at DBH to a depth of 20–30 mm over approximately 1 to 1.2 m (determined by the distance between measurement points). However, log measurements assess resonance throughout the whole log, and are usually considered more accurate than TOF tools (Fig. 2.5). An additional limitation is that AWV, for both logs and trees, provides a single value and cannot assess radial variation (Table 2.2).

Figure 2.5: Acoustic Wave Velocity instruments, used to assess MOE_d in logs (left) and in standing trees (right)

Resistograph

The Resistograph was initially designed to evaluate wood decay in poles, standing trees and structural timbers. However, recent improvements of the instrument have resulted in good correlations with wood density, and thus more widespread adoption for measurement of wood density.

The Resistograph method is based on measuring the drilling resistance to turning (torque) produced when a small needle like drill bit (3 mm diameter) is driven into a tree with a constant speed (feed speed) and rotation rate (rpm). The power consumption of the drilling device is measured electronically. The amplitude of drilling resistance is recorded in relation to the penetration depth of the needle (from bark to bark) (Fig. 2.6).

According to Schimleck *et al*. (2019) the critical features of this tool are its low cost in field application, digital data capture and the relatively high-resolution data. A 400 mm long trace can be taken from a single tree in less than 20 seconds, with tests conservatively showing that 50 to 120 trees per hour can be sampled, depending on terrain, ground cover and the need for defining individual tree identifiers on the instrument interface. The trace represents a profile of resistance every 0.1 mm, resulting in an estimate of the radial variation in wood density (Rinn *et al*. 1996)(Table 2.2). Typically, this level of detail is more than commercial users require.

Figure 2.6. Resistograph trace of *Eucalyptus nitens* (top) and tree assessment with Resistograph (bottom).

Laboratory-based techniques

SilviScan

SilviScan is an instrument that combines different NDE technologies (Fig. 2.7) to analyse the microstructure of the wood through the radius of the stem (Fig. 2.8 and 2.9).

Figure 2.7. SilviScan machine.

The radial samples can be obtained from 12 mm cores or strips from discs (Fig. 2.8) which must be dried, avoiding collapse, to approximately 8% moisture content (Evans 2008).

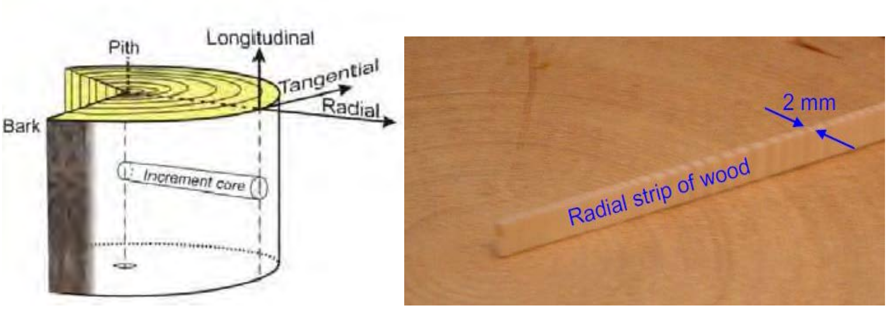


Figure 2.8. SilviScan radial samples from increment core (left) and from a disc (right). (Bowden and Evans, 2012 and Chen, 2016, respectively).

SilviScan can assess many different wood fibre attributes including wood density, MFA and radial fibre diameter and can estimate other attributes such as MOE and shrinkage.

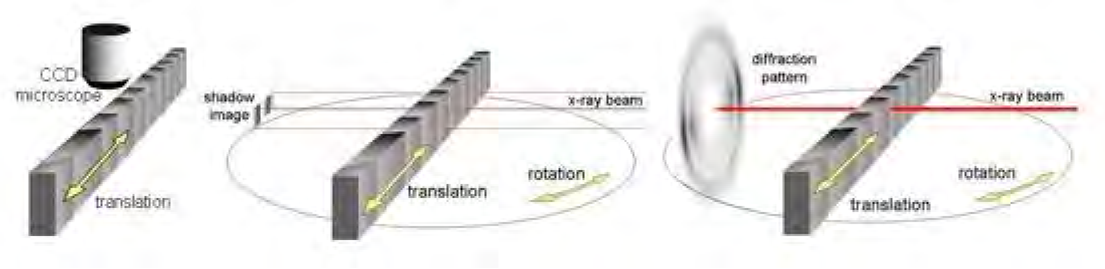


Figure 2.9. The three analysis components of SilviScan (Cell Scanner, Densitometer, Diffractometer).

Wood density is obtained using an X-ray densitometer, and MFA with an X-ray diffractometer, with a maximum resolution for density of 0.025 mm and for MFA of 1 mm.

Modulus of elasticity is estimated indirectly using density and MFA data at the resolution of the MFA data (Fig. 2.9), following the semi-empirical equation (Evans 2008):

$$MOE \approx a(I_{cv}D)^b$$

where:
D is air-dry density determined by X-ray densitometry,
I_{CV} is the coefficient of variation of the amplitude of the azimuthal X-ray diffraction intensity profile,
a is a scaling factor (~0.165), and
b is an exponent to allow for curvature (~0.85).

The measurement units of wood density, MFA and MOE obtained by SilviScan are: air-dry density in kg m^{-3}, the standard deviation of azimuthal diffraction profile in degrees, and the dynamic modulus of elasticity (MOE_d) in GPa, respectively (Evans 2008). While the SilviScan can provide high detail measurements across multiple metrics the disadvantage of this technology is the high cost and slow processing (Table 2.3) due to the need to collect samples in the field (cores or discs) and bring them back into the lab.

Near Infrared (NIR)

Near infrared (NIR) is an NDE technology that is uses the reflected spectra of emitted electromagnetic radiation (in the near infrared range) of an object, in this case wood, to determine the chemical and physical properties of the material (Naes *et al*. 2002) (Fig. 2.10).

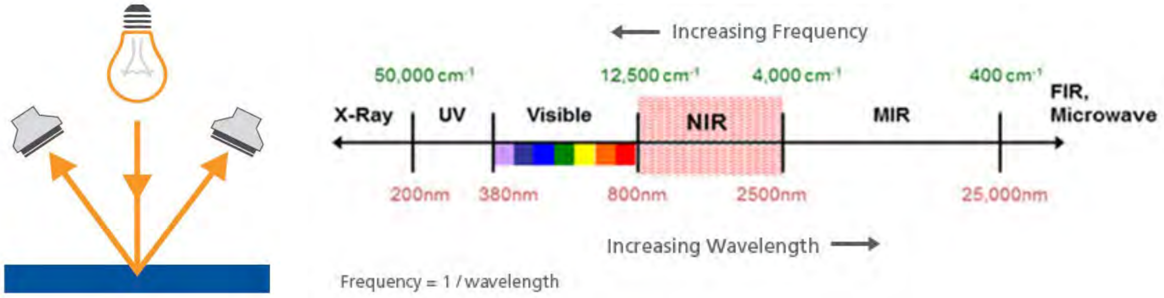


Figure 2.10. An infrared spectrum obtained by reflectance from wooded sample (left) and the electromagnetic spectrum (right). (www.fossanalytics.com)

This technique relies on the development of the multivariate model (calibration) using a set of samples of known properties and the NIR spectra collected from the same samples. The developed calibration is used to predict properties for a set of uncharacterised samples (Schimleck *et al*. 2019). Usually SilviScan is used to characterise the properties of interest (Wentzel-Vietheer 2012). The cost involved in the initial calibration is high, due to the use of the SilviScan, but subsequent NIR measurements can then be made at a fraction of the cost of SilviScan measurements (Downes *et al*. 2009; Schimleck 2008). This method has yielded strong and reliable relationships for chemical wood attributes such as cellulose content, but NIR calibrations for wood density, MFA and MOE_d have shown lower explanatory power, probably as these measures are not as strongly related to wood chemistry and the associated reflectance of NIR radiation (Wentzel-Vietheer 2012).

Standing tree measurements can potentially be achieved using spectra collected on-site with a portable NIR spectrometer or in the lab based on spectra obtained from a milled increment core (Fig. 2.11).
While collecting NIR information on site would be ideal, seasonal variation in pulp yield at the cambial surface (the surface from which a spectrum is collected with a portable spectrometer) has proved too variable to produce consistent calibration performance (Meder *et al*. 2011). Thus, lab-based NIR measurements have provided more consistent results.

Figure 2.11. Portable NIR spectrometer (left) and lab-based NIR (right) (www.forestquality.com).

It has been demonstrated that spectra from milled DBH cores can provide useful information for determining whole-tree properties and this approach has been adopted by several forest industry companies to assess wood attributes in their forest plantations (e.g. Fig. 2.12).

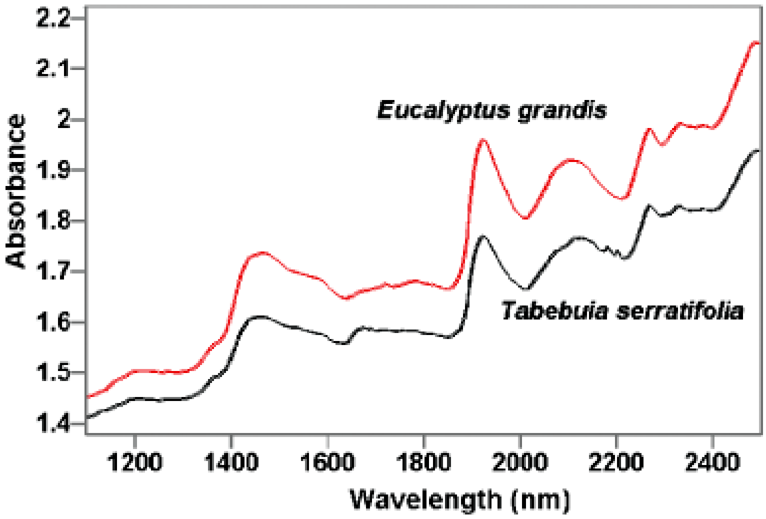


Figure 2.12. Differences of NIR spectra between species (Davrieux *et al*. 2010).
The major limitation of the lab-based NIR technique is the need to collect samples from individual trees in the field and the development of calibrations for each of the wood properties of interest (Table 2.3).

DiscBot

The DiscBot is a robotic machine designed to measure several wood properties in tree discs or strips. DiscBot has been developed by Scion (the New Zealand Forest Research Institute Limited) over the last ten years (Fig. 2.13).

Figure 2.13. Scion's DiscBot.

DiscBot combines multiple NDE techniques (NIR hyperspectral imaging, radial sample acoustics, densitometry, and grain angle scanning) into a single platform to obtain data on the variation in selected physical, mechanical, and chemical properties within a tree.

The DiscBot has five sensors that capture information on the properties of disc samples that are 20–30 mm thick and have been conditioned to achieve an equilibrium moisture content of approximately 12%. Discs are mounted in a frame that moves them past the five sensors and precisely records their position. Combining discs from different heights in the same tree allows DiscBot to be able to characterise the "true" extent of variation of these wood properties within the tree at approximately the cubic centimetre scale.

This instrument estimates the variation in wood properties within a disc collecting information on chemical composition (primarily cellulose, lignin, and hemicellulose content), wood density and MFA (Fig. 2.14). The chemical composition is estimated by NIR, while wood density is calculated from measurements made with an X-ray at approximately 0.5 mm resolution. MFA is predicted from ultrasonic time of flight measurements made with a pair of transducers that roll over the sample. In contrast, MOE is estimated from information on wood density and MFA (Schimleck *et al*. 2019), in a similar manner to SilviScan estimates but with lower resolution. While DiscBot has been tested in *Pinus radiata* with successful results, we were unable to find references about the use of DiscBot in *Eucalyptus* species. In addition to its unknown performance with eucalypt species, the DiscBot is limited by the high cost per sample (Table 2.3) which is a common limitation across the various lab-based techniques.

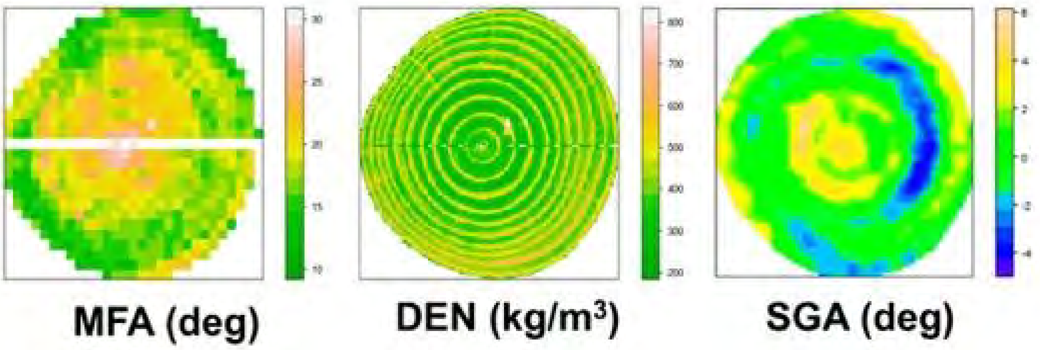


Figure 2.14. Wood property maps produced by the DiscBot for microfibril angle (MFA), wood density (DEN), and grain angle (SGA).

Factors affecting wood properties

The growth of cambial cells (the major component of wood) and their subsequent properties are dependent on the tree's immediate environment, its genetic makeup and its previous history. Understanding the drivers wood properties at the individual tree or even site level is complex as wood property is affected by a broad range of factors. These factors include: climate (Downes and Drew 2008); environmental factors such as soil fertility (Stackpole *et al*. 2010); silviculture (Rocha *et al*. 2019); genetics (Blackburn *et al*. 2012; Hamilton and Potts 2008); and forest characteristics, such as tree age (Greaves *et al*. 1997; Zobel and Buijtenen 1989).

The following section examines the information available on the effects that a range of important site factors have on eucalypt wood properties.

Age

Tree or stand age is recognised as one of, and often the most important, factor influencing wood properties due to its direct effect on the percentage of juvenile or core wood (Zobel and Buijtenen 1989). The wood closest to the pith is known as juvenile wood or core wood on account of the young age of the tree when this layer was formed. Juvenile wood generally has lower wood density and MOE and higher MFA than mature wood or outer wood close to the cambium (Lachenbruch *et al*. 2011). Older trees, which have a higher proportion of mature wood, therefore have higher overall values for wood density and MOE and lower overall values for MFA. According to Kojima *et al*. (2009) wood maturation in *E. globulus* is controlled by cambium age, so the formation of mature wood starts once a certain cambium age is attained. In the case of *E. nitens* plantations in Tasmania, this process starts between 6 and 9 years, depending on the growing conditions (Vega 2016) (Fig. 2.15). Due to the importance of age there is likely to be a large difference in wood properties between trees harvested at different ages. This will be of importance when modelling wood properties across forests grown for different final products and therefore managed under different rotation lengths.

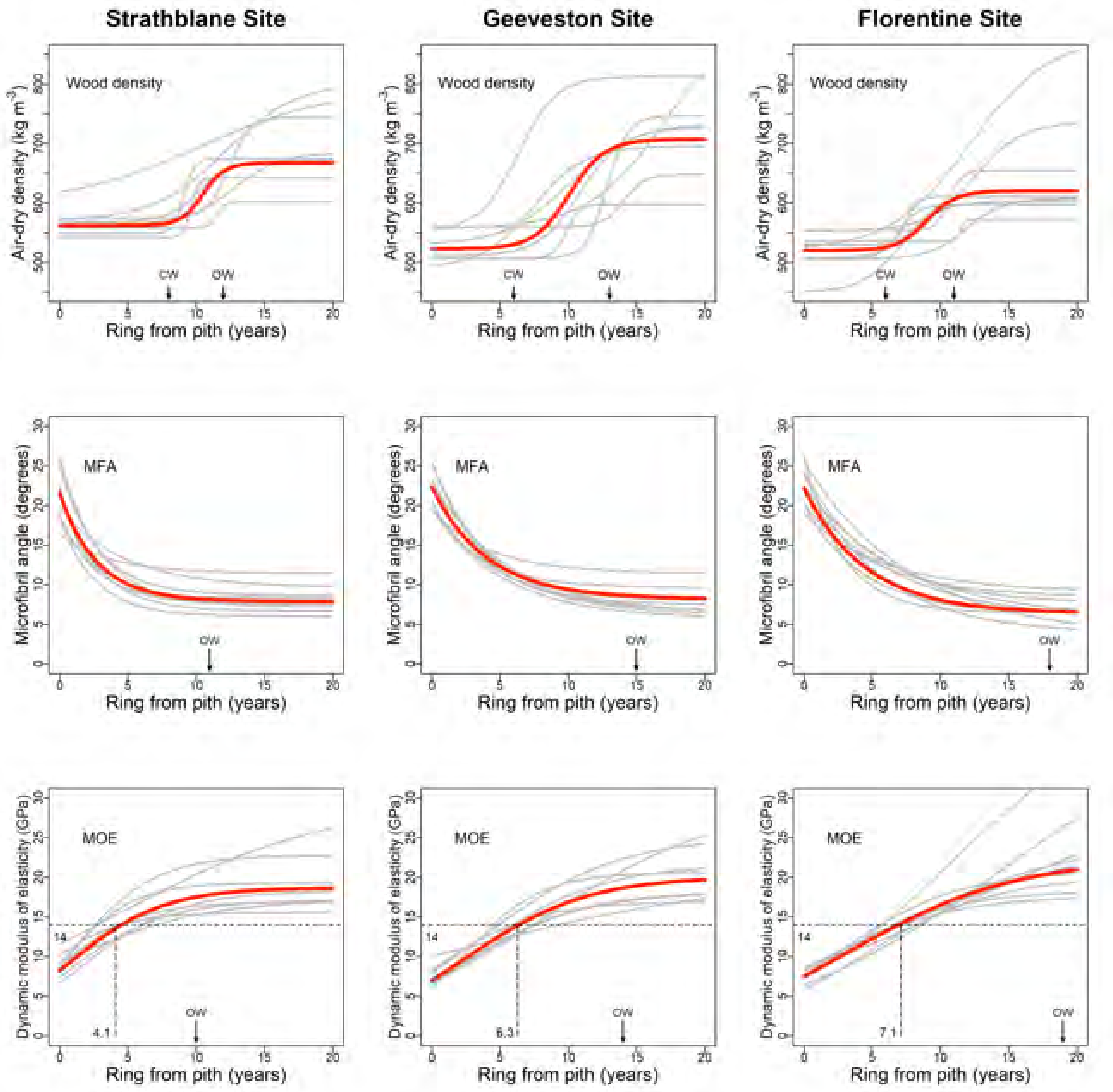


Figure 2.15. Trends of air-dry density (wood density), microfibril angle (MFA) and dynamic modulus of elasticity (MOE) as a function of cambial age (tree with grey line and site with red line). Arrows indicate the boundary of juvenile/corewood (CW) and mature/outerwood (OW). Figure from Vega (2020).

Climate and environment

Although age is predicted to have the most significant impact on wood properties, climatic and environmental factors also significantly influence wood properties. Variation with climate has been observed at multiple measurement scales - from the cellular patterns of seasonal growth to variation between tree due to microsite, to site and regional differences (Downes *et al*. 2006; Drew *et al*. 2009; Filipescu *et al*. 2014; Lessard *et al*. 2014).

Water availability has a substantial effect on wood properties at different scales (Zobel and Buijtenen 1989). At regional scales, water availability for trees is dependent on several other climatic and environmental processes including annual mean temperature, geology, soil type, intensity and frequency of water inputs, runoff and evaporation. Models at a site scale have generally indicated that precipitation variables have been the most predictive for changes in wood properties. From three *E. globulus* study sites, Downes *et al*. (2014) found the highest mean wood density (648 kg m^{-3}) at the site with lowest annual rainfall, lowest climate wetness index and soil water-storage capacity, and lowest density at the site with the highest rainfall.

The mechanism by which variation of water availability influences wood properties is complex and depends on many factors such as species, genetic origin and soil type (Meinzer 2003). However, in the case of wood density, drought directly and indirectly affects the anatomical characteristics of the xylem in hardwoods (Arend and Fromm 2007; Rathgeber *et al*. 2006). In hardwoods in general, reduced water availability appears to result in the production of vessels with smaller lumens and thicker walls (Meinzer 2003; Nabais *et al*. 2018). While such plasticity may reduce water transport efficiency, it is believed to be adaptive as it increases the resistance of the water transport system to cavitation (Meinzer 2003). In the case of eucalypts, Searson *et al*. (2004) reported that the increase in wood density of water limited treatments compared with well-watered controls, was due to the production of more, but smaller, diameter vessels and, in some cases, the embedding of more extractive compounds in the vessel wall. Similar changes to the sapwood vessel size and density with increasing water deficit were reported in *E. globulus*, which increased xylem wall strength, all of which appeared to be a plastic re-adjustment of the stem hydraulic architecture which results in increasing wood density (Mitchell and Worledge 2015).

At a regional scale, elevation is one of the most commonly used environmental variables explaining variation of wood properties (Fischer *et al*. 2016; Lessard *et al*. 2014; Palmer *et al*. 2013). However, this variable reflects the interaction of climatic and topographic gradients across the study area with precipitation tending to increase and temperature decrease with increasing elevation. Geographically, in Tasmania, precipitation tends to increase from north to south and east to west, with temperature having the opposite trend (Jackson 2005). Models developed for Tasmanian *E. nitens* plantations (Vega 2016) showed that lower wood density was predicted to occur in higher elevation areas, principally in the north of the island and on the edges of the Central Plateau. The mountain ranges close to Devonport in the north-west and around Scottsdale east of Launceston have the largest areas likely to produce wood of lower density. Conversely, the northern Midlands were predicted to yield higher density *E. nitens* wood.

The predicted distribution of MFA and MOE_d values follow trends in annual precipitation, but their values were in the opposite direction. In other words, where annual precipitation increased, predicted MFA values increased and MOE_d values decreased (Fig. 2.16).

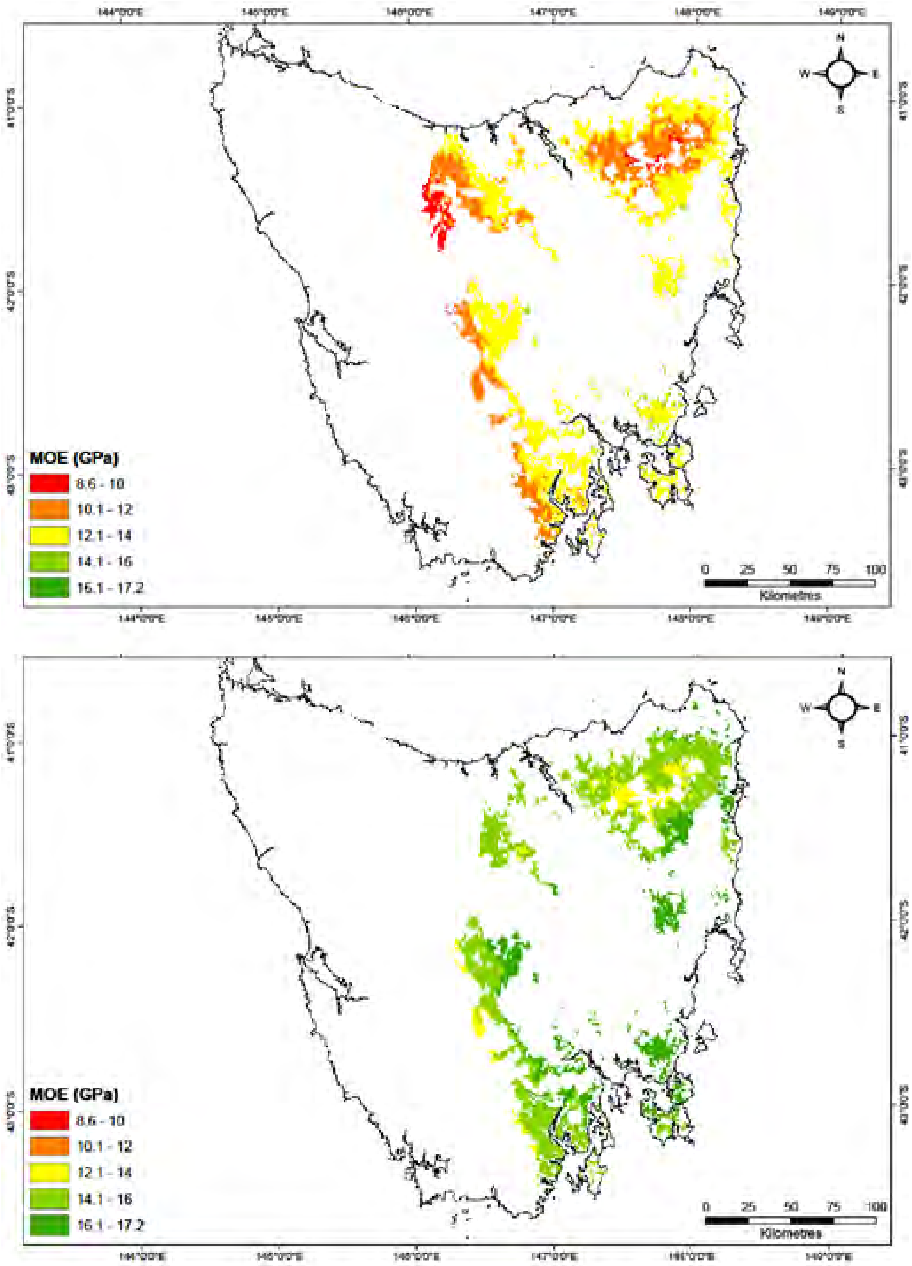


Figure 2.16. The predicted spatial distribution of site dynamic modulus of elasticity (MOE_d) for 10 year (top) and 20 year (bottom) old *E. nitens* plantations growing in Tasmania. MOE_d was assessed at 1.3 m above ground level (Vega 2016).

Genetic

The genetic makeup of trees and their environment influences both rate of growth and the physicochemical nature of tree growth (Savidge 1996). Variations in wood properties also occurs due to within species genetic variability and the interaction between genotype and environment (GxE). This means that that the performance ranking of given genotypes differ when grown in different environments (Raymond *et al*. 2001) for example see Table 2.1. As. While there are some studies of the GxE on wood properties of *Eucalyptus* species (Nickolas *et al*. 2019) at the level of sites, at the regional scale there is little understanding of how the environment affects wood properties, how the GxE interaction varies or the importance of environmental effects relative to genetic effects.

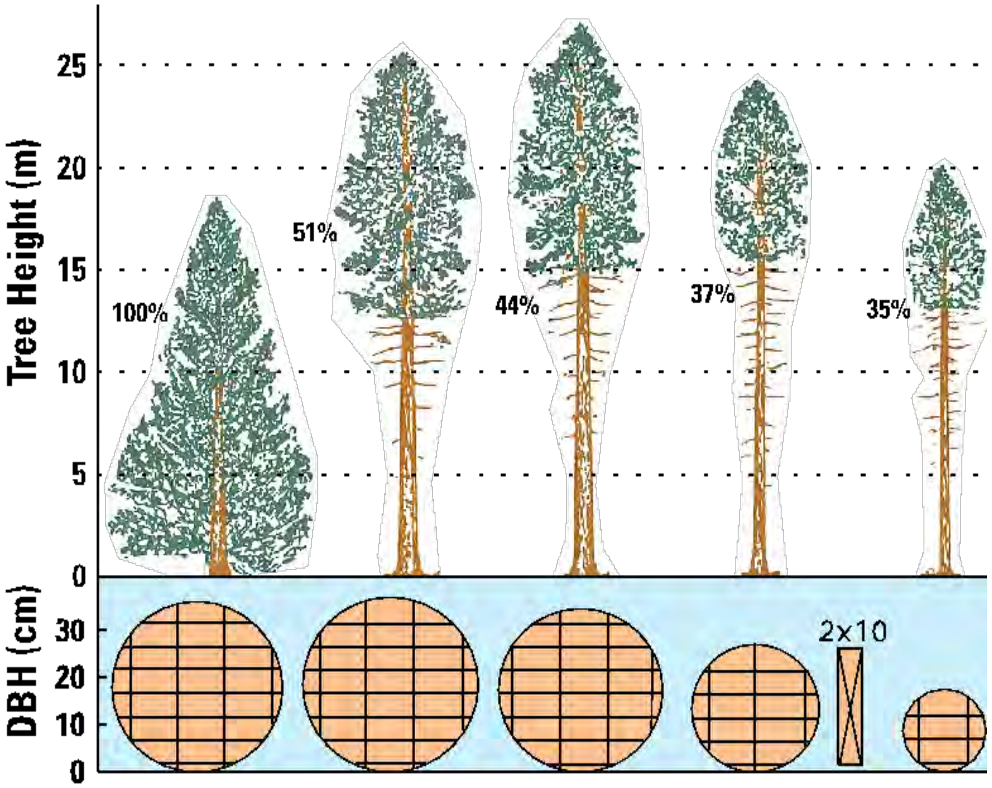
Table 2.1. Example of GxE interaction, indicating sub-race means, standard deviations (SD) and ranking for basic density (kg m^{-3}) and predicted pulp yield (PPY in %) in three Australian sites (Massy Greene, Mt Worth and Flynn) of *Eucalyptus globulus* (Raymond *et al*. 2001).

Trait	Sub-race	Massy Greene Mean (SD)	Rank	Mt Worth Mean (SD)	Rank	Flynn Mean (SD)	Rank
Density	West Otways	469 (33)	6	465 (31)	3	554(31)	3
	Strzelecki	504 (37)	1	474 (30)	1	571 (37)	1
	Madalya Rd	487 (34)	2	463 (33)	4	559 (34)	2
	Furneaux	481 (36)	4	468 (33)	2	533 (32)	5
	NE Tasmania	485 (41)	3	455 (32)	5	538 (28)	4
	SE Tasmania	471 (44)	5	442 (27)	6	504 (32)	6
	King Island	428 (35)	7	423 (34)	7	489 (33)	7
PPY	West Otways	52.0 (1.2)	2	52.3 (1.2)	4	52.1(1.4)	2
	Strzelecki	51.8 (1.0)	5	53.1 (1.3)	2	51.1 (1.3)	7
	Madalya Rd	51.9 (1.1)	3	53.4 (1.3)	1	51.1 (l.4)	6
	Furneaux	51.8 (1.2)	6	52.5 (1.4)	3	51.6 (1.3)	5
	NE Tasmania	51.8 (1.2)	7	51.2 (0.9)	7	51.7 (1.1)	4
	SE Tasmania	52.1 (1.2)	1	52.1 (1.3)	6	52.3 (1.3)	1
	King Island	51.8 (1.2)	4	52.2 (1.2)	5	52.0(1.4)	3

Silviculture

In addition to the influence of genetic and environmental factors, wood properties are also influenced by silvicultural management, e.g., irrigation, thinning, plant spacing, pruning and fertiliser application. All these factors affect tree growth (Zobel 1992), which then have flow-on impacts on wood properties.

Eucalypt tree diameter growth is influenced by tree spacing as the greater the spacing the less the competition among plants and, consequently, the greater the diameter acquired by trees (Forrester *et al*. 2013). Wider spacings, either due to initial spacing or thinning are characteristic of longer rotations and regimes used to produce sawlogs, while closer spacings are often used to produce biomass or pulp-logs on shorter rotations (Forrester *et al*. 2010). Plant spacing and growth rate play an important role in determining wood properties, but these effects are species-specific (Schimleck *et al*. 2018). For example, Hart (2010) showed that with increasing plant spacing, adverse effects on wood intended for structural purposes occur (lower wood density and MOE). Additionally, increased spacing can potentially decrease fibre length and increase knot size and frequency. Silvicultural practices that control stand density, either through initial spacing or thinning or a combination of both, strongly influence both tree growth and wood formation (Fig. 2.17).



DBH (cm)	37.0	37.6	35.7	27.5	17.8
Age (yrs)	71.0	91.0	85.0	121.0	96.0
Stems/ha	1	600	900	1300	1800
Density BH	0.36	0.37	0.38	0.41	0.43
Stem Density	0.37	0.37	0.38	0.39	0.40
Stem Volume	0.81	1.00	0.92	0.47	0.18

Figure 2.17. Example of the effect of the spacing on wood density and production of solid wood boards in Lodgepole Pine (adapted from Jozsa and Middleton 1994). Percentages listed are the area of livecrown.

In conifers the effect of competition on growth rate and the subsequent effect on wood properties is well documented (Krajnc *et al*. 2019; Rocha *et al*. 2019; Russo *et al*. 2019). For Tasmanian eucalypts, Medhurst *et al*. (2012) reported that reduced competition and increased diameter growth rate had no clear effect on wood properties (Fig. 2.18). On the other hand, growth rate in an irrigated treatment of *E. globulus* and *E. nitens* favoured the production of a higher proportion of earlywood, which resulted in wood with lower basic density compared to non-irrigated trees (Downes *et al*. 2006). Rocha *et al*. (2019) reported that larger plant spacing tends to produce eucalypts with denser woods. Due to the limited number of studies and the contrasting results a more comprehensive examination into the effects of silvicultural management on wood properties is required.

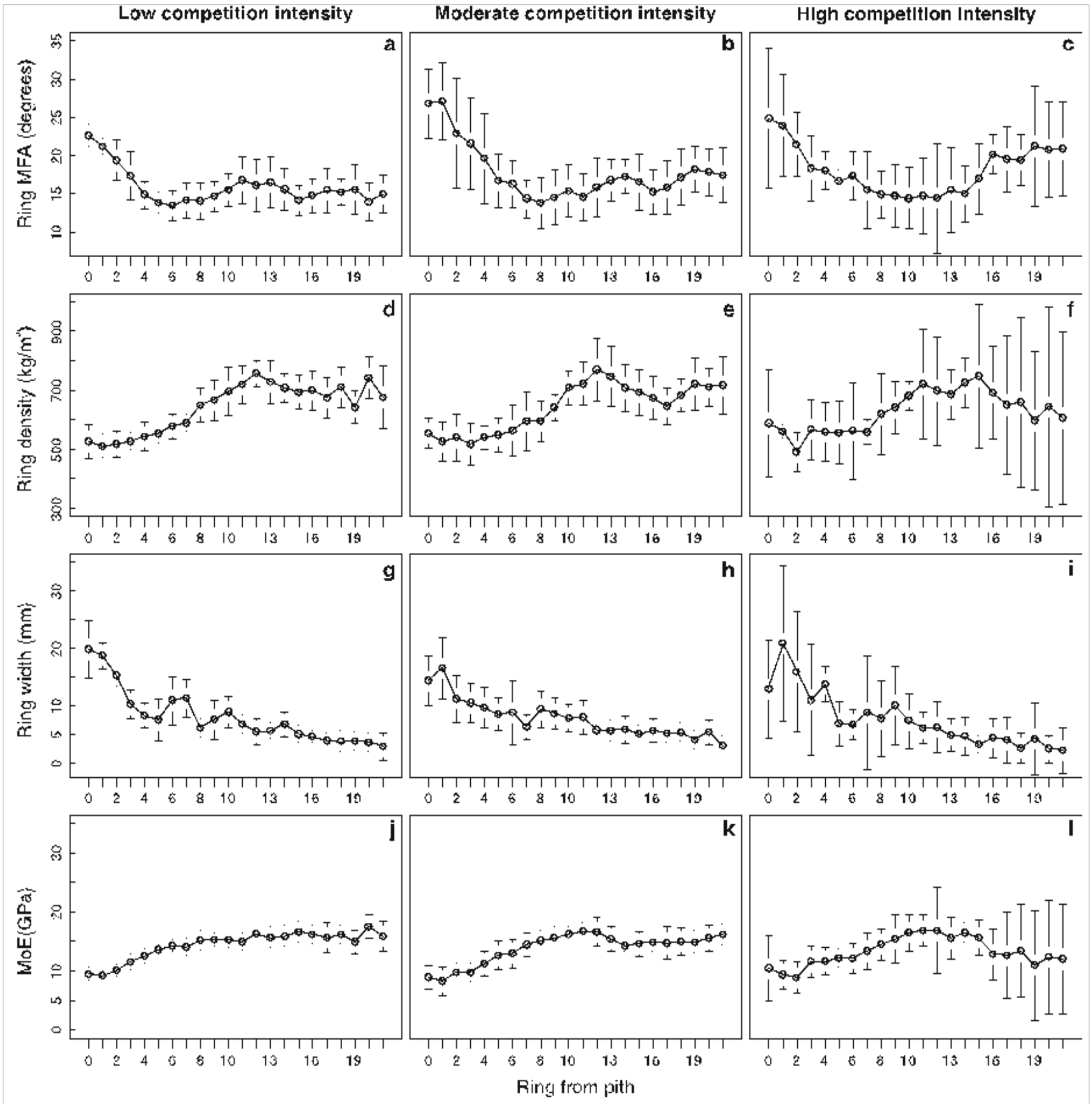


Figure 2.18. Patterns of (a–c) mean ring MFA, (d–f) mean ring density at 8% moisture content, (g–i) mean ring width, and (j–l) mean ring MoE by competition intensity class, Goulds Country thinning trial (Tasmania) (Medhurst *et al*. 2012).

Another important silviculture practice is pruning, which aims to maximise the amount of clear wood (i.e. wood without knots or with straight grain) produced by a tree (Montagu *et al*. 2003). Pruning is performed on branches on the lower portion of the stem, with the goal of manipulating wood development. If branches are properly pruned whilst green, there is a high probability that new wood will grow over the pruned branch stubs and that from then on knot-free clear wood will be produced on the stem. While there is strong evidence of the effect of pruning on the production of clear wood, pruning's effect on wood properties such as wood density, microfibril angle and tracheid length in eucalypts is unclear.

Dominance class effect on wood properties

The position of the tree in the stand, i.e., whether the tree is dominant, co-dominant, intermediate, or suppressed also affects wood properties. Several studies have reported that dominance class effects wood properties in plantations, especially in softwoods. Zhang (1995) and Todaro and Macchioni (2010) observed in softwoods that bigger trees with higher growth rates within a stand generally produced wood of lower stiffness. Proto *et al*. (2017)

applied different thinning treatments and found that there was a strong relationship between dynamic tree MOE and DBH, with the largest diameter trees or dominant trees having lower MOE_d values across all thinning treatments in Calabrian pine (*Pinus brutia Tenore*) plantations in southern Italy. Xiang *et al*. (2014) studied climate influence on wood density among dominance classes in black spruce (*Picea mariana*). They found that wood density differed among dominance classes with density lowest in dominant trees, then increasing in co-dominant and highest in intermediate trees. Dominant trees have a higher proportion of low-density earlywood compared to trees from the other dominant classes, which results in trees of lower stiffness and density.

It is also important to consider the interaction between dominance and age. Deng *et al*. (2014) examined variations of wood density with tree age and social classes in the axial direction within *Pinus massoniana* in Southern China. They reported that suppressed trees had higher whole stem wood density than dominant and intermediate trees, however the youngest trees had lower wood density in suppressed than in dominant and intermediate trees. Chen *et al*. (2017) studied tree growth traits and dominance effects on wood density of pioneer species in a secondary subtropical forest. They found that dominant trees of the pioneer species had a higher wood density than the suppressed trees, but this effect did not occur in the shade-tolerant species (Fig. 2.19). Dominance class effects on wood properties have been examined mostly for softwood species, and information about the effect on hardwoods currently is lacking.

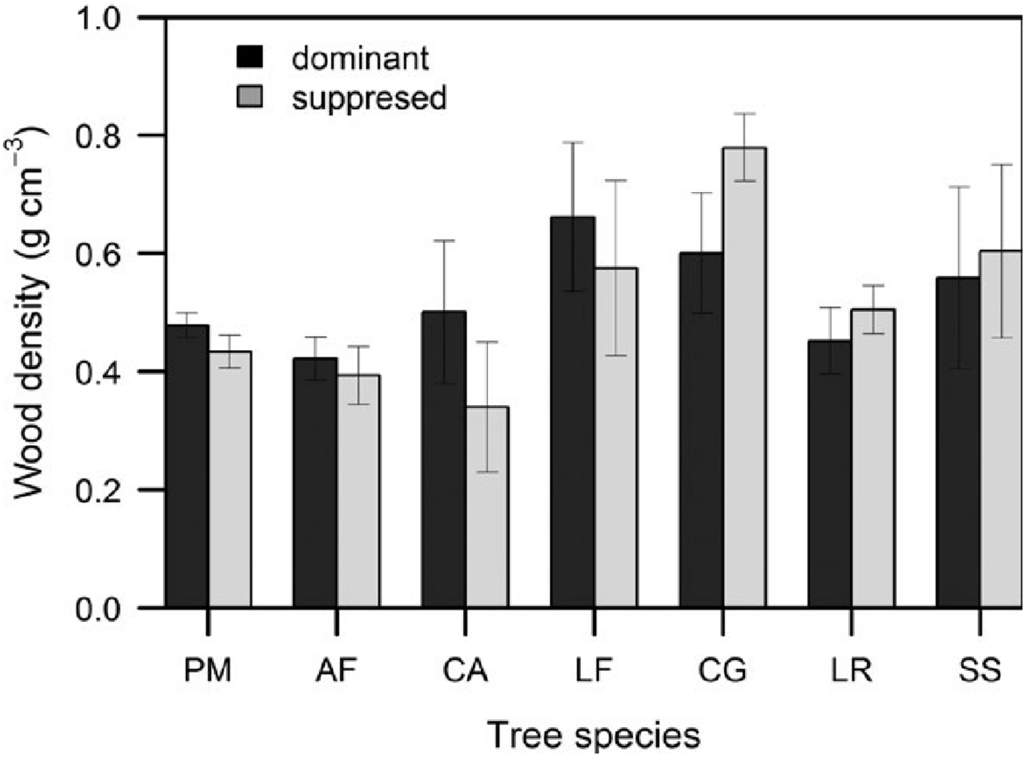


Figure 2.19. Comparison of mean (±SE) stem wood density between dominant and suppressed individuals within the seven tree species. Species abbreviations for each life-history group: pioneers: PM (*Pinus massoniana*), AF (*Alniphyllum fortunei*), CA (*Choerospondias axillaris*), and LF (*Liquidambar formosana*); shade tolerants: CG (*Cyclobalanopsis glauca*), LR (*Litsea rotundifolia*), and SS (*Schima superba*). Figure from Chen *et al*. (2017).

Table 2.2. Applicability of different field-based non-destructive evaluation (NDE) tools to operational and/or research scenarios (adapted from Schimleck *et al*. 2018).

Field tools	Scenario 1: Large-scale assessment of plantation resource	Scenario 2: Examination of wood property variation within trees	Scenario 3: Assessment of silvicultural treatments on wood properties	Scenario 4: Correlation of tree/log stiffness with product properties	Scenario 5: Utilisation in breeding programs/tree improvement	Scenario 6: Utilisation in breeding programs to detect genetic markers
Acoustics: (TOF) (Velocity)	Allows assessment of regional variation in velocity if large number of trees across the landscape are sampled at the same stand age.	N/A	Stand-level comparisons of silvicultural treatments.	N/A	Provide ranking by velocity within stands. Heritability estimates for velocity.	N/A
Acoustics (Log) (Velocity)	Post-harvest, more consistent velocity assessment compared to TOF.	N/A	Stand-level comparisons of silvicultural treatments.	Moderate relationships between log velocity and lumber and veneer stiffness.	Heritability estimates for velocity.	N/A
Resistograph (Density)	Increasingly used to assess regional density variation. Only field tool giving radial variation data.	Potential to be used for examining within-tree variation.	Potential to be used for stand-level comparisons.	Potential to be used for correlation with product properties.	Increasingly used in breeding programs as a surrogate for density, ranking.	N/A

Table 2.3. Applicability of different laboratory-based non-destructive evaluation (NDE) tools to operational and/or research scenarios (adapted from Schimleck *et al*. (2018))

Lab tools	Scenario 1: Large-scale assessment of plantation resource	Scenario 2: Examination of wood property variation within trees	Scenario 3: Assessment of silvicultural treatments on wood properties	Scenario 4: Correlation of tree/log stiffness with product properties	Scenario 5: Utilization in breeding programs/tree improvement	Scenario 6: Utilization in breeding programs for detection of genetic markers
SilviScan (SS)	High resolution and multiple properties. High cost vs. field options may limit application.	Data can examine within-tree variation at high resolution. Detailed tree maps.	Resolution/accuracy sufficient to detect treatment differences (within-ring) for all properties.	N/A	Estimation of genetic parameters, often at ring-level.	Data used to detect markers for properties measured.
NIR Spectroscopy	Only tool to assess PY variation. High cost (NIR calibration required) vs. field options.	Lower resolution than SS. Can provide data for 2D or 3D mapping wood property variation within trees.	Resolution/accuracy sufficient for juvenile wood ring-level responses, groups of rings in mature wood (successful use not reported).	N/A	Assessment of PY and extractives, genetic parameters for many wood properties provided calibration exists.	Data used to detect markers for properties (NIR calibration required).
DiscBot	Reduced resolution vs. SS but higher throughput. High cost but greater resolution vs. field options.	Lower resolution than SS. Can provide data for 3D mapping of wood property variation within trees.	Resolution/accuracy sufficient for juvenile wood ring-level responses, groups of rings in mature wood (use not reported).	N/A	Use not reported but could provide data for all properties measured.	Use not reported but could provide data for all properties measured.

Section Summary

Information regarding the variation of wood properties across geographic locations for production hardwood species is fundamental to optimisation of wood use and to improve competitiveness in the forest industry. Wood properties provide indicators of wood quality that are linked to product potential and performance (i.e., KPY, wood density and stiffness of lumber). World-leading forestry countries, such as those in North America and Scandinavian, have understood the importance of regional-scale information and have been developing extensive characterisations of their forest resource over the past decade. While this information is available for small areas of Tasmania, it is limited to specific species and it is not available across the whole estate.

There are several key wood properties that can be assessed which provide information on the quality of wood for various final products ranging from pulp to structural timber. While it would be ideal to characterise the hardwood estate for all the potential metrics identified, consideration must be given to the feasibility of collecting such data. Techniques such as SilviScan which give microfibril angle, may provide key information for the quality of wood for structural purposes but are expensive, due to the need for both field and lab-based recordings. For the development of statewide modelling where many assessment sites would be required, simpler field-based techniques such as acoustic or resistograph assessments may be more economically feasible (see Section 5 and 6).

In Tasmania, only one forest characterisation has been published, focused on *Eucalyptus nitens* pulpwood plantations (Vega 2016). Sites sampled for this study were mainly in the northeast and southern parts of the forest estate and therefore the findings from that work cannot be directly applied to environmental and climatic conditions outside these areas. Additionally, there is no publicly accessible information on the variation of wood properties across Tasmania for any species in native forests and plantation grown *Eucalyptus globulus*. In addition, forest management companies either do not collect wood property metrics or if they do, they are not at a scale that can be utilised for modelling variation across the Tasmanian estate. Therefore, in order to characterise wood properties across the whole estate wide ranging data collection is required. While a current project in the Australian Research Council Training Centre for Forest Value is addressing some of these shortcomings, more data will be required. Due to complex variation in wood properties with species, genetics, silviculture and age, future proposed projects may have to focus on a specific area of the hardwood estate e.g. a single species at a given age. Forest characterisation at the state level should be prioritised based on the economic impact of the species and the feasibility of the characterisation, particularly with respect to field assessment of relevant wood properties.

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Section 3: Estimating wood volume in Tasmania’s hardwood estate

In order to characterise the hardwood resource and estimate volumes of differing grades of timber across the hardwood estate in Tasmania, the ability to predict production volumes across environmental and climatic gradients is required. In this section we examine the data available as well as the current and potential methods for predicting wood volumes in Tasmania. It is important to note that as with predicting wood properties (see Section 2), wood volume estimates must consider predicted age of harvest, silvicultural management and species. Therefore, many of the methods discussed here may have to be applied individually for species and silvicultural methods.

Creating a statewide model that can predict wood volume could provide key information to the forest industry. Developed models could show potential productivity of new areas for expansion of the timber estate, as well as identify areas for development of new infrastructure. Additionally, spatial volume models that consider environmental conditions could also be used to provide predictions on the impact of short-term climate variability on current growing stocks (Almeida *et al*. 2010, Scolforo *et al*. 2016) and long-term climate change on forecast wood models (González-Rodríguez and Diéguez-Aranda 2020).

This section examines the potential to model potential wood volume of the estate independent of forest age. Models which provide reliable estimates of volume available at specific times would require information of the age structure of the estate and intended harvesting dates. While this would be possible to calculate for a single time period it would quickly become out of date and such an estate-wide model would have to be frequently updated and involve combining potentially commercially sensitive age structure information from individual companies. We therefore recommended the creation of estate models mapping potential productivity.

Impact of climate on wood volume

A number of environmental drivers have been shown to impact the productivity of eucalypts (Battaglia *et al*. 1998, Coops *et al*. 1998, Battaglia *et al*. 1999, Downes *et al*. 1999, Whitehead and Beadle 2004, Scolforo *et al*. 2016, Esther de Lima Costa *et al*. 2020), including:

- temperature
- frosts
- rainfall
- water stress
- water logging
- site nutrition.

The ability to predict stand productivity based on environmental conditions is complex as many predictive environmental variables are spatially correlated, interact in synergistic or antagonistic ways and predictions can be highly influenced by the species grown and silvicultural management (Battaglia *et al*. 1999). While a statewide model of predicted productivity based on climate is currently unavailable for Tasmanian hardwoods, there appears to be enough available data and models that such a map could be produced. Many of the site-based models used to predict timber volumes that are currently available are based on studies of Australian and Tasmanian hardwood species and have been tested in Tasmanian conditions.

To explore the impact of climate, environment and management on the productivity of Tasmanian hardwood species a number of models have been developed at a local level, including the 3-PG (Sands and Landsberg 2002) and the 3-PG-Spatial model e.g. Tickle *et al.* (2001), Battaglia and Sands (1997) and Battaglia *et al.* (1999). These models use climate data to make local scale (site level) predictions of forest growth in native eucalypt forests. Growth models are widely used both within Australia and globally and are continuously being improved to include both environmental and management factors such as fertilisation, irrigation and genotypes e.g. Smethurst et al. (2020).

These and other biometric models have been used to create forest estate modelling tools such as those used by forest management companies for site to estate level planning e.g. McLarin *et al*. (2006) and tools for individual forest owners to predict volumes/productivity e.g. the farm forestry tool box (Goodwin 2020). Biometric models not only help managers predict productivity of current stands but also help investors select areas for acquisition or the extension of planting areas (Caldeira et al. 2020). Depending on the complexity these tools use growth models combined with information on species, age stocking, site quality and management regimes to predict volumes into the future (Roberts *et al*. 2015).

Current estimates of volume at the estate level

Estimates of current wood volume produced are well developed for the Tasmanian hardwood forest estate as a statewide unit. Forecast timber volume production data is publicly available in the five-yearly plantation statistics report of the Australian Bureau of Agricultural and Resource Economics and Sciences (ABARES) that produces *'Australia's plantation log supply'* (ABARES 2016a) which is a comprehensive plantation log availability forecast report that ranges from 2015 -2059. Predicted volumes, in cubic metres, are produced for hardwood and softwood plantations and additionally are divided into forecast volumes for pulp-log and sawlog. However, as mentioned above, predicted volumes are reported for Tasmania as a single unit, and therefore there is no capacity to understand the geographic variation within Tasmania. The 'Australia's plantation log supply' report is produced every 5 years providing a source of regularly updated information, compared to one-off commissioned reports which become quickly outdated.

In addition to the volumes produced by the Tasmanian plantation estate, the volume extracted from the native forest estate can also be estimated at the state level. The maximum volumes of quality eucalypt saw, and veneer logs produced by the Tasmanian public native and plantation hardwood estate are legislated at a given value by the Tasmanian Forest Management Act 2013. While the legislated volume includes both plantation and native forest, Sustainable Timber Tasmania (STT) has predicted the yield produced by the native forest estate for up to 80 years into the future (STT 2017). It is more difficult to predict volumes produced from the private native forest estate as the decision to undertake harvesting operations is at the discretion of the landowner. Past values of both sawlog and pulplog are available via the State of the Forests report (ABARES 2018), which shows that average annual sawlog production from the private native estate was 26,000 m^3 for the reporting period between 2011/12 to 2015/16 and average annual pulp production was 82,000 m^3 for the same period, although this amount was much greater in the previous reporting periods (i.e. annual production of 1,468,000 m^3 from 1992-2011). While production from private forests is small compared to that produced from public forests, the volume is still significant. Native hardwood production is reported at a statewide level and therefore, there is limited public information about the spatial variation in timber volume produced within Tasmania, and how this may vary with environment.

Estimating volume at the site level

In order to characterise the hardwood estate by productivity within Tasmania, estimated timber volumes need to be assessed at the site level. Here we detail the currently available information and potential new techniques that could be used to map volume at fine spatial scales.

Currently, site level assessments are primarily undertaken by forest management companies using inventory plot data fed into predictive models, as well as an on-the-ground measure of site index (tree height at a given age). Predictive models use biometric growth models combined with site conditions and silvicultural management to enable site level volume estimates to be produced, these site level predictions also have the capacity to be combined into estate level predictions (McLarin et al. 2006, Goodwin 2020). The limitation on these tools is that they rely on species and silvicultural specific models which may not be available to all users. For example, the Farm Forestry Tool Box (Goodwin 2020) is often utilised by individual private forest growers to predict volumes for plantation species but not for native forest sites.

In addition to the more complex models predicting volumes, site productivity can be assessed using site index. In many cases, particularly for plantations, site index is recorded on the ground at each coupe. However recent advances have seen site index detected using remote sensing methods e.g. LiDAR, although this is only applicable where the age of the site is known.

The combination of site index or plot inventory data with site based environmental characteristics would allow for the development of a statewide ‘productivity map’. The development of a statewide map of site index matched with key environmental conditions could provide a proxy to model the expected changes in productivity with changing climate, for example see Eckhart *et al.* (2019) or González-Rodríguez and Diéguez-Aranda (2020). These techniques could be easily applied to generate a whole of estate productivity model. However, a major complicating factor for developing such a model across the whole Tasmanian hardwood timber estate will be that the measure of site index will vary depending both on the species, silvicultural type (native or plantation), silvicultural management and variation in the ‘site index’ metric used between different land managers. Additionally, site index is difficult to measure in native forest that hasn’t been previously harvested and therefore is of unknown age which is likely the case for private forest areas not operated by major forest management companies.

Area

If combined with a spatial model of wood properties, the area of timber available may be an alternative measure to determine the amount of timber that could be produced of a given quality. Publicly available spatial maps provide detailed information on the location of production forests across the Tasmanian hardwood estate. The Australian Bureau of Agricultural and Resource Economics and Sciences (ABARES) collects spatial data on forest estates (both productive and non-productive) for a variety of reports. This data is regularly updated and provides a good source of information on area and distribution of hardwood forest estate across Tasmania. Spatial maps of the Tasmanian hardwood estate also allow the estate location to be matched to environmental data to determine the range of conditions over which the estate sits. Area data can also provide useful information when combined with other productivity measures such as site index or even measures such photo inventory (PI) type. PI type is available for a large proportion of the hardwood estate, especially for native forests, and can indicate tree height.

The use of area as a proxy for timber quantity assessments has a few major limitations that need to be considered. Firstly, site productivity will have a major impact on the quantity of timber that is produced at a given location. Secondly, area-based estimates do not provide information on when the timber will be available (although this potentially could be addressed by overlaying data of planting/regeneration age from forestry companies – if available). Thirdly, it is difficult to determine where and how much private native forest will be used for timber production as although areas may be available for timber harvest, they may not be designated for timber production, capable of producing sawlogs or be financially viable. It is therefore difficult to predict the area of timber from private estates.

Area of native forest

As mentioned above, the most comprehensive source for estimating the available native forest timber estate is *'Australia's State of the Forests Report (SOFR)'* (ABARES 2018). This report is released every five years. The SOFR reports on Tasmania as a single unit and provides information on the area of forest available for forest harvesting and log volumes previously produced.

Spatial data on the area available for native forestry is available through the SOFR report. The 2018 report contains data up until 2015-2016, at this period there was 376 000 ha of forest in the permanent timber production zone (PTPZ), with an average of 4 020 ha harvested per year (2011-2016). For the period 2011-2016, the PTPZ land produced an average yearly cut of 121 000 m^3 of high quality sawlog plus a considerable amount of peeler logs and chip logs, although this area of harvested native forest is expected to decrease in the future as high-quality saw and veneer logs are sourced from the public plantation estate. The SOFR states that less information is available surrounding the private native forest estate, therefore the information on the spatial distribution provided from this area may be less refined.

Alongside the SOFR, the Tasmanian ListMap (DPIPWE 2017) also provides spatial data about the PTPZ, with focus on the area of native forest under the management of Sustainable Timber Tasmania (STT) (Fig. 3.1).

Private native forests

One area where it is currently difficult to predict area, and therefore potential available volume, is the private native estate. Some information on the area of the private forest estate is available through from ListMap (DPIPWE 2017) where the area of listed private timber reserves is tracked (Fig. 3.1). Private timber reserves are privately owned parcels of land designated for timber production under the Forest Practices Code (PFT, 2020). However, this area consists of both plantation, native and forest that are intended for future forestry plantings and also incorporates the large plantation estates of private forestry companies. Therefore, this source of information is unlikely to accurately represent the potential area of private native forest that could be used as a source for hardwood timber. In addition, the major issue in determining the private native forest area that could be used for timber production is landholder intent. As many landholders with native forest on them have no intention of harvesting or the area they have is not economically feasible to harvest. Private Forests Tasmania conduct a five-yearly review of private forest harvesting which does provide additional insights into the available area.

One potential method to determine area may be to use information on environmental and climate conditions to determine the area of private native forest which is feasible to harvest and then estimate what percentage of landholders intend to use this area for harvesting.

Determining the area available could be achieved by overlaying land tenure information with available forest class information from ListMap such as TasVeg classifications or even enterprise suitability mapping which is currently available for both *Eucalyptus globulus* and *Eucalyptus* Nitens. Previous landholder surveys such as the "The intent of Tasmania's private forest growers to harvest their forest estate" by Dare and Eversole (2013), could be used to estimate the potential area that would be harvestable, although it is important to note that intent to harvest does not necessarily result in harvesting and does not provide the time frame at which harvesting will occur.

Having a better understanding of the potential area of private native forest that is available for harvesting and characterising it's quality is a key gap in understanding the Tasmanian hardwood resource. A better understanding of this part of the resource could provide further opportunities for industry development and increased capacity to match future increases in demand.

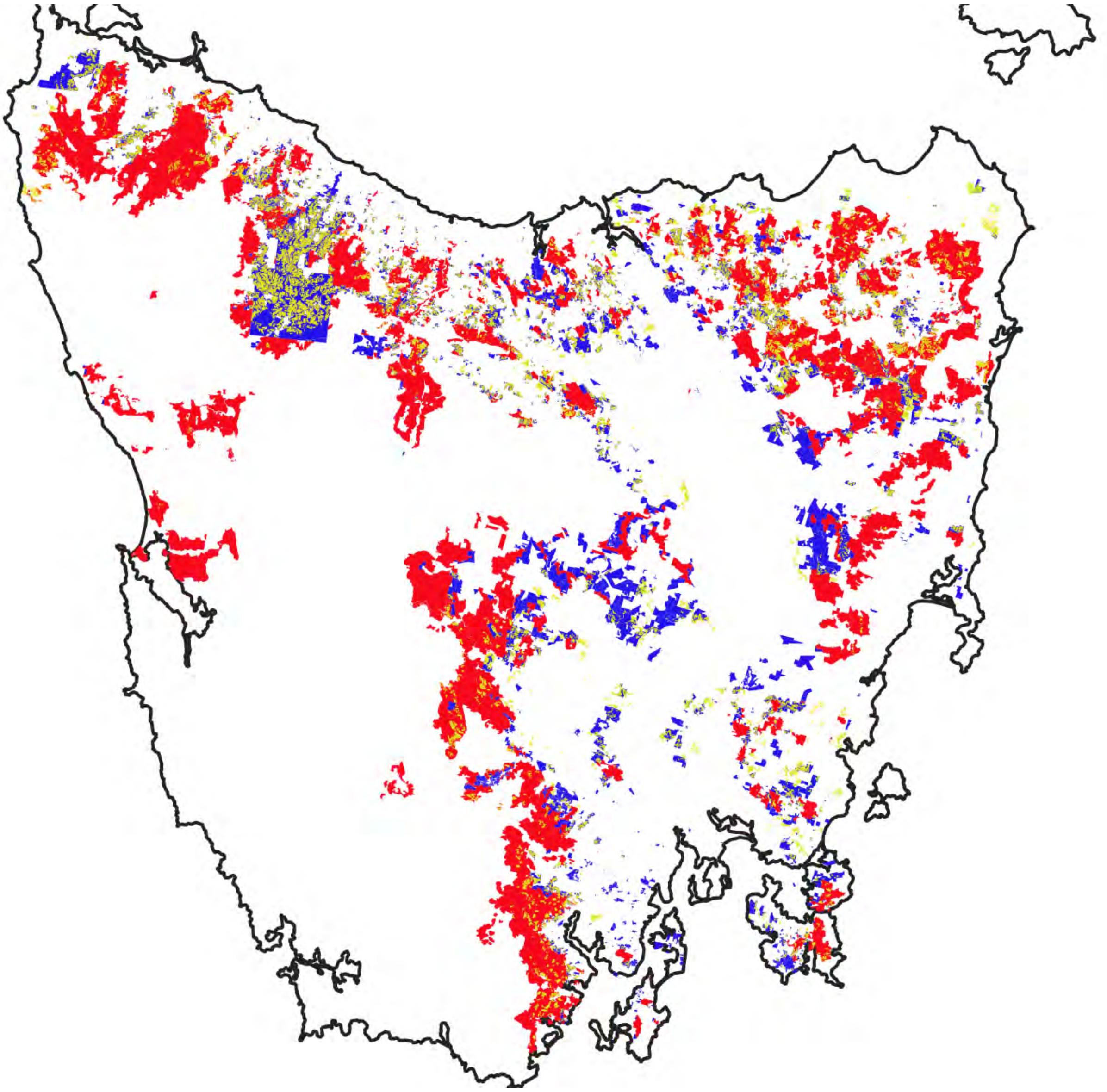

Figure 3.1: Permanent Timber Production Zone (PTPZ) land (Red), plantation hardwood (yellow) and Private Timber reserves (Blue). Both PTPZ and private timber reserves contain areas that are not intended for harvesting.

Area of Plantation Hardwoods:

In Tasmania the dominant production species is *Eucalyptus nitens* (208,200 ha) with some *Eucalyptus globulus* (19,100 ha) and a small area of unassigned hardwood species (6,600 ha) (Downham and Gavran 2019) (Fig. 3.1).

The best available estimates for the area of plantation hardwood logs available is provided by the National Plantation Inventory (NPI) and its current documents *'Australian plantation statistics 2016'* (ABARES 2016b) and *'Australian plantation statistics 2019 update'* (Downham and Gavran 2019). The key difference between these two documents is that the 2016 version is based on spatial data and is revised every five years compared to the update report which is based on tabular data and is updated yearly.

The plantation statistics 2019 update provides an overview of the current hectares of hardwood plantation, including newly established plantation. The report also details ownership of the plantations (private, public or joint ownership), the plantation species being grown, and estimates the percentage of plantation planted for sawlogs versus pulp logs. As mentioned in previous sections, because ABARES reports on Tasmania as a single unit, there is no information available about spatial variation within Tasmania.

The five-yearly produced plantation statistics provide the same basic information as given in the yearly update. The major benefit of the five yearly report is that the spatial data is provided to ABARES by the plantation owners. This data is freely accessible from the ABARES website and shows the geographical spread of hardwood plantations in Tasmania. It is important to note that this spatial data set only contains information on the wood type (hardwood, softwood or other) but not information on what species, the age of the plantation or the silvicultural management. However, understanding the location of the resource has the potential to be linked with environmental data to understand the climatic range of hardwood plantation forests in the Tasmanian estate.

Conclusions – estimating volume at the site level

- Currently difficult to predict volume/area in private native forests as intent to harvest is unknown.
- Modelling site index against climate variables could indicate climatic effects on productivity, although models may have to be produced individually for silvicultural type and species.
- Current spatial maps provide an overview of the area available.

New methods of assessing wood volume

With the recent advancement of remote sensing technologies, multiple new methods for measuring forest volume are in development and have begun to be applied in the management of forests for timber harvesting. Many of these techniques have the potential to aid in characterising the current forest resource and therefore have flow-on benefits to modelling wood volumes in Tasmania. This section examines some of the most applicable new technologies and how they could be used to monitor and predict spatial variation in forest volume within the Tasmanian hardwood estate.

New remote sensing technologies for forest inventories have been the subject of a considerable research effort globally. Recent review articles highlight the key benefits of remotely-sensed forest inventories but also their current limitations (Lu 2006, Lu *et al*. 2016, White *et al*. 2016, Beland *et al*. 2019). Many of the current studies are based outside of

Australia and therefore greater research on Australian species and landscapes is required, particularly as some of the metrics and models derived from remote sensing can vary in accuracy depending on species (Sullivan *et al*. 2017).

An important consideration is that remote sensing methods occur at different spatial scales depending on the collection method. Spatial scales range from very fine (millimetres or centimetres), using terrestrial LiDAR or photogrammetry methods, to coarse (kilometres), which utilise satellite data (Lu 2006). The scale at which data is collected can dictate its use. For example, data collected at fine spatial scales is best to inform site or coupe level decision making, whereas data collected at coarser spatial scales may be appropriate for statewide decisions. While many remote sensing methods have great potential, they still require calibration with on-the-ground measurements, which are currently considered the standardised and accurate method of collection (Lu 2006) and therefore provide a reference value to new measurement techniques. The major concerns about the applicability of remotely sensed volumes are centred around the economics of fine scale data collection, the ability to process large quantities of data (Lu 2006) and complexity of extracting the variable of interest. The variable of interest also has a significant impact on the cost of the remote sensing collection. For example, current data extraction methods for below canopy metrics such as tree diameter or basal area are predominantly manual which can involve a large amount of highly skilled work and therefore come at significant cost, while metrics such as tree height can (at a coarse level) be extracted relatively easily.

The following section outlines several remote sensing technologies currently available for characterising the Tasmanian resource and their potential to monitor variation in timber volume across the state.

Aerial Laser Scanning (ALS)- LiDAR

The use of LiDAR to measure forest metrics has been occurring since the late 1990's (Beland *et al*. 2019). LiDAR is one of the most promising remote sensing methods due to its ability to assess the vertical structure compared to airborne optical sensing methods (Koch 2010, Lu *et al*. 2016). There are currently a range of different systems in use - ranging from terrestrial to satellite based systems. Different systems vary in both the scale at which they operate, the level of detail of the tree that they can best record and their major advantages and disadvantages, see Beland *et al*. (2019) for review. The major limitations of ALS LiDAR technology are the inability to differentiate between different tree species and the high cost of data collection (Koch 2010, Lu *et al*. 2016).

Overseas, ALS technologies have been shown to be applicable to predicting volume in both native and plantation settings (Packalén *et al*. 2011). For example, Noordermeer *et al*. (2020) used repeated ALS data collection to determine site index in Norway's boreal forests and showed that it was useful technology to identify and predict site index in undisturbed forest and over large areas at a finer spatial resolution than is available with field-based measurements. In comparison to other airborne technologies, ALS is generally considered to have better canopy penetration, although with dense canopies the capacity to gather stem information (e.g. stems per hectare or DBH) is limited. In many circumstances the use of terrestrial based assessments removes this limitation (see section below).

A significant area of Tasmania's production forest has been assessed using ALS LiDAR using planes, in the most part this was undertaken by Sustainable Timber Tasmania and was completed in 2015, although other areas of the state have been mapped by various other organisations (Fig. 3.2). The LiDAR data provides accurate information on forest height and density as well as the underlying land surface. Collected LiDAR data has been used to provide site index as it provides a rapid assessment of forest height. LiDAR data has also improved the capacity for forest managers to plan operations through a better understanding of where the resource is and by reducing risk to forest soils and streams via more accurate and comprehensive digital elevation models (STT 2019). LiDAR can inform forest estate growth models by calculating sites with similar structural profile and then impute the growth rates of unknown sites from sites with known growth rates. Operationally this techniques has been used to assess potential special species volumes in the native public forest estate (Forestry Tasmania 2015) but as of yet has not been applied to the hardwood resource and would face limitations at a whole of estate level due to the gaps in LiDAR coverage (Fig 3.2). This technique could be used to estimate many productivity/volume metrics such as height or DBH (Huang et al. 2019).

Examination of the overlap between LiDAR coverage in Tasmania and the hardwood estate shows that the majority of the estate area has been assessed by LiDAR but there are significant proportions such as in the north-west and the midlands/east-coast that do not have data available (Fig. 3.2). Areas not covered by LiDAR mapping tend to be private timber estates and include many privately-owned plantation areas. Unmanned Arial vehicles (UAV) have the capacity to capture LiDAR data at relatively broad scales (Dalla Corte et al. 2020), although not to the level of the whole estate.

In order to use LiDAR to predict timber volumes it is necessary to have multiple measures, particularly for forests of unknown age, as a single acquisition cannot inform how vegetation is changing (Goodbody *et al*. 2019) which is required to predict growth. However, the current cost of large scale LiDAR acquisition means that it is difficult to make an economic case for a secondary capture (Goodbody *et al*. 2019), and there is high cost of entry for individual companies to purchase equipment and a high level of skill and training to operate and extract useful information from the data. For most LiDAR technologies the post-processing tools to get complex measures of forest volume are often time consuming to develop, although research and open source code are aiding in this area (Beland *et al*. 2019) and recently there have been examples of automated detection of individual trees in eucalypt plantations (Picos et al. 2020). For simple LiDAR metrics such as height, which can be used to calculate site index, the tools for post-processing are well developed.

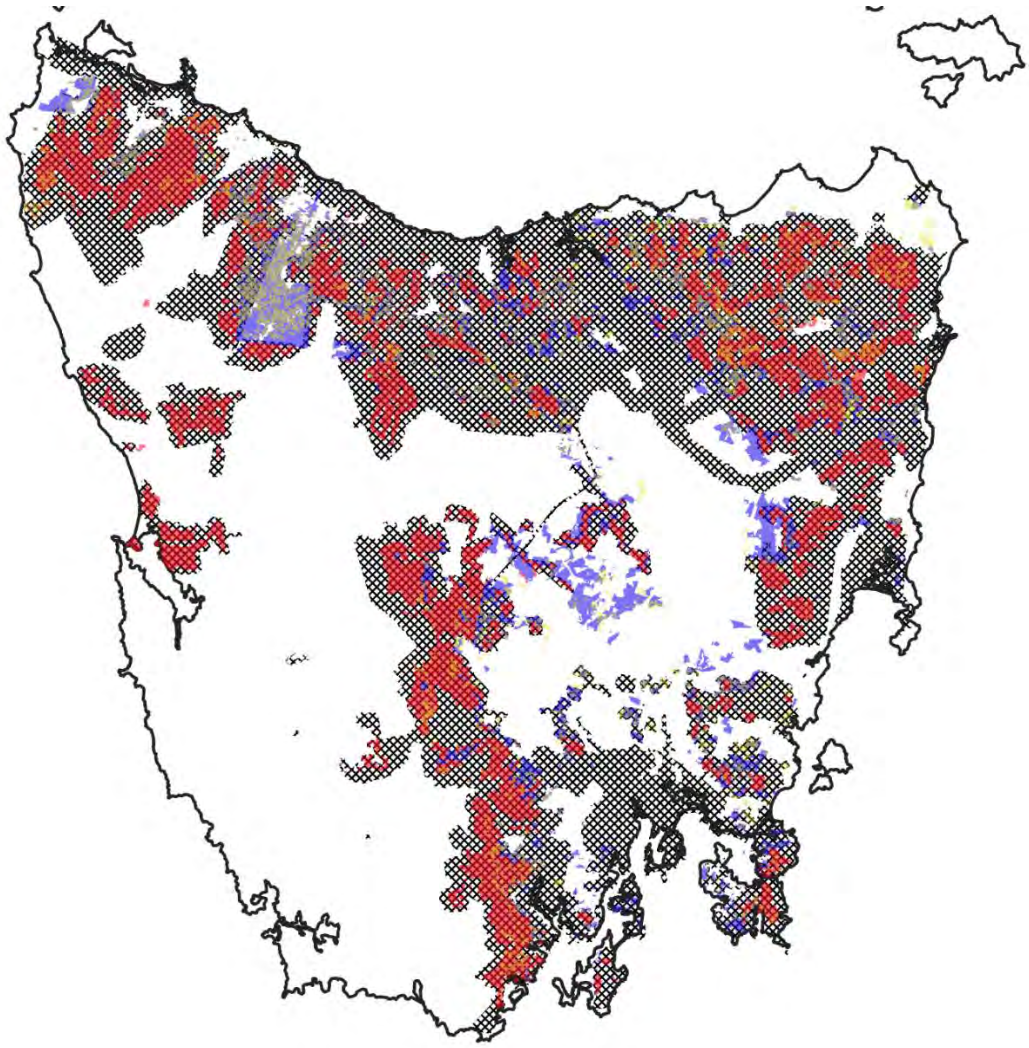

Figure 3.2: The overlap of the LiDAR coverage in Tasmania (hashed) compared to the Tasmanian hardwood estate, PTPZ (Red), private (blue) and plantation (yellow). LiDAR coverage was sourced from the 'LiDAR coverage index - combined' layer in ListMap.

In addition to ALS, satellite-based LiDAR sampling may provide information on forest growth rates. Satellite based laser scanning technology such as GEDI (GEDI 2020) uses LiDAR to provide forest information with a footprint of 25 m at ground level, although information will likely be gridded at 1 km scale. Data from this source is freely available for download, and while the fine-scale e.g. tree based, information may be lacking, it provides a cheap method for assessing some forest characteristics, including tree height, over large scales. The GEDI system is planned to be in operation for a period of two years and will likely re-scan areas multiple times. This will potentially allow a prediction of growth rates.

Terrestrial Laser Scanning

Terrestrial laser scanning is another remote sensing technology that utilises LiDAR (Beland *et al*. 2019). Terrestrial laser scanning occurs under the canopy of the forest and therefore can get a high level of detail on individual tree characteristics such as DBH, volume and stem straightness. Unlike ALS, terrestrial laser scanning operates at a site level, therefore collecting data for whole of estate characterisation would be prohibitively time consuming and costly. TLS is best suited for detailed site-based information. This technology requires the ability to automate the process of tree detection and volume modelling from the point cloud created. Advances in this automated process are currently being undertaken (Buck *et al*. 2019).

Optical technologies

Optical remote sensing technologies could prove beneficial as they are often collected using, and made available through, satellite data. For fine scale wood volume assessment these options may be limited as they tend to perform best when discriminating between distinctly different biomass classes (Koch 2010) or when assessing horizontal rather than vertical vegetation structure (Lu *et al*. 2016). Therefore, while they may be good for detecting change in forest class the potential for rapid assessment of growth and wood volume may be limited.

Aerial photogrammetry:

Aerial photogrammetry captures 3D characteristics of forests using digital imagery. In studies of eucalypt plantations and pine plantations, aerial photogrammetry was shown to be as accurate as ALS in predicting wood volumes (Guerra-Hernández et al. 2019, Iqbal et al. 2019). The use of stereo imagery for the assessment of forest characteristics has been used in multiple studies to date e.g. Latifi et al. (2010), Fassnacht et al. (2017), Hosseini et al. (2019). The benefits of aerial photogrammetry technology for forest inventory are highlighted by a review by Goodbody *et al* (2019). This review highlighted that the major benefits of aerial photogrammetry were that it was half the cost of ALS technology but could generate data which was analogous to ALS. The major limitations listed were that it only records data from the top of the canopy and needs to be paired with ALS data to get information on the location of the ground. Additionally, aerial photogrammetry is not an effective technique in multi-aged forests or for monitoring the sub-dominant canopy layer. This may limit its effectiveness in native forest assessments.

Below canopy photogrammetry

There is currently very little below-canopy photogrammetry being undertaken in production forests, but it is an area where research is currently being undertaken at the University of Tasmania (Sean Krisanski, *pers comms*). Below-canopy aerial photogrammetry can provide many useful forest management metrics such as DBH and stems per hectare. Photogrammetry data can be collected in colour which can lead to easily recognisable images for forest managers. As with terrestrial LiDAR this approach is best suited to getting high level details at individual sites and would be time consuming to operate at an estate level. In addition, this application is currently limited as it is computationally intense and due to the need to photograph points multiple times, from different angles, it can be difficult in dense understories. To be an efficient method of data collection below canopy aerial photography also needs to rely on automated flight for collection with forests and automated data processing, due to the large and complex data generated. Currently these limitations have not been fully addressed although work is ongoing in this area.

Multi-Sensoral

The combination of multiple remote sensing techniques can serve to overcome the limitations of each of the individual techniques (Koch 2010) and combining multiple data sources gives increased capacity to classify forests (Rajbhandari et al. 2019). The combination of radar technologies (e.g. LiDAR) and optical technologies is a promising area for large-area biomass mapping (Lu *et al*. 2016), and is therefore likely to be beneficial for forest volume estimates across a forest estate, although the analytics of combining multiple large data sources is challenging (Koch 2010). For example, merging of aerial laser scans and optical technologies rely on high precision reference systems (global navigation satellite systems - GNSS) for both technologies. This is particularly the case for when one or both technologies cannot obtain ground points through the canopy, which may be an issue in both the native and plantation hardwood estates in Tasmania.

Forest inventory measurements need to be continuously updated to provide accurate information on the currently available resource as the shelf life for remote sensed forest data is approximately 10 years (McRoberts *et al*. 2018). A cheaper technology that provides accurate inventory data, such as aerial photogrammetry, would enable more frequent data collection. Aerial photogrammetry data works best when it is paired with ALS data as it allows the terrain and other below ground features to be accurately determined. For a large proportion of the Tasmanian forestry estate, LiDAR data has already been recorded, therefore the use of aerial photogrammetry technologies may be possible and may provide a more cost-effective technology for future volume assessments of the Tasmanian resource.

Section Summary

A review of the information on volume estimation within the Tasmanian hardwood estate suggests that there is currently enough available data to model the spatial variation of volume across the Tasmanian estate. The major gap in information is the available resource contained in the private native forest estate as intent to harvest making it difficult to predict.

To combine information across the various land managers, modelling techniques such as those demonstrated by González-Rodríguez and Diéguez-Aranda (2020) and Eckhart *et al.* (2019) allow environmental data to be combined with simple productivity metrics, such as site index, to predict not only how they vary spatially but how they may vary under future environmental conditions.

There are currently many developing remote sensing techniques that have the potential to be used for broad scale assessments of key forest characteristics such as growth. Many of these techniques have already been utilised in the Tasmanian forest estate and although they would require large investments in data collection, they would provide high quality data for the assessment of forest growth/volume. Aerial LiDAR data has already been shown to be an effective data collection technique for predicting productivity measures such as site index at an estate scale. However, for more precise volume/growth estimates the need to measure at multiple points in time it may make this technology uneconomic. However, satellite LiDAR collection has recently been undertaken which may solve this problem and should be further investigated.

The development of spatial maps of forest volume will also be a key step in further forest resource characterisation work, such as predicting wood properties (Section 2). As many wood properties are highly variable depending on growth rates, the ability to account for growth either by measured or predicted values will be important, and any potential modelling of wood properties across the Tasmanian hardwood estate needs to consider volume.

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Section 4: Environmental and climate variability

Variation in wood properties and volumes is strongly driven by changes in environment and climate (see Sections 2 and 3). Therefore, in order to accurately model the variation in wood characteristics across the Tasmanian estate, it is important to know the availability of climatic data and the range of conditions in which the hardwood estate currently sits. This information can be used to inform potential sampling strategies for the development of models.

Currently available data

To determine the current environmental range of the Tasmanian Hardwood estate, merging environmental and climatic information with the spatial distribution of the estate is required. The information below details the current resources available to assess the spatial distribution of the hardwood estate and the environmental and climate conditions which it occupies.

Plantations

As mentioned in Section 3, the spatial distribution of the Tasmanian hardwood plantations is available from the 'Australian plantation statistics report' produced by the Australian Bureau of Agricultural and Resource Economics and Sciences (ABARES) (ABARES 2016). This data encompasses data from both public and private plantation estate owners. Information within the data set allows it to be easily split into hardwood and softwood estates and limited to the Tasmanian region.

Native

The area of native forest used in this section was derived from the land allocated to the Permanent Timber Production Zone (PTPZ). This spatial data was sourced from the ListMap. This data set has a few limitations: firstly, it includes both plantation and native estates, and secondly, this data set only accounts for the publicly owned native forest and therefore doesn't encompass potential wood sourced from private native forests. However, the PTPZ is predominantly made up of native forest and provides most of the timber sourced from native forest in Tasmania, and the inclusion of private native forest would include environmental areas not suitable for harvesting. Therefore, the use of this dataset should provide a reasonable estimation of the range of environmental conditions that occur.

Environmental and climatic data

Spatial layers of climatic data are available from a range of sources. Some key examples include WorldClim, CHELSA, ANUCLIM, or spatial data from the Australian Bureau of Meteorology. These spatial datasets provide an estimate of climate generally in grids of kilometres, with the exact scale of the grid vary depending on the source. Climate estimates are based on predictive models using historical meteorological data.

To examine the range of climate conditions over which the Tasmanian hardwood estate occurs, this report uses data derived from CHELSA (Karger *et al*. 2017). The CHELSA data set is a high-resolution climate data set (1km grid) derived from statistical downscaling of atmospheric data. This method provides an accurate climate estimation but at a finer resolution than data sets using interpolations of weather station data. In addition, the CHELSA climate estimations are also available for future climates. This may assist in predicting how the spatial distribution of forest resource characteristics may change over time and may also provide key insights into potential shifts in wood volume in future climates. Environmental data, particularly soil characteristics, also have a large impact on wood properties and quantity. Spatial soil characteristic datasets are available and can be merged with forest estate datasets. For this report we have used the data sourced from the Australian node of the *GlobalSoilMap* project (Viscarra Rossel *et al*. 2015). This data set included fine scale (~90 m grid) soil information. Available soil characteristics include sand %, silt % clay % bulk density, organic carbon, total nitrogen, total phosphorus, pH, available water capacity, depth of soil, plant exploitable depth and coarse fragments.

For this study we examined the variation in hardwood estate in total phosphorus and plant exploitable soil depth, however further projects should consider a wide range of the soil characteristics available to best determine which factors are most predictive of wood properties and wood quantity. Other soil data bases are available, although they tend to be at coarser scales and have a more limited number of variables.

Merging data sets

There are a range of software programs available for the merging of spatial data sets. Programs such as ArcGIS provide mapping and analytic platforms for analysis of spatial data for a subscription fee and there are also a range of free open source options such as QGIS. Further projects in this space should not be limited to a specific GIS platform and should utilise the available expertise as there is often a learning curve associated with each platform. For the merging of environmental and estate data in this report, the statistical program R was used, utilising the libraries ‘sp’ (Bivand *et al*. 2013), ‘sf’ (Pebesma 2018) and ‘tmap’ (Tennekes 2018).

To merge the environmental and estate level data, both data sets were read into R. All data sets were projected to the same coordinate reference system (CRS) and data sets were then cropped to the Tasmanian reporting region as defined by ABARES. The environmental conditions within areas defined as hardwood estate were then extracted and the range of conditions were examined.

Environmental Summary of Tasmanian Hardwood estate

Plantation estate

The Tasmanian plantation hardwood estate occurs over a wide range of environmental conditions (Table 4.1). Plantations occur over a large range of rainfall conditions (500 to 2,200 mm), with the majority of plantation area receiving 800-850 mm of rain (Fig. 4.1). In addition, plantations also occur over a range of temperature conditions, for example, plantations occur in areas that have a minimum temperature of the coldest month between 3 and 8 degrees (Table 4.1). It is also important to note that while many of the temperature related climate variable are highly correlated there is low correlation between annual precipitation and the minimum temperature of the coldest month ($R^2 = 0.17$). Therefore, potential sampling across environmental gradients will need to be more intensive to account for interactions on their effects on wood properties and volume.

Table 4.1: Climatic ranges of the plantation and native hardwood estates in Tasmania

Climate	Plantation	Native
Mean temp	7.6 - 13.9	5.7 - 13.9
Max temp (warmest month)	15.6 - 21.3	14.9 -21.1
Min temp (coldest month)	0.3 - 9.9	-1.2 - 10.1
annual rainfall	458 - 2417	498 - 3158
Phosphorus	0 - 0.16	0 - 0.17
Plant exploitable depth	11.3 - 199	0 - 200

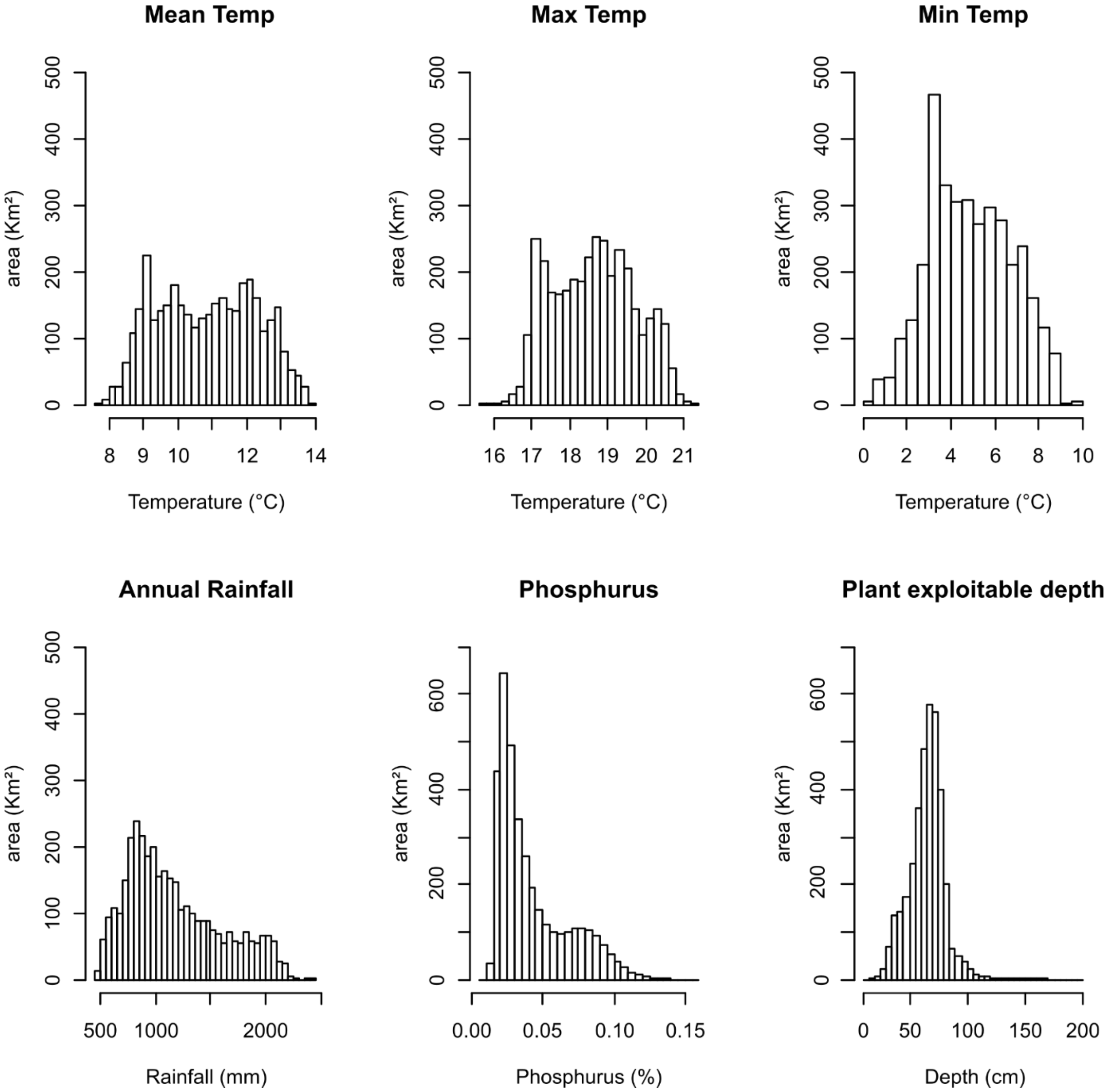

Figure 4.1: The distribution of plantation area across four climatic variables. Mean Temp represents average yearly temperature, Min Temp is the minimum temperature of the coldest month, Max Temp is the maximum temperature of the warmest month and Annual Rainfall is the amount of precipitation received over the year.

Native estate

The range of conditions over which the permanent timber production zone (PTPZ) sits for the four climatic variables examined was generally wider compared to the plantation estate (Table 4.1). In particular, the PTPZ extends into areas with higher rainfall, have colder minimum and average temperatures and into more soil conditions. It is also important to note that as well as differing ranges, the plantation estate (Fig. 4.1) and the PTPZ (Fig. 4.2) have different climatic distributions. Therefore, the sampling design required to model each estate may have to be targeted to the individual estate.

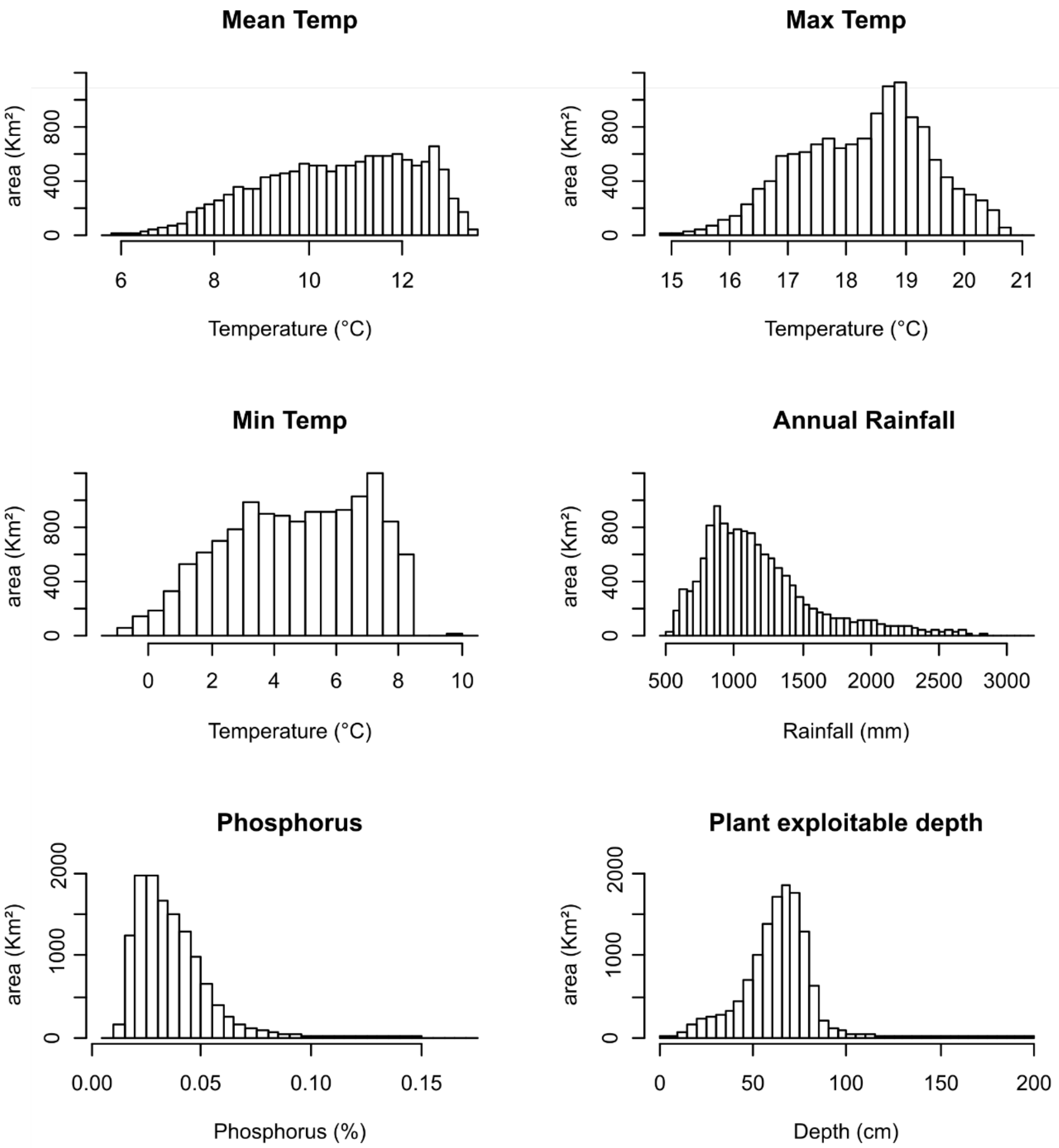

Figure 4.2: The distribution of plantation area across four climatic variables and two soil characteristics. Mean Temp represents average yearly temperature, Min Temp is the minimum temperature of the coldest month, Max Temp if the maximum temperature of the warmest month and Annual Rainfall is the amount of precipitation received over the year.

However, it is important to note that the range of native forest conditions (Table 4.1) and their distributions (Fig. 4.2) only encompass areas within the public PTPZ estate. Data from privately owned native forest may extend the environmental range. Sampling at the extremes of the ranges for both native and plantation estates will also be particularly important to provide information about estate expansion or potential climate responses.

Section Summary

The environmental and climate data currently available provide a key source of information to enable the variation of both wood properties and wood volume to be modelled. The scale at which this information occurs is appropriate to model variation at an estate level.

Both the plantation and native forest hardwood estates encompass a wide variety of environmental conditions. Therefore, any potential modelling of wood properties and quantity variation across the estate will have to rely on data collected from a wide range of sites.

Adding complexity to any potential data sampling is that while some environmental variables, such as many of the temperature-based indices, are correlated, many are not. As a result, increased sampling would be required to factor in any potential interaction between unrelated environmental variables.

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Section 5: Project recommendations and feasibility

The development of a method to characterise the Tasmanian hardwood estate in terms of wood properties and volume would be beneficial to the forest and forest products industry. Mapping wood characteristics will provide the opportunity to understand the amount and location of timber with specific properties in order to align production with primary product outcomes to maximise resource value.

A review of the information currently available within the Tasmanian hardwood estate for both wood properties (Section 2) and wood volume (Section 3) has shown that there are currently some key gaps in our ability to develop characterisation models across the whole estate. For the Tasmanian hardwood estate, the capacity to predict wood properties is limited as insufficient data has been collected to date. However, there are many wood property metrics available that provide information about the quality of logs for specific end-products, and there are well developed assessment techniques and local expertise that exists with the Tasmanian industry for these metrics. As result the collection of data to model wood properties across the Tasmanian estate would be feasible.

The ability to predict variation in wood volume is more advanced as many forest managers collect growth metrics e.g. site index, standing volumes, harvested volumes. While specific volumes produced in Tasmania are tracked and reported yearly, these measures typically occur at a regional level and therefore may not be suited to within estate modelling. However, while individual forestry companies may have the capacity to predict wood volumes at site level with high accuracy, this is not publicly available across the whole of Tasmania. The ability to predict volumes across the whole of the Tasmanian estate will be beneficial as it will increase the capacity to predict areas outside the current estate that may have timber growing potential; and predict future changes in production due to changing climates. In addition, the ability to predict volume will greatly improve predictions of internal wood properties.
Due to limitations in the information currently available on characteristics of the Tasmanian hardwood estate this report recommends the development of projects that can address some of the current gaps. Areas of focus should include

- The variation of wood properties with environmental conditions
- The interaction of wood properties, environmental conditions, and volume
- Statewide modelling of wood volume.
- Predicting available area of private native hardwood forests.

Feasibility

Wood properties and wood volume

Variation in wood properties and wood volume occurs due to a variety of reasons (Section 2 and 3). One of the key requirements to be able to map spatial variation in wood characteristics is the need to understand variation with environmental and climatic conditions. Due to the large range of environmental and climatic conditions across which the plantation and native forest estate occur in Tasmania (Section 4), data collection to accurately predict wood properties will require many sampling sites (see below).

Due to the variability between species and silvicultural management a similar sampling intensity would likely be required per species in both native and plantation silviculture. Therefore, this report recommends that the most feasible approach will be to focus on a single silvicultural type and a single species. Pending the success and usefulness of a single study system the approach could then be expanded.

Eucalyptus nitens plantations would be the most feasible system for which to predict wood properties across Tasmania. Historically, Tasmanian native forest has supplied high-quality sawlogs to the forestry industry however the future sawlog supply will increasingly rely on a mix of native and plantation forests. Additionally, plantation forests are single species, often of known genetic stock and age and occur over a smaller climatic footprint than the native estate (Section 4). In comparison, Tasmanian native forests have high species diversity and can be multi-aged, so a forest characterisation would require a higher-intensity sampling strategy with correspondingly higher costs. *Eucalyptus nitens* appears to be the most appropriate study species as it represents 89% of the state plantation area, so a benefit derived from a forest characterisation of this resource would have a greater impact on the economy of the state. In addition, the small amount of characterisation studies done within Tasmania have been undertaken on *E. nitens* which could be combined with future data collection to increase the accuracy and power of predictive models. Consequently, we suggest that plantation *E. nitens* is the most feasible option for resource characterisation.

Proposed projects

Wood properties and volume characterisation

The following proposed projects focus on the development of a forest resource characterisation for plantation grown *Eucalyptus nitens*. The various alternatives listed below provide an indication of the economic and resource costs that would be required. If these projects were to be expanded to other areas of the hardwood estate, we would expect similar costs to be incurred.

We propose to focus on Tasmanian *E. nitens* plantations which are managed for pulp or solid timber and are at harvestable age for pulp (~15yrs). Focus on a single age group is required due to the high variability in wood properties due to age (Section 2). Due to the range of environmental and climatic conditions over which the plantation estate occurs (Section 4), we propose 250 sample sites should be utilised encompassing the range of environmental conditions. This distribution of sites should be split across five main regions: Northeast; South; Northwest; Central Plateau; and East Coast, to ensure geographic variation is captured. The recommendation of 250 sample size is based on the limited previous studies on wood quality variation in eucalypt plantation in Tasmania. Models produced by Vega (2016) used 46 sample sites for a single region in Tasmania. As this project identifies five main regions to be tested, we recommend ~50 sites per region. Models produced by Vega (2016) showed that the error (RSME) on the model prediction was ± 66.1 kg/m^3 for density, ± 2.3 degrees for Micro fibril angle and ± 2.5 GPa for Modulus of Elasticity. We would expect smaller estimates due to the greatly increased sampling. In addition, two additional studies are currently being undertaken at the University of Tasmania's Centre for Forest Value (CFV). These studies should provide additional information on the statistical strength associated with the recommended sample size. Results of these studies are expected at the end of 2020 and should be consulted before the finalisation of any sampling strategy. Globally, in a comprehensive study by Lessard *et al* (2014) in the boreal forests of Newfoundland 194 sample sites were used, however this study did not encompass the rainfall and elevation gradients experienced in Tasmania. Other studies have used fewer sample sites e.g. 62 sites in Wilhelmsson *et al* (2002) study in pine tree in Sweden. This demonstrates that a smaller study would be feasible, however a greater degree of model error would be expected from this level of replication.

We recommend sites be selected based on coupe locations as a single coupe will provide a unique combination of environmental and climate conditions. Based on consultation with plantation hardwood estate managers, in order to locate 250 sample coupes, it is likely that a three-year age range will need to be employed to capture sufficient spatial and environmental variation. This suggested age range is due to the number of coupes available for a given age and the fact that many coupes of the same age will be similar locations and therefore may have overlapping environments. The number of coupes available for a given age class will be highly variable due to historic planting and harvesting rates.

For most wood property measurements, 25 trees per site should be sampled, and measures of wood volume should be calculated per tree to be able to determine the relationship between volume and wood properties.

This level of sampling will give a strong base model from which further information can be derived. For example, the extending this information out to additional age classes would require a smaller study of a second age to determine if the effect of environment remains consistent across age classes. This strategy could also be employed across species and silvicultural type.

The selection of the most appropriate wood property metrics and assessment techniques for the below proposed project was based on the review of wood properties identified in Section 2 and the selection of the species of interest. We determined the relevant wood properties and their assessment techniques based on two central aspects;

- Metrics that are most applicable to the current Tasmanian forest industry operation and potential forest products that would be developed in the future.
- Existing local expertise in using the field and laboratory technologies to assess the wood property.

From this we identified three alternatives for wood properties assessment. The expected cost of each alternative is listed in Section 6. The specific metric that will be of most interest will be determined by the processors as they are most impacted by wood quality. However due to the currently unknown nature of the suitability of plantation *E. nitens* to be used for a range of wood products, choosing a preferred metric is difficult. We therefore recommend that when processors are confident in the utilisation of the resource, the metrics most applicable to the product are identified from the below alternatives.

Alternative 1: Wood density only, measured in the field using resistographs.
This alternative is the simplest one. The information provided would be useful for the solid wood and pulp industry, but with limitations as explained previously in the report (Section 2). Density is correlated with many other wood properties so can provide general information for a range of important wood properties. The method of assessment means that more sites can be assessed per day resulting in reduced costs. In addition, there is less laboratory work required compared with the other alternatives which further decreases expenses.

Alternative 2: Wood density (as above) plus MOE, measured with acoustic field tools.
This alternative differs from the previous one because here the information provided would be in the same unit that is used to produce structural solid wood products (e.g. plywood, LVL, and timber). This alternative increases the amount of data available but due to the increase in the expected time it takes to collect this data the field costs increase by 35% and due to need

to calibrate the MOE measurement between sites using green density and moisture content there are additional laboratory costs.

Alternative 3: As per Alternative 2 plus pulp properties and MFA, measured with laboratory tools; NIR and SilviScan.
This alternative would allow a comprehensive assessment of the relevant wood properties for the solid wood and pulp industries, yielding information such as KPY, cellulose content and MFA. This is the most extensive assessment proposal with the cost for data collection in the field expected to more than double compared to alternative 2 due to the destructive sampling techniques that require the use of chainsaw operations. Laboratory sampling costs are also significantly more expensive (approximately 3 times more than alternative 2) due to the cost per sample of the NIR and SilviScan equipment.

Wood volume

While characterisation of the hardwood resource for wood properties requires additional data collection, there are also some feasible projects that could develop an estate wide characterisation of volume.

Volume based maps could be created by using environmental and climatic variables to predict variables correlated with volume such as site index. Environmental data is widely available (Section 4) and site index is commonly collected through forest management companies, particularly for plantation forests. As a result, this project would have limited in-field data collection, although would rely on the in-kind contributions of forest managers. This project could be applied across the whole estate, both plantation and native forest hardwoods for multiple species.

New remote sensing technologies do not appear feasible at this stage to generate estate wide volume predictions due to the cost of the technology and the issue surrounding the complexity of processing data. However, satellite collected LiDAR appears to be a potential cost-effective resource for modelling growth. While at this stage the multiple measures required to predict growth are not available, they likely will be soon, therefore the potential for utilising this resource should be monitored.

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Section 6: Budgets

The calculations for the proposed projects listed in Section 5 are contained in a separate excel spreadsheet. The information below is a summary of these calculations and includes costs for staff, travel and equipment. Budget estimates do not include in-kind contributions or potential on-costs of the organisation operating the project.

Table 6.1: Projected budgets for proposed projects design to collected data and model wood properties and volume characteristics for the Tasmanian estate of plantation *Eucalyptus nitens*. Further project details can be found in Section 5.

Costs	Alternative 1	Alternative 2	Alternative 3
Field	$129,216	$183,049	$383,912
Laboratory	$9,319	$18,638	$525,351
Modelling	$87,396	$119,529	$173,793
Total	$225,931	$321,216	$1,083,056

Table 6.2: Projected budgets for proposed project estimating wood volume across the Tasmanian hardwood estate. Budget estimates do not include in-kind contributions or potential on-costs of the organisation operating the project.

Costs	Site Index modelling
Data collection	$5,977
Modelling	$65,224
Total	$71,201

Section 7: Industry Feedback/Key considerations

This section of the report is a summary of the key discussion points raised by industry partners of the project from a Steering Committee meeting (13th May 2020) and subsequent communications. Discussion focuses on the project report and possible future projects. Discussion points identify potential issues/questions that will need to be considered in any future development of a project aiming to characterise the Tasmanian hardwood estate. The steering committee included both managers of the Tasmanian hardwood estate and processors of hardwood products

Below each discussion point is a response by the project researchers of how the feedback has been incorporated into the report and also into the proposed project design.

Temporal variability in volume:

Volume, particularly in terms of volume available for use, is difficult to measure without knowledge of factors such as age, planting rates over time, area harvested and intended harvesting date. Due to many factors there will be peaks and troughs in availability.
For specific silvicultural types it is possible to calculate an average estimated cut, similar to the sustainable yields estimates in the public native estate provided by Sustainable Timber Tasmania. However, annual yields will be highly dependent on the previous planting history and market demand so will be highly variable. In addition, where the timber is sourced and therefore the ability to predict its wood properties will be dependent on the harvesting plans of individual companies which undergo continuous re-adjustment to account for growth and market conditions.

We would recommend that initial steps should focus on creating a statewide map showing which areas are the most productive, independent of the age of the forest. While this may not provide available volumes, it could be used to plan future estate expansion or used as a base map to understand potential estate wide-effects of changing climates.

There may be merit in moving forward on a project to understand volume by species, age and silvicultural regime. A similar understanding would be useful for wood quality but problematic.
The data to calculate this information for volume would need to be sourced from individual forest management companies to create an estate-wide overview. It would also need to be updated regularly as it would become rapidly outdated as companies make alterations to their estate and would require the use of longer-term data sharing arrangements. As such may not be suitable for one-off grant funding.

Understanding this information for wood properties is problematic due to the lack of data available. The projects proposed in this report would be the first steps in gaining this understanding.

The development of models mapping spatial variation in wood properties and volume could be paired with the spatial estate data that is regularly collected by ABARES to give areas of specific volumes/wood properties. Given the spatial estate data is regularly collected this would provide an easy updatable mechanism, although age data is not included and therefore this would not provide an estimate of total available volume for a given year.

Private Native forests

How can landowner intent be determined and how can models for estimating volume be applied across the private native forest estate? Suggestion in the report was to confine future projects to plantation estates in the first instance and to ensure it captures a wide range of environmental conditions.

Estimating characteristics of private native forest presents some difficulties for both volume and wood properties. Modelling both volume and wood properties across the private native estate would need to ensure that a) metrics are collected within the private native forest estate, which may involve some on-ground sampling, or b) samples used from the public estate are targeted so that the range of environmental conditions found in the private estate are encompassed.

Understanding landholder intent is a similar issue to understanding the temporal variability in volume. This report would recommend that the first aim of any potential estate-wide modelling be the classification of areas by the type of wood properties/volume they could produce. This information could then be used by private landholders to inform; areas most economic to harvest, potential buyers and silvicultural options for re-establishment.

Sampling design

When sampling wood properties, what sort of sampling regime would be required to provide a statistically relevant basis for modelling and what is the confidence in the estimates.

Understanding the exact level of error is difficult as there will be variation within and between trees and within and between sites. However, previous studies of smaller parts of the plantation estate give a rough indication of the error we can expect, and the sampling intensity required. The Root Mean Square Error (RMSE) of a wood properties model produced by Vega (2016) showed that estimates varied by ± 66.1 kg/m^3 for density, ± 2.3 degrees for Micro fibril angle and ± 2.5 GPa for Modulus of Elasticity. This error was based on 46 sample sites but data collection was performed on a larger range of forest ages than we recommend in this report which will have inflated the error. In addition, two additional studies currently being undertaken at the University of Tasmania's Centre for Forest Value (CFV) should provide further information on the statistical strength associated with a recommended sample size. Results of these studies are expected at the end of 2020 and should be consulted before the finalisation of any sampling strategy.

With the sampling intensity recommended by this report and the suggested approach of targeting a single species at a single age class, we would expect the error generated by the model to be reduced to acceptable levels.

There is some uncertainty about what the most important focus is for modelling work in terms of species and quality/quantity parameters. The traits which are important to understand should be guided by the processors.

For sampling plantation *Eucalytpus nitens* (The species recommended by this report), its capacity to be used for a range of timber products is currently unknown. Studies are being undertaken through the CFV and the Centre for Sustainable Architecture in Wood (CSAW) to determine if this plantation species is suitable for a range of products and what key wood property indicators will determine its suitability. Results of the current studies will further inform any study design.

In addition, the key wood property metrics that should be modelled will vary depending on the intended purpose of the timber. Previous research suggests which wood properties are critical for specific timber process e.g. modulus of elasticity (stiffness) is a key indicator of structural timber in *E. nitens*, however we must first be sure that the resource examined can be used for such a purpose to ensure models will be useful. For this purpose, we have identified and budgeted three potential projects to model a range of estate wide wood properties.

Could modelling be extended out beyond the sampled age for growth and wood properties? From Figure 2.15, the curves are flattening at age 15 across the traits and sites. Potentially there is some confidence in extrapolating forward, perhaps backed up with a modest increase in field sampling. This information would greatly expand the usefulness of the data to those making decisions about investments in silviculture (thinning pruning and rotation length) and processing (peeling and/or sawing).

Data collection for estate wide modelling is best suited at a restricted age range as it removes variability associated with different tree ages and therefore reduces the sampling intensity required. However, silvicultural regimes differ in harvest age and therefore understanding potential variation in wood properties with age and establishing whether the impacts of environment/climate stay consistent with increasing rotation is critical. Results from studies such as those presented in Fig 2.15 do suggest that wood properties stabilise at a certain age depending on the wood property evaluated. For example, in *E. nitens* there is no apparent increase in wood density with age after 15 years. However, the models presented (Fig 2.15) were developed for specific sites, therefore would require validation in different growing conditions and silviculture. A potential solution would be to conduct an intensive sampling design at a single age (as proposed) and then a smaller study of a second age to determine if the effect of environment remains consistent across age class. This strategy could also be employed across species and silvicultural type.

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