# Application of non-destructive evaluation techniques to the prediction of solid-wood suitability of plantation-grown *Eucalyptus nitens* logs

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# Declarations

This thesis contains no material which has been accepted for a degree or diploma by the University or any other institution, except by way of background information and duly acknowledged in the thesis, and to the best of my knowledge and belief no material previously published or written by another person except where due acknowledgement is made in the text of the thesis.

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# Abstract

Non-destructive evaluation measurements of longitudinal growth strain (*LGS*) and acoustic wave velocity (*AWV*) were collected on 22-year-old *Eucalyptus nitens* trees from a plantation thinning trial in Tasmania. A total of 81 trees from five residual stocking treatments including an unthinned control were assessed. *LGS* was measured at breast height at four aspects per tree. Standing tree-*AWV* was determined at two opposite aspects per tree. Log-*AWV* was collected on the 5.7 m-long bush-logs and on 162 lower and upper 2.7 m-long sawlogs. Sawlogs from 41 trees with diameter over bark (*DBHOB*) under 43 cm were back-sawn, and those from 40 trees with *DBHOB* over 43 cm were quarter-sawn. Wood shrinkage and basic density were measured on 25x25x40 mm wood blocks cut from wood disks immediately above the first and second sawlogs of the back-sawn trees at heights of approximately 3m and 6 m above ground. Three blocks were cut at each height, at radial distances 25%, 50% and 75% from pith to cambium. Linear mixed models and multiple linear regressions (MLR) were applied to examine: a) effects of stocking, *DBHOB* and other factors on *LGS, AWV* and wood block traits; and b) the ability to predict sawing traits (log end-splitting; sawn-board distortion, shrinkage and checking propensity), product recoveries and value; and wood mechanical properties (timber stiffness, strength and hardness).

Stocking was significantly positively related only to log-*AWV*. *DBHOB* was negatively related to standing tree-*AWV* and log-*AWV*, and positively related to log end-splitting, which was also higher in the upper sawlogs and positively related to *LGS* and log-*AWV*. Measurement aspect affected both *LGS* and *AWV* with higher levels on the north-west and sout-west aspects, facing the prevailing wind direction.

Basic density increased with stem height and from pith to cambium, whereas tangential and radial shrinkage and collapse were lower at the upper sampling point, while they also increased from pith to cambium. *LGS* was positively associated with sawn-board distortion and losses of board volume from end-docking. Standing tree-*AWV*, log-*AWV* and basic density were positively related to wood mechanical properties. Log-*AWV* was also positively related to board bow, shrinkage, select recovery and product value. Levels of shrinkage and collapse in wood-blocks were related to board shrinkage (positive), internal checking (positive), select recovery (negative) and product value (negative). Overall *LGS, AWV* and block traits had a modest capability to predict sawlog performance, explaining respectively up to 20%, 17% and 6% of additional variance in log end-splitting, timber stiffness, and product value, in those MLR that already incorporated significant explanatory factors such as sawing method, *DBHOB* and log position.

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# Table of contents

# Format of thesis chapters

Chapter 1 provides a general introduction, with an overview of pertinent literature and a short background to the current study. Detailed literature reviews are included in the two experimental chapters of this thesis (Chapters 2 to 3) which have been written in the format of scientific journal articles. Because Chapters 2 and 3 are intended for separate publication (see following page), they repeat part of the general introduction in Chapter 1. Chapter 4 gives a general discussion, synthesizing the most important findings and identifying those areas in which the research undertaken can contribute understanding and practical applications. While the abstracts for Chapters 2 and 3 have been kept in the form in which they will be published, figures and tables have been renumbered for this thesis, and the acknowledgements and lists of references have been combined into a single version.

# Publications arising from MSc candidature

**Publications submitted and in preparation**

Valencia, J, Harwood, C, Washusen, R, Morrow, A, Wood, M, Volker, P. (submitted) Longitudinal growth strain as a log and wood quality predictor for plantation-grown *Eucalyptus nitens* sawlogs. *Forest Ecology and Management.*

Valencia, J, Harwood, C, Washusen, R, Morrow, A, Yang, J, Bojadzic, M, Innes, T, Farrell, R. (in preparation) Predicting *Eucalyptus nitens* plantation-grown sawlog suitability from acoustic wave velocity and wood shrinkage data.

**Research reports**

Beadle, CL , Forrester, D, Wood, M, Valencia, J, and Medhurst, J (unpublished) Effects of silviculture and the environment on the variables that determine outcomes from eucalypt plantations managed for solid-wood products. Technical Report 173, 2007. Cooperative Research Centre for Forestry, Hobart, Australia.

Washusen, R., Morrow, A., Harwood, C., Valencia, JC, Volker, P., Wood, M., Inness, T., Ngo, D., Northway, R. (unpublished) Gould's Country *E. nitens* spacing trial; solid wood quality and processing performance using conventional processing strategies. Technical Report 168, 2007. Cooperative Research Centre for Forestry, Hobart, Australia.

# CHAPTER 1

## General introduction

This chapter provides a literature review on non-destructive evaluation (*NDE*) techniques relevant for sampling plantation-grown eucalypts for sawlog production and a background to the research undertaken. More specific literature reviews and detailed descriptions of the study carried out are both included in chapters 2 and 3, which report the experimental work undertaken.

### 1.1 Sawn timber production from plantation-grown eucalypts: wood quality limitations and NDE techniques

#### *1.1.1 Plantation-grown eucalypts for sawlog production: current progress*

The total area planted with eucalypt species world-wide has been estimated to reach over 20 million hectares by 2010 (Keane *et al.* 2000; Lindenmayer 2002). Nowadays, nearly two-thirds of eucalypt plantations are established in sub-tropical and tropical zones of countries such as Brazil, South Africa, Uruguay, China, India and Vietnam, using *E. grandis, E. urophylla* and their hybrids as the most important planted species (Cossalter and Pye-Smith 2003). One-third is established in temperate zones in countries such as Australia, Chile, Portugal and Spain, using temperate species such as *E. globulus* and *E. nitens*.

Overall, commercial plantation-grown eucalypts have been established as mono-specific stands, managed under unthinned silvicultural regimes in relatively short rotations (up to 15 years) with the aim of supplying wood fibre for pulp and paper manufacturing (Cossalter and Pye-Smith 2003; Montagu *et al.* 2003; Nutto *et al.* 2006). During the last two decades, a small but increasing area of eucalypt plantations, of the same species, has been managed by thinning and pruning to produce appearance and/or structural timber (Baker and Volker 2007; Nolan *et al.* 2005; Nutto and Touza 2004).

A decline in the availability of sawlogs from traditional native forest sources, a rapid increase in the planted area of eucalypts and some technical-economic stand level considerations have been cited as reasons for some growers to shift towards the establishment and management of eucalyptus plantations for high-value solid and/or engineered wood products (Flynn 2005; Forrester and Baker 2005; Nolan *et al.* 2005; Nutto and Touza 2004). South Africa, Brazil and Argentina have developed some important knowledge on silviculture, processing and market for high value timber production from *E. grandis* and other species well adapted to grow in sub-tropical and tropical zones (Donnelly and Flynn 2004; Kolln 2000; Malan 2003; Malan 2005; Shield 2004; Verryn *et al.* 2005). Examples of industrialization of eucalypt plantation-grown timber are well represented by Lyptus® in Brazil and Grandis® in Argentina.

Less development of sawlog silviculture has occurred in temperate eucalypt plantations to date. The majority of technical knowledge for temperate species has been developed in Spain on *E. globulus* (Nutto and Touza 2004; Nutto *et al.* 2003; Touza 2001a; Touza 2001b) and in Australia in species such as *E. globulus* and *E.*

*nitens* (Baker and Volker 2007; Forrester and Baker 2005; Gerrand *et al.* 1997a; Gerrand *et al.* 1997b; Washusen and Innes 2007). Examples of recent industrialization are Ibersilva-Plantation Wood® in Spain (ENCE 2006) and EcoAsh™ in Australia (Cannon and Innes 2007). Recent research efforts on silviculture and processing; and early industrial processing of *E. nitens* plantation-grown timber are also taking place in Chile (INFOR 2004a).

The experience gained in processing plantation-grown eucalypts for high-value timber worldwide indicate a strong potential for commercial processing (Nutto and Touza 2004; Touza 2001b; Verryn *et al.* 2005; Washusen and Innes 2007), provided there are further improvements in some critical solid-wood quality constraints and progress in processing and drying technologies.

### *1.1.2 Wood quality constraints and solid-wood drivers*

Despite the promising experiences described, the industrialization of plantation-grown eucalypts for solid-wood production for both appearance and structural markets is still at a preliminary stage (Malan 2003; Nolan *et al.* 2005). Uncertainties in the market for plantation-grown sawlogs and some financial cost considerations linked to growing more expensive and longer rotation regimes have resulted in some level of reluctance among forest growers to undertake more investment in large scale plantation-grown eucalypts for sawlog. Conversely pulpwood regimes are commonly seen as a shorter and lower-risk investment (Nolan *et al.* 2005).

Poor wood quality as a consequence of higher levels of growth stresses, excessive shrinkage and collapse, occurrence of tension wood formation, checking propensity and variation in strength and hardness is a primary limiting factor (Malan 2003; Washusen *et al.* 2004; Yang and Pongracic 2004; Yang and Fife 2003). In addition, wood product quality may be negatively influenced by current silviculture practices and genetic material, with most plantations grown primarily for pulpwood production (Nolan *et al.* 2005; Raymond 2002). The following is list of some solid-wood quality constraints, that have been mentioned to be particularly critical for younger plantation-grown timber of eucalypts (Armstrong 2003; Lewty *et al.* 2001; Malan 1995; McKenzie *et al.* 2003a; Washusen and Innes 2007; Yang *et al.* 2003):

a) ***Both green and dead knots*** and also the pith may be primary grade-limiting defects for both appearance and structural applications. This is more frequent when the plantations are grown un-thinned and/or unpruned, and is particularly important in eucalypts species with limited ability for self-pruning such as *E. nitens*, and when plantations are harvested at relatively young age or when the stand has not been pruned to restrict the diameter of the knotty core.

b) ***High levels of longitudinal growth stress*** and its adverse effects on wood quality when released during harvest and processing. Release of growth stresses during tree felling and crosscutting of logs can lead to a high incidence and severity of log end-splitting. Brittle heart associated with high growth stress may produce weak material in the log core. During sawing there may be constraints on the application of sawing strategies as a consequence of growth stresses. High growth stresses may also contribute to flitch and board deflection (spring, bow and cupping due to stress re-balance), board width and thickness variation, and increase end-splits in cants and boards during sawing. These negative consequences may reduce volume recovery and product value through material loss from board end-docking, reduced sawn-board length and width and product downgrading. Increased processing costs and reduced mill economic performance are also likely.

c) ***Excessive shrinkage and collapse, and their variation*** resulting in poor drying performance, reduced choice of sawing patterns, sawn-board dimensional instability, rough surfacing, honeycombing and checking, reduced value of appearance grade sawn-products through a relationship between shrinkage and checking propensity. Internal and surface checks are the most serious forms of drying degrade, affecting grade recovery and are particularly important in limiting the value of plantation-grown *E. niten*s. Most eucalypts have a strong tendency to check on the wide faces of back sawn boards; and internal checking and its severity generally increases with collapse. Therefore in those cases where check prone eucalypts species such as *E. nitens* are established to produce appearance sawn-timber, the financial pressure to keep production cost levels low by producing medium sized back-sawn sawlogs rather quarter-sawn logs (which require prolonged rotation age to reach suitable log sizes for processing) may result in higher checking incidence and therefore reduced product value per log input.

d) ***Tension wood occurrence and severity*** determining poor drying performance of solid timber due to the occurrence of abnormal shrinkage; high longitudinal shrinkage when the tension wood occurs at the stem periphery and surface irregularity, determining downgrade or the need for skip-dressing, reducing recoveries.

Overall, the size and occurrence of knots can be overcome using timely pruning regimes aimed to restrict the defective knotty core (Montagu *et al.* 2003). Therefore checking propensity (critical only for appearance solid-wood products) and higher levels of growth stresses, and board stability may be considered as the most important processing and value limiting factors for solid-wood production from young fast-grown eucalyptus plantation timber (Waugh 2005; Yang and Waugh 2001).

Particularly during the last 10 years several studies carried out worldwide have started to contribute more understanding to the commercial potential of plantation-grown eucalypts for solid-wood production. They also have given insights into the feasibility of improving solid-wood quality constraints by genetic improvement, enhanced silvicultural practices and processing strategies. There are several examples of recent studies on processing performance undertaken in temperate eucalypts growing in Spain, New Zealand and Australia (Brennan *et al.* 2004; ENCE 2006; INFOR 2004b; McKenzie *et al.* 2003a; McKenzie *et al.* 2003b; Nutto and Touza 2004; Shelbourne *et al.* 2002; Washusen and Innes 2007; Washusen *et al.* 2004). In sub-tropical and tropical eucalypt species the research on processing performance is being undertaken mainly in Brazil, Argentina, Australia and South Africa for species such as *E. grandis* and its hybrids (Aparicio *et al.* 2005; DPI Department of Primary Industries and Fisheries 2005; Lima *et al.* 2002; Lima 2005; Verryn *et al.* 2005). Studies aiming to examine the genetic control of growth stress related traits have been carried out in *E. dunnii* (Henson *et al.* 2005; Murphy *et al.* 2005) and *E. grandis* (Barros *et al.* 2002; Pádua *et al.* 2004). Other examples of similar studies aimed at determining the genetic control of some wood properties relevant to solid-wood production such as shrinkage, collapse, checking propensity, spiral and interlocking grain or sawn board distortion have been carried out in *E. dunnii* (Harwood *et al.* 2005; Henson *et al.* 2005; Thinley *et al.* 2005), *E. nitens* (Hamilton 2007; Kube and Raymond 2005), *E. globulus* (Greaves *et al.* 2004b; Hamilton *et al.* 2007), *E. grandis* (Santos *et al.* 2004), and *E. pilularis* (Smith) (Pelletier *et al.* 2007). The majority of these studies have found exploitable levels of genetic control, which is promising for breeding programmes for solid-wood production. Comparatively less research has been done to date on the effects and interactions between silviculture practices and critical solid-wood quality traits (Volker 2007). Some recent studies have given some insight into the effects of plantation density, thinning intensity, tree size and age on some traits such as wood density, longitudinal growth strain (*LGS),* tension wood, log end-splitting and sawn board distortion in species such as *E. grandis* (Lima *et al.* 2006; Lima *et al.* 2000a; Trugilho *et al.* 2007a), *E. dunnii* (Murphy *et al.* 2005; Trugilho *et al.* 2004), *E. globulus* (Touza 2001b) and *E. nitens* (Washusen *et al.* 2008).

Further progress in improving the value chain for plantation-grown eucalypts relies on developing an improved understanding of the relationship among genetics, silviculture and processing with critical solid-wood traits (Volker 2007). In this context the wood quality assessment will play a relevant role, particularly the development of cost-effective and reliable non-destructive evaluation (*NDE*) techniques suitable for screening a large number of samples and traits (Raymond 2002; Raymond *et al.* 2004; Raymond and Muneri 2001).

*1.1.3 Non-destructive evaluation techniques to assess solid-wood quality traits*

The application of *NDE* techniques to assess wood quality in plantation-grown eucalypts has been well understood and developed for pulpwood silviculture (Downes *et al.* 1997; Raymond and Muneri 2001; Raymond *et al.* 2001). In this case the plantation objective is to produce wood fibre for cellulose. Therefore the plantations are managed to be profitable producing large amounts of wood volumes of small-diameter logs as quickly as possible, considering wood basic density, pulp yield and cellulose content as critical wood quality traits. Consequently, the *NDE* techniques utilized such as gravimetric assessment of basic density, SilviScan™ and near-infrared spectroscopy (*NIR*) has been calibrated to develop reliable predictors of these traits using 12mm wood cores extracted from standing trees or harvested logs (Evans 2001; Raymond and Muneri 2001; Schimleck *et al.* 2006)

Plantation-grown eucalypts for solid-wood production must be managed for the profitable sale of sawlogs suitable for processing into structural and/or appearance grade products, with residual wood (reject trees and upper logs) sold as pulpwood. From the silvicultural perspective this requires, in the majority of the cases, the application of thinning and pruning regimes. These silvicultural practices may have important effects on solid-wood quality traits, although their impacts have not yet been well-quantified. From the processor and marketing point of view, the wood quality requirements of sawlogs, either for appearance and/or structural applications, may be markedly different. Given the relatively recent history of silviculture and processing of plantation-grown eucalypt timber, there has been comparatively less progress in the development of *NDE* techniques and cost-effective and reliable indicators of sawlog quality (Raymond 2002). Nevertheless, numerous *NDE* methods such as acoustic wave velocity (*AWV*) tools; extensometers; *NIR* technology; X-ray densitometry, diffractometry; high resolution image analysis and computed tomography, are now been progressively studied in eucalypts to develop predictors of raw material suitability and solid-wood product value (Armstrong 2003; Dickson *et al.* 2003; Harwood *et al.* 2005; McConnochie *et al.* 2004; Raymond *et al.* 2004; Yang 2007). The most studied *NDE* technologies suitable for plantation-grown eucalyptus for sawlog are:

a) ***Extensometers to collect longitudinal growth strain (LGS)*:** several instruments such as dial, resistance and transducer strain gauges have been developed to estimate growth stress in standing trees or harvested logs (Yang *et al.* 2005). As growth stress is defined by the product between *strain* and the modulus of elasticity (MOE), the extensometers can measure *LGS* and therefore give an indirect estimation of growth stress. If *MOE* is known, growth stress can be calculated. The CIRAD-Forêt growth strain gauge is one of the most commonly used devices to measure *LGS* at the wood surface of standing trees and logs (Cassens and Serrano 2004; Yang *et al.* 2005). The CIRAD-Forêt growth strain gauge is based on measuring the distance between two reference points (pins driven into the stem) before and after a hole centred between these points is drilled. The amount of displacement (separation) of the pins as the result of the drilling of the hole is registered using a dial gauge and is regarded as a direct measure of the strain released: the greater the displacement, the greater the strain (de Fégely 2004 ; Raymond *et al.* 2004). The CIRAD-Forêt growth strain gauge has been used with plantation-grown eucalypt species such as *E. dunnii* in Australia (Murphy *et al.* 2005), *E. grandis* and its hybrids in South Africa and Brazil (Trugilho *et al.* 2006; Verryn *et al.* 2005), in *E.*

*globulus* grown in Australia (Raymond *et al.* 2004; Yang 2005; Yang *et al.* 2002) and in *E. nitens* in Chile (Valdés 2004). Some of these studies have found significant relationships between *LGS* and stocking rate (stems $ha^{-1}$); and also between *LGS* and tree diameter, but not always giving similar conclusions. These studies have also found significant relationships among *LGS* and some processing traits such as log-end splitting and sawn-board distortion, but have not always given concrete indications of predictive power or cost involved in sampling. In addition, the majority of these studies have been carried out on a small number of trees and also in plantation-grown trees managed without thinning or pruning regimes.

**b)** ***Acoustic wave velocity (AWV) measurements*****:** wood mechanical properties such as timber stiffness (static modulus of elasticity, $MOE_S$) have traditionally been determined by the time consuming and expensive bending test on wood samples which record deflection as load is applied (Carter *et al.* 2005). Therefore this method is not suitable to screen large numbers of trees aiming to select among large populations for breeding improvement or to segregate timber in an operational way (Dickson *et al.* 2003). Obtaining samples also results in the destruction of the standing tree. From previous research, mainly developed in softwood species (Carter *et al.* 2005; Carter *et al.* 2006; Wang *et al.* 2005a; Wang *et al.* 2001), it is well known that the stress acoustic wave propagation properties of the timber, either measured on standing trees, logs or sawn-boards, are well correlated with mechanical properties, particularly with $MOE_S$ (Huang *et al.* 2003). In fact the dynamic modulus of elasticity ($MOE_D$) along the fibre, which is a function of acoustic wave velocity (*AWV*) and wood density, has been shown to be well correlated with $MOE_S$ (Carter *et al.* 2005;

Toulmin and Raymond 2007), and therefore generally also with timber strength (modulus of rupture, *MOR*), due to the moderate correlation between $MOE_S$ and *MOR* (Lei *et al.* 2005; Steele and Cooper 2003). *NDE* methodologies and acoustics tools have been developed to calculate $MOE_D$ with the aim of predicting $MOE_S$ and other related mechanical properties such as *MOR* (Huang *et al.* 2003).

The transit time-of-flight (*TOF*) method, which can be applied in standing trees, logs or sawn-timber, and the sonic resonance method, which can be applied in logs and sawn-timber, are the two main *NDE* techniques to measure *AWV* (Carter *et al.* 2005; Carter *et al.* 2006). *TOF* acoustic tools such as the FAKOPP ™ Microsecond Timer, give the transit time of an introduced stress wave (sound impulse) during its propagation into a wood sample between two probes (Fakopp 2000). Using the distance between the probes and the stress wave transit time, *AWV* is calculated. In tools using the resonance method such as DIRECTOR HM200™, the stress wave is introduced by hammering at one end of the specimen (log or board), and it travels along the specimen until it gets reflected (Fibre-Gen 2007). The reflected wave is measured at the same end of the specimen as where the wave was launched (Carter *et al.* 2005; Carter *et al.* 2006; Waghorn 2006). The resonance method tends to measure the average velocity of a number of reverberating waves, rather than the time of arrival of a first wave front as the *TOF* does. Both techniques have been successful in relating *AWV* measurements with $MOE_S$ in natural softwood forests (Wang *et al.* 2005a) and in *Pinus radiata* D. Don plantations (Lasserre *et al.* 2005; Tsehaye *et al.* 2000). *AWV* is now used to assist selection of better genotypes, support silvicultural practices and segregate pine logs at the mill to improve structural grade recoveries (Dickson *et al.* 2004; Grabianowski *et al.* 2004; Lasserre *et al.* 2005; Lasserre *et al.* 2007; Lindstrom *et al.* 2002). To date, there are few published studies in which *AWV* has been related to mechanical properties in plantation-grown eucalypt timber (Dickson *et al.* 2003; Henson *et al.* 2005). These studies in *E. dunnii* and a study done in *E. nitens* and *E. globulus* (Harwood *et al.*, unpublished), have given some insights in the capability of *AWV* to predic $MOE_S$, and also some indications about genetic variation and heritability in $MOE_S$ estimated from *AWV*. Less progress has been made in studying the effects of silvicultural practices (*e.g.* thinning) on *AWV* and $MOE_S$; and the capability of *AWV* to reliably predict sawing performance and value limiting appearance defects.

c) ***NDE sampling methods for assessing shrinkage and collapse*:** Variation in shrinkage and collapse behaviour have been related to drying degrade problems such as checking (Greaves *et al.* 2004b; Hamilton 2007; Yang and Fife 2003), which is a value limiting factor for appearance end-uses, particularly in *E. nitens* plantations grown for sawlogs (Shelbourne *et al.* 2002; Washusen and Innes 2007). Variations and patterns of wood shrinkage, collapse and basic density has been non-destructively assessed from fixed-height wood cores (12 mm diameter, pith to bark or bark to bark) from standing trees and logs, information which also has been used to explore the relationships with other solid-wood traits such as checking propensity. This *NDE* technique has been recently applied to support tree breeding programmes in species such as *E. nitens* (Hamilton 2007), *E. globulus* Labill. (Raymond *et al.*, unpublished data), *E. dunnii* Maiden (Harwood *et al.* 2005) and *E. pilularis* (Smith) (Pelletier *et al.* 2007). Nevertheless, this *NDE* technique has not yet been fully validated and uncertainty remains as to its reliability for the prediction of sawlog quality in eucalypts (Harwood *et al.* 2005; Pelletier *et al.* 2007).

**d) *SilviScan™ technology and NIR spectroscopy*:** are promising *NDE* techniques for sampling eucalypts for solid-wood production. Using only small wood samples such as wood cores and wood strips, SilviScan™ has been used for instance to estimate tension wood occurrence and severity in *E. globulus* (Washusen 2002); wood density and density variation in *E. nitens* (Evans *et al.* 2000); and wood stiffness and *MFA* variations in *E. globulus, E. nitens* and *E. regans* (Evans *et al.* 1999; Yang and Evans 2003); and prediction of wood tangential shrinkage in *E. globulus* (Washusen and Evans 2001). The technique also has been recently used to predict *LGS* levels using information on microfibril angle (*MFA*) and cellulose crystallite width ($W_{\text{cryst}}$) in *E. globulus* (Yang *et al.* 2006). NIR spectral bands of ground wood-meal samples have been used in *E. globulus* to estimate *LGS* (Baillères *et al.* 2003), and could be also used to predict $MOE_S$, *MOR* and wood density (Schimleck *et al.* 2003; Tsuchikawa 2007).

These *NDE* techniques are now being studied in eucalypts to find reliable solid-wood quality indicators such as *LGS, AWV,* $MOE_D$, wood basic density (and its variations), *MFA* and $W_{cryst}$ that alone or in conjunction may be able to explain enough variance (predictive power) of critical factors limiting the value of solid-wood, after accounting for traditional tree and log information such as tree diameter (D), total tree height (H) and H/D. Overall, predictive models based on multiple regression modelling techniques have been studied in eucalypts with this aim (Verryn *et al.*

2005; Washusen and Evans 2001). A comprehensive assessment of potential sawlog quality indicators for *E. globulus* has been carried out by Yang (2007).

## 1.2 Study background

### *1.2.1 Context and aims*

The Master of Science (MSc) by research reported in this thesis was carried out under the Cooperative Research Centre for Forestry Research Programme 2: ***High-value wood resources*** (CRC Programme 2 hereafter), which aims to increase profitability and investor confidence in planting and managing eucalypts for pulpwood, engineered and solid-wood products (CRC for Forestry 2007). One programme goal is to improve the understanding of the technical and economic feasibility of utilising plantation-grown eucalypts for solid-wood production. CRC Programme 2 includes five research projects, and its research project 2.4 ***"Incorporating wood quality into plantation estate management"*** was the technical framework for undertaking this MSc research. One objective of research project 2.4 was to develop effective sampling protocols to describe solid/engineered log value, for temperate eucalypts species such as *Eucalyptus nitens*. In this context the current MSc research was designed to assess the utility of *NDE* techniques applied on standing trees and harvested logs for predicting critical solid-wood quality traits from a full rotation 22-year-old *E. nitens* plantation, managed as a thinning trial from age six years. The *NDE* techniques studied were:

a) ***peripheral longitudinal growth strain (LGS)*** measured on standing trees; and

b) ***acoustic wave velocity (AWV)*** measurements on both standing trees and harvested logs.

A destructive sampling designed to measure wood tangential and radial shrinkage and collapse and basic density of small wood-blocks taken from the logs was also implemented.

Linear mixed models and multiple linear regressions (*MLR*) were applied to explore:

a) ***sources of variation in each NDE measurement and wood-block trait***, examining the effects of thinning treatment, tree diameter and other experimental design factors on *LGS, AWV* and wood-blocks traits; and

b) ***capability of LGS, AWV and wood-block traits to individually predict***: **critical sawing traits** such as log end-splitting, sawn-board distortion (bow and spring), board shrinkage (in thickness and width), board end-splitting and checking propensity, product recoveries and product value per cubic metre of log input; and **wood mechanical properties** such as static modulus of elasticity ($MOE_S$ or timber stiffness); modulus of rupture (*MOR* or strength); and Janka hardness.

This research aimed to contribute to:

a) ***improved understanding of the usefulness of NDE techniques*** in ***evaluating trees and logs*** in *E. nitens* plantation-grown for solid-wood production, and

**b)** ***technical information required for defining future solid-wood NDE sampling protocols*** suitable for plantation-grown eucalypt timber.

The application of reliable and cost-effective *NDE* sampling techniques for solid-wood production may be a powerful tool for:

**a)** ***selecting better genotypes*** for breeding of trees with favourable wood quality and processing performance;

**b)** ***study of wood properties over time***, improving and supporting silviculture interventions (e.g. thinning regimes) to produce high-value sawlogs and informing decisions on optimal rotation age;

**c)** ***better resource characterization and stand valuation*** through sampling regimes that characterise log suitability for different end uses; and

**d)** ***more efficient and profitable processing*** due to improved log segregation strategies before processing (allocation of raw material fit for purpose), better wood quality classification after processing, improved recoveries of both appearance and structural grade seasoned sawn products and reduced processing cost.

*1.2.2 Goulds Country silvicultural trial and processing study*

A 22-year-old plantation of *E. nitens* located at Gould's Country (41°05′ S, 148°06′ E, altitude 120 masl, mean annual rainfall 779 mm) in the northeast of Tasmania, Australia, was studied (Figure 1.1). The plantation was established at 3.5 x 2.5 m spacing (1143 trees $ha^{-1}$) by Forestry Tasmania in 1984, using seedlings raised from the Toorongo Plateau (Victoria) provenance. The trial tested the effects of both thinning intensity and a single pruning treatment on stand productivity, individual tree growth and form, and subsequently on processing efficiency and product quality (Washusen *et al.* 2008). Four thinning treatments (*STOCKING*), expressed as stems $ha^{-1}$ retained, were imposed at age six years: 100, 200, 300, 400 stems $ha^{-1}$, in addition to an unthinned control treatment, which after natural mortality retained approximately 750 stems $ha^{-1}$ at age 22 years. The treatments were applied using a randomized block design with four replicates; two replicates were unpruned and two replicates were pruned to 6.4 m in a single lift, immediately prior to thinning when mean dominant height of the stand was 13.8 m. Plot size was 25 m x 40 m (0.1 ha) and a buffer row surrounding each plot was treated with the same thinning and pruning treatments. The thinning was executed from below with selection of final crop trees based on a combination of superior stem form and tree vigour while ensuring that retained trees in the thinned treatments were not immediately adjacent. The trial presents one of the first opportunities to study relationships between thinning intensity and critical solid wood traits in this species. A full discussion of the stand level responses to pruning and thinning up to and including age 22 years is given by Wood and Volker (in preparation). Additional information can also be consulted in Gerrand *et al.* (1997a), Medhurst and Beadle (2001) and Medhurst *et al.* (2001).

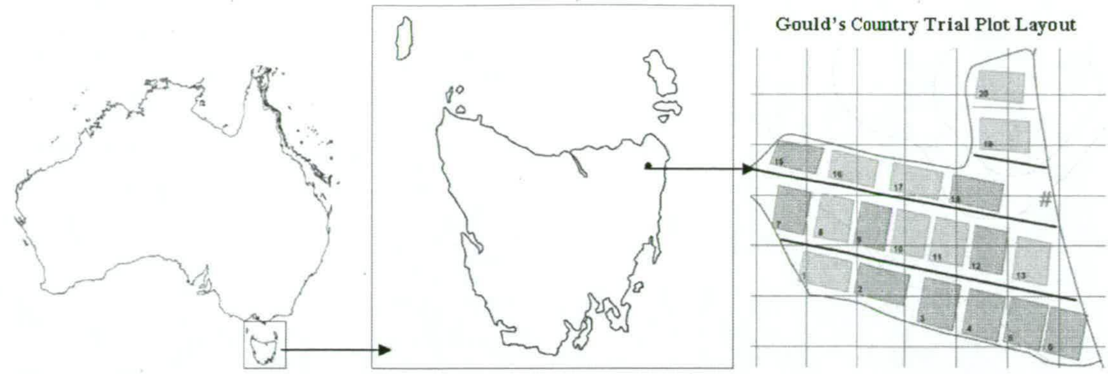


Figure 1.1. Goulds Country thinning trial location and plot layout

In May 2006, a total of 81 pruned trees were selected for a sawing study carried out by the CRC for Forestry (Washusen *et al.* 2008). A stratification and accrual selection strategy was applied because log diameter was known to affect processing performance, the aim was to obtain, as closely as possible, matching sets of trees with a similar range of diameter at breast height over bark (*DBHOB*) for the five stocking treatments (Table 1.1). As a consequence of the tree selection and sawing strategy, only dominant trees were selected from the higher stocking treatments (400 stems $ha^{-1}$ and unthinned control).

Table 1.1 Tree diameter distributions by thinning treatment for the trial population (pruned replicates) and the trees selected to be sawn

| | Unit | STOCKING (stems $ha^{-1}$) | | | | | |
|---|---|---|---|---|---|---|---|
| | | 100 | 200 | 300 | 400 | Control | **Trial** |
| Population | | | | | | | |
| Number of trees | | 20 | 36 | 56 | 80 | 122 | 314 |
| Mean *DBHOB* | cm | 50.2 | 44.1 | 37.7 | 33.8 | 24.3 | 33.0 |
| *DBHOB* range | cm | 27.9-63.9 | 26.3-60.1 | 17.2-59.4 | 18.7-52.9 | 6.6-47.2 | 6.6-63.9 |
| Sampled trees | | | | | | | |
| Number of trees | | 12 | 21 | 20 | 16 | 12 | 81 |
| Mean *DBHOB* | cm | 50.02 | 43.63 | 43.08 | 40.84 | 37.86 | 43.03 |
| *DBHOB* range | cm | 39.4-60.6 | 32.3-60.1 | 31.4-59.4 | 31.4-52.9 | 30.3-47.2 | 30.3-60.6 |

After collecting standing tree *NDE* data, the 81 trees were mechanically felled, cross-cut and debarked, to produce 81 pruned bush-logs at least 5.7 m in length, which were tagged, their log ends sealed with wax and gang nailed to prevent further development of any end splits. The bush-logs were transported to a sawmill located at St Helens, Tasmania where they were cross-cut again, producing a total of 162 sawlogs, each at least 2.7 m in length; thus each tree produced a lower and upper sawlog (Washusen *et al.* 2008). Sawlogs from 41 trees with diameter over bark (*DBHOB*) under 43 cm were back-sawn, and those from 40 trees with *DBHOB* over 43 cm were quarter-sawn. Sawing strategies aimed to produce 25 mm thick dried boards while maximizing board width. A central cant from each log was painted on the southwest (SW) side of the stem and a total of 213 back-sawn and 329 quarter-sawn boards were collected for intensive assessment from within the painted zones of the cants. Each set of boards provided a sample of boards from the SW side of the log, whether back-sawn or quarter-sawn. As a result, different sized logs gave different numbers of boards representative of what could be recovered pith to bark on the SW aspect (Washusen *et al.* 2008). The back-sawn boards selected from the painted cant were pre-dried in a small kiln at the University of Tasmania using a schedule in which relative humidity was progressively lowered from 90% to 60% and dry bulb temperature increased from 20 to 25°C over a two-month period. Kiln air-speed was set at 0.5 m $s^{-1}$. Pre-drying was continued until average moisture content was below 20% as indicated by sample boards and confirmed by using a resistance moisture meter. The quarter-sawn boards and the remainder of the boards from the back-sawn logs were initially pre-dried using similar conditions to those used for the back-sawn boards. Due to the volume of the material for drying some wood had a period of air-drying prior to reconditioning and final drying. Weighting of drying stacks was minimal. Once below fibre saturation point all the boards were reconditioned and kiln dried at ITC Timbers Ltd, Launceston (Washusen *et al.* 2008). Due to commercial constraints the kiln schedule cannot be reported, but they are considered to be typical of current commercial practice for drying boards sawn from native eucalypt forest logs in Tasmania.

Several log traits, sawn-board traits, product recoveries and product value characteristics were measured in this sawing trial, and their values have been reported in a CRC for Forestry Technical Report (Washusen *et al.* 2008). From this sawing study, the following log quality, sawing traits and mechanical properties were utilized to determine their relationships with the *NDE* measurements and wood-blocks traits previously gathered from standing trees and harvested logs:

**a)** ***Log end-splitting index:*** determined at both butt and top log ends, following the methodology described by Yang *et al.* (2005) which is detailed in Chapter 2,

**b)** ***Sawing traits***: flitch and slab distortion (from quarter-sawn material), board bow and board spring in green and dry condition, presence of surface and internal checks per board, sawn-board shrinkage in width and thickness, board end-splitting extent before and after drying, losses of board volume from end-docking, total recovery, grade recoveries (select, standard and utility) and product value per cubic metre of log input,

**c)** ***Wood mechanical properties***: $MOE_S$, *MOR* and Janka hardness, which were determined according to AS/NZS 4063:1992 (Australian/New Zealand Standard 1992), from a subsample of 332 dried boards randomly selected from the remaining boards generated by the processing trial. This sample strategy was adopted as a second best option after the intensively assessed boards from the SW cants were lost in the sawmill.

Specifically chapter 2 details the study aimed to analyse sources of variation of *LGS* measured on standing trees in a full rotation *E. nitens* plantation, exploring its capability to predict sawlog processing performance. Similarly the experimental chapter 3 gives the results on the predictive power of acoustic wave velocity data measured on both standing trees and logs, and shrinkage properties measured on wood blocks. Chapter 4 is a general discussion, analysing those areas in which the *NDE* techniques studied could be applied.

# CHAPTER 2

## Longitudinal growth strain as a log and wood quality predictor for plantation-grown *Eucalyptus nitens* sawlogs

### 2.1 Abstract

Longitudinal growth stress was assessed by measuring peripheral longitudinal growth strain (*LGS*) on 22-year-old pruned *Eucalyptus nitens* trees from a plantation thinning trial in Tasmania. A total of 81 trees selected from five residual stocking treatments; 100, 200, 300 and 400 stems $ha^{-1}$, and an unthinned control treatment with about 750 stems $ha^{-1}$ (initially 1100 $ha^{-1}$) were assessed. *LGS* was measured at four cardinal directions at breast height on each tree. The effects of stocking treatment and tree size on *LGS* and the relationships between *LGS* and solid-wood traits from a subsequent processing study were examined. *LGS* levels were low relative to other published values for plantation-grown eucalypts and they were not significantly affected by either stocking level or tree diameter at breast height over bark (*DBHOB*). *LGS* was significantly ($P<0.001$) higher on the western aspect, which was the direction of the prevailing wind. An index of log end-splitting (*SPLITINDEX*) was not affected by stocking, but was positively related with *DBHOB* ($P<0.001$), log position within stem ($P<0.001$, higher log end-splitting for the second, upper sawlog), and positively related with *LGS* ($P<0.001$). Overall, tree-mean *LGS* explained up to an additional 20% of the variance in *SPLITINDEX* after *DBHOB* and log position were accounted for in a linear regression model. Tree mean *LGS* was positively associated with some detrimental processing performance

characteristics including green (*P<0.001*) and dry (*P<0.01*) board bow, green board spring (*P<0.05*), dry board end-splitting (*P<0.05*), and loss of green board volume from end-docking (*P<0.05*). *SPLITINDEX* had a significant positive relationship with slab distortion (*P<0.05*), dry bow (*P<0.05*), green board bow (*P<0.01*) and dry board spring (*P<0.01*), and negative (*P<0.05*) relationship with total sawn-board recovery. *SPLITINDEX* was also a good indicator of volume losses from docking board end-splits; the higher the index the higher the timber losses. *LGS* and *SPLITINDEX* were not significantly associated with levels of board shrinkage and the occurrence of surface and internal checks.

## 2.2 Introduction

*Eucalyptus nitens* (Dean and Maiden) Maiden has been extensively planted in Australia, Chile, New Zealand and South Africa for production of wood fibre for the pulp and paper industry. Some plantations are now thinned, pruned and grown on longer rotations, in order to produce pruned sawlogs suitable for high-value solid-wood applications (Nolan *et al.* 2005). The shift to solid-wood products from plantations is also occurring with other eucalypt species, such as *E. grandis* and *E. globulus* in an attempt to develop new hardwood markets and improve plantation profitability for grower organizations (Nutto *et al.* 2006). Nonetheless a global solid-wood industry based on plantation-grown eucalypt timber is still at an early stage of development. Poor wood quality as a consequence of growth stresses, excessive shrinkage and collapse, occurrence of tension wood, checking propensity and variation in strength and hardness is a primary limiting factor (Chafe 1990; Ilic 1999; Malan 2003; Washusen and Innes 2007; Washusen *et al.* 2004; Yang and Pongracic 2004; Yang and Fife 2003). Wood product quality may be negatively influenced by current silviculture practices and genetic material, with most plantations grown primarily for pulpwood production (Nolan *et al.* 2005; Raymond 2002).

In some eucalyptus species, high levels of growth stresses in both standing trees and harvested logs have been mentioned as an important limitation to solid-wood quality (Waugh 2005; Yang and Waugh 2001). Growth stresses released during tree felling and crosscutting logs can lead to log end-splitting. Wood brittleness in the centre core of the stem (brittle heart) associated with high growth stress may produce weak material in the log core. During sawing there may be constraints on the application of sawing strategies as a consequence of growth stresses. High growth stresses may also contribute to flitch and board deflection, board width and thickness variation, and increase end-splits in cants and boards during sawing. These consequences of growth stresses may reduce volume recovery and product value through material loss from board end-docking, reduced sawn-board length and width and product downgrading. Consequently, growth stresses have been widely studied since the 1930s (Boyd 1950; Jacobs 1938; Kubler 1959; Malan 1995; Nicholson 1971 ; Raymond *et al.* 2004; Touza 2001a; Trugilho *et al.* 2006; Yang 2005; Yang and Waugh 2001).

Growth stresses are tensile and compressive forces distributed orthotropically in the longitudinal, tangential and radial directions in the tree stem, held in a natural balance within standing trees, developed as a result of cumulative self-generated forces during wood-fibre formation (*maturation stresses*) and the effects of tree weight and wind (*supporting stresses*). The longitudinal component of growth stress has been considered the most significant from a solid-wood quality point of view, because of its greater influence on log processing performance (Jacobs 1938; Kubler 1959; Yang and Waugh 2001). Growth stress is defined as a function of the strain caused by cell maturation and the modulus of elasticity of the wood (*MOE*) (Yang and Waugh 2001). Growth stress cannot be measured directly, but it can be calculated from *MOE* and strain measurements. Assuming *MOE* to be approximately constant between and within trees, longitudinal growth strain (*LGS*), which can be non-destructively measured at both stem or log surface (Yang *et al.* 2005), is regarded as a direct estimator of longitudinal growth stress. When the *LGS* levels are high and/or asymmetrically distributed across the stem diameter, or when the tension to compressive strain gradient from pith to cambium is pronounced, reduced sawlog processing performance is anticipated (Yang 2005). For instance, peripheral *LGS* levels have been found to be significantly positively related to log end-splitting and sawn board distortion in a 32-year-old *E. globulus* thinned plantation growth in Victoria, Australia (Yang and Pongracic 2004), to sawn timber distortion (bow and spring) in 23-year-old *E. cloeziana* plantation (Muneri *et al.* 1999) and to board bow and board end-splitting in *Liriodendron tulipifera* L. plantation (Cassens and Serrano 2004).

Genetic improvement and intra-specific competition management have been mentioned as potential strategies to minimize negative consequences of higher levels of *LGS* on sawlog performance (Murphy *et al.* 2005; Nutto and Touza 2004; Raymond *et al.* 2004). Studies undertaken on *E. dunnii* (Murphy *et al.* 2005) and eucalypt clones (Trugilho *et al.* 2007a) have demonstrated sufficient genetic variation and heritability in *LGS* to suggest that selection and breeding for reduced *LGS* could be effective. In 10-year-old *E. nitens* plantations in Chile significant differences in *LGS* values between 3 provenance and 10 families were found (Valdés 2004). Despite the amount of information available so far on the relationship between *LGS* and silviculture practices such as spacing or thinning (Ferrand 1983;

Lima *et al.* 2006; Lima *et al.* 2000b; Malan 1995; Wahyudi *et al.* 2001; Wilkins and Kitahara 1991a; Wilkins and Kitahara 1991b), uncertainties persist about the effectiveness of stand density control as a silvicultural practice to control growth stress levels in standing trees. There are also still doubts about the ability of *LGS* to reliably predict solid-wood quality in some fast-grown eucalypt plantation species such as *E. globulus* (Raymond *et al.* 2004) and *E. grandis* Hill ex Maiden (Lima *et al.* 2004; Verryn *et al.* 2005).

In temperate eucalypts species, a few studies have delivered valuable insights in the prediction of sawlog suitability of *E. globulus* plantation-grown timber from standing tree growth strain measurements, log end-splitting and wood-core information (Yang 2007; Yang 2005) and from shrinkage and collapse measurements to identify check propensity (Yang and Fife 2003). No similar studies have been carried out in *E. nitens* so far, and there have been no studies on *LGS* in *E. nitens* grown over a full sawlog rotation because of the scarcity of mature plantations managed under a sawlog regime. Consequently, there is limited progress towards identifying reliable and non-destructive indicators of *E. nitens* sawlog quality, and also inadequate understanding of the silvicultural control of growth stress and its consequences in this species.

Trials of *E. nitens* grown under sawlog silvicultural regimes by Forestry Tasmania are now approaching full rotation age (Baker and Volker 2007). In 2006 the Cooperative Research Centre for Forestry, Australia (CRC for Forestry) conducted a sawing study on a 22-year-old *E. nitens* plantation in which a thinning intensity trial had been imposed, to determine the sawn product recovery and sawlog value using conventional processing methods (Washusen *et al.* 2007). This sawing study is one of the most detailed undertaken to date on plantation *E. nitens* grown for solid-wood production, and the first opportunity to study relationships between thinning intensity and important solid-wood traits in this species. Allied to this sawing study, the ability of several *NDE* methods including *LGS*, acoustic wave velocity and destructive measurement of shrinkage properties in small wood samples to predict the sawing performance of plantation-grown *Eucalyptus nitens* were assessed. Here we report variation in *LGS* in standing trees selected from four thinning intensity treatments and an unthinned control, in a full rotation *E. nitens* plantation, and its relationship with sawing traits obtained from a sawing trial, to assess the capability of standing tree *LGS* data to predict plantation-grown sawlog performance.

## 2.3 Materials and methods

### *2.3.1 Non-destructive measurements of longitudinal growth strain at standing trees*

One week before the mechanical harvest, *LGS* was measured on the 81 selected trees (Table 1.1), using the CIRAD-Forêt strain gauge as described in Yang *et al.* (2005). Four measurements per standing tree at breast height (1.3 m) were collected from the northwest, southwest, northeast and southeast stem aspects, to cover potential circumferential variation arising from prevailing wind effects and/or tree-crown asymmetry (de Fégely 2004 ; Touza 2001a). The CIRAD-Forêt strain gauge has a micrometer that measures the longitudinal movement at the wood surface induced by the release of *LGS* in the standing tree after a hole centred between two points is drilled. The displacement (strain or *LGS*) is regarded as an estimate of the stress released, the greater the strain, the greater the growth stress level in general.

*2.3.2 Information from a subsequent sawing trial*

Immediately after felling the 81 selected trees at a stump height of 0.2-0.4 m, logs were cross-cut to produce 81 bush logs at least 5.7 m in length, which were tagged, their log ends sealed with wax and gang nailed to prevent further development of any end splits, and debarked. The bush logs were transported to a sawmill located at St Helens, Tasmania where they were cross-cut again, producing a total of 162 sawlogs, each at least 2.7 m in length; thus each tree produced a lower and upper sawlog (Washusen *et al.* 2007). A log-end split index was measured on each log end of each sawlog after removing gang nails. Subsequently the two sawlogs of each tree were either both back-sawn or both quarter-sawn, according to their tree *DBHOB* class, with the exception of the upper sawlog of one of the quarter-sawn trees from the 100 stems $ha^{-1}$ treatment, which was discarded because of excessive felling damage. Sawing strategies aimed to produce 25 mm thick dried boards while maximizing board width. A central cant from each log was marked on the southwest side of the stem and a total of 213 back-sawn and 329 quarter-sawn boards were collected from within the marked zones cants for intensive assessment. From this sawing study, the following log quality and processing variables were analysed to determine their relationships with standing tree *LGS* data gathered.

a) ***Log end splitting index (SPLITINDEX)***: for each of the 161 sawlogs both log end-split lengths on the logs ends and extent of the splits along the stem were recorded after removing gang nails. Using these data, a log end-splitting index for both log ends, butt and top, was separately calculated for each log end, using Equation 2.1 (Yang 2005).

$$SPLITINDEX = \left[ (SL_{END})^2 / 2 + (SL_{SURFACE} \times SL_{END}) \right] / (R_{MEAN})^2 \qquad (2.1)$$

Where:
*SPLITINDEX* is the log-end split index either on the butt log end (*SPLITINDEX-BUTT*) or on the top log-end (*SPLITINDEX-TOP*), the higher the index the higher the splitting severity.
$SL_{END}$ the split length on the log end.
$SL_{SURFACE}$ the split length on the log surface.
$R_{MEAN}$ the mean radius of the log end.
The sum of both butt and top log end-splitting indices was then expressed as a total value of log end-splitting per sawlog (*SPLITINDEX-SUM*).

**b)** ***Flitch and slab distortion****:* collected on two occasions during sawing of each of the 77 quarter-sawn logs. The distortion was measured to the nearest mm, in flitches after the logs were halved on the first breakdown saw, measuring the distortion in each half of the log (the southwest and northeast halves), and in the form of spring, measured in the centre slab from each half of the log immediately after it was sawn on the second breakdown saw.

**c)** ***Sawn-board distortion****:* collected on the 542 intensively assessed boards, both spring and bow in green and dry conditions, measured to the nearest mm, at the maximum point of distortion.

**d)** ***Sawn-board shrinkage****:* collected on the intensively assessed boards, and calculated as percent change from green to dry condition in board thickness and width, at three positions per board: 25%, 50% and 75% of board length.

**e)** ***Board end-splitting and losses of green board volume by end-docking****:* The length of the longest splits located at both ends of each one of the 542 intensively assessed boards was measured after drying. Using this information and the board dimensions, a predicted loss of green volume due to docking end splits after drying was calculated, and expressed as a percent of green board volume.

f) ***Checking propensity:*** after surface dressing, board docking and mill grading, the occurrence and extent of both surface and internal checking were measured in each one of the intensively assessed boards. The number and length of internal checks were measured at two positions per board by sectioning at 33% and 66% of board length after end-docking. The surface checks were measured along the board surface area on its better face, to subsequently calculate a total surface check length per $m^2$ of board area.

g) ***Product recovery:*** Total recovery and product grade recoveries per sawlog were determined using the log volume and the board volumes produced after surface dressing and docking end-splits, considering three product grades: Select; Standard (medium feature grade) and Utility (high feature or common grade), defined according to a modified grading strategy based on mill grading to meet the requirements of Australian Standard AS2796.1 (Standard Australia 1999) and a regrading strategy according to CSIRO standards (Washusen *et al.* 2007). The sawn-boards were end-docked according to standard mill procedures, and therefore do not necessarily coincide with the theoretical losses of board volume calculated from board end-splitting length.

## 2.4 Statistical analyses

Statistical analyses were performed using the SAS statistical program package 9.1 (SAS Institute Inc 2004), and were structured using the following experimental strata: tree, log (upper/lower sawlog, two sawlogs per tree) and board within log. Table 2.1 summarizes the stratum positions and the relevant experimental factors, including the non-destructive measurements and the processing performance variates examined in the current study.

Table 2.1 Stratum positions of measurements and potential explanatory factors/variables

| Stratum | Variates/factors | Distribution/ Transformation | Symbol / Description | Unit |
|---|---|---|---|---|
| Tree | Diameter at breast height over bark | continuous | *DBHOB* | cm |
| | Peripheral longitudinal growth strain | continuous | *LGS* | mm |
| | *LGS* measurements per tree (*ASPECT*) | category | *NE; SE; SW; NW* | 1 to 4 |
| | Thinning treatment (*STOCKING*) | category | 100; 200; 300; 400; C | 1 to 5 |
| Log | Log position within the tree (*LOG*) | category | Lower; Upper | 1 or 2 |
| | Log end splitting index | continuous | *SPLITINDEX* | Number |
| | Log end splitting index at the butt log end | continuous[1] | *SPLITINDEX-BUTT* | Number |
| | Log end splitting index at the top log end | continuous[1] | *SPLITINDEX-TOP* | Number |
| | Sum of Butt and Top splitting indices | continuous[1] | *SPLITINDEX-SUM* | Number |
| | Sawing method (*SAWMETH*) | category | Back-sawn; Quarter-sawn | 1 or 2 |
| | Total sawn-board recovery | continuous | Total recovery | % |
| | Flitch deflection[1] (*) | continuous[1] | Flitch deflection | mm |
| | Slab deflection (*) | continuous | Slab deflection | mm |
| | Product value per cubic meter log input | continuous | *PVPCMLI* | $\$/m^3$ |
| Board | Bow | continuous[1] | Bow | mm |
| | Spring | continuous[1] | Spring | mm |
| | Internal check category | category[2] | Zero checks; Otherwise | 1 or 2 |
| | Surface check category | category[2] | < 20mm; Otherwise | 1 or 2 |
| | Sum of end-split length (both board ends) | continuous[1] | BoardSplit -green / dry | mm |
| | Losses of volume from end-docking | continuous[1] | End-dock-vol-green | % |
| | Mean shrinkage in the board thickness | continuous | Shrinkage-thickness | % |
| | Mean shrinkage in the board width | continuous | Shrinkage-width | % |

C= control unthinned.
(*) Flitch and slab distortion were only measured on quarter sawn material.
[1] Variable square-root transformed to obtain normality before mixed models were fitted.
[2] Variable with binomial distribution.

### *2.4.1 Silvicultural effects on longitudinal growth strain of standing trees*

Univariate analyses with linear mixed model were fitted to analyse the impact of *DBHOB*, thinning treatments (*STOCKING*), measurement aspect (*ASPECT*) and

*TREE* identity on *LGS* specified as the dependent variable. A mixed model as per Equation 2.2 was fitted.

$$Y = MEAN + DBHOB + STOCKING + DBHOB.STOCKING + ASPECT + STOCKING.ASPECT + TREE + RESIDUAL \quad (2.2)$$

where:
*Y* is a vector of observations.
*MEAN* is the overall mean.
*DBHOB* (as a covariate), *STOCKING* and *ASPECT* are the tree diameter, stocking treatment and measurement aspect fitted as fixed effects, respectively.
*TREE* is an individual tree random effect.
*RESIDUAL* is the vector of residual errors.

A mixed model was fitted by the method of restricted maximum likelihood (REML) using the SAS MIXED procedure (SAS Institute Inc 2004). The statistical significance of the fixed effects was tested using the $F$-value specifying a Type I (sequential) expected mean squares for model effects. The significance of *TREE* identity as a random factor was tested using the $Z$-test.

*2.4.2 Relationships between standing tree growth strain and sawing performance*

A similar approach was used to examine the relationship between *LGS* and the sawing performance variables under assessment. Univariate mixed models were fitted as follows to test the factors affecting log end-splitting index:

$$Y = MEAN + DBHOB + STOCKING + DBHOB.STOCKING + LGS + LOG + + DBHOB.LOG + TREE + RESIDUAL \quad (2.3)$$

and the factors affecting each sawing trait:

$$Y = MEAN + SAWMETH + DBHOB + STOCKING + LGS + LOG + SAWMETH.LOG + SPLITINDEX + TREE + RESIDUAL \quad (2.4)$$

Model terms were as in Equation 2.2, with *LGS* (tree mean value of growth strain calculated from the four cardinal directions) as a covariate, *LOG* (log position: upper or lower), *SAWMETH* (sawing method: back-sawing or quarter-sawing) and *SPLITINDEX* (mean value of log end-splitting index) as additional fixed effects. For several dependent variables, square root transformations were required in order to obtain normality of the residual errors (Table 2.1). The models were structured at the tree stratum with *SAWMETH* declared first, then *DBHOB* and *STOCKING*, and then *LGS*, then *TREE* as a random term. At the log stratum, *LOG* was declared first, then the interaction of *SAWMETH* and *LOG*, then *SPLITINDEX*.

For category variates such as internal and surface checking occurrence, generalised linear mixed models (Schall 1991), were fitted using the SAS GLIMMIX procedure (SAS Institute Inc 2005), assuming a binomial distribution of residuals, logit link function, an estimation technique based on residual log pseudo-likelihood and the Type I (sequential) test of fixed effects (Equation 2.5).

$$Y = MEAN + SAWMETH + DBHOB + STOCKING + LGS + TREE + + LOG + SPLITINDEX + RESIDUAL \quad (2.5)$$

where:
*Y* is the probability that either surface check or internal checks category is 1 (either less than 20 mm of check length for surface checking, or no occurrence for internal checking).
Model terms were as in Equation 2.4, with *TREE* identity also as a random effect.

Replicate was initially fitted as a random effect in all the models (Equations 2.2 to 2.5), but differences between replicates were very minor and the replicate effect was not significant in any of the models. To simplify presentation of results, replicate was therefore omitted from models 2.2-2.5. In addition, multiple linear regressions (*MLR*) modelling were applied using the SAS REG procedure to determine the degree of improvement in predicting processing performance characteristics, when *LGS* and end *SPLITINDEX* were added to models that already took into account significant explanatory factors shown to be significant in the mixed model analysis, for instance *SAWMETH*, tree *DBHOB* and/or *LOG* position.

## 2.5 Results and discussion

### *2.5.1 Longitudinal growth strain: levels, sources of variation and relationships*

The *LGS* values collected at Gould's Country ranged from 0.028 to 0.230 mm with a trial mean of 0.070 mm. These levels of *LGS* are markedly lower than the *LGS* in *E. nitens* reported by Valdes (2004), who, using the CIRAD-Forêt method, found individual tree values ranging from 0.080 to 0.530 mm with an overall mean of 0.244 mm for 200 13-year-old *E. nitens* trees selected from ten families and three provenances grown in two progeny trials in Chile. The trees in his study had been planted at 3 x 2m spacing (1666 stems $ha^{-1}$) and thinned to a final 400 stems $ha^{-1}$. Higher levels of *LGS* were also reported by Raymond *et al.* (2004) (*E. globulus*), Trugilho *et al.* (2004) (*E. dunnii*), and Trugilho *et al.* (2006) (six *Eucalyptus* clones).

From the mixed model analysis to study sources of variation in standing tree *LGS*, only measurement *ASPECT* and *TREE* identity were found to have significant effects

(*P<0.001*) on *LGS*. No significant effect of *STOCKING* was found. No significant differences in *LGS* were attributable to the interactions either between *DBHOB* and *STOCKING* or between *STOCKING* and *ASPECT* (Table 2.2).

Table 2.2 Significance of factors affecting longitudinal growth strain in standing trees

| Fixed effect | Degrees of freedom | | *LGS* |
|---|---|---|---|
| | N | D | *F*-Value |
| *DBHOB* | 1 | 71 | $1.45^{ns}$ |
| *STOCKING* | 4 | 71.2 | $0.29^{ns}$ |
| *DBHOB * STOCKING* | 4 | 71.6 | $1.05^{ns}$ |
| *ASPECT* | 3 | 225 | 8.1*** |
| *STOCKING * ASPECT* | 12 | 225 | $1.49^{ns}$ |
| Random effect | | | *Z*-test |
| Tree | | | 4.75*** |

N= Numerator; D= Denominator
ns = not significant (*P>0.05*)
* =*P <0.05*.
*** = *P<0.001*.

The *LGS* levels of the *NW* and *SW* cardinal directions, facing the prevailing westerly wind direction, were significantly higher than those of the *NE* and *SE* cardinal directions (Figure 2.1).

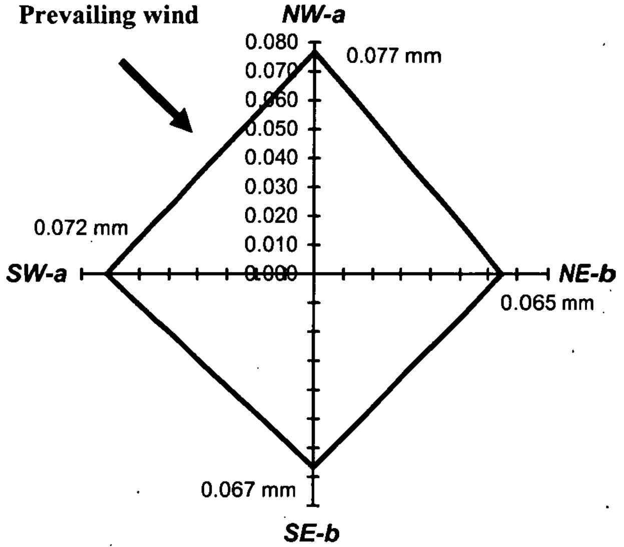


Figure 2.1. Mean values of *LGS* (mm) at breast height (1.3 m), according to stem aspect (*NW* = northwest, *NE* = northeast, *SE* = southeast and *SW* = southwest). Aspects followed by the same letter are not significantly different at *P<0.05*.

A sub-sample of the trees selected from the 200 stems $ha^{-1}$ and control treatments had asymmetrical crowns, with greater crown mass on the *NE* side of the trees, this effect being more pronounced at the wider spacing (Medhurst *et al.* unpublished). Two factors, force of the prevailing wind and tree crown asymmetry increasing the supporting growth stress component, might therefore explain the higher levels of *LGS* on the *NW* and *SW* aspects. Significant differences in *LGS* levels between stem aspects have also been reported in eucalypt plantations by Trugilho *et al.* (2006), Cardoso *et al.* (2005), Yang (2005) and Raymond *et al.* (2004). In a sub-sample of 12 *E. globulus* trees studied by Raymond *et al.* (2004) in plantations sampled in North-East Tasmania, the two individual aspects with the highest correlations with whole tree *LGS* were North and East aspects.

*STOCKING* and *DBHOB* did not influence the *LGS* in the trees studied, which were dominant in the control and 400 stems per hectare treatments, and dominant and co-dominant in the other treatments with lower stocking. Previous studies undertaken on plantation-grown eucalypts have not demonstrated consistent relationships between *LGS* and either *DBHOB* or stocking rate, citing either positive or inverse relationships or non-significance. For instance, Murphy *et al.* (2005) studying 9-year-old plantation-grown *E. dunnii* and Trugilho *et al.* (2007b) working with hybrid eucalypt clones did not find a significant relationship between *LGS* and tree diameter; Cardoso *et al.* (2005) working with clones of *E. grandis* found a linear reduction in *LGS* with increased spacing; Ferrand (1983) found *LGS* to be lower in heavily thinned treatments, but did not find any effect for low intensity thinning. In contrast, Trugilho *et al.* (2004) and Valdes (2004) found a positive relationship between *LGS* and tree diameter for 15 and 19 year-old *E. dunnii* and 13-year-old *E. nitens*, respectively.

The result obtained is consistent with that obtained by Trugilho *et al.* (2007b) on six hybrid eucalypt clones, where no relationship was detected between longitudinal strain and tree growth. However, after accounting for *STOCKING* and *DBHOB* in the statistical model, there were highly significant ($P<0.001$) differences in mean *LGS* of individual trees. Because the trial was not pedigreed, it was not possible to determine the extent to which these between-tree differences were under genetic control.

From regression modelling, it was found that tree mean *LGS* values could be predicted with good precision from two opposite *LGS* measurements. For instance, *LGS* from the *SW* and *NE* measures explained 89% of the variance in tree means values of *LGS*, compared to 70% of variance explained if the best single aspect (*NW*) was used to predict mean *LGS* (analysis not presented). Similarly, Raymond *et al.* (2004) found in *E. globulus* plantations a correlation of 0.86 between the mean of two strain measurements collected at breast height on opposite sides of the tree and the average strain values determined in the lower logs.

*2.5.2 Standing tree longitudinal growth strain as predictor of sawlog quality*

**a) *Log end-splitting index***

The upper sawlogs had significantly (*P<0.001*) greater levels of *SPLITINDEX* than the lower sawlogs, and within individual logs, the top ends showed more splitting than the butt ends (Figure 2.2).

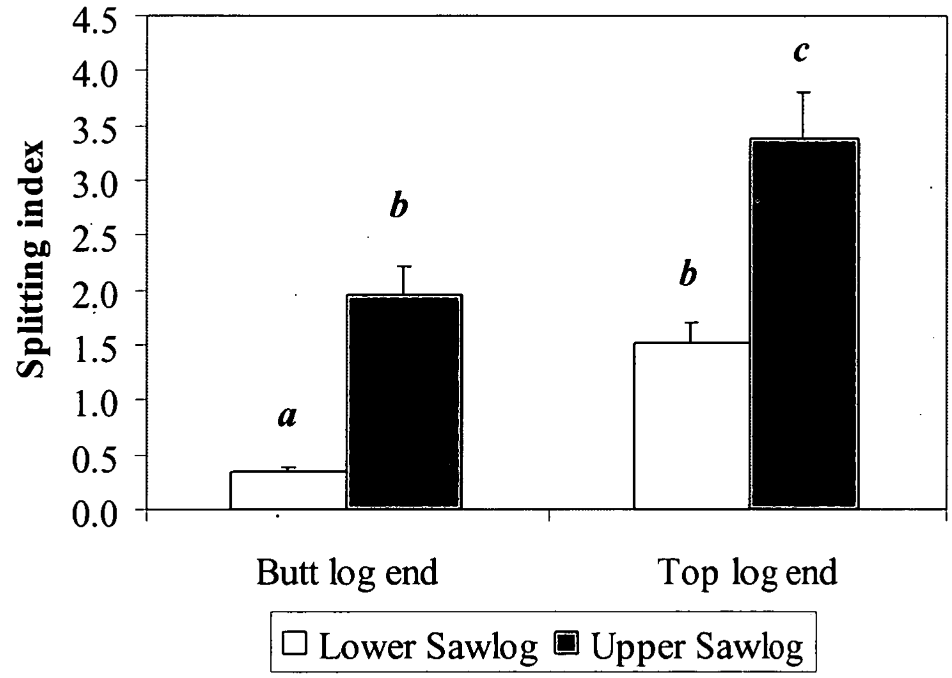


Figure 2.2. Mean trial values and standard error of log-end split index for both log ends (*SPLITINDEX-BUTT* and *SPLITINDEX-TOP*) of lower and upper sawlogs. Bars with the same letter are not significantly different at $P<0.05$.

There was a highly significant relationship ($P<0.001$) with *DBHOB* and mean *LGS* on *SPLITINDEX* in both log ends (Butt and Top) assessed as dependent variables (Table 2.3). Higher *DBHOB* and/or higher mean levels of *LGS* measured in standing trees were associated with higher values of *SPLITINDEX*. Positive relationships between log end-splitting indices and *LGS* were also found in previous studies (Lima *et al.* 2000a; Yang 2005). A similar trend for log end-splitting levels and log position was reported by Lima *et al.* (2000a) in *E. grandis*. *STOCKING* treatment was not a significant predictor of *SPLITINDEX*, once *DBHOB* was accounted for.

Table 2.3 Significance of factors affecting log end split index.

| Fixed effect | NDF | *SPLITINDEX-BUTT* | | *SPLITINDEX-TOP* *F*-Value | | *SPLITINDEX-SUM* *F*-Value | |
|---|---|---|---|---|---|---|---|
| | | DDF | *F*-Value | DDF | *F*-Value | DDF | *F*-Value |
| *DBHOB* | 1 | 153 | 17.81*** | 74 | 12.89*** | 74 | 15.60*** |
| *STOCKING* | 4 | 153 | $1.55^{ns}$ | 74 | $2.26^{ns}$ | 74 | $2.09^{ns}$ |
| *Mean LGS* | 1 | 153 | 45.34*** | 74 | 28.91*** | 74 | 37.15*** |
| *LOG* | 1 | 153 | 92.20*** | 79 | 58.18*** | 79 | 102.44*** |
| *DBHOB x LOG* | 1 | 153 | 7.01** | 79 | $1.55^{ns}$ | 79 | 4.53* |
| Random effect | | *Z*-test | | *Z*-test | | *Z*-test | |
| Tree | | $0.03^{ns}$ | | 4.11*** | | 3.91*** | |

NDF= Numerator degrees of freedom; DDF= Denominator degrees of freedom
ns = not significant *(P>0.05)*
* =*P <0.05.*
** = *P <0.01.*
*** = *P<0.001.*

The higher levels of *SPLITINDEX* observed on the upper sawlogs may be a consequence of a combined effect of higher levels of growth stress at greater tree heights and a more pronounced growth stress gradient from pith to cambium due to reduced log diameter in comparison with lower sawlog. The mechanized harvester used for tree felling might also have influenced this result, since the stem section corresponding to the upper sawlog may have experienced greater bending stress during felling. The lower stem section (the bottom section of the lower sawlog) was held by the harvester head during felling. As only one method of felling was conducted the importance of stresses during tree felling cannot be assessed.

The trend of increasing *LGS* with tree height has been reported by Raymond *et al.* (2004) in 20 and 23-year-old *E. globulus* plantations grown in Tasmania studying strain levels at heights of up to 4 m above ground, and also by a study carried out by Chafe (1985) in 8-year-old *E. nitens* plantation. However this trend was not the same in a 10-year-old *E. globulus* plantation grown in South Australia (Yang *et al.* 2001) in which no significant differences in mean *LGS* with sampling heights up the stem were found. We cannot determine whether there is a similar trend in the *E. nitens* trees we studied, as the *LGS* data were only gathered at breast height.

**b)** ***Flitch and board deflection and board shrinkage***

The mean values of both flitch and slab distortion assessed in quarter-sawn material was higher in upper sawlogs than those calculated for lower sawlogs. Besides, mean values of slab distortion were double the mean flitch distortion (Table 2.4).

Table 2.4 Mean values for processing performance for different log positions and sawing methods.

| Flitch and board deflection and board shrinkage | | | | Board end splitting, checks and total recovery | | | |
|---|---|---|---|---|---|---|---|
| Sawlog position | | Lower | Upper | Sawlog position | | Lower | Upper |
| Mean flitch distortion | mm | 5.44 | 7.50 | Internal checks per board | number | 5.5 | 1.2 |
| Mean slab distortion | mm | 10.3 | 14.5 | Surface check extent | mm/m$^2$ | 514.1 | 227.7 |
| Mean shrinkage width | % | 4.95 | 5.03 | Internal check category | scale | 1.73 | 1.27 |
| Mean shrinkage thickness | % | 5.58 | 5.93 | Surface check category | scale | 1.41 | 1.25 |
| Bow-green | mm | 3.08 | 4.60 | End-dock-volume-green | % | 4.5 | 7.1 |
| Bow-dry | mm | 5.60 | 6.20 | Sum board end split-green | mm | 77 | 94 |
| Spring-green | mm | 2.88 | 2.80 | Sum board end split -dry | mm | 121 | 191 |
| Spring-dry | mm | 6.14 | 6.04 | Total recovery | % | 28.4 | 29.6 |
| Sawing method | | Back-sawn | Quarter-sawn | Sawing method | | Back-sawn | Quarter-sawn |
| Mean Flitch distortion | mm | - | 6.44 | Internal check per board | number | 4.7 | 2.4 |
| Mean slab distortion | mm | - | 12.4 | Surface check extent | mm/m$^2$ | 776.5 | 102.3 |
| Mean shrinkage W* | % | 6.36 | 4.11 | Internal check category | scale | 1.54 | 1.47 |
| Mean shrinkage T* | % | 5.35 | 6.02 | Surface check category | scale | 1.57 | 1.17 |
| Bow-green | mm | 7.66 | 1.40 | End-dock-volume-green | % | 7.3 | 4.9 |
| Bow-dry | mm | 9.98 | 3.27 | Sum board end split-green | mm | 78 | 91 |
| Spring-green | mm | 3.56 | 2.37 | Sum board end split -dry | mm | 196 | 131 |
| Spring-dry | mm | 6.11 | 6.07 | Total recovery | % | 30.5 | 27.4 |

* W= board width; T= board thickness

Considering flitch distortion (square-root transformed) as a dependent variable, only *LOG* position was found to have a significant ($P$<0.05) effect, with higher distortion in upper sawlogs than lower sawlogs (Table 2.5). Slab distortion was also significantly ($P$<0.001) related to *LOG* position and levels of *SPLITINDEX* ($P$<0.05) (Table 2.5).

Table 2.5 Significance of factors affecting flitch and slab distortion in quarter-sawn logs.

| *Fixed effect* | NDF | Flitch distortion | | Slab distortion | |
|---|---|---|---|---|---|
| | | DDF | *F*-Value | DDF | *F*-Value |
| *DBHOB* | 1 | 141 | $0.31^{ns}$ | 32.4 | $2.50^{ns}$ |
| *STOCKING* | 4 | 141 | $0.37^{ns}$ | 31 | $2.05^{ns}$ |
| *Mean LGS* | 1 | 141 | $1.17^{ns}$ | 31.5 | $1.43^{ns}$ |
| *LOG* | 1 | 141 | 6.64* | 113 | 27.43*** |
| *ASPECT* | 1 | 141 | $0.20^{ns}$ | 110 | $2.95^{ns}$ |
| *LOG x ASPECT* | 1 | 141 | $0.95^{ns}$ | 110 | $0.66^{ns}$ |
| *SPLITINDEX-SUM* | 1 | 141 | $2.18^{ns}$ | 67.6 | 6.20* |
| *Random effect* | | *Z*-test | | *Z*-test | |
| Tree | | $0.00^{ns}$ | | $0.02^{ns}$ | |

NDF= Numerator degrees of freedom; DDF= Denominator degrees of freedom
ns = not significant *(P>0.05)*
* = *P <0.05.*
*** = *P<0.001.*

The mean board bow was higher in dry than in green boards, higher in back-sawn than in quarter-sawn boards and in boards from the upper sawlog (Table 2.4). As expected it was clear that sawing method had a dominant effect on bow, with significantly greater bow in back-sawn boards (*P<.001*) (Table 2.6). After accounting for *SAWMETH*, *DBHOB*, *STOCKING* and *LOG* position, mean *LGS* had a significant relationship (*P*<0.001 and *P*<0.05, respectively) with green and dry bow (Table 2.6).

Table 2.6 Significance of factors affecting mean board distortion and mean board shrinkage.

| *Fixed effect* | | Bow-dry | | Spring-dry | | Shrinkage-Width | | Shrinkage-Thickness | |
|---|---|---|---|---|---|---|---|---|---|
| | NDF | DDF | *F*-Value | DDF | *F*-Value | DDF | *F*-Value | DDF | *F*-Value |
| *SAWMETH* | 1 | 85.6 | 288.51 *** | 74.7 | $0.36^{ns}$ | 72.2 | 205.00 *** | 70.4 | 13.12 *** |
| *DBHOB* | 1 | 64.6 | $2.66^{ns}$ | 67.6 | $0.00^{ns}$ | 61.2 | $2.53^{ns}$ | 63.1 | $0.00^{ns}$ |
| *STOCKING* | 4 | 81.6 | $1.36^{ns}$ | 75 | $0.09^{ns}$ | 71.3 | 2.70* | 70.6 | $1.80^{ns}$ |
| *Mean LGS* | 1 | 108 | 6.88** | 84.9 | $0.34^{ns}$ | 86.3 | $3.17^{ns}$ | 80.9 | $0.16^{ns}$ |
| *LOG* | 1 | 504 | $0.82^{ns}$ | 482 | $0.51^{ns}$ | 487 | $1.25^{ns}$ | 480 | 7.77** |
| *SAWMETH x LOG* | 1 | 505 | 5.49* | 483 | $1.11^{ns}$ | 489 | 16.23 *** | 482 | 4.63* |
| *SPLITINDEX-SUM* | 1 | 257 | 5.18* | 321 | 7.42** | 264 | 3.92* | 300 | $0.00^{ns}$ |
| *Random effect* | | *Z*-test | | | | | | | |
| Tree | | $1.44^{ns}$ | | 3.66*** | | 2.60** | | 3.36*** | |

NDF= Numerator degrees of freedom; DDF= Denominator degrees of freedom
ns = not significant *(P>0.05)*
* = *P <0.05.*
** = *P <0.01.*
*** = *P<0.001.*

The mean board spring values for dry boards were nearly double the values for green boards (Table 2.4). However spring was not significantly related either to sawing method or to *LOG* position. *SPLITINDEX* was the only significant predictor of dry board spring (*P*<0.01), with no effects of *LGS* (Table 2.6). However, mean *LGS* had a significant (*P*<0.05) relationship with green board spring (analysis not presented).

From previous studies undertaken on plantation-grown eucalypts both standing tree *LGS* and *SPLITINDEX* have been shown to be significantly positively related to slab and board distortion. For instance Yang *et al.* (2002) found a positive relationship between *LGS* and excessive board distortion in 10-year-old *E. globulus,* as did Yang (2005), working with 32-year-old *E. globulus* plantation-grown sawlogs. However Telles (2002) did not find significant relationships between log end-splitting indices and board distortion among 21 provenances of *E. grandis*, and Raymond *et al.* (2004) did not find significant relationships between *LGS* and board distortion in *E. globulus* trees from two plantations sampled in North-East Tasmania. These different results may be attributed to differences in sampling, processing strategies, differences in the material studied and the *LGS* levels observed.

*LGS* had no significant effect on mean shrinkage values in either board width or thickness (Table 2.6). A previous study carried out on *E. nitens* (Chauhan and Walker 2004), standing tree *LGS* was moderately but significantly related to volumetric shrinkage of the outerwood and also with volumetric shrinkage differential (difference between outerwood and corewood shrinkage). Similarly, in 20-year-old plantation-grown *Acacia auriculiformis* A. Cunn. ex Benth., *LGS* measured on logs was significantly positively related to both volumetric and radial shrinkage measured in matched samples where *LGS* was collected (Aggarwal *et al.* 2002). The low range and mean of *LGS* levels we found and the fact that *LGS* is the mean strain at the stem periphery at 1.3 m height above ground reduced the chances of detecting significant relationships for board shrinkage in our study.

**c) *Losses of volume due to end-docking and checking propensity***

The mean values for estimated losses of board green volume by end docking were higher in the upper sawlogs than lower sawlogs and lower in quarter-sawn boards than back-sawn boards (Table 2.4).

From the mixed models fitted (Table 2.7), in addition to the significant effects of *SAWMETH, DBHOB* and *LOG* position, significant relationships between mean *LGS* ($P<0.05$), and *SPLITINDEX-SUM* ($P<0.001$) on green volume loss were found. A similar significance was found for board end-split length in dry boards (Table 2.7).

Table 2.7 Factors affecting board end splitting, green board volume loss due to end docking and total product recovery.

| *Fixed effect* | NDF | Board end-splitting-green | | Board end-splitting-dry | | Loss end-docking-green | | Total recovery | |
|---|---|---|---|---|---|---|---|---|---|
| | | DDF | *F*-Value | DDF | *F*-Value | DDF | *F*-Value | DDF | *F*-Value |
| *SAWMETH* | 1 | 73.8 | $0.24^{ns}$ | 64.7 | 4.08* | 64.7 | 4.05* | 71.4 | 12.59 *** |
| *DBHOB* | 1 | 60.8 | $2.24^{ns}$ | 57.1 | 9.00** | 57.1 | 9.06** | 71 | 3.99* |
| *STOCKING* | 4 | 72.3 | $1.15^{ns}$ | 64.6 | $0.49^{ns}$ | 64.6 | $0.49^{ns}$ | 71.6 | $0.23^{ns}$ |
| *Mean LGS* | 1 | 89.8 | $1.09^{ns}$ | 75.2 | 4.72* | 75.2 | 4.71* | 71.5 | $1.96^{ns}$ |
| *LOG* | 1 | 491 | 4.21* | 477 | 9.90** | 477 | 9.96** | 77.3 | $2.72^{ns}$ |
| *SAWMETH x LOG* | 1 | 493 | $0.39^{ns}$ | 479 | 4.91* | 479 | 4.90* | 77.3 | $0.10^{ns}$ |
| *SPLITINDEX-SUM* | 1 | 254 | $2.96^{ns}$ | 275 | 11.13 *** | 275 | 11.06 *** | 146 | 5.95* |
| *Random effect* | | *Z*-test | | | | | | | |
| Tree | | 2.26* | | 3.02** | | 3.01** | | $1.55^{ns}$ | |

NDF= Numerator degrees of freedom; DDF= Denominator degrees of freedom
ns = not significant *(P>0.05)*
* =*P <0.05.*
** = *P<0.01.*
*** = *P<0.001.*

From the analysis obtained from the model fitted using the GLIMMIX SAS procedure, the occurrence of internal checking was found to be affected only by *LOG* position (*P<0.001*), with higher checking propensity in lower sawlogs than upper sawlogs. Neither *LGS* nor *SPLITINDEX-SUM* had significant relationships (Table 2.8). Similarly, neither *LGS* nor *SPLITINDEX-SUM* had significant relationships with the occurrence of board surface checking. *SAWMETH* and *LOG* position had highly significant impacts on surface checking (*P<0.001*) (Table 2.8), with higher checking propensity in both lower sawlogs and back-sawn boards (Table 2.4).

Table 2.8 Factors affecting checking propensity.

| *Fixed Effects* | NDF | Internal checks | | Surface checks | |
|---|---|---|---|---|---|
| | | DDF | *F*-Value | DDF | *F*-Value |
| *SAWMETH* | 1 | 458 | $1.49^{ns}$ | 458 | 82.39*** |
| *DBHOB* | 1 | 458 | $2.00^{ns}$ | 458 | $0.30^{ns}$ |
| *STOCKING* | 4 | 458 | $2.01^{ns}$ | 458 | $1.05^{ns}$ |
| *Mean LGS* | 1 | 458 | $0.92^{ns}$ | 458 | $0.66^{ns}$ |
| *LOG* | 1 | 458 | 109.47*** | 458 | 18.36*** |
| *SPLITINDEX-SUM* | 1 | 458 | $0.58^{ns}$ | 458 | $2.48^{ns}$ |
| *Random effect* | | Estimate | Standard error | Estimate | Standard error |
| Tree | | 1.2042 | 0.4008 | 0.06777 | 0.1575 |

NDF= Numerator degrees of freedom; DDF= Denominator degrees of freedom
ns = not significant *(P>0.05)*
*** = *P<0.001.*

**d)** ***Total product recovery***

The mean values observed for total product recovery were higher in back-sawn logs than quarter-sawn logs, with no significant differences regardless of *LOG* position. *LGS* was not a significant predictor of total recovery (Table 2.7), while *DBHOB* and *SPLITINDEX-SUM* were significantly related to recovery ($P<0.05$).

Overall, the significant relationships among traits we found are consistent with previous findings reported by Shelbourne *et al.* (2001), who carried out an individual-tree processing study in New Zealand using fifteen 15-year-old *E. nitens* pruned trees. Their study found high correlations between growth strain measurements in standing trees, using a simplified version of Nicholson's method, and board bow, board end-splitting and reduced timber conversion. Nevertheless, some factors that were found to be significant in the current study, particularly those where the probability is only in the range $P<0.01$ to $P<0.05$, should be interpreted with caution, because techniques to adjust p-values so as to control false discovery rates arising from multiple testing using Bonferroni-type procedures (Benjamini and Hochberg 1995) were not performed.

*2.5.3 LGS and log end-splitting as predictors of solid-wood traits*

Tree mean *LGS* was found to be significantly positively related to log end splitting index, sawn-board bow in both green and dry condition, mean values of losses of board green volume due to end-docking and board end splitting after drying. Nevertheless, the capability of *LGS* to predict sawing performance traits was modest, as evidenced by the modest improvements in the coefficients of determination ($r^2$) for these variables in *MLR* models that already accounted for other significant factors

(Table 2.9). To the prediction of *SPLITINDEX-BUTT*, *SPLITINDEX-TOP* or *SPLITINDEX-SUM*, the inclusion of *LGS* explained an additional 14.6, 17.8 and 19.5% of the variance, respectively, after accounting for *DBHOB* and *LOG* position. In the *MLR* equations fitted to predict green and dry board bow and volume loss to end docking, the inclusion of mean tree *LGS* accounted for an additional 3%, 2% and 2% of variance respectively.

On other hand, *SPLITINDEX* was found to be significantly related to end splitting of dried boards (positive), losses of board green volume due to end-docking (positive), slab distortion on quarter-sawn logs (positive), sawn-board bow and spring (positive) and total recovery (negative). However, the capability of *SPLITINDEX* to predict sawing performance traits was also modest (Table 2.9). For instance to predict slab distortion in the quarter-sawn logs, the inclusion of *SPLITINDEX-SUM* explained an additional 4% of variation, after accounting for *LOG* position which alone explained 14% of variation. Similarly, the inclusion of *SPLITINDEX-SUM*, after the inclusion of mean *LGS*, explained an additional 4% and 2% of variance respectively of green and dry board bow, and accounted for additional of 5% of the variance in volume loss to end docking. The addition of *SPLITINDEX-SUM* to a *MLR* equation that already included *SAWMETH* and *DBHOB* only explained an additional 2% of variance in product recovery.

*SAWMETH, DBHOB* and *LOG* position were generally more relevant factors than *LGS* and *SPLITINDEX* in terms of variance explained on the majority of the traits analysed, as reported by Washusen *et al.* (2008).

Table 2.9 Additional variance gained when the standing tree growth strain (*LGS*) is included in regression equations predicting log and board performance traits

| Processing trait | *Factors included*[1] | $r^2$ *x 100 without LGS* | *Extra gain in* $r^2$ *due to LGS* | *Relationship*[2] |
|---|---|---|---|---|
| SPLITINDEX-BUTT | *DBHOB LOG* | 34.2 | 14.6 | Positive |
| SPLITINDEX-TOP | *DBHOB LOG* | 18.2 | 17.8 | Positive |
| SPLITINDEX-SUM | *DBHOB LOG* | 25.0 | 19.5 | Positive |
| Flitch distortion | *LOG* | 4.2 | 0.3 | Positive |
| Slab distortion | *LOG* | 14 | 0 | |
| Slab distortion | *LOG SPLITINDEX-SUM* | 18 | 0 | |
| Bow-Green | *SAWMETH* | 42.9 | 3 | Positive |
| Bow-Green | *SAWMETH SPLITINDEX-SUM* | 47.0 | 1 | Positive |
| Bow-Dry | *SAWMETH* | 39 | 2 | Positive |
| Bow-Dry | *SAWMETH SPLITINDEX-SUM* | 41 | 1 | Positive |
| Spring-Green | *SAWMETH DBHOB* | 2.8 | 1.2 | Positive |
| Spring-Dry | *SPLITINDEX-SUM* | 0.7 | 0.5 | Positive |
| Mean shrinkage width | *SAWMETHOD* | 35.2 | 0.2 | Positive |
| Mean shrinkage width | *SAWMETHOD SPLITINDEX-SUM* | 36.3 | 0 | |
| Board end split extent-Dry | *SAWMETH DBHOB LOG* | 5.4 | 2.1 | Positive |
| Loss from end-docking-Green | *SAWMETH DBHOB LOG* | 5.4 | 2.1 | Positive |
| Loss from end-docking -Green | *SAWMETH DBHOB LOG SPLITINDEX-SUM* | 10.3 | 0.3 | Positive |
| Total recovery | *SAWMETH DBHOB* | 11 | 1.3 | Negative |
| Total recovery | *SAWMETH DBHOB SPLITINDEX-SUM* | 12.8 | 0.4 | Negative |

[1] which were found to be significant ($P<0.05$) in the mixed models analysis (Tables 2.3, 2.5,2.6, 2.7 and 2.8).
[2] between *LGS* and processing trait

### *2.5.4 Application of results*

Selection, breeding and deployment of the best genotypes, together with implementation of best silvicultural practices based on stand density control during the rotation have been promoted as suitable strategies to partially solve the negative consequences of growth stress on plantation-grown eucalypts for sawlogs (Brennan *et al.* 2004; Nutto *et al.* 2006; Touza 2001a). These strategies require reliable and cost-effective information about the processing suitability of the material (Harwood *et al.* 2005). *LGS* has been suggested as one of the best predictors of the negative consequences of growth stress relief on solid-wood quality (Yang and Waugh 2001), however some studies have reported poor relationships between growth strain and potential sawing problems such as board deflection and end splitting (Raymond *et al.* 2004). There are also concerns about both the somewhat destructive impact on the tree and the time and cost involved in collecting growth strain measurements

(Baillères *et al.* 2003; Raymond *et al.* 2004; Yang *et al.* 2006). Nonetheless the current study found higher *LGS* levels were significantly related with some potential sawing problems, particularly log end-splitting, bow and spring and board end-splitting, which may cause important economic losses in the mill (Yang 2005). Therefore *LGS* may be considered as a useful predictor in *E. nitens* to identify material less prone to log end-splitting and board distortion. In stands where average levels of *LGS* are higher than those in our study, or there is a greater range of *LGS* levels, the impact of growth strain on processing performance could well be greater.

It would be highly desirable to reduce the cost of measurement of *LGS*. In the current study, using the CIRAD Forêt gauge it was difficult to measure *LGS* in more than 30 trees per day, and this work rate was reduced during windy conditions. A sampling strategy based on two measurements per tree at two opposite stem aspects would provide a sufficiently precise estimate of mean *LGS*, reducing both the cost of sampling and tree damage, relative to the four measurements per tree that were carried out by the current study. It is suggested that a first measure be taken facing the prevailing wind direction, and the second opposite to the first. Alternatively two measurements taken at right angle may be recommended when the prevailing wind direction is either unknown or variable. Taking only two measures per tree would roughly double the output, but even at 60 trees per day the technique would be prohibitively expensive as a routine measure for screening individual trees for processing performance, or for genetic studies where hundreds of trees need to be assessed. It would, however, be feasible to use the method to evaluate the range of *LGS* in stands of trees under consideration for solid-wood processing, by sampling a limited number of trees per stand. Prediction of *LGS* and associated processing performance using near infrared spectroscopy (Baillères *et al.* 2003) or other indirect methods might be a better strategy where lower-cost measurement is required.

*LGS* was found to be significant and positively correlated with log end splitting, which was a reliable predictor of losses of green volume due to end split docking. Splitting index might also be used in log segregation strategies in the forest or in the mill. From the results of the current study, log end splitting could be measured only at the top end of sawlogs, where it is more severe, reducing measurement cost.

Neither *LGS* nor log end-splitting indices were influenced by stocking level for the trees studied, once the effect of *DBHOB* was accounted for. At the higher stocking treatments (control and 400 stems $ha^{-1}$), the sampled trees were mainly dominant trees, whereas trees more representative of the overall *DBHOB* distribution were sampled in the lower stocking treatments (100, 200 and 300 stems $ha^{-1}$). Therefore early thinning in this trial did not affect the propensity of trees to develop higher levels of growth strain and log end splitting index, relative to those of the dominant trees in the high-stocking treatments. This result has important implications for thinning strategies of plantation-grown eucalypts for solid wood production. However further studies should be undertaken under different site conditions and for different eucalypts species already considered for solid-wood production. Finally, significant variation between trees in growth strain extent, log end splitting and also in the sawing characteristics assessed that were found in this study might have a genetic basis. We advocate the need for genetic and silviculture interaction studies to determine if there is a genetic basis to these solid-wood characteristics.

## 2.6 Conclusions

Peripheral longitudinal growth strain in 22-year-old *E. nitens* plantation-grown for sawlogs at Gould's Country, Tasmania was at the lower end of the reported range for eucalyptus plantations. Nonetheless, standing tree mean levels of *LGS* were significantly positively related to some potential sawing problems, notably log end-splitting propensity, sawn-board distortion traits such as bow and losses of board volume due to end-docking. *LGS* was found to be higher on the side of the stem facing the prevailing wind. Neither stocking treatment nor tree diameter significantly affected standing tree growth strain levels gathered from the 81 dominant and co-dominant trees studied. Also, thinning levels did not affect log end-splitting index, nor most solid-wood traits and product recoveries, after accounting for *DBHOB* and sawing method. Log end-splitting was positively related to *DBHOB*, higher in upper log than lower log position within the tree, and it was significantly positively related to the tree mean *LGS* levels. While *LGS* may be used to screen and/or select standing *E. nitens* trees that are less prone to splitting and board distortion, its predictive capability was low and its measurement was time-consuming. Further studies are required to improve knowledge about site and genetic effects and their interactions.

# CHAPTER 3

## Predicting *Eucalyptus nitens* plantation-grown sawlog quality from acoustic wave velocity and wood shrinkage data

### 3.1 Abstract

Standing tree and harvested log acoustic wave velocity (*AWV*) in the longitudinal direction, wood shrinkage and wood basic density data were collected in a 22-year-old *Eucalyptus nitens* plantation thinning trial in Tasmania. Standing tree *AWV* was determined using the FAKOPP ™ Microsecond Timer on 81 pruned trees, selected from five residual stocking treatments (*STOCKING*), collecting two *AWV* data per tree. *AWV* of debarked logs was collected using DIRECTOR HM200™ in the 81 5.7-m crosscut bush-logs and also on 162 2.7-m sawlogs, crosscut from bush-logs. Sawlogs from 41 trees with diameter over bark (*DBHOB*) under 43 cm were back-sawn, and those from 40 trees with DBHOB over 43 cm were quarter-sawn. The wood-block traits (*BLOCKTRAITS*) of tangential and radial shrinkage and wood basic density were determined in a total of 246 25 x 25 x 40 mm wood-blocks extracted from the 41 back-sawn trees. Six wood-blocks per tree were cut from two stem heights (*BLOCKHEIGHT*, 3.0m and 5.7m above ground) and from three radial distances from the pith to cambium (*BLOCKDISTANCE*, 25%, 50% and 75%). Variation in *AWV* and *BLOCKTRAITS* and their relationship with sawing traits and wood mechanical properties on a selected centre cant of boards were examined. Standing tree *AWV* was significantly different between stem aspects (*P<0.001*). *DBHOB* was significantly (*P<0.001*) negatively related to both standing tree and log

*AWV*. Log *AWV* was also related to *STOCKING* (*P<0.05*, being higher in the unthinned control) and log position (*P*<0.001, higher in upper sawlogs). *AWV* measurements differed significantly (*P*<0.001) among trees within stocking treatments. Standing tree *AWV* predicted 58% of *AWV* variation in the lower sawlogs and 35% in the upper sawlogs. Wood basic density and shrinkage traits were significantly related to *BLOCKHEIGHT* (*P*<0.001, higher in upper sawlogs) and to *BLOCKDISTANCE* (*P*<0.001, increasing from pith to cambium). Standing tree AWV was associated with green board bow (*P*<0.05). Log *AWV* was significantly positively related to log end-splitting (*P*<0.05), green board bow (*P*<0.001), mean board shrinkage in width (*P*<0.01), select recovery (*P*<0.01) and product value (*P*<0.05). Both standing tree and log *AWV* were significantly (*P*<0.001) positively related to timber stiffness, strength and Janka hardness. Shrinkage and collapse measured in wood-blocks were significantly (from *P*<0.05 to *P*<0.001) related to board width shrinkage (positive), internal checking propensity (positive), select recovery (negative) and product value (negative), but no significant relationships between block shrinkage traits and timber mechanical properties were found. Mean wood basic density was not related to sawing traits, but was significantly (*P*<0.001) positively related to *AWV* and timber mechanical properties. Together, *AWV* and *BLOCKTRAITS* explained a low to moderate amount of variance in the solid-wood traits analysed, after accounting for the effects of thinning treatment, sawing method, log position and log diameter.

## 3.2 Introduction

Wood mechanical properties such as timber stiffness and strength, and drying degrade problems such as surface and internal checking propensity are becoming increasingly important as technical and economic drivers to define the suitability of younger plantation-grown eucalypt sawlogs as raw material for both structural and appearance end-uses (Dickson *et al.* 2003; Washusen and Innes 2007). Timber stiffness (static modulus of elasticity, $MOE_S$) and timber strength (modulus of rupture, *MOR*) are the most relevant wood properties for evaluating structural timber suitability for residential, commercial and industrial construction (Armstrong 2003). Using $MOE_S$ and *MOR,* timber can be classified into Strength Groups (Standards Australia 2000). $MOE_S$ (determined by bending) represents the ability of the timber to resist deflection under loads applied perpendicular to the fibre orientation, and *MOR* reflects the maximum load-carrying capacity of a piece of timber in bending (Green 2001). Timber hardness (resistance to penetration) is also important for younger eucalypt plantation-grown timber, since its gives information on timber suitability for flooring and furniture (Nolan *et al.* 2005; Timber Development Association 2003). These mechanical properties, are generally positively associated with wood density (Dickson *et al.* 2003; Lima and Garcia 2005; Nolan *et al.* 2005). Wood mechanical properties have been gaining increasing attention in research as eucalypt plantation-grown timber, particularly *Eucalyptus nitens,* has started to access timber structural markets traditionally dominated by softwood plantation-grown timber such as *Pinus radiata* D Don. (Cannon and Innes 2007).

Wood shrinkage and collapse are important physical properties due to their impact on processing cost, product recoveries of seasoned products and dimensional stability

(Chafe and Ilic 1992; Silva *et al.* 2006). Variation in shrinkage and collapse behaviour have been related to drying degrade problems such as checking (Greaves *et al.* 2004b; Hamilton 2007), which are a value limiting factor for appearance end-uses, particularly in *E. nitens* plantations grown for sawlogs (Shelbourne *et al.* 2002; Washusen and Innes 2007). In order for eucalypt plantations worldwide to supply more sawlogs for both structural and appearance markets, improvement of wood mechanical properties and management of shrinkage related traits through breeding, silviculture and processing technology are becoming more important to improve technical and economic viability.

Nowadays it is well understood that the traditional methods used to quantify these crucial solid-wood properties are destructive of the standing tree and time consuming (Armstrong 2003; Dickson *et al.* 2003; Tsehaye *et al.* 2000). For example, $MOE_S$ has been traditionally determined by the time consuming and expensive bending tests on wood samples recording the deflection as load is applied (Carter *et al.* 2005). This method is not practical for screening large numbers of trees for breeding, or segregating logs for structural timber (Carter *et al.* 2005; Dickson *et al.* 2003). Cost-effective and reliable non-destructive evaluation (NDE) techniques applied to trees or logs, to predict solid-wood quality traits will contribute to the improvement of plantation-grown eucalypt timber (Dickson *et al.* 2003; Raymond *et al.* 2004). Previous research, mainly in softwood species (Carter *et al.* 2005; Carter *et al.* 2006; Wang *et al.* 2005a; Wang *et al.* 2001), has found that the acoustic wave propagation, measured on standing trees, logs or sawn-boards, is well correlated with mechanical properties, particularly with $MOE_S$ (Huang *et al.* 2003). In fact, the dynamic modulus of elasticity ($MOE_D$) along the fibre, which is a function of acoustic wave velocity ($AWV$) and wood density (Equation 3.1), has shown to be well correlated with $MOE_S$

(Carter *et al.* 2005; Toulmin and Raymond 2007), and less strongly with *MOR*, due to the moderate correlation between $MOE_S$ and *MOR* (Lei *et al.* 2005; Steele and Cooper 2003). $MOE_D$ is predicted from the Equation 3.1 (Huang *et al.* 2003).

$$MOE_D = \left[\left(\frac{\rho}{g}\right) \times AVW^2\right] \qquad (3.1)$$

where:

$MOE_D$ is dynamic modulus of elasticity (GPa),
$\rho$ is green density of the material (kg $m^{-3}$),
$g$ is gravitational acceleration constant,
*AWV* is the velocity of the stress wave in the fibre direction (km $s^{-1}$).

When $\rho$ is assumed to be constant, $MOE_D$ is directly related to the square of *AWV*. Therefore, acoustic tools have been developed to calculate $MOE_D$ using Equation 3.1 so as to predict $MOE_S$ and other related mechanical properties such as *MOR* (Huang *et al.* 2003). The transit time-of-flight (*TOF*) method, which can be applied in standing trees, logs or sawn-timber, and the sonic resonance method, which can be applied in logs and sawn-timber, are the two main *NDE* techniques to measure *AWV* (Carter *et al.* 2005; Carter *et al.* 2006). *TOF* acoustic tools such as the FAKOPP ™ Microsecond Timer, give the transit time of an introduced stress wave (sound impulse) during its propagation into a wood sample between two probes (Fakopp 2000). *AWV* is calculated using the distance between the probes and the stress wave transit time. In tools using the resonance method such as DIRECTOR HM200™, the stress wave is introduced by hammering at one end of the specimen (log or board), and it travels along the specimen until it gets reflected (Fibre-Gen 2007). The reflected wave is measured at the same end of the specimen as where the wave was launched (Carter *et al.* 2005; Carter *et al.* 2006; Waghorn 2006). The resonance method tends to measure the average velocity of a number of reverberating waves, rather than the time of arrival of a first wave front as the *TOF* does. Therefore, *AWV* measured using *TOF* tools is generally higher than that calculated using resonance method when both are used in the same sample (Kawamoto *et al.* 2005). Both techniques have been successful in relating *AWV* measurements with $MOE_S$ in natural softwood forests (Wang *et al.* 2005a) and in *Pinus radiata* D. Don plantations. The corewood of *P. radiata* can be unsuitable for structural applications due its low $MOE_S$ (Lasserre *et al.* 2005; Tsehaye *et al.* 2000). *AWV* is now used to assist selection of better genotypes, support silvicultural practices and segregate logs at the mill to improve structural grade recoveries (Dickson *et al.* 2004; Grabianowski *et al.* 2004; Lasserre *et al.* 2005; Lasserre *et al.* 2007; Lindstrom *et al.* 2002). To date, there are few published studies in which *AWV* has been related to mechanical properties in plantation-grown timber of eucalypts (Dickson *et al.* 2003; Henson *et al.* 2005). These studies in *Eucalyptus dunnii* Maiden, and a study done in *E. nitens* and *E. globulus* (Harwood *et al.*, unpublished), have given some insights in to the predictive capability of *AWV* to the prediction of $MOE_S$, and also some indications about genetic variation and heritability in $MOE_S$ estimated from *AWV*. However, there is little information available on: a) the effect of silvicultural practices (*e.g.* thinning) on *AWV* and $MOE_S$; and b) the capability of *AWV* to reliably predict sawing performance and value limiting appearance defects.

Other promising *NDE* techniques have related patterns of wood shrinkage, collapse and basic density in fixed-height wood cores to solid-wood traits such as checking propensity, in order to support tree breeding programmes in species such as *E. nitens* (Hamilton 2007), *E. globulus* Labill. (Raymond *et al.*, unpublished), *E. dunnii* Maiden (Harwood *et al.* 2005) and *E. pilularis* (Smith) (Pelletier *et al.* 2007). These techniques have not yet been fully validated and uncertainty remains as to the reliability of wood shrinkage data from small samples to predict sawlog quality

(Hamilton 2007; Pelletier *et al.* 2007). *E. nitens* silvicultural trials grown under sawlog silvicultural regimes by Forestry Tasmania are now approaching full rotation age, allowing NDE assessments to be linked to processing studies. One of these trials was used by the Cooperative Research Centre for Forestry, Australia in 2006 to conduct a processing study to determine product recovery and value using conventional sawing methods (Washusen *et al.* 2008). The current study is aligned with this processing trial, and reports: a) variation in *AWV* measured in both standing trees and logs, and in wood shrinkage, collapse and basic density measured on small wood-blocks, and b) the capability of *AWV* and wood-blocks traits to predict sawlog quality traits and board mechanical properties established by the processing study.

## 3.3 Materials and methods

### *3.3.1 AWV measurements on standing trees*

One week before the mechanical harvest, *AWV* was collected from each of the 81 selected trees (refer to Table 1.1), using FAKOPP, which gives the transit time of a stress wave (*READING*) between the start and the stop transducers mounted onto probes, after hitting the starting probe. The *READING* is registered in a spectrometer (Fakopp 2000). Two *READINGS* per tree were collected from the south-west (*SW*) and northeast (*NE*) stem aspects. Each *READING* was taken with the starting probe at 0.30 m above the ground and the stop probe vertically above it at 1.52 m above the ground, giving a distance of 1.22 m between probes (*DISTANCE*). When a knot occupied one of these probe positions, that probe was moved one cm horizontally and located in clear, knot-free wood, thus avoiding the effect of the knot on the *READING*. The *DISTANCE* we used is the same as that successfully used in previous research in softwood (Wang *et al.* 2007a) and it is within the range used in previous studies carried out in both softwoods and eucalypt species (Chauhan and Walker 2006b; Dickson *et al.* 2003; Toulmin and Raymond 2007). Using *DISTANCE*, *READING*, and a time correction factor (Fakopp 2007), the standing tree *AWV* was calculated from Equation 3.2.

$$FAKOPPAWV = 1000xDISTANCE/(READING - CORRECTION) \qquad (3.2)$$

where:

*FAKOPPAWV* is the calculated standing tree *AVW* (km $s^{-1}$),
*DISTANCE* is the distance between start and stop transducers (1.22m),
*READING* is the read out in microseconds ($\mu s$)
*CORRECTION* is the time correction ($\mu s$) that includes a correction due to the transit time inside the transducers and a correction due to a reduction of *DISTANCE* due to the transducer's needle penetration into the bark and wood.

Based on the FAKOPP manufacturer recommendations (Fakopp 2000; Fakopp 2007), the current study used 25 $\mu s$ as *CORRECTION,* which includes 6.1 $\mu s$ due to transit time inside the transducers and a reduction of 18.9 $\mu s$ due to the effect of the transducer needles penetration, assuming 20 mm of mean bark thickness and 40 mm of transducer needle penetration into the stem at 45° inclination angle to the longitudinal direction of the stem. As average bark thickness in these selected trees was close to 20 mm (Wang *et al.* 2007b), we were sure that the probes were inserted into the outer ring radius generally at least 10 mm, which would be deep enough to minimize any effect of bark on stress wave measurement (Wang *et al.* 2001).

### *3.3.2 AWV measurements at bush-logs and sawlogs*

Immediately after felling the selected trees, 81 5.7-m bush-logs were crosscut, debarked, tagged, end sealed, gang nailed, and transported to a sawmill located at St

Helens, Tasmania. In the log yard the length of each bush-log was measured and their *AWV* determined using DIRECTOR HM200™. Subsequently, each bush-log was crosscut, producing 162 sawlogs. The sawlog length was measured and the *AWV* was also determined using DIRECTOR HM200™, following the method set out by Carter *et al.* (2005). In brief the log length was entered and the tool was pressed against the butt log-end; when the sensor head signalled that it had contact, the log end was hammered. The sensor picks up the acoustic wave signal as it passes back and forth along the length of the log at a rate of a few hundred passes per second. Software included in DIRECTOR HM200™ processes the signal and displays the *AWV*.

### *3.3.3 Wood shrinkage, collapse and wood basic density from small wood-blocks*

From the 41 trees that were back-sawn, 70-mm thick wood-discs were cut at the log-yard during the bush-log crosscutting process to produce sawlogs. Two wood-discs per tree were cut at approximately 3.0 m and 5.7 m above ground. The wood-discs were wrapped in plastic film to prevent loss of moisture and stored in cool room conditions (4°C) for 3 months. They were treated with fungicidal solution to prevent fungal attack, after which they were sawn to produce 82 pith-to-cambium radial strips orientated to the south-west aspect of the tree stem. These radial strips were then soaked in water for a 20 minute period, wrapped and stored in cool room conditions for 1 month. Subsequently from each radial strip three wood-blocks 25mm (tangential) by 25 mm (radial), by 40 mm (longitudinal), perfectly oriented to radial and tangential directions were cut following the methodology of Kingston and Risdon (1961), modified by reduction of the longitudinal block length. The wood-blocks were cut at three locations (*BLOCKDISTANCE*) along the pith-to-cambium transect: 25%, 50% and 75%. These wood-blocks were marked to identify their trial identity; the block radial position within the tree and the measurement locations for both radial and tangential directions, after which they were wrapped and stored in cool room conditions for one day. The dimensions of the wood-blocks were measured in the green condition and also after drying in a temperature and humidity-conditioned chamber, before and after reconditioning to uniform moisture content (MC) of about 12% MC. Radial and tangential dimensions were measured using a digital displacement gauge with readings graduated to 0.001 mm. The longitudinal dimension was measured with a horizontal digital displacement gauge with readings graduated to 0.001 mm in a specially built jig. Green volume was calculated from the measured dimensions in the green condition, and shrinkage and collapse were determined according to changes in the respective dimensions from green to 12% MC, before and after reconditioning. Each wood-block was also weighed after oven drying at 103±2°C, until a constant dry weight was established with a balance graduated to 0.001 g and the wood basic density (*BBDENSITY*) was calculated from oven-dry mass and green volume. The choice of using wood-block shrinkage before reconditioning as an additional predictor of board traits rather than using true shrinkage or collapse was chosen to test the predictor capability of this less expensive evaluation techniques which does not include reconditioning procedures. In addition, the use of wood-block shrinkage before reconditioning as a potential sawn board quality predictor may have the advantage of synthesising two different drying traits (true shrinkage and collapse) that have been related with checking propensity in previous studies (Yang and Fife 2003).

*3.3.4 Information utilized from the sawing trial*

*AWV* and wood-blocks traits data were related to the following variates:

**a)** ***Longitudinal growth strain (LGS):*** *NDE* data on *LGS* collected at standing trees using the CIRAD Forêt method detailed in Chapter 2,

**b)** ***log end-splitting index*** **(*SPLITINDEX*)** from Washusen *et al.* (2008) and detailed in Chapter 2.

**c)** ***Sawing traits***: determined from a central cant of boards from each log in the sawing trial carried out by CRC for Forestry (Washusen *et al.* 2008). The current study used the same sawing traits and detailed in Chapter 2 to explore relationships between *LGS* and sawlog quality: flitch (*FLITCH*) and slab (*SLAB*) distortion (only measured in quarter-sawn material), board bow (*BOW)* and board spring (*SPRING)* in green and dry condition, presence of surface and internal checks per board (*SURFCHECK* and *INTCHECK*), mean sawn-board shrinkage in width (*SHRINKAGE-WIDTH*) and thickness (*SHRINKAGE-THICK*), board end-splitting (*ENDSPLIT*) in green and dry condition, losses of board volume from end-docking (*ENDOCKING*), total recovery (*TOTALRECOVERY*), grade recoveries: *SELECT, STANDARD* and *UTILITY* and product value per cubic metre of log input (*PVPCMLI*).

**d)** ***Wood mechanical properties***: $MOE_S$, *MOR* and Janka hardness (HARDNESS) were determined in a random subsample of two sawn boards per log. The testing on small clear samples was carried out by the Timber Research Unit, University of Tasmania, on a subsample of 332 dried sawn-boards of random selection. Small clear samples were prepared from the middle of each board, and utilized for bending and hardness tests to determine mechanical properties (*MOEs*, *MOR* and *HARDNESS*) as described by Mack (1979) and specified in AS2878:2000 (Australian/New Zealand Standard 2000).

### 3.4 Statistical analyses

All statistical analyses were performed using the SAS statistical program package 9.1 (SAS Institute Inc 2004), with the experimental strata used in Chapter 2 to analyse variations in *LGS* and its relationships with sawing traits. These strata were: *TREE*, *LOG* position (upper/lower sawlog, two sawlogs per tree) and *BOARD* within log. The stratum positions and the relevant experimental factors, including *AWV* traits, wood-blocks traits and the wood mechanical properties included in the current study are shown in Table 3.1. Since we used a similar analytical framework to that used in Chapter 2, some variates and factors such as the sawing traits have been deliberately excluded in Table 3.1, however they are available in Chapter 2, Table 2.1.

In all the mixed models fitted, the replicate effect (*REP*) was included as a random effect, however it did not have any significant relationship ($P$>0.05) with the dependent variates assessed, therefore *REP* is not shown in the results section. No procedure such as the Bonferroni method (Benjamini and Hochberg 1995) was implemented to reduce the chance of potential false positives arising from multiple testing. Therefore, given the large number of tests undertaken, significant p-values close to 0.05 should be considered with caution.

Table 3.1 Stratum positions of measurements and new potential explanatory factors/variables included to study *AWV* and wood-blocks traits

| Stratum | Variates/factors | Distribution | Symbols | Unit |
|---|---|---|---|---|
| Tree | Thinning treatment (stems $ha^{-1}$) (*STOCKING*) | category | 100; 200; 300; 400; C | 1 to 5 |
| | Standing tree acoustic wave velocity | continuous | *FAKOPPAWV* | $km\ s^{-1}$ |
| | FAKOPP measurement aspects per tree | category | *SW; NE* | 1 - 2 |
| Log | Bush-log acoustic wave velocity | continuous | *BUSHLOG-AWV* | $km\ s^{-1}$ |
| | Sawing method (*SAWMETH*) | category | Back-sawn ; Quarter-sawn | 1 or 2 |
| | Sawlog acoustic wave velocity | continuous | *SAWLOG-AWV* | $km\ s^{-1}$ |
| | Block height (*BLOCKHEIGHT*) | category | 3.0m ; 5.7m | 1 or 2 |
| | Block distance from pith (*BLOCKDISTANCE*) | category | 25%, 50%, 75% | 1 to 3 |
| | Block tangential shrinkage 12%MC-BR* | continuous | *BTSHRINKAGE*[1] | % |
| | Block radial shrinkage 12%MC-BR* | continuous | *BRSHRINKAGE*[1] | % |
| | Block tangential to radial shrinkage ratio | continuous | *BTRSHRINKAGE*[1] | number |
| | Block tangential collapse 12%MC | continuous | *BTCOLLAPSE*[1] | % |
| | Block radial collapse 12%MC | continuous | *BRCOLLAPSE*[1] | % |
| | Block wood basic density | continuous | *BBDENSITY*[1] | $kg\ m^{-3}$ |
| | Static modulus of elasticity | continuous | $MOE_S$ | GPa |
| Board | Modulus of rupture | continuous | *MOR* | MPa |
| | Average Janka hardness tangential | continuous | *HARDNESS* | kN |

C= control unthinned
* MC-BR: moisture content, before reconditioning.
[1] Average wood-block value per *BLOCKHEIGHT* is mentioned with a capital "M" prior the symbol.

### *3.4.1 Effects of silvicultural treatments on AWV and wood-blocks traits*

Univariate analyses with linear mixed models were fitted to analyse the impact of *DBHOB, STOCKING*, measurement aspect (*ASPECT*) and *TREE* identity on *FAKOPPAWV, BUSHLOG-AWV* and *SAWLOG-AWV* specified as dependent variables. Mixed models as per Equations 3.3, 3.4 and 3.5 were fitted.

$$Y_{FAKOPPAWV} = MEAN + DBHOB + STOCKING + DBHOB.STOCKING + ASPECT + STOCKING.ASPECT + LGS + REP + REP.TREE + RESIDUAL \quad (3.3)$$

$$Y_{BUSHLOG-AWV} = MEAN + DBHOB + STOCKING + DBHOB.STOCKING + MFAKOPPAWV + LGS + REP + REP.TREE + RESIDUAL \quad (3.4)$$

$$Y_{SAWLOG-AWV} = MEAN + DBHOB + STOCKING + DBHOB.STOCKING + MFAKOPPAWV + LGS + LOG + STOCKING.LOG + REP + REP.TREE + RESIDUAL \quad (3.5)$$

where:

$Y$ is a vector of *AWV* observations,
*MEAN* is the overall mean,
*DBHOB*, *STOCKING* and *ASPECT* are the tree diameter (as a covariate), stocking treatment and measurement aspect effects fitted as fixed factors, respectively.
*MFAKOPPAWV* is the mean value of standing tree *AWV* calculated from the two measured aspect per tree, included as a covariate,
*LGS* is the tree mean value of longitudinal growth strain from four measurements per tree at breast height, included as a covariate. These values were obtained from the study reported in Chapter 2,
*LOG* is the sawlog position within the tree (as a fixed effect),
*REP* is the replicate as a random factor,
*REP.TREE* is tree within replicate as a random factor, and
*RESIDUAL* is the vector of residual errors.

Similarly, linear mixed models were fitted to analyse the impact of *DBHOB*, *STOCKING*, *BLOCKHEIGHT* and *BLOCKDISTANCE* and *TREE* identity on each *BLOCKTRAIT* specified as dependent variables. A mixed model as per Equation 3.6 was fitted for wood-block shrinkage traits (*BSHRNKAGETRAIT*) and Equation 3.7 was fitted for wood-block basic density (*BBDENSITY*).

$$\begin{aligned} Y_{BSHRINKAGETRAIT} = {} & MEAN + DBHOB + STOCKING + DBHOB.STOCKING + \\ & MFAKOPPAWV + LGS + BLOCKHEIGHT + \\ & BLOCKDISTANCE + BLOCKHEIGHT.BLOCKDISTANCE + \\ & BBDENSITY + REP + REP.TREE + RESIDUAL \end{aligned} \tag{3.6}$$

$$\begin{aligned} Y_{BBDENSITY} = {} & MEAN + DBHOB + STOCKING + DBHOB.STOCKING + \\ & MFAKOPPAWV + LGS + BLOCKHEIGHT + \\ & BLOCKDISTANCE + BLOCKHEIGHT.BLOCKDISTANCE + \\ & REP + REP.TREE + RESIDUAL \end{aligned} \tag{3.7}$$

where:

$Y_{BSHRINKAGETRAIT}$ is the vector of observations of either *BTSHRINKAGE*, *BRSHRINKAGE*, *BTRSHRINKAGE*, *BTCOLLAPSE* or *BRCOLLAPSE*.
$Y_{BBDENSITY}$ is the vector of observations of *BBDENSITY*. The other model terms were as in equation 3.5, with *BLOCKHEIGHT* (position within tree stem) and *BLOCKDISTANCE* (position from pith to cambium), and their interaction included as fixed effects in the model.

Mixed models were fitted by the method of restricted maximum likelihood (REML) using the SAS MIXED procedure (SAS Institute Inc 2004). The statistical significance of the fixed effects was tested using the $F$-value specifying a Type I (sequential) expected mean squares for model effects, which provides $F$-values that depend on the sequence in which the effects are included in the model. The significance of random factors was tested using the $Z$-test. Residual errors were approximately normally distributed and no data transformations were required for *AWV* or wood-block traits.

*3.4.2 AWV as a predictor of sawing traits and wood mechanical properties*

A similar approach was used to examine the relationship between the *AWV* and the sawlog suitability variables under assessment. Univariate mixed models were fitted as follows to test the factors affecting log splitting index (*SPLITINDEX*):

$$\begin{aligned} Y_{SPLITINDEX} = {} & MEAN + DBHOB + STOCKING + DBHOB.STOCKING + \\ & MFAKOPPAWV + LOG + DBHOB.LOG + REP + REP.TREE + \\ & RESIDUAL \end{aligned} \tag{3.8}$$

and the factors affecting each sawing trait and mechanical wood property:

$$\begin{aligned} Y_{QUALITY\text{-}TRAIT} = {} & MEAN + SAWMETH + DBHOB + STOCKING + \\ & MFAKOPPAWV + LOG + SAWMETH.LOG + REP + \\ & REP.TREE + RESIDUAL \end{aligned} \tag{3.9}$$

where:

$Y_{SPLITINDEX}$ is the vector of observations of log end-splitting index (either *BUTT* log end position, *TOP* log end position or *SUM* of *SPLITINDEX-BUTT* and *SPLITINDEX-TOP*)

$Y_{QUALITY-TRAIT}$ is the vector of observations of a particular sawing trait or wood mechanical property. The others model terms were as in previous equations.

Equations 3.8 and 3.9 were also fitted substituting either *BUSHLOG-AWV* or *SAWLOG-AWV* in place of *MFAKOPPAWV* as an explanatory variable. For several dependent variables (sawing traits) square root transformations were required in order to obtain normality of the residual errors (refer to Chapter 2, Table 2.1). However, no transformations were required for *AWV* or wood block traits. The variates fitted using model 3.9, were structured at the tree stratum with *SAWMETH* declared first, then *DBHOB* and *STOCKING*, and then *MFAKOPPAWV*. At the log stratum, *LOG* was declared first, then the interaction of *SAWMETH* and *LOG*, and then the random terms.

For category variates of sawn-board checking propensity (*CHECKTRAIT*) such as internal and surface checking occurrence (*INTCHECK* and *SURFCHECK* respectively), a generalised linear mixed model (Schall 1991) was fitted using the model shown in Equation 3.10. The SAS GLIMMIX procedure was used (SAS Institute Inc 2005), assuming a binomial distribution of residuals, logit link function, an estimation technique based on residual log pseudo-likelihood and the Type I (sequential) test of fixed effects.

$$\begin{aligned} Y_{CHECKTRAIT} = {} & MEAN + SAWMETH + DBHOB + STOCKING + \\ & MFAKOPPAWV + LOG + SAWMETH.LOG + REP + \\ & REP.TREE + RESIDUAL \end{aligned} \qquad (3.10)$$

where:

$Y_{CHECKTRAIT}$ is the probability that either *SURFCHECK* or *INTCHECK* category is 1 (less than 20 mm of check extent for *SURFCHECK*, and no check occurrence for *INTCHECK*). The others model terms were as in Equation 3.9.

Model 3.10 was also fitted substituting either *BUSHLOG-AWV* or *SAWLOGAWV* in place of *FAKOPPAWV*. Finally multiple linear regressions (MLR) modelling (SAS REG procedure) was used to determine the degree of improvement in predicting the sawlog suitability variables under assessment, when either *MFAKOPPAWV* or *SAWLOG-AWV* were added to models that already took into account explanatory factors shown to be significant in the mixed model analysis.

### *3.4.3 Wood-block traits as predictors of sawing traits and mechanical properties*

The relationship between *BLOCKTRAIT* and the sawlog suitability variables assessed were also examined applying univariate mixed models. The model fitted to test the significance of mean values of any *BLOCKTRAIT* on *SPLITINDEX* determined in the back-sawn sawlogs was:

$$\begin{aligned} Y_{SPLITINDEX} = {} & MEAN + DBHOB + STOCKING + DBHOB.STOCKING + \\ & LOG + MBLOCKTRAIT + REP + REP.TREE + RESIDUAL \end{aligned} \tag{3.11}$$

where:

*MBLOCKTRAIT* is the mean value of a wood-block trait per *DISC* position, and can be either *BTSHRINKAGE, BRSHRINKAGE, BTRSHRINKAGE, BTCOLLAPSE, BRCOLLAPSE* or *MBBDENSITY,* included as a fixed factor.

Model 3.11 was fitted 6 times to assess independently the effect of each *MBLOCKTRAIT* on *SPLITINDEX.* Likewise, the relationship between *MBLOCKTRAIT* and each sawing trait and mechanical wood property determined from the back-sawn material, were also examined fitting the following model:

$$\begin{aligned} Y_{QUALITY-TRAIT} = {} & MEAN + DBHOB + STOCKING + LOG + MBLOCKTRAIT + \\ & REP + REP.TREE + RESIDUAL \end{aligned} \tag{3.12}$$

As applied with *AWV* traits, both *SURFCHECK* and *INTCHECK* models were fitted using the SAS GLIMMIX procedure Equation 3.13.

$$\begin{aligned} Y_{CHECKTRAIT} = {} & MEAN + DBHOB + STOCKING + LOG + MBLOCKTRAIT + \\ & REP + REP.TREE + RESIDUAL \end{aligned} \quad (3.13)$$

The SAS REG procedure was also applied to determine the degree of improvement in predicting sawlog suitability traits, when a *MBLOCKTRAIT* was added to models that already took into account significant explanatory factors shown to be significant in the mixed model analysis.

## 3.5 Results and discussion`

### *3.5.1 AWV measurements: levels and sources of variations*

The standing tree *AWV* values ranged from 2.95 to 4.22 km $s^{-1}$ with a trial mean value of 3.64 km $s^{-1}$ (Figure 3.1), agreeing with *AWV* values for *E. nitens* trees reported by Farrell *et al.* (2008) in a study of 9- and 13-year old Tasmanian plantation-grown *E. nitens*. These levels of *AWV* are nearly twice the standing tree *AWV* values reported in both 9 and 25-year-old *E. dunnii* plantations (Dickson *et al.* 2003; Joe *et al.* 2004). The different branching habit of *E. dunnii* and the fact that FAKOPP probes were inserted 1 m apart and on opposite sides of the tree (diagonally across the stem), could be possible causes of the lower velocities recorded in the *E. dunnii* study, compared with the reported values described in this study.

Comparing the standing tree *AWV* mean and range values with those values reported for some softwood species in Wang *et al.* (2005a), in which the *TOF* method was also used along the fibre direction in the same stem side such as our study, the standing tree *AWV* of *E. nitens* at Gould's Country can be considered similar to *Tsuga heterophylla* (Raf.) Sarg, 1.0 to 1.5 km $s^{-1}$ higher than 8, 16 and 25 year-old-*P. radiata* D. Don., and 0.6 km $s^{-1}$ lower than 40-year-old *Pinus banksiana* Lamb.

The *BUSHLOG-AWV* ranged from 3.30 to 4.10 km $s^{-1}$, with a trial average of 3.72 km $s^{-1}$ (Figure 3.1). These velocities are fairly similar to those *AWV* values measured using the DIRECTOR HM200™ reported by Farrell *et al.* (2008) on 5.4m de-barked logs from 8 and 13-year-old un-thinned / unpruned *E. nitens* plantations. They are also similar to the *AWV* measured using both FAKOPP and DIRECTOR HM200™ reported by Dickson *et al.* (2003) and Joe *et al.* (2004) on 5.3 and 4.2 m butt logs (with bark) from 9 and 25-year-old *E. dunnii* plantations. The range and mean values of *BUSHLOG-AWV* we found are higher than those for 3.22m logs of softwood species also determined using DIRECTOR HM200™ by Wang *et al.* (2005a), a trend which is inverse to that for standing trees. A possible explanation is the debarked condition of our logs, since the same logs without bark have been found to deliver significantly higher *AWV* than logs with bark when the resonance method is used, as Lasserre *et al.* (2007) found in *P. radiata*.

In the current study *BUSHLOG-AWV* values were significantly higher than the standing tree *AWV*, higher than the *SAWLOG-AWV* measured on lower sawlogs, but were significantly lower than those measured on upper sawlogs (Figure 3.1). From Lasserre *et al.* (2007) we infer that the debarked condition of our logs resulted in an increased *AWV* explaining also why *BUSHLOG-AWV* was higher than standing tree

*AWV*. For instance if we reduce *BUSHLOG-AWV* by 8% (the difference found by Lasserre *et al.* (2007) in *P. radiata)* the standing tree *AWV* will become higher than that of the bush-log, and then it will be consistent with the expected trend found in other studies (Wang *et al.* 2005a). Nevertheless, standing tree *AWV* was significantly ($P<0.01$) higher than the *SAWLOG-AWV* measured on 2.7-m lower sawlogs (debarked), which is consistent with the trend expected from previous studies carried out in *P. radiata* (Chauhan and Walker 2006a).

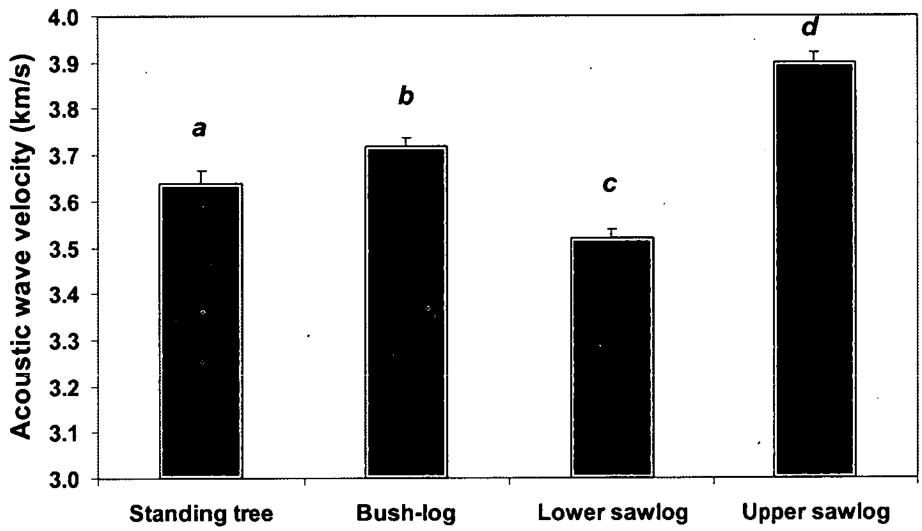


Figure 3.1. Mean trial values and standard errors of acoustic wave velocity (km $s^{-1}$) measured on standing trees, bush-log, lower sawlog and upper sawlog. Bars with the same letter are not significantly different at *P<0.01*.

From the MIXED analysis performed to study the sources of variation in both standing tree and log *AWV, DBHOB* was found to be significantly ($P<0.001$) related to *AVW* (Table 3.2), the higher *DBHOB* the lower standing tree and log *AWV* (Figure 3.2). Although we did not find a significant effect of *STOCKING* on standing tree *AWV* (Table 3.2), *STOCKING* was found to be significantly positively related to *BUSHLOG-AVW* ($P<0.001$) and *SAWLOG-AWV* ($P<0.01$). Therefore lower stocking could lead to lower log *AWV* in plantation-grown eucalypt timber.

Table 3.2 Significance of factors affecting acoustic wave velocity traits. Replicate was not a significant random effect and was omitted in this table.

| | *FAKOPPAWV*[1] | | |
|---|---|---|---|
| Fixed effect | Degrees of freedom | | *F* Value |
| | N | D | |
| *DBHOB* | 1 | 69.9 | 19.78*** |
| *STOCKING* | 4 | 70.2 | 1.50$^{ns}$ |
| *DBHOB * STOCKING* | 4 | 70.7 | 2.15$^{ns}$ |
| *ASPECT* | 1 | 73.7 | 15.49*** |
| *STOCKING*ASPECT* | 4 | 73.7 | 1.92$^{ns}$ |
| *LGS* | 1 | 69.9 | 7.50** |
| *Random effect* | | | *Z* test |
| *REP.TREE* | | | 5.25*** |
| | *BUSHLOG-AWV* | | |
| Fixed effect | Degrees of freedom | | *F* Value |
| | N | D | |
| *DBHOB* | 1 | 69 | 24.96*** |
| *STOCKING* | 4 | 69 | 5.78*** |
| *DBHOB * STOCKING* | 4 | 69 | 1.47$^{ns}$ |
| *FAKOPPAWV* | 1 | 69 | 61.71*** |
| *LGS* | 1 | 69 | 0.18$^{ns}$ |
| *Random effect* | | | *Z* test |
| *REP.TREE* | | | 5.87*** |
| | *SAWLOG-AWV* | | |
| Fixed effect | Degrees of freedom | | *F* Value |
| | N | D | |
| *DBHOB* | 1 | 69 | 39.06*** |
| *STOCKING* | 4 | 69 | 4.90** |
| *DBHOB * STOCKING* | 4 | 69 | 0.96$^{ns}$ |
| *FAKOPPAWV* | 1 | 69 | 58.07*** |
| *LGS* | 1 | 69 | 0.31$^{ns}$ |
| *LOG* | 1 | 76 | 1210.66*** |
| *STOCKING *LOG* | 4 | 76 | 1.56$^{ns}$ |
| *Random effect* | | | *Z* test |
| *REP.TREE* | | | 4.69*** |

[1]one tree was excluded in this analysis due a presence of one outlier of mean tree *LGS* value
N= numerator; D= denominator
ns = not significant *(P>0.05)*
* =*P <0.05.*
** = *P<0.01.*
*** = *P<0.001.*

Examples of significant negative relationships between tree diameter and either *AWV* or $MOE_D$ calculated on standing trees have also been found in 11-year-old *P. radiata* (Lasserre *et al.* 2005), in a *P. ponderosa* progeny trial (McKimmy and King 1980), in *Pseudotsuga menziesii* (Mirbel) Franco (Carter *et al.* 2005) and in the study carried out by Dickson *et al.* (2004) on 316 30-year old *P. radiata* trees grown in a progeny trial in Australia. Nonetheless, in a study carried out on 9 and 25-year old *E. dunnii* plantation-grown material (Dickson *et al.* 2003), there was not significant relationships between tree diameter and standing tree *AWV*, in contrast to our results. However these authors did find a significant ($P<0.05$) negative relationship between tree diameter and log *AWV* measured by the *TOF* method from the 9 year-old *E. dunnii* plantation.

The significant positive relationship we found between *STOCKING* and *AWV* measured in standing trees and logs is also supported by a previous study undertaken in *P. radiata* reported by Lasserre *et al.* (2005). In this case *AWV* and timber stiffness were significantly positively influenced by planting density, which was the most important explanatory factor in their study. The same significant relationship has also been mentioned by Carter *et al.* (2005) and found by Wang *et al.* (2001) in *T. heterophylla* and *P. sitchensis* growing under different thinning strategies. These authors concluded that higher *AWV* and higher timber stiffness were more often found in unthinned control stands than in heavy and medium thinning treatment stands. Therefore, lower stocking rates from either lower planting densities or early thinning interventions may lead to decreased *AWV* and decreased timber stiffness when compared with the same genetic stock growing at higher stocking rates. Because of the growth response commonly obtained, it is likely that thinned stands will have larger log diameters at harvest, leading to differences in processing strategy.

Standing tree *AWV* was also significantly ($P<0.001$) affected by *ASPECT*, being higher in the *SW* stem cardinal direction (Table 3.2). This relationship was consistent across trees, and mean standing tree *AWV* could be reliably predicted from either the *SW* or *NE* measurement which explained 93 and 92% of the variance in mean *FAKOPPA WV* (analysis not presented). Significant differences in standing *AWV* between stem aspects, measured using the Treetap tool, have also been found in *P. radiata,* where the variation between aspects accounted for 14% of the total variation (Toulmin and Raymond 2007). To account for within-tree variability, we therefore recommend a sampling strategy with a minimum of two *TOF* readings per standing tree at opposite stem aspects, which is consistent with the Toulmin and Raymond (2007) recommendation for sampling *P. radiata*.

When the standing tree *LGS* mean value was included as a covariate after accounting for *DBHOB, STOCKING* and *ASPECT*, a significant ($P<0.05$) positive relationship with standing tree *AWV* was found. However, from the regression modelling the relationship between mean *LGS* values and standing tree *AWV* accounted for only 3% of variance after accounting for *DBHOB*, revealing a poor predictive capability (analysis not presented). Also, mean standing tree *LGS* values were not significantly related to either *BUSHLOG-AWV* or *SAWLOG-AWV* (Table 3.2). This is consistent with previous studies where no reliable relationships between standing tree *LGS* and either standing tree *AWV* or $MOE_D$ have been found for *P. radiata* by Chauhan *et al.* (2007) and by Chauhan and Walker (2004), respectively. As expected, mean standing tree *AVW* was found to be significantly ($P<0.001$) and positively related to both *BUSHLOG-AWV* and *SAWLOG-AWV* (Table 3.2), however their correlations (Figure 3.2) were lower than those found in previous research done in softwood species, where coefficient of determination ($r^2$) ranged from 0.71 to 0.93 (Wang *et al.* 2007a). The relatively lower $r^2$ values we obtained may be partially explained due to the fact that standing tree *AVW* in our study was determined from a short section (1.22 m) of knot-free outer wood that has a higher basic density and stiffer wood than the timber close to the pith, whereas the resonance method gives the average of the whole section, including the knotty core wood. Furthermore, hardwood timber and wood properties are different and more complex than softwood timber (Boyd 1977), which may accentuate the differences between *TOF* and resonance methods. Also softwoods when compared to hardwoods have more prominent and defined growth rings structures, higher differences between earlywood and latewood densities, higher earlywood/latewood proportions and also higher changes in properties from juvenile to mature wood, which for some fast-growing pines such as *P. radiata* will be considerably more than for any eucalypt. All these wood structure differences would be expected to result in quite different responses in wood shrinkage and distortion behaviour across board profiles for softwoods, compared with hardwoods (Walker 2006).

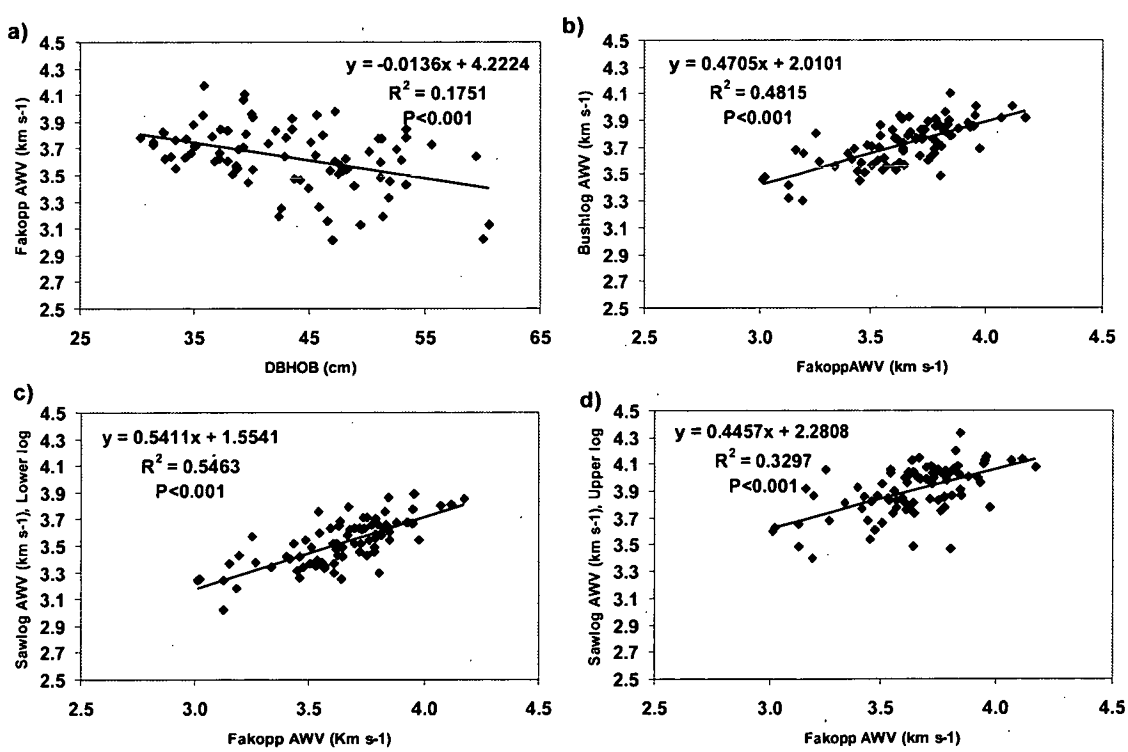


Figure 3.2. Relationships between *FAKOPPAWV* and: a) *DBHOB*; b) *BUSHLOG-AWV*; c) *SAWLOG-AWV* (lower log); and d) *SAWLOG-AWV* (upper log)

The variation in *AWV* with tree height was confirmed with the highly significant relationship we found in *SAWLOG-AWV* according to *LOG* position (Table 3.2). Upper sawlogs had significantly higher *AWV* than lower sawlogs, which in part may be explained by patterns of variation in both wood basic density (increased) and *MFA* (decreased) with height in the stem (Evans *et al.* 2000). No significant difference in levels of either *BUSHLOG-AWV* or *SAWLOG-AWV* was attributable to the interaction between *DBHOB* and *STOCKING*.

After accounting for *DBHOB, ASPECT, STOCKING* and *REP,* differences in *AWV* among individual trees were found to be significant (Table 3.2), which is consistent with studies on *P. radiata* (Toulmin and Raymond 2007) where the largest contributor to total variance in *AWV* across all age classes assessed (10, 15 and 20-year-old) was the difference between trees. Because the Gould's Country trial was not pedigreed, it was not possible to determine the extent to which these between-tree differences were under genetic control. *REP* was not significant for any *AWV* trait assessed.

*3.5.2 Wood-blocks traits: levels and sources of variation*

The mean tangential and radial wood shrinkage values determined at 12% MC-NR on 246 small wood blocks were 7.53 % (SD 2.94%; CV 39.06%) and 4.34 % (SD 2.27%; CV 52.43%), respectively, with a mean value of tangential to radial shrinkage ratio of 1.94 (SD 0.59; CV30.41%), which was consistent with the expected value in plantation-grown eucalypt wood found by Raymond *et al.* (unpublished). The mean values of tangential and radial collapse (12% MC) were 2.34% (SD 1.99%, CV 85.11%) and 1.75% (SD1.60%, CV 91.20%), respectively.

The shrinkage and collapse data we found are within the range of values found by Raymond *et al.* (unpublished) in their study carried out on *E. globulus* and *E. nitens* plantation-grown material from three states of Australia, in which the wood-blocks were air dried and wood shrinkage was determined after reconditioning.

Wood-block tangential shrinkage (*BTSHRINKAGE*), radial shrinkage (*BRSHRINKAGE*), tangential collapse (*BTCOLLAPSE*) and radial collapse (*BRCOLLAPSE*) were significantly ($P$<0.001) lower at the top end of the upper sawlog (upper *BLOCKHEIGHT*) than those values measured at the top end of the lower sawlog (lower *BLOCKHEIGHT*) and also were found to be significantly ($P$<0.001) higher closer to cambium (at 75% *BLOCKDISTANCE*) than those close to the pith (at 25% *BLOCKDISTANCE*) (Figure 3.3 and Table 3.3). Similar patterns of shrinkage and collapse behaviour according to tree height and pith to cambium location has also been reported by Hamilton *et al.* (2007) in *E. globulus*, and also by Raymond *et al.* (unpublished) for *E. globulus* and *E. nitens*.

Wood-block basic density (*BBDENSITY*) was also significantly related to *BLOCKHEIGHT* and *BLOCKDISTANCE*, increasing with tree height and increasing from pith to cambium (Figure 3.3 and Table 3.3). Previous research carried out in *E. nitens* plantation-grown trees from six sites in New Zealand also found significantly higher wood basic density in upper logs (Shelbourne *et al.* 2002).

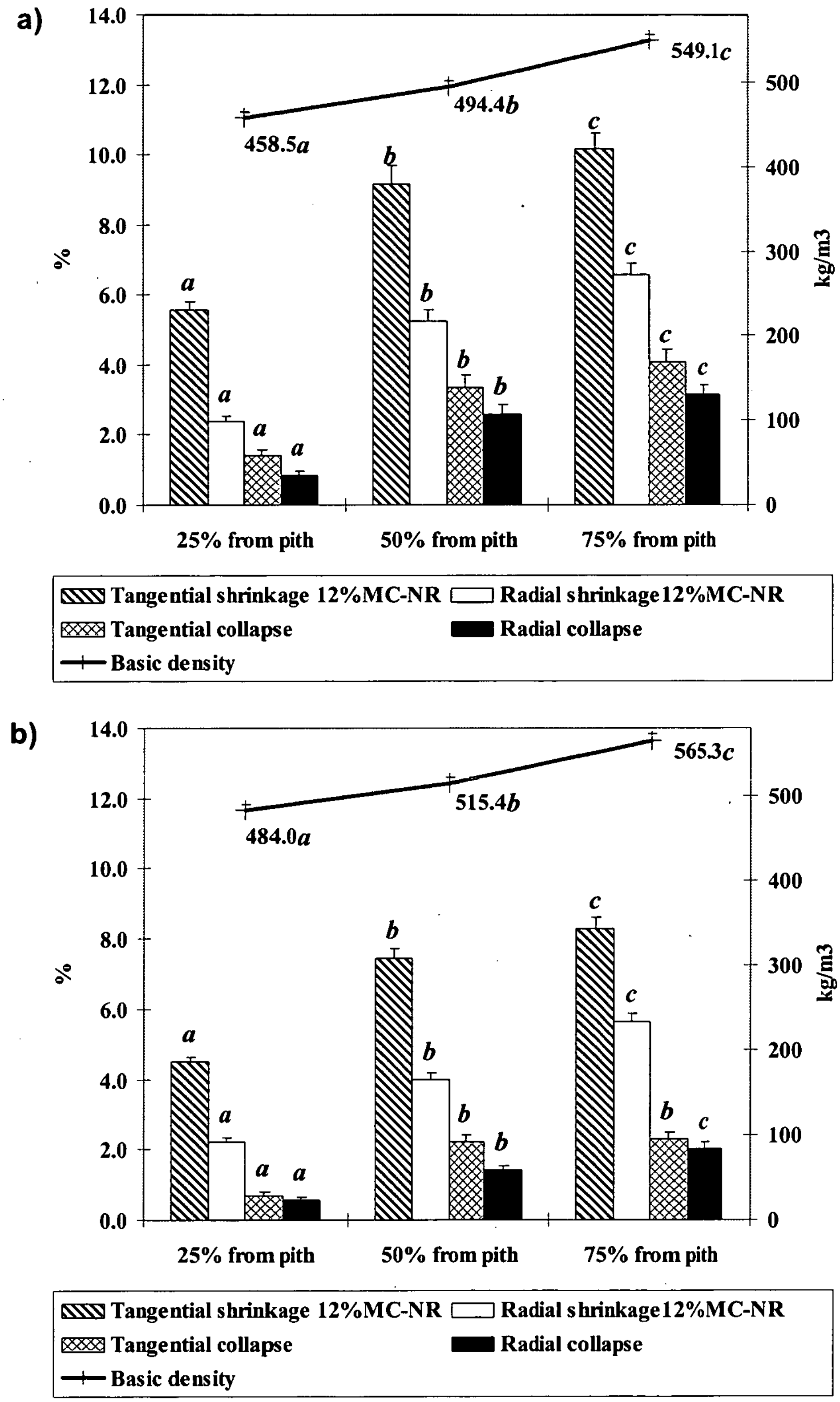


Figure 3.3. Percentage of tangential and radial wood shrinkage at 12% moisture content non reconditioned (MC-NR), percentage of tangential and radial collapse at 12% MC and wood basic density (kg $m^{-3}$), according to *BLOCKDISTANCE* for a) lower *BLOCKHEIGHT* and b) upper *BLOCKHEIGHT*. Within each graph and series, bars with the same letter are not significantly different at *$P<0.05$*.

Table 3.3 Significance of factors affecting non-reconditioned wood shrinkage and collapse traits and wood basic density.

| *Fixed effect* | NDF | Tangential Shrinkage 12MCNR | Radial shrinkage 12MCNR | Shrinkage ratio 12MCNR | Tangential collapse 12MC | Radial collapse 12MC | Basic density |
|---|---|---|---|---|---|---|---|
| | | | | *F-Value* | | | |
| *DBHOB* | 1 | 0.33$^{ns}$ | 0.16$^{ns}$ | 2.64$^{ns}$ | 0.02$^{ns}$ | 0.17$^{ns}$ | 0.35$^{ns}$ |
| STOCKING | 4 | 1.21$^{ns}$ | 0.96$^{ns}$ | 0.14$^{ns}$ | 0.88$^{ns}$ | 1.04$^{ns}$ | 0.36$^{ns}$ |
| *DBHOB* * STOCKING | 4 | 0.16$^{ns}$ | 0.46$^{ns}$ | 1.38$^{ns}$ | 0.15$^{ns}$ | 0.38$^{ns}$ | 0.81$^{ns}$ |
| FAKOPPAWV | 1 | 0.06$^{ns}$ | 0.61$^{ns}$ | 0.04$^{ns}$ | 0.68$^{ns}$ | 1.49$^{ns}$ | 14.22*** |
| LGS | 1 | 0.49$^{ns}$ | 1.30$^{ns}$ | 1.36$^{ns}$ | 0.66$^{ns}$ | 1.20$^{ns}$ | 1.48$^{ns}$ |
| BLOCKHEIGHT | 1 | 51.5*** | 27.9*** | 5.03* | 55.1*** | 49.0*** | 25.3*** |
| BLOCKDISTANCE | 2 | 141.2*** | 217.3*** | 73.28*** | 63.5*** | 81.2*** | 145.0*** |
| BLOCKHEIGHT*BLOCKDISTANCE | 2 | 1.42$^{ns}$ | 4.55* | 6.35** | 3.67* | 5.89** | 0.42$^{ns}$ |
| BDENSITY | 1 | 0.95$^{ns}$ | 4.45* | 28.39*** | 0.10$^{ns}$ | 11.9*** | |
| *Random effect* | | | | *Z* test | | | |
| REP*TREE | | 3.17*** | 3.22*** | 2.84** | 3.11*** | 3.18*** | 3.23*** |

*NDF= Numerator degrees of freedom*
ns = not significant *(P>0.05)*
* =*P <0.05.*
** = *P<0.01.*
*** = *P<0.001.*

Both the higher *MBBDENSITY* we found in the upper stem (Figure 3.3) and the significantly positive relationship between *MBBDENSITY* and *AWV* traits (Table 3.3) may explain in part the higher *SAWLOG-AWV* in the upper log position than lower sawlog, and the intermediate value of *BUSHLOG-AWV*. Similarly, wood basic density differences may also explain in part the higher *AWV* found on bush-logs than standing trees *AWV,* which was calculated in the lower stem section in which we infer the outerwood basic density is significantly lower than the outerwood basic density at higher stem heights, as we found in wood-blocks (Figure 3.3).

### *3.5.3 Predicting sawing traits and mechanical properties from AWV and block traits*

#### a) ***Log end splitting index, flitch and board deflection and board shrinkage***

Table 3.4 summarizes the significance of the relationship between 11 dependent variables (sawing traits) and 9 potential explanatory variables (*AWV* traits and *MBLOCKTRAITS*). Each explanatory variable was included independently in the mixed model together with other pertinent fixed effects and random factors as detailed in the analysis section and also described in detail in Chapter 2. A total of 9 mixed models were fitted for each 11 dependent variables indicated in Table 3.4. Relationships between *AWV* traits and sawing traits were assessed analysing the entire data set of back-sawn and quarter-sawn material. As *BLOCKTRAITS* were determined only in back-sawn trees, their relationship with sawing traits was assessed using only the back-sawn data set.

Table 3.4 and Table 3.9 show that standing tree *AWV* was found to be significantly ($P<0.05$) positively related only to board *BOW* in the green condition; after accounting for significant fixed effects for these traits such as *SAWMETH* (see Chapter 2). *BUSHLOG-AWV* and *SAWLOG-AWV* were also significantly positively ($P<0.001$) related with board *BOW* in the green condition.

Significant relationships between *AWV* data collected on standing trees, logs and sawn-timber with sawn board distortion propensity were also found in *Pinus ponderosa* (Wang and Simpson 2005; Wang *et al.* 2005b), however in their studies the relationships were negative. Log *AWV* was also found to be significantly positively related to both *SPLITINDEX* and mean board *SHRINKAGE-WIDTH* (Table 3.4 and Table 3.9). No *AWV* traits were found to affect either *FLITCH* and *SLAB* distortion in quarter sawn material, *BOW* in dry condition, *SPRING* in both the green and dry condition, or mean board *SHRINKAGE-THICK* (Table 3.4).

Table 3.4 Significance of *AWV* and blocks traits on log end-splitting index, flitch and slab distortion and sawn-board stability traits.

| Dependent variable | Standing tree velocity | Bush-log velocity | Sawlog velocity | Tang. Shrink. 12% MC BR | Radial shrink. 12% MC BR | Shrink. ratio 12% MC BR | Tang. collapse | Radial collapse | Basic density |
|---|---|---|---|---|---|---|---|---|---|
| | F-Value | | | | | | | | |
| SPLITIND EX-BUTT | $1.29^{ns}$ | 5.14* | 8.90** | $0.18^{ns}$ | $0.84^{ns}$ | 6.56* | $0.37^{ns}$ | $0.86^{ns}$ | 5.61* |
| SPLITIND EX-TOP | $0.59^{ns}$ | $3.65^{ns}$ | $3.77^{ns}$ | $0.37^{ns}$ | $1.63^{ns}$ | $2.10^{ns}$ | $0.33^{ns}$ | $1.96^{ns}$ | $0.83^{ns}$ |
| SPLITIND EX-SUM | $0.86^{ns}$ | 4.30* | 5.94* | $0.04^{ns}$ | $1.06^{ns}$ | $2.82^{ns}$ | $0.00^{ns}$ | $1.27^{ns}$ | $2.63^{ns}$ |
| FLITCH | $0.23^{ns}$ | $0.26^{ns}$ | $0.03^{ns}$ | | | | | | |
| SLAB | $0.67^{ns}$ | $0.77^{ns}$ | $0.59^{ns}$ | | | | | | |
| BOW-GREEN | 6.86* | 11.1*** | 17.5*** | $0.01^{ns}$ | $0.25^{ns}$ | $0.08^{ns}$ | $0.06^{ns}$ | $0.36^{ns}$ | $0.08^{ns}$ |
| BOW-DRY | $0.99^{ns}$ | $1.02^{ns}$ | $0.15^{ns}$ | $1.46^{ns}$ | $1.67^{ns}$ | $0.00^{ns}$ | $1.10^{ns}$ | $0.96^{ns}$ | $0.57^{ns}$ |
| SPRING-GREEN | $0.09^{ns}$ | $0.17^{ns}$ | $0.79^{ns}$ | $0.92^{ns}$ | $3.13^{ns}$ | $0.64^{ns}$ | $1.09^{ns}$ | $4.01^{ns}$ | $0.27^{ns}$ |
| SPRING-DRY | $0.06^{ns}$ | $0.16^{ns}$ | $0.02^{ns}$ | 7.90** | $3.13^{ns}$ | $0.21^{ns}$ | 8.79** | $3.31^{ns}$ | $1.18^{ns}$ |
| SHRINKAGE-THICK | $0.22^{ns}$ | $1.30^{ns}$ | $3.71^{ns}$ | $2.73^{ns}$ | $3.54^{ns}$ | $0.40^{ns}$ | $1.99^{ns}$ | $3.32^{ns}$ | $0.01^{ns}$ |
| SHRINKAGE-WIDTH | $1.70^{ns}$ | 5.31* | 7.25** | 10.07** | 7.54* | $0.02^{ns}$ | 7.67** | 5.16* | $0.01^{ns}$ |

Models fitted for dependent variables that include AWV traits as explanatory variable were fitted using Equations 3.8 and 3.9.
Models fitted for dependent variables that include wood-block traits as explanatory variable were fitted using Equations 3.11 and 3.12.
MC BR = moisture content before reconditioning
ns = not significant *(P>0.05)*
* = *P <0.05.*
** = *P<0.01.*
*** = *P<0.001.*

From previous research carried out in plantation-grown eucalypt material on the relationships between anatomical characteristics and shrinkage behaviour (Wu *et al.* 2006) and the study undertaken by Abe and Yamamoto (2006) on the role of *MFA* in wood shrinkage on *Chamaecyparis obtuse* Endl., it is hypothesised that our positive association between *SAWLOG-AWV* and mean board *SHRINKAGE-WIDTH* may be partially explained by a combined effect of: a) reduced mean value of *MFA* in the $S_2$ cell wall layer in those logs with higher *AWV,* since lower *MFA* has been associated with higher tangential and radial shrinkage; and b) the higher mean value of wood density in those logs with higher *AWV,* since higher wood basic density has been associated with higher volumetric, tangential and radial shrinkage in previous research carried out in eucalypts (Hamilton 2007; Wu *et al.* 2006).

Table 3.4 also shows that *MBTSHRINKAGE*, included as an explanatory variable in the MIXED analysis, was found to be significantly positive ($P$<0.01) related to *SPRING-DRY*, and as expected was also significantly ($P$<0.01) and positively related to mean board *SHRINKAGE-WIDTH* in the intensively assessed back-sawn boards. The same significant relationships ($P$<0.01) were found for *MBTCOLLAPSE*. The *MBRSHRINKAGE* was only significantly ($P$<0.05) related to mean board *SHRINKAGE-WIDTH* (Table 3.4) as expected. The same significant relationship ($P$<0.05) was found between *MBRCOLLAPSE* with mean board *SHRINKAGE-WIDTH*. *MBBDENSITY* was only significantly ($P$<0.05) related to the *SPLITINDEX-BUTT*.

**b) *Sawn-board checking propensity, product recovery and value***

Table 3.5 summarizes the significance of the relationship among 8 dependent variables (sawing traits) and the same 9 explanatory variables described above. Standing tree *AWV* was not significantly related to any *CHECKTRAIT*, product recoveries or product value (Table 3.5). Conversely, *BUSHLOG-AWV* and *SAWLOG-AWV* were significantly and positively related to *SELECT* recovery ($P$<0.05 and $P$<0.01, respectively) and to *PVPCMLI* ($P$<0.05) (Tables 3.5 and 3.9). The difference in significance we obtained between standing tree *AWV* and log *AWV* for *SELECT* recovery and *PVPCMLI* can to some extent be explained by the difference between the *TOF* and resonance methods. The resonance method gives a more representative value of the whole log AWV, whereas the *TOF* method as used in our study relates to outerwood only. No significant relationships between *AWV* traits and checking propensity were found in our study (Table 3.5).

Table 3.5 Significance of *AWV* traits and wood-blocks traits in checking propensity, product recoveries and product value.

| Dependent variable | Explanatory variable | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Standing tree velocity | Bush-log velocity | Sawlog velocity | Tang. Shrink. 12% MC BR | Radial shrink. 12% MC BR | Shrink. ratio 12% MC BR | Tang. collapse | Radial collapse | Basic density |
| | F-Value | | | | | | | | |
| *SURFCHECK* | 0.04$^{ns}$ | 2.48$^{ns}$ | 2.33$^{ns}$ | 2.37$^{ns}$ | 1.46$^{ns}$ | 0.02$^{ns}$ | 2.42$^{ns}$ | 1.84$^{ns}$ | 0.26$^{ns}$ |
| *INTCHECK* | 3.58$^{ns}$ | 1.71$^{ns}$ | 2.29$^{ns}$ | 5.60* | 4.44* | 1.19$^{ns}$ | 7.80** | 4.52* | 0.37$^{ns}$ |
| *ENDSPLIT-GREEN* | 0.12$^{ns}$ | 0.05$^{ns}$ | 0.06$^{ns}$ | 2.34$^{ns}$ | 0.47$^{ns}$ | 1.26$^{ns}$ | 1.64$^{ns}$ | 0.21$^{ns}$ | 0.85$^{ns}$ |
| *ENDSPLIT-DRY* | 0.04$^{ns}$ | 1.09$^{ns}$ | 1.02$^{ns}$ | 0.36$^{ns}$ | 0.98$^{ns}$ | 0.05$^{ns}$ | 0.75$^{ns}$ | 0.73$^{ns}$ | 2.01$^{ns}$ |
| *ENDOCK-GREEN* | 0.04$^{ns}$ | 1.11$^{ns}$ | 1.05$^{ns}$ | 0.35$^{ns}$ | 0.99$^{ns}$ | 0.06$^{ns}$ | 0.73$^{ns}$ | 0.74$^{ns}$ | 1.97$^{ns}$ |
| *TOTALRECOVERY* | 1.47$^{ns}$ | 1.28$^{ns}$ | 0.87$^{ns}$ | 4.67* | 1.38$^{ns}$ | 0.72$^{ns}$ | 3.86$^{ns}$ | 1.39$^{ns}$ | 0.78$^{ns}$ |
| *SELECT* | 0.27$^{ns}$ | 6.38* | 7.77** | 15.8*** | 12.3*** | 0.39$^{ns}$ | 17.2*** | 15.6*** | 0.41$^{ns}$ |
| *PVPCMLI* | 0.53$^{ns}$ | 5.61* | 6.13* | 15.3*** | 10.0** | 0.12$^{ns}$ | 16.0*** | 13.2*** | 0.17$^{ns}$ |

Models fitted for dependent variables that include *AWV* traits as explanatory variable were fitted using Equations 3.9 and 3.10.
Models fitted for dependent variables that include wood-block traits as explanatory variable were fitted using Equations 3.12 and 3.13
MC BR = moisture content before reconditioning
ns = not significant *(P>0.05)*
* = *P <0.05.*
** = *P<0.01.*
*** = *P<0.001.*

*MBTSHRINKAGE, MBRSHRINKAGE, MBTCOLLAPSE* and *MBRCOLLAPSE* had highly significant (*P*<0.001) negative relationships with both *SELECT* recovery and *PVPCMLI* (Table 3.5 and Table 3.10). *MBTSHRINKAGE* was also significantly negatively related to *TOTALRECOVERY.*

*INTCHECK* was found to be significantly related to *MBTCOLLAPSE* (*P*<0.01), *MBTSHRINKAGE* (*P*<0.05), *MBRSHRINKAGE* (*P*<0.05), and *MBRCOLLAPSE* (*P*<0.05) (Table 3.5 and Table 3.10). Conversely *SURFCHECK* did not have any significant relationship with the blocks traits measured.

*MBTRSHRINKAGE* and *MBBDENSITY* did not have any significant relationship with any sawn-board checking propensity, product recovery and value traits (Table 3.5). As with *AWV* traits, no wood-block trait had a significant relationship with board *ENDSPLIT* (in green and dry condition) or *ENDOCKING* in green condition, which in turn have been found to be related to standing tree *LGS* (refer to Chapter 2).

c) ***Timber stiffness, strength and hardness: levels and sources of variation***

Table 3.6 summarizes the mean values and value range of $MOE_S$, *MOR* and *HARDNESS* according to *LOG* position and *SAWMETH*. Overall $MOE_S$ and *MOR* were higher on boards from upper logs than lower logs. The levels of $MOE_S$ values can be considered higher than those recorded in softwood species such as *T. heterophylla* and *P. sitchensis* (Wang *et al.* 2001), higher than those reported by Armstrong and Heathcote (2003) on 7-year-old *E. grandis*, quite similar but higher than those reported by McGavin *et al.* (2006) on 8-year-old *Eucalyptus cloeziana*, 9-year-old *E. pilularis* and 8.5-year-old *E. pellita*, similar to those obtained in 9-year-old *E. nitens* (Harwood *et al.*, unpublished), but less than those reported by (Yang 2007) on 32-year-old plantation *Eucalyptus globulus* Labill and also lower than those reported by Dickson *et al.* (2003) on 9 and 25-year-old plantation-grown *E. dunnii* timber. Nonetheless the mechanical properties are within the thresholds suitable for a broad range of structural applications. For instance, based on the preliminary classification values for seasoned timber in AS/NZS 2878:2000 (Standard Australia 2000), the mean $MOE_S$ and *MOR* values in Table 3.6 would give a strength group rating of SD5 and SD4, respectively, which combined would give the 22-year-old *E. nitens* an overall Strength Group of SD4. This result is consistent with the Strength Group for seasoned *E. nitens* natural-grown timber indicated by AS/NZS 2878:2000. This is two strength groups stronger than that the Strength Group reported for softwoods such as *P. sitchensis, T. heterophylla* and *P. radiata* which are classified as SD6 (Standard Australia 2000). It is also interesting to note the wide range of wood mechanical properties values obtained, which indicates the potential benefits that could be obtained by segregating material into different grades.

Table 3.6 Mean values for $MOE_S$, *MOR* and hardness traits, for different log positions and sawing methods.

| Variable | Unit | | *LOG position* | | *SAWMETH* | |
|---|---|---|---|---|---|---|
| | | | Lower | Upper | Back-sawn | Quarter-sawn |
| $MOE_S$ | GPa | Mean | 11.7 | 13.0 | 12.6 | 12.0 |
| | | Range | 6.5-17.5 | 6.9-19.1 | 8.0-19.1 | 6.5-16.9 |
| | | N | 163 | 159 | 164 | 158 |
| MOR | MPa | Mean | 98.2 | 106.2 | 103.5 | 100.7 |
| | | Range | 49.1-162.8 | 54.8-157.9 | 49.1-157.9 | 54.8-162.8 |
| | | N | 163 | 159 | 164 | 158 |
| Janka *HARDNESS* tangential (average) | kN | Mean | 5.04 | 4.99 | 5.01 | 5.05 |
| | | Range | 2.5-9.8 | 2.6-9.0 | 2.5-9.8 | 3.0-8.0 |
| | | N | 106 | 99 | 163 | 42 |

GPa: gigapascal; MPa: megapascal; kN: kilonewton

From the mixed models fitted, neither *SAWMETH, DBHOB* nor *STOCKING,* were significantly related either to $MOE_S$, *MOR* or *HARDNESS* (Table 3.7). Conversely, *LOG* position had a highly significant ($P<0.001$) relationship with $MOE_S$ and *MOR,* but not with *HARDNESS.* Therefore upper sawlogs produced stiffer and stronger sawn-timber than lower sawlogs.

As expected, the *AWV* traits assessed, standing tree *AWV* and log *AWV*, were significantly ($P<0.001$) positively associated to $MOE_S$, *MOR* and *HARDNESS*, after accounting for *LOG* position (Tables 3.7 and 3.9). Individual trees differed significantly in their $MOE_S$ ($P<0.01$) and *HARDNESS* ($P<0.05$). As in the previous analyses, the replicate effect was not significant. The significant positive relationships between *AWV* traits measured on standing trees and harvested logs and timber mechanical properties we found are consistent with the results reported for *E. dunnii* plantations (Dickson *et al.* 2003) and are consistent with the expected relationship between *AWV* and wood mechanical properties (Huang *et al.* 2003).

Table 3.7 Significance of factors affecting wood mechanical properties.

| Fixed effect | NDF | $MOE_S$ | | MOR | | HARDNESS tangential | |
|---|---|---|---|---|---|---|---|
| | | DDF | F-Value | DDF | F-Value | DDF | F-Value |
| *SAWMETH* | 1 | 72.6 | $3.91^{ns}$ | 70.7 | $1.54^{ns}$ | 88.2 | $0.05^{ns}$ |
| *DBHOB* | 1 | 68.9 | $0.27^{ns}$ | 65.5 | $2.45^{ns}$ | 58.3 | $0.39^{ns}$ |
| *STOCKING* | 4 | 73.2 | $0.91^{ns}$ | 71.3 | $2.04^{ns}$ | 53.9 | $0.34^{ns}$ |
| *FAKOPPAWV* | 1 | 70.8 | 35.14*** | 68.5 | 31.90*** | 61 | 18.52*** |
| *LOG* | 1 | 244 | 48.37*** | 245 | 17.77*** | 160 | $0.10^{ns}$ |
| *SAWMETH*LOG* | 1 | 244 | $0.39^{ns}$ | 245 | $0.11^{ns}$ | 195 | $0.25^{ns}$ |
| *BUSHLOG-AWV*[a] | 1 | 68.8 | 53.15*** | 68.6 | 27.49*** | 52.4 | 16.07*** |
| *SAWLOG-AWV*[a] | 1 | 101 | 44.57*** | 95.2 | 21.60*** | 76.3 | 12.76*** |
| *Random effect* | | | | Z test | | | |
| *REP*TREE* | | 3.01** | | $1.45^{ns}$ | | 1.84* | |

[a] either BUSHLOGAWV or SAWLOGAWV were included instead of FAKOPPAWV
NDF= Numerator degrees of freedom; DDF= Denominator degrees of freedom
ns = not significant *(P>0.05)*
* =*P <0.05.*
** = *P 0<0.01.*
*** = *P<0.001.*

The lack of significant relationships between wood mechanical properties assessed with *DBHOB* and *STOCKING* contrasted with the relationships of *AWV* traits to *DBHOB* and *STOCKING.* However our results are quite similar to those reported by Dickson *et al.* (2003) in 9 and 25-year-old *E. dunnii* plantation-grown timber, where tree diameter was only weakly significantly ($P$<0.05) related to *MOR* in 25-year-old material and significantly ($P$<0.01) negatively related to hardness, but no significant relationship was found between tree diameter and $MOE_S$ with either 9 or 25 year-old material.

As was stated in Chapter 1, the boards used to assess mechanical properties were different to those intensively assessed from the SW cants, therefore these results related to timber mechanical properties were less representative, as the board position within each log used to determine $MOE_S$, *MOR* and hardness was not controlled. The use of log end templates to track the board position within log, would help overcome this kind of problem in future sawing trials.

From previous research carried out in softwood plantation species such as *P. radiata* (Lasserre *et al.* 2005), a significant negative relationship has been found between $MOE_S$ and tree diameter and a significant positive relationships between $MOE_S$ and *MOR* and stand density (stocking rate) in plantations of the same age.

*SHRINKAGETRAITS* were not found to be a significant explanatory factor of either $MOE_S$, *MOR* or *HARDNESS* (Table 3.8). The only exception was the significant ($P<0.05$) negative relationships found between *MBTCOLLAPSE* and *MOR* (Table 3.8 and Table 3.10). As expected, the *MBBDENSITY* had a significant positive relationship to $MOE_S$ ($P<0.05$), *MOR* ($P<0.001$) and *HARDNESS* ($P<0.001$) (Table 3.8 and Table 3.10).

Table 3.8 Significance of wood-blocks traits in wood mechanical properties determined in back-sawn boards.

| Fixed effect | NDF | $MOE_S$ | | *MOR* | | *HARDNESS* | |
|---|---|---|---|---|---|---|---|
| | | DDF | F-Value | DDF | F-Value | DDF | F-Value |
| *DBHOB* | 1 | 27.3 | $0.32^{ns}$ | 26 | $0.80^{ns}$ | 28.6 | $0.02^{ns}$ |
| *STOCKING* | 4 | 27.3 | $0.53^{ns}$ | 26.2 | $0.68^{ns}$ | 28.4 | $0.50^{ns}$ |
| *DBHOB*STOCKING* | 4 | 27.7 | $1.95^{ns}$ | 26.7 | $1.25^{ns}$ | 29.2 | $1.46^{ns}$ |
| *LOG* | 1 | 116 | 18.62*** | 115 | 9.39** | 116 | $0.02^{ns}$ |
| *MBLOCKTRAIT* | | | | | | | |
| *MBTSHRINKAGE* | 1 | 70.6 | $1.02^{ns}$ | 52.6 | $2.25^{ns}$ | 59.5 | $0.00^{ns}$ |
| *MBRSHRINKAGE* | 1 | 57.1 | $0.44^{ns}$ | 43.3 | $1.86^{ns}$ | 50.8 | $0.05^{ns}$ |
| *MBTRSHRINKAGE* | 1 | 86.5 | $0.18^{ns}$ | 64.4 | $0.49^{ns}$ | 69.8 | $0.22^{ns}$ |
| *MBTCOLLAPSE* | 1 | 74.5 | $2.50^{ns}$ | 54 | 4.62* | 66.2 | $0.47^{ns}$ |
| *MBRCOLLAPSE* | 1 | 57.3 | $1.22^{ns}$ | 42.2 | $3.61^{ns}$ | 53.3 | $0.01^{ns}$ |
| *MBBDENSITY* | 1 | 55.3 | 4.88* | 36.5 | 15.0*** | 44.7 | 16.51*** |
| *Random effect* | | Z test | | | | | |
| *REP*TREE* | | 2.37* | | $1.64^{ns}$ | | $0.95^{ns}$ | |

[a] *MBRAIT* can be either *MBTSHRINKAGE, MBRSHRINKAGE, MBTRSHRINKAGE, MBTCOLLAPSE, MBRCOLLAPSE* or *MBBDENSITY*

NDF= Numerator degrees of freedom; DDF= Denominator degrees of freedom

ns = not significant *(P>0.05)*

* =*P <0.05.*

** = *P 0<0.01.*

*** = *P<0.001.*

**d)** ***Capability of AWV measurements to predict sawlog quality***

Despite the significant relationship we found between *AWV* traits and some sawing traits, the predictive capability of *AWV* was modest as evidenced by the modest improvements in the coefficient of determination ($r^2$) for these variables in MLR models that already accounted for other significant factors (Table 3.9). For instance, standing tree *AWV* only gives an extra 1.6% of variance explained in *BOW-GREEN*, after accounting for sawing method. The inclusion of *SAWLOG-AWV* gives only 5% and 5.5% of extra variance accounted for in *SPLITINDEX-SUM* and in *BOW-GREEN*, respectively. Similarly, the inclusion of *SAWLOG-AWV* in the *MLR* for the prediction of either *SELECTRECOVERY* or *PVPCMLI* gives an extra 3.2% and 4.0% respectively, of variance explained after accounting for sawing method, *DBHOB* and *LOG* position.

Higher levels of improvements in $r^2$ were obtained in the prediction of mechanical properties from AWV traits (Table 3.9). From the *MLR* equations fitted to predict $MOE_S$, the inclusion of either mean *FAKOPPAWV or SAWLOG-AWV* in the equations, give 14.2% and 17.4% of extra variation explained, after taking into account *LOG* position (Table 3.9). Similarly, they explained an additional 9.6% and 9.1% of variance in the prediction of *MOR*. *LOG* position alone can explain only 9.2% and 4.2% of the $MOE_S$ and *MOR* variation respectively.

Table 3.9 Amount of variance of sawlog suitability traits gained when an *AWV* trait is included in regression equations and the direction of their relationship.

| Sawing trait/wood property | *Factors included*[a] | $r^2$ *x 100 without AWV trait* | *Extra gain in* $r^2$ *x 100 due to AWV trait*[b] | *Relationship* |
|---|---|---|---|---|
| *SPLITINDEX-SUM* | *DBHOB LOG* | 25.0 | 5.0 (2) | Positive |
| *Wood basic density*[c] | *BLOCKHEIGHT BLOCKDISTANCE* | 36.6 | 10.0 (1) | Positive |
| Bow-Green | *SAWMETH* | 42.9 | 1.6 (1) | Positive |
| Bow-Green | *SAWMETH* | 42.9 | 5.5 (2) | Positive |
| Mean board shrinkage-width | *SAWMETH STOCKING LOG* | 35.2 | 1.2 (2) | Positive |
| *MOEs* | *LOG* | 9.2 | 14.2 (1) | Positive |
| *MOEs* | *LOG* | 9.2 | 17.4 (2) | Positive |
| *MOR* | *LOG* | 4.2 | 9.6 (1) | Positive |
| *MOR* | *LOG* | 4.2 | 9.1 (2) | Positive |
| *HARDNESS* | *No significant fixed factor found* | 0 | 6.5 (1) | Positive |
| *HARDNESS* | *No significant fixed factor found* | 0 | 1.3 (2) | Positive |
| Select recovery | *SAWMETH LOG* | 38.2 | 3.2 (2) | Positive |
| Product value per cubic metre | *SAWMETH DBHOB LOG* | 30.5 | 4.0 (2) | Positive |

[a] which were found to have significant ($P<0.05$) effects on processing traits, according to the mixed models performed in Chapter 2 and Washusen *et al.* (2008)
[b] *AWV* trait included considers (1): *FAKOPPAWV*, or (2): *SAWLOGAWV*.
[c] only assessed on backsaw-material

We suggest that the modest level of improvement in $r^2$ we obtained from the current study using *AWV* traits for the prediction of wood mechanical properties could be higher as we only randomly sampled a minimum of two boards per log without controlling the board position within each log.

**e) *Capability of wood-block measurements to predict sawlog quality***

As described earlier, many wood-block shrinkage and collapse traits (*MBSHRINKAGETRAITS)* analysed were found to be significantly related to a few sawing traits assessed such as board *SPRING-DRY*, mean board *SHRINKAGE-WIDTH*, board *INTCHECK, SELECT recovery and PVPCMLI.* However, *MBSHRINKAGETRAITS* had low power to predict these sawing traits as evidenced by the modest improvements in $r^2$ (Table 3.10). In the best case, *MBTSHRINKAGE* accounted for an extra 6.1% of the variance explained in mean board *SHRINKAGE-WIDTH*, after accounting for *STOCKING* and *LOG* position, which together only explain 2.5% of the variance.

Higher values of $r^2$ improvement were observed in the prediction of wood mechanical properties from *MBBDENSITY*, which, when included in the MLR equations added 7.9%, 10.6% and 13.7% to the variance explained in $MOE_S$, *MOR* and *HARDNESS*, respectively, after accounting for *LOG* position (Table 3.10), which alone can explain only 8%, 5% and 0% of the variation respectively. *MBTCOLLAPSE* can explain an extra 4.3% of variance in timber strength after accounting for *LOG* position.

Table 3.10 Amount of variance of sawlog suitability traits gained when wood-block traits are included in the regression equations.

| Sawing trait/wood property | *Factors included*[a] | $r^2$ *x 100 without block data* | *Extra gain in* $r^2$ *due to block data* | *Relationship* |
|---|---|---|---|---|
| *Standing tree acoustic velocity* | *DBHOB* | 3.4 | 19.8 (BD) | Positive |
| *Sawlog acoustic velocity* | *DBHOB STOCKING LOG* | 59.7 | 7.2 (BD) | Positive |
| Spring-Dry | *No significant fixed factor found* | 0 | 0.9 (TS) | Negative |
| Spring-Dry | *No significant fixed factor found* | 0 | 2.0 (TC) | Negative |
| Mean board shrinkage-width | *STOCKING LOG* | 2.5 | 6.1 (TS) | Positive |
| Mean board shrinkage-width | *STOCKING LOG* | 2.5 | 4.6 (RS) | Positive |
| Mean board shrinkage-width | *STOCKING LOG* | 2.5 | 3.7 (TC) | Positive |
| Mean board shrinkage-width | *STOCKING LOG* | 2.5 | 3.1 (RC) | Positive |
| Internal check occurrence | *LOG* | 15.3 | 2.5 (TS) | Positive |
| Internal check occurrence | *LOG* | 15.3 | 2.8 (RS) | Positive |
| Internal check occurrence | *LOG* | 15.3 | 4.0 (TC) | Positive |
| Internal check occurrence | *LOG* | 15.3 | 3.1 (RC) | Positive |
| Timber stiffness ($MOE_S$) | *LOG* | 8.0 | 7.9 (BD) | Positive |
| Timber strength (*MOR*) | *LOG* | 5.0 | 10.6 (BD) | Positive |
| Timber strength (*MOR*) | *LOG* | 5.0 | 4.3 (TC) | Negative |
| Timber strength (*MOR*) | *LOG BD* | 15.6 | 2.5 (TC) | Negative |
| Janka hardness (*HARDNESS*) | *No significant fixed factor found* | 0 | 13.7 (BD) | Positive |
| Total recovery | *DBHOB* | 7.5 | 4.6 (TS) | Negative |
| Select recovery | *LOG* | 33.3 | 4.2 (TS) | Negative |
| Select recovery | *LOG* | 33.3 | 5.9 (RS) | Negative |
| Select recovery | *LOG* | 33.3 | 5.0 (TC) | Negative |
| Select recovery | *LOG* | 33.3 | 6.0 (RC) | Negative |
| Select recovery | *LOG SAWLOG-AWV* | 38.2 | 3.8 (TC) | Negative |
| Product value per cubic metre | *DBHOB LOG* | 28.2 | 5.7 (TS) | Negative |
| Product value per cubic metre | *DBHOB LOG* | 28.2 | 5.6 (RS) | Negative |
| Product value per cubic metre | *DBHOB LOG* | 28.2 | 6.2 (TC) | Negative |
| Product value per cubic metre | *DBHOB LOG* | 28.2 | 5.8 (RC) | Negative |
| Product value per cubic metre | *DBHOB LOG SAWLOG-AWV* | 31.9 | 4.9 (TC) | Negative |

[a] which were found to have significant (*P<0.05*) effects on processing and wood block traits, accordingly the mixed models performed in the current Chapter.

[b] Blocks trait included considers (BD): *MBBDENSITY*, or (TS): *MBTSHRINKAGE*; (RS): *MBRSHRINKAGE*; (TC): *MBTCOLLAPSE*; (RC): *MBRCOLLPASE*.

*3.5.4 Application of results*

**a) *AWV measurements***

The *TOF* method utilized to collect *AWV* data on standing trees using FAKOPP and the resonance methods utilized to collect *AWV* data on logs using DIRECTOR HM200™ were both able to identify significant differences in *AWV* propagation behaviour between trees and logs of *E. nitens* plantation-grown timber. These findings confirm the capability of acoustic tools to screen and segregate eucalypt plantation-grown trees and logs according to their *AWV*, as has been found by Dickson *et al.* (2003) for both 9 and 25-year-old *E. dunnii* plantation-grown material. The above capability plus the simplicity of using *AWV* tools and the reduced time involved in collecting *AWV* readings, relative to traditional methods for determining wood mechanical properties, make them potentially useful tools for supporting tree breeding programs (for selection of genotypes with better wood mechanical properties), silvicultural management (thinning selection criteria to leave the stiffer trees for final harvest), and log segregation (for processing stiffer logs, improving the structural products grade recoveries at the mill). In those eucalypt plantation-grown trees close to rotation age, as for the resource studied, we recommend performing a standing tree sampling strategy based on two *TOF* measurements per tree at two opposite stem aspects to account for the within tree variation in *AWV*. Further research under different site conditions and stand ages are recommended to explore site effects on *AWV* traits and measurements.

In the current study, there was a significant negative relationship between *AWV*, collected on both standing trees and sawlogs, and tree diameter. In addition, log *AWV* was significantly greater at higher stockings. Therefore the silvicultural control of stand density over the rotation may be a useful tool for producing *E. nitens* plantation-grown timber with higher *AWV* and improved mechanical properties such as $MOE_S$, *MOR* and hardness. Further studies should be undertaken under different site conditions and stand ages. We also found significant positive relationships between sawlog *AWV* and appearance solid-wood traits including select grade recovery and product value per cubic metre of log input.

Although we found a relatively low coefficient of determination in the regression between standing tree *AWV* and sawlog *AWV* ($r^2$= 0.58 for the lower sawlog and $r^2$= 0.35 for the upper sawlog), both standing tree *AWV* and sawlog *AWV* had a similar predictive capability of $MOE_S$ and *MOR* assessed on clearwood samples. Standing tree *AWV* was a better predictor of Janka Hardness than sawlog *AWV*. Therefore the *TOF* method could be as effective as resonance methods used on logs for evaluation of mature *E. nitens* plantation-grown stands managed for solid-wood production. When the sampling aims also include appearance traits, sawlog *AWV* could provide better prediction of select recovery and product value. The significant relationship between sawlog *AWV* and select recovery and product value found must be interpreted with caution as we could not find any significant relationship between *AWV* traits and either surface or internal check occurrence, which were the main value-limiting factors in the Gould's Country sawing trial (Washusen *et al.* 2008).

**b) *Wood block traits***

Wood total shrinkage, collapse and wood basic density levels measured in small blocks extracted from the 41 back-sawn trees were found to be significantly related to the longitudinal and radial location of the blocks within the tree stem. Shrinkage was greater, and density higher, in the outer wood close to cambium than in the blocks close to the pith, so the two traits showed similar trends in the radial direction. In contrast, both wood shrinkage and collapse decreased longitudinally being lower in the blocks from above the second sawlog, whereas wood basic density increased longitudinally, being greater above the upper sawlog than above the lower sawlog.

Neither *DBHOB* nor *STOCKING* was significantly related to any block trait measured, suggesting that controlling stand density would not effectively manage these wood properties. We found highly significant ($P<0.001$) negative relationships between tangential and radial shrinkage, and also tangential and radial collapse, and select recovery and product value traits. No block trait was significantly related to the occurrence of surface checks. However, internal checking was significantly positively related to tangential shrinkage ($P<0.05$), radial shrinkage ($P<0.05$), tangential collapse ($P<0.01$) and radial collapse ($P<0.05$). Despite the relatively low capability of shrinkage and collapse traits measured in small blocks to predict select recovery, product value and internal checking, our findings support previous research in which shrinkage traits have been used to select better genotypes for solid wood production in *E. nitens* (Hamilton 2007). Mean values of block wood basic density were found to be significantly positively related to *AWV* traits, significantly negatively related to mean value of both block radial shrinkage ($P<0.05$) and block radial collapse ($P<0.001$), significantly positively related to mean value of block tangential to radial shrinkage ratio ($P<0.001$) and also significantly positively related with $MOE_S$ ($P<0.05$), *MOR* ($P<0.001$) and hardness ($P<0.001$). However basic density was not significantly related to any sawn-board processing trait assessed such as board end-splitting, board checking propensity, recoveries and product value. Further studies should be undertaken under different site conditions, genotypes and stand ages in order to evaluate the capability of wood basic density to predict sawn-timber appearance traits. Finally, significant variation between trees in *AWV* traits, block shrinkage, collapse and basic density and also in some mechanical properties found in this study might have a genetic basis, suggesting that selection of better genotypes for solid-wood production could lead to improved processing performance. Some factors that were found to be significant, particularly those where probability was in the range $P<0.01$ to $P<0.05$, should be interpreted with caution, since techniques to adjust p-values so as to control false discovery rates arising from multiple testing (Benjamini and Hochberg 1995) were not performed as was indicated in Chapter 1.

### 3.6 Conclusions

In a 22-year-old *E. nitens* plantation, acoustic wave velocity (*AWV*) levels measured on 81 standing trees using a time-of-flight based tool and on 161 2.7-m sawlogs measured by a resonance tool were significantly positively related to wood mechanical properties. Standing tree *AWV* and sawlog *AWV* had a similar ability to predict timber stiffness ($MOE_S$) and strength (*MOR*). In the particular case of sawlog *AWV*, a significant positive relationship with both select recovery and product value was also found. Therefore both FAKOPP and DIRECTOR HM200™ may be considered as suitable tools to identity *E. nitens* trees and logs that may be most suitable for structural and appearance end-uses.

Standing tree *AWV* was significantly negatively related to tree diameter and was found to be significantly different between the two cardinal directions in which the reading was collected, being higher in the southwest aspect. Sawlog *AWV* was also related to tree diameter, but also positively related to stocking rate, indicating that thinning intensity had a significant influence in the mean value of the *AWV* behaviour. Therefore stand density control may be a useful tool to improve timber stiffness in *E. nitens* plantation-grown trees, however further studies are required to support this finding.

From the shrinkage, collapse and wood basic density data collected from small wood-blocks, significant relationships with internal checking, select recovery and product value were found. Among the wood-block traits, tangential collapse was the best predictor of internal checking occurrence and product value. Mean values of wood basic density per disc position were significantly positively related to acoustic wave velocity traits, significantly negatively related to radial collapse and significantly positively related to wood mechanical properties, having a moderate predictive capability. No significant relationships between wood basic density and any sawing trait such as board end-splitting, board checking propensity, recoveries and product value were found. Tree diameter and stocking rate did not have any significant relationship to the shrinkage and collapse traits or with wood basic density measured on small wood-blocks.

# CHAPTER 4

## Non-destructive predictors of wood quality for sustaining the value-chain of plantation-grown eucalypts for sawlog production

The development, validation and application of cost-effective and reliable non-destructive wood and log quality predictors (hereafter referred to as NDE wood quality predictors), is becoming a critical issue for supporting tree breeding programs, silvicultural management and commercial processing of plantation-grown eucalypts grown for high-value solid and engineered wood products worldwide (Verryn *et al.* 2005; Yang 2007; Yin *et al.* 2007).

### 4.1 Application of NDE wood quality predictors in tree breeding

Tree breeding is required to continually improve economically important traits such as tree growth and form, frost, pest and disease resistance and wood quality in the new generations of plantations (Greaves *et al.* 2003; Powell *et al.* 2004). Modern tree breeding programs typically aim to maximize the profitability of growers and/or processors through an economic breeding objective – which involves improvement of a set of rotation-age objective traits, with appropriate economic weights to determine relative emphasis on the different traits. Breeders select better individuals in breeding trials using a set of selection traits that have sufficient heritability and variability to make genetic gain. The selection traits are linked to the objective traits through a set of genetic and phenotypic correlations (Bush 2007; Greaves *et al.* 2004a). The subsequent mass-production and deployment of seedlings or clonal plants derived from these selected trees delivers the improved genetic stock required to establish more profitable plantations. Therefore the cost-effective and reliable assessment of pertinent selection traits is fundamental to the success of tree breeding programs. Examples of selection traits studied and utilized in breeding programs for pulpwood are tree diameter, pilodyn penetration and wood core basic density, and in some cases kraft pulp yield predicted from wood core samples using near-infrared analysis (Greaves *et al.* 2004a).

In the particular case of solid wood production, the eucalypt plantation can be technically managed to produce logs suitable for processing into either structural and/or appearance sawn-timber and/or veneer products, which can have different economic breeding objectives, increasing the difficulty of identifying a common set of selection traits. Obvious candidate selection traits for solid-wood production may be measures of tree growth.such as diameter, stem form, and wood properties of critical importance for the production system such as wood density, collapse and checking, shrinkage behavior, predictors of timber stiffness and predictors of growth stress (Bush 2007; Greaves *et al.* 2004a; Raymond 2002).

Although the current study was undertaken on rotation-age trees and did not extend to the definition of economic breeding objectives, it is possible to give the following insights about the application of the NDE wood quality predictors studied to tree breeding for solid-wood production:

**a)** ***Standing tree LGS***: some studies undertaken to date (Yang 2007; Yang 2005), and the current research, have found *LGS* levels measured in standing trees to be significantly related to some potential objective traits such as log-end splitting, sawn-board distortion, board end-splitting and total sawn-timber recovery, which are important for both appearance and structural products. In addition, in a study carried out in *E. dunnii* (Murphy *et al.* 2005), *LGS* was found to be sufficiently heritable ($h^2$=0.3-0.5) for potential genetic improvement. These results may encourage the use of *LGS* as a potential selection trait to minimize production cost and/or maximize total product recovery. Unfortunately, in the current study *LGS* measured using the CIRAD method had a low capability to predict log-end splitting and sawn-board distortion, and could not contribute to the prediction of sawn-board recoveries in 22-year-old *E. nitens*. The low levels of *LGS* in the current study could in part explain this low predictive ability. Similar studies for both sawn-timber and veneer production using logs grown under different site conditions and with a wider range of genetic material of *E. nitens* are recommended to clarify the predictive potential of *LGS*. Furthermore, in the current study, the CIRAD method was shown to be time-consuming (up to 40 trees per day per person under ideal weather conditions, performing 2 measurements per tree) and strongly dependent on calm wind conditions, which could limit its suitability as an NDE method for screening large number of trees in breeding programs. Therefore, the development of new methods of estimation is strongly recommended to reduce sampling cost and tree damage. For instance, NIR analysis and SilviScan technology (determining crystallite width, $W_{cryst}$, and microfibril angle, *MFA*) have been used in *E. globulus* and other eucalypt species to predict *LGS* (Baillères *et al.* 2003; Yang *et al.* 2006). $W_{cryst}$ was found to be suitable for the prediction of *LGS* at a moderate level of reliability in *E. globulus* (Yang *et al.* 2006). However, log end splitting, sawn board distortion and losses of sawn-timber volume due to removing board distortion and end splits in sawn boards were found to be weakly related to some SilviScan measurements such as *MFA* and $W_{cryst}$ in *E. globulus* (Yang 2007).

**b)** ***Standing tree AWV***: The research done to date in *E. dunnii* (Dickson *et al.* 2003; Henson *et al.* 2005) and also in *E. nitens* by the current study, has found moderate to strong predictive power of standing tree *AWV* to predict timber stiffness, strength and hardness. Therefore standing tree *AWV* is a potential selection trait for structural eucalypt timber. Acoustic tools such as FAKOPP and ST300 are non-destructive, have demonstrated capability to detect significant variation in the acoustic properties of the timber in standing trees, are already being used commercially for softwood species (Carter *et al.* 2005). They are easy to use, allowing a relatively large number of trees to be sampled per day (up to 70 trees per day, performing two measurements per tree), which is an important issue for breeding. In addition, these tools do not require calm conditions for their use.

**c)** ***Shrinkage properties***: Some studies carried out in *E. nitens* and *E. globulus* undertaken by Hamilton (2007) and Yang and Fife (2003) respectively, have analyzed wood core shrinkage properties (*e.g.* tangential shrinkage and tangential collapse) as potential selection traits for reducing checking propensity, which is a value limiting factor particularly important in *E. nitens* for appearance-grade sawn-timber. However, the use of fixed height wood cores alone to analyze genetic variation of shrinkage properties in *E. pilularis* (Pelletier *et al.* 2007) was found to be insufficient for genetic assessment due the low correlations found with block samples, and therefore its reliability and its predictive power to be used as a selection trait for minimize checking propensity is doubtful. Other traits analyzed such as wood density, growth strain, *MFA* and $W_{cryst}$ have not been found useful for predicting checking propensity in *E. globulus* (Yang and Fife 2003). In the current study, neither *LGS* nor *AWV* were related to checking propensity. However, in the destructive technique applied by the current study, there was a significant, positive relationship between the extent of shrinkage and collapse in 25 x 25 x 40 mm wood-blocks, particularly in the tangential direction, with board checking propensity. This finding suggests it would be worthwhile to develop new techniques to predict checking propensity from shrinkage data collected in standing trees using small wood specimens (e.g. 30mm tangential; 30 mm radial; 50 mm longitudinal) extracted from the outerwood of standing trees at one or two standard stem heights. However this technique would be appropriate as a non-destructive technique only in circumstances where it did not lead to subsequent stem damage, breakage or wood decay. These wood-blocks could also deliver important information on wood basic density, which in the current study was found to be significantly positively related to wood mechanical properties such as timber stiffness, strength and hardness. In addition, wood basic density is a crucial selection trait for pulpwood, which also is important in sawlog regimes where up to half of the stand volume is directed to pulpwood (Volker 2007).

Nevertheless, the benefits and feasibility of using these NDE wood quality predictors in tree breeding will be only clarified when new studies explore the relationships (phenotypic and genetic correlations) between young age solid-wood selection traits (*LGS, AWV* and/or shrinkage properties) and objective traits such as log end-splitting, and product grade recoveries at harvest age. Further studies on genetic control and variation in these *LGS, AWV* and/or shrinkage properties are also required.

## 4.2 Application of NDE wood quality predictors in sawlog silviculture

Supporting silvicultural management for eucalypt solid-wood production is another relevant area of application for NDE wood quality predictors. Thinning regimes could be assisted by NDE sampling to select either stiffer trees or trees with lower levels of *LGS* for final harvest. In the current study *LGS* levels measured at harvest age were not significantly affected by either stocking rate or tree diameter growth. However, the sampled trees studied were dominant and co-dominants, whereas sub-dominant trees may have been subject to higher levels of intra-specific competition during the rotation. In the unthinned control treatment, the trees studied were only dominant trees. It is feasible to speculate that these trees grew with less competition. This fact is important as higher levels of competition, which can affect tree growth in height and crown reorientation strategies, has been identified as one of the most important sources of higher levels of *LGS* in plantation-grown *E. globulus* trees (Touza 2001b). Therefore, the lack of an effect of stocking rate on *LGS* levels measured in dominant and co-dominant *E. nitens* trees in the current study is quite consistent with the experience observed in *E. globulus* in Spain (Touza 2001b) and observations made by Kubler (1988). Both authors recommend applying silvicultural interventions to provide uniform growing conditions and uniform tree spatial distribution in order to avoid high levels of *LGS*. The levels of *LGS* found by the current study were low in comparison with other species, as explained in detail in Chapter 2. Site factors may determine differences in average levels of *LGS*. For instance it is possible to speculate that for *E. nitens* plantations grown on highly productive sites and/or regularly fertilized, competition could start earlier in the rotation (for the same initial stocking) and eventually affect also dominant and co-dominant trees.

Also there is evidence that different provenance and families of *E. nitens* can have significantly different levels of *LGS* (Valdés 2004). Therefore further studies on *LGS* levels in standing trees growing under different site conditions and with different genetic backgrounds are also recommended to improve our understanding of silvicultural effects on *LGS* levels in this species.

Based on both the relatively low predictive power of *LGS* to explain variance in processing performance and the lack of effect of both stocking rate and tree diameter on *LGS* levels, the range of thinning regimes examined in this study is unlikely to produce potential negative impacts of *LGS* levels on processing performance. However, further studies that relate stocking rate and *LGS* levels under different site conditions and ages are also recommended to define precisely the influence of these potential silvicultural control variables on *LGS*.

In plantation-grown *E. nitens* managed for structural production, where thinning practices are applied, new studies oriented to analyzing the correlation between standing tree *AWV* at thinning age and harvest age might be warranted. This is because if the correlation is high, *AWV* could be used as a complementary criterion (together with tree diameter, stem form, vigor and residual spacing) for early age selection of stiffer trees (with higher *AWV*) to retain for final harvest.

### 4.3 Application of NDE wood quality predictors for stand valuation and log segregation

Finally, NDE wood quality predictors can also have an important role in both stand valuation and log segregation before processing. Regression modeling techniques such as those applied by the current study can be used to predict the log processing performance and product value. For instance, the product value per cubic meter of log input could be predicted fitting models that take into account significant factors such as *DBHOB*, sawing method, log position, and NDE wood quality predictors such as *LGS* and *AWV* data if they are shown to be significant. However, the cost of NDE sampling must be more than covered by the potential benefits derived from the additional explanatory power that could be provided by NDE wood quality predictors. In stand valuation, traits such as tree diameter, log position, *LGS* levels, wood shrinkage data non-destructively measured and *AWV* levels on standing trees represent a potential list of pertinent predictor traits. The cost of sampling wood-quality traits such as *LGS* and shrinkage would restrict their application to situations where the information obtained was of particular value. For instance, using the variance of mean values of *LGS* estimated from the pooled data from the current study, a sampling intensity of 50 trees would be a large enough sample size to estimate the mean *LGS* value of a similar stand with an acceptable error of ±0.005 mm (significance level=0.05). If the acceptable error was increased to ±0.0075 mm, a sampling strategy of 23 trees will be enough. However, based on the models fitted by the current study to predict log end-splitting, *LGS* can explain only up to 20% of the variance after accounting for DBHOB and log position (which alone explained 25%). This extra gain in predictive power in log end splitting should be further analyzed in terms of costs and benefits to justify the cost of sampling *LGS* in standing trees. Therefore the potential application is for determining average *LGS* levels in the stand, in order to get a better valuation and idea about its processing potentiality for solid-wood production, which would be important for buying and selling plantation-grown eucalypts for sawlog production.

Similarly, using the variance of standing tree *AWV* estimated by the current study, a total of 20 trees would be a suitable sample size to estimate mean standing tree *AWV* levels (significant level=0.05; and error of 0.1 km $s^{-1}$). However, based on the models fitted by the current study to the prediction of timber stiffness, standing tree *AWV* can explain up to 14% of the variance, after accounting for log position, which alone explained 9%. This extra gain in predictive power should be further analyzed in terms of costs and benefits analysis to justify the sampling cost.

Therefore for stand valuation these extra gains from sampling NDE wood quality predictors would be useful to get a better approach to the real value and commercial processing potential of the resource, but require a cost-benefit analysis for their operational implementation.

For log segregation in the forest or the log yard before processing, the application of NDE wood quality predictors could be also valuable. *AWV* segregation of logs using resonance tools such as DIRECTOR HM200™ before processing could contribute to increased product value per cubic meter of log input (for both structural and appearance objectives) and reduced processing costs as unsuitable logs would not be processed (in this case the segregation could take place in the forest). For instance, based on the results from the current research, log *AWV* data increased the predictive power of timber stiffness and product value per cubic meter of log input by 17% and 4% respectively (after accounting for significant factors such as sawing method, tree diameter, and log position). Again, this extra predictive power should also be assessed in terms of costs and benefits before its implementation by the industry.

Similarly, log end-splitting index could be also important, due its relationship with loss of green board volume due end docking (5% of extra predictive power) and total recovery (2% of extra predictive power), however less time-consuming techniques would be desirable for operational purposes. In this case studies to assess the feasibility of using image analysis and scan technology in line implemented to measure log splitting index are recommended. Initial studies aimed at defining the log-end splitting threshold at which processing costs and recoveries are significantly reduced for a particular processing objective are required.

Log position studied was shown to be a significant term in several predictive models of solid-wood processing performance traits assessed. However its application within predictive models at sawmills may not be practical because of the difficulty of identifying log position at the sawmill.

As discussed, NDE wood-quality predictors have a relevant role in sampling and screening to improving the technical and economic feasibility to profitably breed, grow and commercially process plantation-grown *E. nitens* for solid wood production. The improved understanding gained in the above matters from the current MSc research, and from the new lines of research proposed in this study, will positively contribute to make commercial timber processing of plantation-grown temperate eucalypts more profitable and technically feasible.

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