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Development of Non-Destructive-Testing Based Selection and Grading Strategies for Plantation *Eucalyptus nitens* Sawn Boards

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Abstract: Stiffness is considered one of the most important structural properties for sawn timber used in buildings and laminated structures including mass timber elements. There is great potential to use plantation *Eucalyptus* timber for structural applications, and the successful development of a plantation timber supply chain for structural products will depend on the accurate selection and grading of the resource. In this study we aimed to investigate the suitability of non-destructive testing (NDT) to improve selection and grading of sawn boards sourced from a young *E. nitens* plantation. We studied 268 sawn boards traced from the tree through to final processing stages. We found high and positive correlations between stiffness (measured as dynamic modulus of elasticity) tested at each board processing stage through acoustic wave velocity (AWV) and the static board modulus of elasticity measured through mechanical testing on dressed boards. Position of the board in the stem and sawn board processing treatment significantly impacted board modulus of elasticity, indicating that early selection of logs would allow larger yield of stiffer boards. We investigated the grading of boards through the traditional Australian Standards using a visual-grading system and through AWV, finding a classification error of 82.5% and 45.2%, respectively. We developed a linear model which was used to re-classify the boards, obtaining a smaller classification error, including fewer boards being over-graded. Our results demonstrate that AWV can be used as an early selection method for structural boards and can also be employed to satisfactorily grade *E. nitens* plantation boards to be used in building structures and as elements of mass timber.

Keywords: *Eucalyptus* plantations; stiffness; acoustic wave velocity; non-destructive techniques; grading; structural timber

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1. Introduction

The increased demand for timber products is stimulating the use of alternative sources of raw forest materials, increasing the demand on plantation forestry. In the past two decades there was a rapid expansion of plantation forestry, especially in the southern hemisphere [1]. The dominant hardwoods being planted are from the *Eucalyptus* genus and, in Australia, eucalypts account for over 884,000 ha, which annually generate over 10 million m^3 of pulp logs [2]. The use of eucalypt timber fast grown in plantations is currently being explored as a complement to the softwood used in structural products and for native forest timber. Although bearing large potential to be used in different timber products, the characteristics of eucalypt plantation timber, its processing, and its use in mass timber elements for buildings is still a novel area of research [3].

Eucalypt timber grown in plantations is routinely harvested on 15-year rotations. Stands are established at high stocking rates to favor competition and fast growth and are managed mostly without silvicultural treatments such as thinning or pruning. Consequently, the timber derived from plantations includes certain characteristics such as knots, derived from the branching habits of the trees, drying features such as checks and

splits [4,5], dimensional instability [6] (due to fast growth), presence of large amounts of checks on the surface and in the timber elements [7] (due to the high growth stress of the wood) and is generally less dense than native timbers given the very young age at harvest. All of these factors, although extremely relevant for structural products, might not be an obstacle in the use of plantation timber for construction elements, as it has been demonstrated that engineered and mass timber can minimize the detrimental consequences of these characteristics and satisfactorily achieve desired structural properties [8].

Traditionally, timber characteristics and features are used to grade the timber and assign boards to structural grades which engineers and builders can confidently use for building structures with minimum 'fit-for-purpose' requirements. These grading systems are mostly derived from studies on native and old-growth forests and the relevant structural grading standard in Australia (Australian Standard (AS) 2082) [9] is based on visual assessments of timber features on sawn boards which is used to allocate them into structural grades (Visual-Stress-Grading (VSG)). These structural grades, combined with the mechanical properties of the species, lead to the classification of sawn boards into stress grades (F-grades), which have associated design values required by architects and timber engineers [10]. This derives from the assumption of a direct correlation of the visual characteristics of timber and its structural properties (strength and stiffness) [5]. This grading system is reliable for native timbers, for which it was developed, but is less reliable for hardwood plantation timber, as the timber presents several features that do not meet VSG standards, even though the boards might achieve acceptable levels of stiffness and strength [11].

Alternative grading methods to overcome this issue need to be examined, and non-destructive testing (NDT) techniques have emerged as alternative tools to rapidly test timber and determine its structural properties [12,13]. Non-destructive testing techniques measuring acoustic wave velocity (AWV) inside timber are of interest, given known correlations between stiffness tested through AWV and actual timber stiffness (measured as modulus of elasticity, MOE) assessed through mechanical tests [14,15]. Although largely studied as wood quality testing tools on trees and logs, very little is known of the potential of AWV as a grading tool for structural timber. Sawn boards processed from plantation logs might differ significantly in their properties and stiffness due to the characteristics of the wood, log position in the tree, processing methods and wood treatments, and early testing of sawn boards can be advantageous to select the best and stiffer material as early in the processing cycle as possible. Furthermore, the use of AWV as a rapid grading tool can be an effective means of classifying sawn boards into stress grades useful for timber users. Given the limited knowledge on the use of AWV for sawn-board segregation and grading tools, this study's objective was to investigate the suitability of NDT-acoustic wave velocity-based strategies to improve the segregation and grading of structural boards sourced from plantation *Eucalyptus nitens* logs.

Acoustic wave velocity was employed as a non-destructive technique to test mechanical properties at the early processing stages and its capability as a grading and segregation tool on sawn boards was evaluated. The specific aims of the study were to:

1. Examine the effect of log position in the stem and board treatment stage on sawn boards' stiffness, measured as dynamic modulus of elasticity (MOE_{dyn}).
2. Understand the correlative relationship between MOE_{dyn} measured using NDT-acoustic wave velocity at different processing stages and the actual stiffness of sawn boards (static modulus of elasticity, MOE_{stat}).
3. Analyze the accuracy of the Visual-Stress-Grading (VSG) method and AWV in estimating the MOE_{stat} of sawn boards.
4. Improve the accuracy of VSG method in predicting the MOE_{stat} of sawn boards using AWV.

2. Materials and Methods

2.1. Timber Resource

The material used in this study was sourced from a 21-year-old *E. nitens* plantation located in southern Tasmania, Australia (latitude 43°03′ S, longitude 146°59′ E). Trees were originally planted for the production of fiber and were harvested during a commercial pulpwood operation in the winter of 2018. For the study, a total of 18.5 m^3 of logs were harvested from 15 selected stems and all logs up to a small-end diameter of 185 mm were used as sawlogs for the study. Up to four logs were recovered per tree, recorded as log A, log B, log C, and log D (for the bottom, second, third and top log, respectively). A coloring pattern was applied to the end of the logs to maintain traceability during the processing stages. Logs were sawn into boards of four nominal widths of 75 mm, 100 mm, 125 mm, 150 mm, a nominal 45 mm thickness and average length of 5500 mm. A back-sawing pattern was chosen to maximize timber recovery, while retaining sapwood. A total of 268 boards were cut, block-stacked, tallied, and transported to the drying mill.

2.2. Board Treatment Stages and Testing

Prior to drying, each board was measured on 5 points along its length for width and thickness to assess individual board volume, and the board stiffness was measured using AWV with the acoustic resonance device Director HM200 (Fibre-gen, New Zealand). Each single board was tested alone on insulated trestles, to avoid transmission of the waves to the supports or to other timber. The test consisted of tapping with a hammer at one end of the board and reading the AWV value with the hand-held tool. Each board was weighed on a calibrated scale and the mass was used with the board volume to calculate the green density (GD, kg/m^3) of the boards. The dynamic MOE ($MOE_{dyn,}$ GPa) of each sawn board was then calculated as

$$MOE_{dyn} = GD * AWV^2 \quad (1)$$

This set of measurements is referred to as 'green-stage', with moisture content (MC) of the boards being more than 25%, due to the large amount of water contained in the freshly cut timber. The boards were then air-dried for a period of fourteen months and reconditioned prior to final kiln drying. The same measurements performed on the green boards were repeated on the air-dried boards to record volume, mass, and AWV, referred to as 'air-dry-stage', in which the MC was tested at the mill to be at 12%. The boards were reconditioned and kiln dried, employing the operational drying schedule used for eucalypt material in the mill, to a nominal MC of 12%. After kiln-drying, the same measurements were performed on the boards to record volume, mass and AWV at the 'kiln-dry-stage'. The dried boards were square dressed (planed on the width) to final widths of 70, 90, 120, 140, 165 mm (five boards were over-sized as green), planed to a final thickness of 35 mm, and to an average board length of 5.5 m, maintaining the boards' identity. The boards were transported to the engineering laboratory at the University of Tasmania, where volume, mass, and AWV were measured, and this stage is referred to as 'dressed stage', where the boards' MC was at 12%. Each board was visually assessed and characteristics were recorded according to the Visual-Stress-Grading (VSG) method adopted for structural boards in Australia following AS 2082 [16]. Important features to estimate the board grade through the VSG were also noted as part of the investigation, and the total number of knots, knot type (sound/unsound), number of major knots, number of knot clusters, presence of board checking (checks deeper than 3 mm or longer than $\frac{1}{4}$ the length of the board), presence of pith in the boards, presence of rot, wane, gum vein, and insect traces were all recorded.

Using the VSG method, we placed the sawn boards into structural grades and the relevant F-grade (stress grade) could be allocated, which corresponded to the expected MOE_{stat} listed in AS 1720.1 [10]. The relevant grades are outlined in Table 1, reporting the expected minimum MOE values per each F-grade.

Table 1. Structural grades assigned to the sawn boards after mechanical testing according to (Australian Standard) AS 4063.1 [17] and the corresponding Modulus of Elasticity (MOE) outlined in the Australian Standard 1720.1, Table H2.1.

Structural Grade [a]	Stress Grade (F-Grade) [a]	Board Modulus of Elasticity (MOE_{stat}, GPa) [b]
Structural grade No. 1	F22	16
Structural grade No. 2	F17	14
Structural grade No. 3	F14	12
Structural grade No. 4	F11	10.5

[a] AS 2082 [16]. [b] AS 1720.1, Table H2.1 [10].

After VSG, structural tests were performed. The static modulus of elasticity (MOE_{stat}, GPa) of the boards was tested in an edge-wise four-point static bending-test, in accordance with the test procedures outlined in AS 4063.1 [17], and calculated according to Equation (2):

$$MOE_{stat} = \frac{3al^2 - 4a^3}{4bd^3\left(\frac{\varphi_2 - \varphi_1}{F_2 - F_1}\right)} \quad (2)$$

with b and d being the thickness and the width of the board (mm) and l the span length, corresponding to 18 times the width (mm). a corresponds to 6 times the board width (mm). F_2 and F_1 correspond to 40% and 10% of the maximum load at failure point (Fmax). φ_2 and φ_1 are respectively the maximum displacement (mm) at F_2 and F_1 loads.

Two samples of timber were recovered from each tested board, consistently cut from the top and bottom ends, to measure Basic Density (BD) and MC according to the procedure described in AS 1080.3 and AS 1080.1 [18,19] and the following Equations (3) and (4). The test was performed to record the density of the timber at the time of the mechanical testing as required by the Australian Standards. The average density of the timber was 578.9 kg/m^3.

$$BD = \frac{m_1}{V} \times \frac{100}{(100 + MC)} \quad (3)$$

$$MC = \frac{m_1 - m_0}{m_0} \times 100 \quad (4)$$

where m_1 is the mass of the sample at the time of the testing (kg), V is the volume of the sample before oven-drying (m^3), and m_0 is the mass of the sample after oven drying (kg). The MC and BD of each board were calculated as an average of the samples at the bottom and top ends of each board. The MOE_{stat} values obtained were adjusted based on the MC of each board, according to AS 2878 [20].

2.3. Statistical Analysis

Statistical analyses were performed using R studio statistical software [21].

We used the Kolmogorov–Smirnov test and Levene's tests to verify the normality and homogeneity of variance in the data. We inspected the dataset for outliers using Tukey's fences method [22] and visual inspection of plots. We investigated differences in MOE_{dyn} of the boards sourced from different positions in the stem (A, B, C, D) at different treatment stages (green, air-dry, kiln-dry, and dressed) through two-way repeated measures analysis of variance (ANOVA), comparing the means of MOE_{dyn} of the boards at different treatment stages and between logs. We used tree as a random effect to account for non-independence of logs coming from the same tree. The repeated-measures model considered log position (four fixed levels), treatment stage (four fixed levels), and their interaction (nine fixed levels). Significance levels were kept at $p = 0.05$. We used multiple pairwise comparisons as post-hoc tests to identify differences between boards MOE_{dyn} in the treatment stages and TukeyHSD test to investigate differences in board MOE_{dyn} among log positions.

We investigated differences in modulus of elasticity of the boards as measured through AWV at the green and dressed stage and modulus of elasticity measured mechanically at the dressed stage, thus comparing the MOE_{dyn} of green or dressed boards and MOE_{stat} of dressed boards. We used two-way ANOVA to account for log position, obtaining a repeated measure model consisting of log position (four fixed levels), measurement stage (three fixed levels), and their interaction (six fixed levels). We used multiple pairwise comparisons as post-hoc tests to identify differences between board modulus of elasticity among the two measurements. We then modelled the relationship between MOE_{dyn} of the boards measured at different stages (green, air-dry, kiln-dry, and dressed) and MOE_{stat} using linear regression.

To analyze the results of the visual grading (VSG) and non-destructive grading (NDT) we compared the grade classification of the dressed boards from the two system with the actual board MOE_{stat} tested through mechanical testing. We used one-way ANOVA to compare the means of dressed board modulus of elasticity (MOE_{dyn} and MOE_{stat}) using the F-grade determined through VSG as the factor variable.

We used Pearsons correlation coefficient at a probability level of 0.05 to test the correlation among board features and board MOE_{stat}. If significantly correlated, those features could be included as variables into multiple regression modelling with MOE_{dyn} to predict MOE_{stat}. We used linear regression to model the relationship between MOE_{dyn} and MOE_{stat} and used the predicted values to classify the boards and then compared that classification with the classifications presented for VSG and AWV.

3. Results

3.1. Board Treatment Stages

Data followed normality and homogeneity of variance. The dynamic board modulus of elasticity measured at different treatment stages is represented in Figure 1. There was a general increase in MOE_{dyn} from the green to the kiln-dry stage, after which the MOE_{dyn} recorded for the dressed stage decreased. Differences in MOE_{dyn} were due both to the position of the log in the tree and to the treatment; however, the interaction between log position and treatment was not significant (Table 2).

Figure 1. Modulus of elasticity of boards measured at different treatment stages. On the *x*-axis dynamic modulus of elasticity (MOE_{dyn}) measured through acoustic wave velocity (AWV) is reported at each stage (green, air-dry, kiln-dry, and dressed). Letters (A, B, C, D) indicate the log position, with increasing position in the stem from A to D. Standard errors for green and dressed stages are reported in Table 3. Standard errors for air-dry stage are: Log A (3.12), log B (3.18), log C (2.77), log D (1.22), and for kiln-dry stage are: Log A (3.28), log B (3.30), log C (2.36), log D (1.41).

Table 2. Significance of log position and treatment stage on modulus of elasticity (measured as MOE_{dyn}) of the boards. The repeated measures model considers log position (degrees of freedom (df) = 3) and treatment stage (df = 3) and their interaction (df = 9) as fixed terms. The residual degrees of freedom are 1042.

Fixed Terms	F Value	*p* Value
Log position	24.6	<0.001 ***
Treatment stage	53.9	<0.001 ***
Log position × Treatment stage	0.09	1

*** Significance with $p < 0.001$.

Air-dry and kiln-dry MOE_{dyn} values were significantly higher than green MOE_{dyn} for all log positions (Figure 1). Dressed MOE_{dyn} was not significantly different between green MOE_{dyn} for boards coming from the first, second, and top logs (log A t(106) = 2.53, $p = 0.07$, log B t(83) = 2.31, $p = 0.14$, log D t(14) = 0.09, $p = 1$), but significantly different for boards coming from third logs (log C t(65) = 3.42, $p < 0.05$). Dressed MOE_{dyn} was also significantly lower than kiln-dry MOE_{dyn} (log A t(106) = 17.7, $p < 0.001$, log B t(83) = 13.9, $p < 0.001$, log C t(65) = 20.5, $p < 0.001$, log D t(14) = 6.72, $p < 0.001$).

There were no significant differences between modulus of elasticity measured at the green stage or dressed stage through AWV and actual modulus of elasticity measured at the dressed stage via mechanical testing (F = 1.94, $p = 0.15$); however, significant differences among log positions were present (F = 17.3, $p < 0.001$). There was no interaction between log position and measurement type (F = 0.17, $p = 0.99$). Table 3 reports the values of modulus of elasticity at the green and dressed stages measured via AWV (MOE_{dyn}) and actual modulus of elasticity measured mechanically (MOE_{stat}).

Table 3. Repeated measures ANOVA results table of modulus of elasticity measured at different green and dressed stages (as MOE_{dyn} and MOE_{stat}) in boards coming from logs of different positions in the stems (bottom A, middle B and C and top logs D). Different letters across rows denote differences in modulus of elasticity at the various processing stages for boards coming from the same log.

Log Position	Stage		
	Green	Dressed	
	MOE_{dyn} (GPa)	MOE_{dyn} (GPa)	MOE_{stat} (GPa)
A	13.3 (2.88) a	13.0 (2.96) b	12.9 (2.25) ab
B	14.4 (2.67) a	14.1 (2.95) a	14.2 (2.30) a
C	14.3 (1.95) a	14.0 (2.23) b	13.8 (2.00) ab
D	14.0 (1.23) a	14.0 (1.67) a	14.3 (1.87) a

Log position in the stem influenced the modulus of elasticity of boards (Figure 1). Boards coming from bottom logs (log A) had consistently lower modulus of elasticity than boards from other positions in all treatment stages, but this relationship was not always significant. Although lower, the modulus of elasticity of boards from bottom logs (A) was not significantly different than that of boards from top logs (D), but significantly lower than that of boards from middle positions in the stems (log B and C).

The correlations between AWV MOE_{dyn} measured at different stages and actual MOE_{stat} were strong and significant at the 0.001 level (Figure 2). Considering specifically the first and last panel, measurement of MOE_{dyn} on green boards through AWV can explain almost 60% of the variability in actual MOE_{stat}, and measurement of MOE_{dyn} on dressed boards through AWV can explain almost 70% of the variability in actual MOE_{stat}.

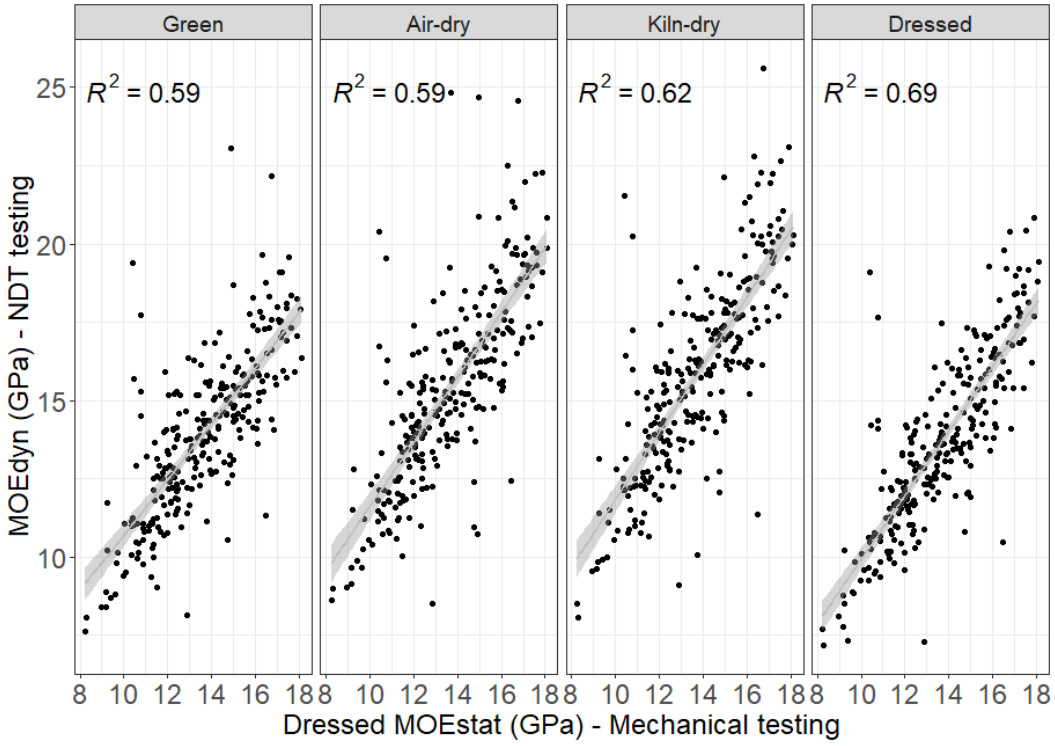

Figure 2. Relationships between MOE_{dyn} of boards (NDT measure) at the green, air-dry, kiln-dry, and dressed stages with the MOE_{stat} (mechanical testing) of the dressed boards.

3.2. Grading Systems

The results of the allocation of boards to F-grades according to both visual grading (VSG) and AWV are presented in Tables 4 and 5, respectively. These are reported alongside the F-grade of the boards determined using the actual modulus of elasticity of the boards measured through mechanical testing (MOE_{stat}). The VSG method had a large error, misclassifying the boards with an 82.5% rate of error. 70.2% of the board F-grades were underestimated, while 12.3% were overestimated, in respect to the actual MOE_{stat} of the boards.

Table 4. Classification of boards via the visual stress grading (VSG) method and relative error. Grades are ordered from the highest grade (F22) to the lowest (F11) following the Australian Standard for *E. nitens*. UG: boards that are under-grade, with MOE_{stat} lower than the lowest limit in the Australian Standard for *E. nitens*.

VSG Grade	% Grade *	Actual F-Grade Determined through MOE_{stat} (%)					Total Error VSG ** (%)
		F22	F17	F14	F11	UG	
F22	4.48	0.37	1.49	1.87	0.37	0.37	4.10
F17	3.36	0.75	1.87	0.37	-	0.37	1.49
F14	23.1	7.09	5.60	5.60	3.73	1.12	17.5
F11	29.9	4.85	6.72	9.33	6.34	2.61	23.5
UG	39.2	6.34	8.96	14.2	6.34	3.36	35.8
Total	**100**	**19.4**	**24.6**	**31.3**	**16.8**	**7.84**	**82.5**

* Percentage of boards in F-grades determined via VSG (Visual Stress Grading). ** Total error determined as sum of the percentage of boards misclassified (minus the percentage of boards placed into the correct F-grade). As an example, the total VSG error for UG boards is the sum of boards that should have been placed in F22, F17, F14, and F11 grades, 6.34 + 8.96 + 14.2 + 6.34 = 35.8% total error.

The classification error was considerably lower when utilizing the non-destructive technique of AWV to classify the boards into F-grades. A total error of 45.2% was recorded, with 22% of the boards being underestimated in their grade and 23.5% being overestimated. The indirect measure of MOE_{dyn} via AWV is correlated with the actual MOE_{stat} of the

boards (last panel of Figure 2), which is likely the reason for a better classification of boards compared to the VSG method. Table 6 presents the comparison of AWV MOE_{dyn} and actual MOE_{stat} of the F-grades determined through VSG method. No significant difference was detected between the MOE_{stat} of the grades, except for MOE_{stat} of F17 and F11 which were found to be significantly different ($p < 0.05$). This further strengthens the lack of reliability of the VSG to be applied to plantation *E. nitens* timber in detecting the actual stiffness of the boards, either measured as MOE_{dyn} or MOE_{stat}.

Table 5. Classification of boards via AWV and relative error. Board grades are as described in Table 4.

AWV Grade	% Grade *	Actual F-Grade Determined through MOE_{stat} (%)					Total Error AWV (%) **
		F22	F17	F14	F11	UG	
F22	22.8	14.2	7.09	0.75	0.37	0.75	8.58
F17	23.9	4.48	10.5	7.84	1.12	-	13.4
F14	29.1	0.37	6.72	17.2	4.85	-	11.9
F11	12.3	0.37	0.37	4.10	6.72	0.75	5.60
UG	11.9	-	-	1.49	4.10	6.34	5.60
Total	**100**	**19.4**	**24.6**	**31.3**	**17.2**	**7.84**	**45.2**

* Percentage of boards in F-grades determined through classification via AWV. ** Total error determined as sum of the percentage of boards misclassified (minus the percentage of boards placed into the correct F-grade). See Table 4 for example.

Table 6. Actual stiffness (MOE_{dyn} and MOE_{stat}) of dressed boards ($n = 268$) classified by the Visual Stress Grading (VSG) grades. Comparisons among grades are made separately for MOE_{dyn} and for MOE_{stat}, respectively, and different letters within columns indicate significant differences. Board grades are as described in Table 4.

VSG F-Grade	MOE_{dyn} (GPa)	MOE_{stat} (GPa)
F22	13.1 (2.58) a	13.4 (2.21) ab
F17	14.1 (2.83) a	14.2 (2.31) a
F14	15.6 (3.31) a	14.4 (2.22) ab
F11	13.3 (2.37) a	13.1 (1.76) b
UG	13.5 (2.82) a	13.4 (2.23) ab

We found that the features of boards that are mostly correlated with actual MOE_{stat} were board density ($r = 0.66$, $p < 0.001$), number of sound knots ($r = -0.40$, $p < 0.001$), number of knots ($r = -0.37$, $p < 0.001$), number of major knots ($r = -0.27$, $p < 0.001$), presence of pith in the boards ($r = -0.38$, $p < 0.001$), and presence of checks deeper than 3 mm ($r = -0.18$, $p < 0.01$). Although significantly correlated with the modulus of elasticity of the boards, those features did not contribute to improving the correlation between MOE_{dyn} measured via AWV and actual MOE_{stat}. Therefore, we modelled MOE_{stat} only using MOE_{dyn} as tested with AWV, without accounting further for board features. The predictions of this model were validated against the observed MOE_{stat} values and it was found that the model could explain 69% of the variability in actual MOE_{stat} of the boards with a RMSE of 1.26 GPa (Figure 3a). The residuals of this model were normally distributed and did not show apparent bias with the fitted values (Figure 3b).

The regression equation showed that for an increase of 0.67 GPa in MOE_{dyn} there would be a corresponding increase in MOE_{stat} of 1 GPa. Using this model, the actual MOE_{stat} was predicted on the overall dataset, obtaining the classification of boards as presented in Table 7. The overall error was less than both the VSG and the classification made directly with the MOE_{dyn} values tested through AWV, for a total of 43.3%. Using the regression equation to predict the MOE_{stat} of the boards, 18.3% of the boards would be over-estimated, while 25% would be underestimated. In respect to the actual values recorded through AWV, the overestimation is lower, and the underestimation is higher.

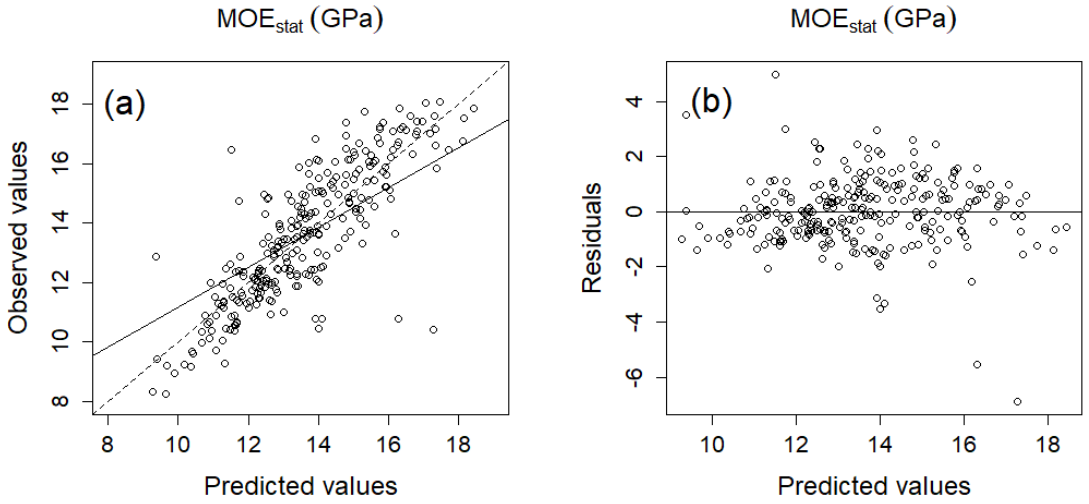

Figure 3. (**a**) Observed vs. predicted boards Static Modulus of Elasticity (GPa) for the entire dataset, (**b**) residuals (*n* boards = 268). Solid line represents the regression line.

Table 7. Classification of boards via the equation developed through AWV and relative error.

Predicted AWV Grade	% Grade *	Actual F-Grade Determined through MOE$_{stat}$ (%)					Total Error AWV ** (%)
		F22	F17	F14	F11	UG	
F22	19.4	10.8	7.84	0.37	0.37	-	8.58
F17	24.6	2.99	14.2	7.46	-	-	10.5
F14	31.3	0.37	7.46	21.3	1.87	0.37	10.1
F11	17.2	0.37	1.12	8.58	7.09	-	10.1
UG	7.46	0.37	-	-	3.73	3.36	4.10
Total	**100**	**14.9**	**30.6**	**37.7**	**13.1**	**3.73**	**43.3**

* Percentage of boards in F-grades determined through classification via AWV. ** Total error determined as sum of the percentage of boards misclassified (minus the percentage of boards placed into the correct F-grade). See Table 4 for example.

4. Discussion

4.1. Board Treatment Stages

This work investigated sources of variation in stiffness, measured as modulus of elasticity of *E. nitens* sawn boards, and examined the potential for non-destructive testing (NDT) techniques to depict actual board stiffness and grading of boards. We found that an indirect measure of modulus of elasticity through acoustic wave velocity (AWV) at the earliest stage of log sawing corresponds well to the values that can be recorded from the dressed timber, allowing for the use of this technology as a viable substitute for cumbersome mechanical testing. Furthermore, AWV can be used as a segregation tool to select the stiffer boards early in the production chain, allowing only the best boards to be directed through the lengthy drying and reconditioning process, and re-purposing the lower-grade boards to other processing streams, thus saving resources by processing only high-quality boards.

We found that modulus of elasticity varies due to log position in the stem and board treatment stage, but there was no interaction between log position and treatment stage. The influence of log position on board modulus of elasticity and its independence from the treatments applied during timber processing is a finding of considerable impact for the timber processing industry. It suggests that log selection prior to sawmilling could increase the possibility of obtaining timber of higher stiffness, thus reducing the large costs associated with board drying, storing, treatments, and dressing. In this study, logs sourced from the bottom of the stems delivered boards of lower stiffness and values did not change considerably after board treatment and processing. During the treatment stages there were significant changes in the modulus of elasticity of the boards. There was an increase from the green to the dried stages (air-dry and kiln-dry), but after the dressing stage modulus

of elasticity was not significantly different from the values measured at the green stage, when boards were freshly sawn. The apparent increase in modulus of elasticity during the drying stages is due to the impact on moisture content of boards, which affects both AWV and timber density [23].

We tested differences between modulus of elasticity measured through AWV and actual modulus of elasticity measured through mechanical testing, which we used as a benchmark test of the actual structural properties of the boards. We found that modulus of elasticity measured through AWV at the green or dressed stage did not significantly differ from the actual board modulus of elasticity. When modulus of elasticity is measured through AWV it is recorded as dynamic modulus of elasticity (MOE_{dyn}), which differs from actual modulus of elasticity measured through mechanical testing, recorded as static modulus of elasticity (MOE_{stat}). Usually, lower values of modulus of elasticity are found when measured as MOE_{stat} in respect to MOE_{dyn}, due to the nature of the measurement, where the static modulus of elasticity is recorded through mechanical bending tests, and the dynamic measurement is through the use of stress waves exerted into the timber [9]. MOE_{dyn} is also influenced by the density of the sample, which in the earliest stages of processing is higher due to a larger moisture content in the timber. At the dressed stage, with the samples being tested at the same moisture content and density, we found very consistent values between the two measurements (MOE_{dyn} and MOE_{stat}). The accordance between the AWV method and the mechanical testing again demonstrates the reliability of the former in detecting the stiffness of the boards. We modelled the relationship between MOE_{dyn} measured at each stage and MOE_{stat}, finding strong and significant correlations between the two measurements. Our results concur with previous research on differences among measurements for modulus of elasticity on boards [13,24], where dynamic modulus of elasticity measured through acoustic waves provides great reliability in measuring stiffness which would otherwise be tested through more cumbersome mechanical testing.

4.2. Grading Systems

Currently, dressed boards require appropriate grading to be classified into structural grades, and our study has compared traditional visual-stress grading (VSG) to the grading of boards via AWV. Visual-Stress Grading was designed to grade native timbers and does not account for species grown in plantation settings. The latter, such as the widely grown *E. nitens*, present features which are classified as impermissible in the VSG system (as large number of knots or checks) and this renders the boards to be down-graded, while their actual stiffness might be suitable for high-grades. Visual-Stress Grading of the boards in this study led to a large classification error (82.5%) with most of the boards being under-graded.

This result is aligned with previous research on the same species [11] although with a more pronounced classification error. The boards utilized in this study developed rot signs during the processing, which, although not impacting the structural properties, have affected the classification of the majority of the boards as under-grade, according to the Australian Standard, where there is little allowance for signs of rot in structural boards [9]. This led to a large number of boards being allocated to the under-grade class (UG) (39.2%), which according to the actual modulus of elasticity of the boards should have been placed in other categories. The downgrading of the boards to the UG class alone led to a classification error of almost 36%. Other characteristics, including presence of major knots and checking, severely impacted the classification of the boards, placing the majority of stiffer boards into low-grade categories, due to the restrictions in knot size and checking presence in the standard. These features might not actually impact the modulus of elasticity of the timber, and in fact, we found that the average modulus of elasticity of boards as classified through VSG was not different among grades. This result is concerning, as it highlights that applying VSG to plantation timber not only misclassifies boards either by down-grading or over-grading, but does not actually produce any meaningful grade classification.

Boards of higher grades such as F22 and F17 are sought after for construction purposes and need to adhere to a minimum stiffness threshold to be used in buildings. Hence, they

are priced differently than lower grades, which might be utilized for other, non-structural purposes. Grading of timber needs to be applied with a standard that takes into account the silvicultural history and the characteristics of the timber, and VSG was originally designed for native timbers grown in remarkably different settings than plantations. Thus, the problem of how to classify plantation timber needs careful consideration to encourage use of these timbers for construction purposes. We tested the use of AWV as an alternative grading method, obtaining a considerably lower classification error (45.2%), with 22% underestimation of grade and 23.5% overestimation. This result is mostly due to the agreement between the modulus of elasticity tested through AWV and the actual stiffness of the boards, of which the relationship explained almost 70% of the variability in boards' actual modulus of elasticity. While 30% of the variation remains unexplained, this may be a suitable way to classify plantation *E. nitens* sawn boards. We accounted for features which are originally important in VSG, such as the presence of major knots and checks, and although they were correlated with board modulus of elasticity, they did not contribute to an increase in the predictive power of the model of modulus of elasticity measured through AWV and actual modulus of elasticity, a finding noted also on other species [25].

Using the model developed only with modulus of elasticity tested through AWV we re-classified the boards, obtaining a final classification error of 43.3%, with more boards being underestimated in their grade than overestimated (18.3% over-estimation and 25% underestimation). From an operational perspective there might be an advantage to under-grade the boards rather than over-grade, thus avoiding false attribution of boards to a higher stiffness category in respect to the actual stiffness value [11]. This result showed that acoustic measurements not only can be used as a classification tool for structural boards, but will achieve better results than the traditional visual stress grading method. Future research might focus on studying how features important for structural board use can be accounted for in a combined VSG and AWV grading method, including more features or other characteristics, to achieve the best results with minimal classification errors and satisfying the requirements of engineers and designers who would have to use the timber in structures.

5. Conclusions

This study presents novel findings on grading and structural properties of plantation *E. nitens* sawn boards. We found that board stiffness is significantly impacted by the position of the log in the stem, as well as by the treatment applied to the boards. Boards originating from logs at the bottom of the stems presented significantly lower stiffness, with boards of higher stiffness found in the middle part of the stems. Stiffness tested through AWV is a reliable measure, being highly and significantly correlated with the actual stiffness measured through mechanical testing, and can be used as a grading tool as early as the stage of log breakdown at the mill. *A priori* log selection would allow for only the best logs to be allocated for sawing, and after sawing only the best boards could be directed for further processing. Once dried and dressed, the grading of boards needs to take into account the peculiarities of the species grown in plantation settings, which render the traditional visual-stress grading system unsuitable for grading plantation hardwood timber. We found that AWV -based grading can be used as an alternative with remarkably low classification error. This study showed how early timber selection can improve the yield of structurally stiffer timber through fast and reliable NDT methods, which can also be used as grading tools, providing insights on possible methods which can be implemented in future grading standards and upscaled to industrial timber processing on the production lines of saw millers.

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