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Prediction of Static Bending Properties of *Eucalyptus* Clones Using Stress Wave Measurements on Standing Trees, Logs and Small Clear Specimens

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Abstract: In this study, we used both nondestructive and destructive methods for assessing solid wood properties in six Vietnamese grown *Eucalyptus* clones at 6 years after planting. We measured stress wave velocity in standing sample trees (SWV_T), logs (SWV_L), and small clear specimens (SWV_S) obtained from the trees and logs, and to measure static properties, we used MOE—modulus of elasticity and MOR—modulus of rupture. The highest average MOE and MOR were detected in clones 3 and 5, suggesting that these clones might be more appropriate for breeding programs focused on improving wood quality of *Eucalyptus* grown in Vietnam. Mean MOE and MOR of the lumber had significant ($p < 0.001$) relationships with SWV_T ($r = 0.61$ and 0.53, respectively) and SWV_L ($r = 0.76$ and 0.71, respectively). Stress wave velocity measurements of both standing trees and logs can be useful for further segregating Vietnam's *Eucalyptus* timber resource based on MOE and MOR. For the small clear specimens, the best prediction of stiffness (dynamic modulus of elasticity (MOE_d)) was obtained when both SWV_S and air-dry density (AD) were used. The coefficient of correlation between MOE and MOE_d was 0.93.

Keywords: *Eucalyptus*; stress wave velocity; MOE; MOR; wood quality

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1. Introduction

In Vietnam, the shift from harvesting native forest to plantations has occurred because forest plantations grow much faster than native forests and provide an alternative fiber source, protecting mature forests. Since the 1990s, approximately 4.4 million ha of predominately acacia and eucalypt plantations have been established [1]. In addition, a high demand for woodchips has encouraged smallholder farmers to invest in short-rotation species for pulpwood plantations that provide a relatively quick financial return from their forestry land [2]. In recent years, Vietnam has become one of the world's largest exporters of timber and non-timber forest products with revenue reaching a record high of USD 15.6 billion in 2021, an increase of 18% compared to 2020 [3]. To meet predicted timber production targets for export markets, the Vietnam Government is encouraging tree growers to increase rotation lengths of plantations (typically 5–6 years for Vietnamese acacia and eucalypt plantations) and produce sawlogs. Growing short-rotation sawlogs would add value to this resource compared to pulpwood, which sells at a lower price when compared to solid wood. Eucalypt wood is an important source of raw material for the wood industry, and it may also be used for the production of saw timber and other engineered panels in Vietnam.

Eucalyptus urophylla occurs naturally in Indonesia with the most extensive natural populations occurring on the islands of Alor, Flores, Pantar, Timor, and Wetar [4]. *E. urophylla* was introduced into Vietnam in the 1980s and has been widely planted since the early 1990s [5]. In 2015, Vietnam had about 211,000 ha of *E. urophylla* plantations located mainly in the northeast (118,000 ha), north central (24,000 ha), and south central regions (48,000 ha) [6].

Since *E. urophylla* is easy to hybridize and clonally propagate, much of the scientific efforts have focused on exploiting hybrid vigor [7]. From 2006–2010, the Vietnamese Academy of Forest Sciences selected superior *Eucalyptus* clones through inter-specific hybridization between *E. urophylla* and other eucalypt species, such as *Eucalyptus pellita*, via natural or controlled pollination, with a focus on volume production, stem form, and pest and disease resistance [8]. For example, Thinh et al. [8] reported that *E. urophylla* × *E. pellita* hybrids (also known as U × P hybrids) planted in Vietnam had 20%–50% higher stem volume, compared to *E. urophylla* or *E. pellita* planted in the same trials. There is little information available to eucalypt breeding programs in Vietnam regarding wood properties for determining the quality of solid products, however, research in Australia and New Zealand indicates that wood quality is of concern, owing to the presence of tension wood, excessive longitudinal growth strain (and various related issues regarding wood product manufacture), and internal checking and collapse when drying lumber [9–11], emphasizing the importance of incorporating wood quality information into selection decisions.

Modulus of elasticity (MOE) and modulus of ruptures (MOR) are important properties of wood and major determinants of potential end-use products [12]. A common way to measure wood stiffness and strength is via three-point static bending tests on small clear samples. An alternative to static bending tests is using nondestructive assessment methods. The development of acoustic tools has paved the way for assessing static properties on standing trees before harvest or sorting logs and before processing to ensure lumber meets specified mechanical property design values. Tree breeders also prefer non-destructive methods because it makes the rapid assessment of wood properties of standing trees possible and allows the retention of individual trees for crossing and/or propagation [13]. Moderate-to-good relationships have been observed between tree or log acoustic velocity and MOE of lumber or small wood specimens. For example, in Douglas-fir (*Pseudotsuga menziesii*), Wang et al. [14] found a moderate correlation ($R^2 = 0.40$) between log acoustic velocity and average MOE of the lumber produced from the logs. Butler et al. [15] found a similar relationship ($R^2 = 0.49$) in loblolly pine (*Pinus taeda*) between mean MOE of the lumber and log acoustic velocity. Tumenjargal et al. [16] found significant positive correlations between stress wave velocity of trees and average MOE ($r = 0.77$) and MOR ($r = 0.70$) of lumber in *Larix sibirica*, while Duong et al. [17] reported that *Acacia auriculiformis* trees with potential to produce high and low stiffness and strength lumber can be identified by measuring stress wave velocity in standing trees alone.

The main objective of this study was to link stress wave velocity from standing trees, logs, and small clear specimens with lumber properties tested in static bending for six different *Eucalyptus* clones planted in Vietnam. In addition, radial and among-clonal variations in stress wave velocity, air-dry density, MOE, and MOR of small clear wood specimens was also examined. This information will be used to develop appropriate selection strategies for *Eucalyptus* breeding programs for lumber production in Vietnam.

2. Materials and Methods

2.1. Sample Origin

The materials for the study were collected from an *Eucalyptus* clonal trial established by the Vietnamese Academy of Forest Sciences in Cam Hieu commune, Cam Lo district, Quang Tri province, Vietnam (16°45′56″ N and 107°01′32″ E). Three hybrid eucalypt clones (*E. urophylla* × *E. pellita*) and three *E. urophylla* clones were planted to assess growth rate and stem quality. The trial design was full randomized block, with 5 replicates, 49 ramets/plot (7 rows × 7 ramets/row). The initial spacing between ramets was 3 × 2 m (1660 trees/ha) with a core area for growth measurements of 25 ramets/plot. Seedlings were planted in December 2014 with common planting practices homogenously applied for every tree [18].

2.2. Sampling and Measurements

Data for assessing wood properties were collected in December 2020 at an age of 6 years. A total of 30 ramets from three hybrid eucalypt clones (UP54, UP95, and UP99) and three *E. urophylla* clones (U892, U1427, and PN14) with 5 ramets per clone were chosen based on straightness, branching, and absence of disease or pest symptoms. Before felling, stem diameter at a height of 1.3 m was measured and the north and south sides were marked for all sampled ramets, and once felled, total height was measured (Table 1). A Fakopp Microsecond Timer (Fakopp Enterprise Bt., Agfalva, Hungary) was used for measuring stress wave velocity on selected ramets prior to felling, logs, and small defect-free wood specimens obtained from the logs.

Table 1. Mean values and standard deviations of stem diameter and tree height for each clone.

Clone	Species	Code	*n*	DBH (cm)	Tree Height (m)
UP54	*E. urophylla* × *E. pellita*	1	5	14.24 ± 0.88	18.81 ± 0.54
UP95	*E. urophylla* × *E. pellita*	2	5	15.43 ± 0.58	20.01 ± 0.38
UP99	*E. urophylla* × *E. pellita*	3	5	13.17 ± 0.93	18.40 ± 0.60
U892	*E. urophylla*	4	5	14.18 ± 1.96	18.08 ± 0.63
U1427	*E. urophylla*	5	5	14.06 ± 1.09	16.48 ± 0.65
PN14	*E. urophylla*	6	5	13.83 ± 1.18	15.23 ± 0.30

Note: DBH is diameter at breast height (1.3 m above the ground); *n* is number of sampled ramets.

Standing trees stress wave velocity (SWV_T) was assessed, as described by Ishiguri et al. [19]. Start and stop sensors were inserted into the stem at 1.50 m and 0.50 m above ground level. One stress wave measurement was recorded for each tree using the average of five readings. SWV_T was calculated by dividing the span between sensors (1.0 m) by average stress wave transmission time.

A 1.0 m log was collected between 0.5 to 1.5 m from each sampled stem, then each log was nondestructively tested using a Fakopp Microsecond Timer to obtain a stress wave velocity for the log (SWV_L) within 24 h of felling. During log testing, start and stop sensors were inserted at the middle position from pith to bark (transverse face) at each end of the log, as shown in Figure 1. SWV_L (m/s) of a log was determined by dividing log length by average of five readings of stress wave propagation time between sensors.

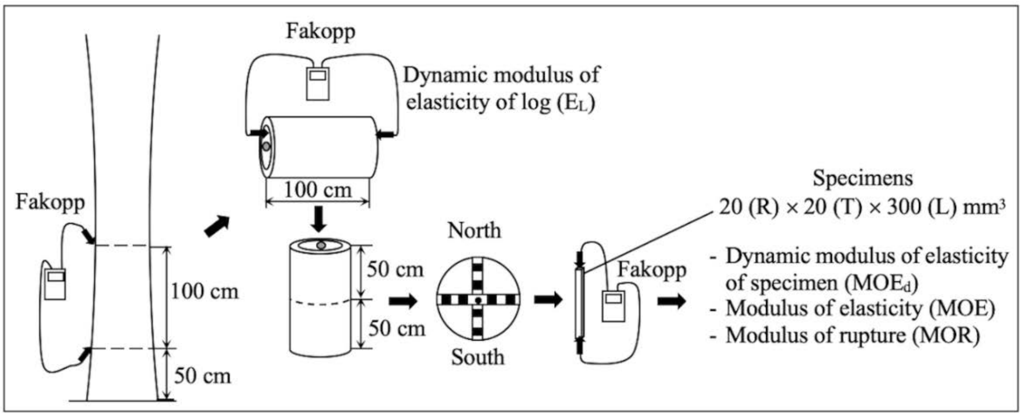

Figure 1. Illustration of experimental procedures.

After air-drying in a room at ambient conditions (no humidity control) for approximately 2 months, each 1.0 m log was cut to two 0.5 m logs for preparation of small clear specimens for three-point static bending tests. From each 0.5 m log, specimens with dimensions of 20 (radial) × 20 (tangential) × 300 (longitudinal) mm^3 [20] were carefully cut from near the pith and near the bark in each cardinal direction (north–south and east–west) (Figure 1). The small size of the logs only allowed test specimens to be cut in the north–south direction. Overall, a total of 392 small clear wood specimens were prepared, as shown in Figure 2. These were then dried to approximately 12% moisture content in a conditioning room, maintained at 60% relative humidity and 20 °C for one month.

Figure 2. The experimental procedures: Measurement of acoustic velocity in standing trees (**a**), one meter logs from each sampled stem (**b**), and static bending samples (**c**).

Before the bending tests were conducted, the weight and volume of each specimen was measured. Air-dry density of the specimens (AD) was calculated by dividing the mass of each small clear specimen by its volume. Longitudinal stress wave was also measured for each specimen using a Fakopp Microsecond Timer. Transducers were inserted in the ends of the specimens and an acoustic signal was created by a hammer strike on the start transducer. Measurement of propagation time was repeated six times for each specimen, and an average value was used for data analysis. Stress wave velocity of specimen (SWV_S) was calculated as specimen length divided by the propagation time (end-to-end). Dynamic modulus of elasticity of each specimen (MOE_d) was estimated using the following formula:

$$MOE_d = AD \times SWV_S^2 \times 10^{-9}\ (GPa) \tag{1}$$

where: MOE_d is the dynamic modulus of elasticity of specimen (GPa); AD is air-dry density of specimen (kg/m^3); SWV_S is stress wave velocity of specimen (m/s).

Static bending tests were conducted in three-point bending using a universal testing machine (QTEST/25, MTS Systems, Eden Prairie, MI, USA), with a test span of 260 mm. The load was applied to the radial face at the center of each specimen at a constant speed of 5 mm per minute to failure.

2.3. Data Analysis

Analysis of variance (ANOVA) for SWV_S, AD, MOE_d, MOE, and MOR was performed by mixed model to test the significance of clone, ramet, and radial position effects, relying on the following equation:

$$Y_{ijk} = \mu + C_i + T_j + R_k + (CR)_{ik} + (TR)_{jk} + e_{ijk} \tag{2}$$

where: Y_{ijk} is the observation in the *ijk*th ramet; μ is the intercept of the model; C_i and R_k are fixed effects of clone and radial position, respectively; T_j is the random effect of ramet within clone; $(CR)_{ik}$ is the interaction between clone and radial position effect; $(TR)_{jk}$ is the interaction between ramet within clone and radial position effect; and e_{ijk} is the random error term.

A one-way analysis of variance test was applied to evaluate the differences between radial positions or among clones in stress wave velocity and wood properties followed by Tukey's HSD test with the level of significant differences at $p < 0.05$. All statistical analysis of the measurement data was performed using R software version 4.0.0 [21].

3. Results and Discussion

3.1. Stress Wave Measurements in Trees and Logs

Table 2 presents descriptive statistics (mean, standard deviation, range, and analysis of variance) obtained for SWV_T and SWV_L among six different *Eucalyptus* clones planted in Vietnam. For all clones combined mean SWV_T and SWV_L were 3341 m/s (range 2686 to 3759 m/s) and 3503 m/s (range 2898 to 3989 m/s), respectively. Multiple means comparison tests showed a significant difference among *Eucalyptus* clones both in SWV_T and SWV_L (Table 2). The highest mean SWV_T among clones was for clone 3 (3662 m/s), which also had the highest SWV_L (3884 m/s). Clones 1 and 6 had the lowest SWV_T and SWV_L values. SWV_T values obtained in this study were comparable with those reported in other *Eucalyptus* species. Ishiguri et al. [19] reported a mean SWV_T value of 3450 m/s for eight 4-year-old *Eucalyptus camaldulensis* families planted in Thailand, and Blackburn et al. [22] reported values of 3360, 3230, and 3180 m/s, respectively, for three 13-year-old *Eucalyptus nitens* provenances grown in Australia. In addition, Wu et al. [7] reported SWV_T values that ranged from 2780 to 4030 m/s for 4-year-old *Eucalyptus* hybrid clones planted in China.

Table 2. Statistical values of SWV_T and SWV_L for six *Eucalyptus* clones.

Clone	n	SWV_T (m/s)			SWV_L (m/s)		
		Mean	SD	Range	Mean	SD	Range
1	5	3151^{cd}	101	3047–3299	3229^{c}	55	3166–3285
2	5	3559^{ab}	129	3399–3704	3569^{b}	85	3498–3714
3	5	3662^{a}	86	3546–3759	3844^{a}	91	3762–3989
4	5	3375^{bc}	95	3279–3521	3588^{b}	106	3449–3706
5	5	3288^{c}	123	3160–3450	3553^{b}	137	3354–3714
6	5	3013^{d}	214	2686–3219	3231^{c}	206	2989–3404
Mean	30	3341	256	2686–3759	3503	246	2898–3989

Note: The same letter associated with mean values indicate no significant differences among clones based on Tukey’s HSD test at 5%.

A strong relationship between SWV_T and SWV_L was observed (Figure 3) for *Eucalyptus* clones planted in Vietnam under the conditions described earlier, characterized by a coefficient of correlation (r) of 0.85. Several studies have examined the relationship between acoustic velocities measured on standing trees and logs; however, most of these studies were on softwood species. For example, Mora et al. [23] reported a relationship of 0.81 between tree and log acoustic velocities for *Pinus taeda* and Ishiguri et al. [24] reported a similar correlation (r = 0.87) in Japanese larch (*Larix kaempferi*). Little information is available on the relationship between SWV_T and SWV_L on young *Eucalyptus*. Dickson et al. [25] found a statistically significant coefficient of correlation between SWV_T and SWV_L (r = 0.62) measured using the Fakopp microsecond timer for *Eucalyptus dunnii* grown in New South Wales, Australia.

3.2. Radial and Among-Clonal Variations of SWV_S and Wood Properties

Radial and among-clonal variation for SWV_S and wood properties for the six *Eucalyptus* clones are summarized in Table 3. The overall mean values of SWV_S, AD, MOE_d, MOE, and MOR were 4142 m/s, 0.52 g/cm^3, 8.86 GPa, 7.48 GPa, and 72.47 MPa, respectively (Table 3). Comparison with air-dry density and mechanical properties found in the literature for *Eucalyptus* and other fast-growing species are given in Table 4. Our mean values for AD and static bending properties were similar to values reported for *E. camaldulensis* [26] but lower than mean values reported for *Eucalyptus tereticornis* by Kothiyal and Raturi [27]. Compared to other fast-growing species planted at the same sites to the *Eucalyptus* clones in this study, AD and MOE_d were comparable with those of *Acacia auriculiformis* and higher than values reported for *Acacia mangium*. MOE and MOR values were lower than those found for *A. auriculiformis* but similar to those reported for *A. mangium* (Table 4).

Variation among these studies could be explained by the effect of differences in genetics, environmental factors, or their interaction [28].

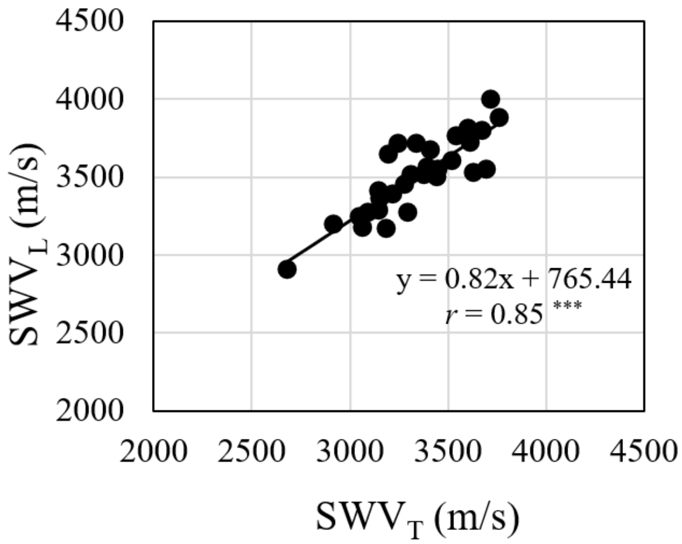

Figure 3. Relationship between stress wave velocities measured on standing trees (SWV_T) and logs (SWV_L) (***: $p < 0.001$).

Table 3. Stress wave velocity and wood properties of six different *Eucalyptus* clones planted in Vietnam.

Variable	Description		*n*	SWV_S (m/s)	AD (g/cm^3)	MOE_d (GPa)	MOE (GPa)	MOR (MPa)
Radial positions	1	Near pith	40	4021 ^{b} ± 128	0.43 ^{b} ± 0.02	6.99 ^{b} ± 0.62	5.96 ^{b} ± 0.51	56.50 ^{b} ± 4.63
		Near bark	40	4244 ^{a} ± 168	0.48 ^{a} ± 0.02	8.71 ^{a} ± 0.84	7.38 ^{a} ± 0.69	69.59 ^{a} ± 4.69
	2	Near pith	40	4229 ^{b} ± 131	0.46 ^{b} ± 0.02	8.27 ^{b} ± 0.70	6.57 ^{b} ± 0.57	62.37 ^{b} ± 7.01
		Near bark	40	4353 ^{a} ± 57	0.51 ^{a} ± 0.01	9.69 ^{a} ± 0.39	7.92 ^{a} ± 0.60	76.22 ^{a} ± 4.88
	3	Near pith	28	4226 ^{b} ± 122	0.53 ^{b} ± 0.07	9.52 ^{b} ± 1.86	8.24 ^{b} ± 1.71	77.45 ^{b} ± 14.60
		Near bark	28	4421 ^{a} ± 122	0.58 ^{a} ± 0.05	11.42 ^{a} ± 1.28	9.73 ^{a} ± 1.23	92.50 ^{a} ± 11.71
	4	Near pith	28	4234 ^{b} ± 153	0.47 ^{b} ± 0.03	8.39 ^{b} ± 1.08	7.30 ^{b} ± 0.92	65.09 ^{b} ± 6.36
		Near bark	28	4360 ^{a} ± 125	0.52 ^{a} ± 0.03	9.84 ^{a} ± 0.89	8.63 ^{a} ± 1.02	76.36 ^{a} ± 4.90
	5	Near pith	32	3744 ^{b} ± 149	0.59 ^{a} ± 0.02	8.32 ^{b} ± 0.74	7.02 ^{b} ± 0.77	80.42 ^{b} ± 6.16
		Near bark	32	4016 ^{a} ± 83	0.60 ^{a} ± 0.03	9.61 ^{a} ± 0.67	8.39 ^{a} ± 0.66	87.47 ^{a} ± 4.63
	6	Near pith	28	3772 ^{b} ± 144	0.50 ^{b} ± 0.03	7.07 ^{b} ± 0.77	5.97 ^{b} ± 0.78	57.01 ^{b} ± 11.10
		Near bark	28	4034 ^{a} ± 186	0.57 ^{a} ± 0.02	9.25 ^{a} ± 0.72	7.50 ^{a} ± 0.83	76.13 ^{a} ± 6.10
Clones	1		80	4133 ^{b} ± 186	0.46 ^{e} ± 0.03	7.85 ^{c} ± 1.14	6.67 ^{d} ± 0.94	63.05 ^{c} ± 8.05
	2		80	4291 ^{a} ± 118	0.49 ^{d} ± 0.03	8.98 ^{b} ± 0.91	7.24 ^{bc} ± 0.89	69.30 ^{b} ± 9.20
	3		56	4323 ^{a} ± 194	0.56 ^{b} ± 0.06	10.47 ^{a} ± 1.85	8.98 ^{a} ± 1.65	84.98 ^{a} ± 15.15
	4		56	4297 ^{a} ± 152	0.49 ^{d} ± 0.04	9.12 ^{b} ± 1.22	7.97 ^{b} ± 1.17	70.73 ^{b} ± 8.00
	5		64	3880 ^{c} ± 182	0.60 ^{a} ± 0.03	8.97 ^{b} ± 0.96	7.70 ^{b} ± 0.99	83.94 ^{a} ± 6.47
	6		56	3903 ^{c} ± 211	0.53 ^{c} ± 0.05	8.16 ^{c} ± 1.33	6.73 ^{cd} ± 1.11	66.57 ^{bc} ± 13.11
	Mean		392	4142 ± 249	0.52 ± 0.06	8.86 ± 1.48	7.48 ± 1.36	72.47 ± 13.11

Note: Mean values are followed by standard deviation; *n* number of wood specimens; SWV_S = stress wave velocity of specimens; AD = air-dry density; MOE_d = dynamic modulus of elasticity of specimens; MOE = modulus of elasticity; MOR = modulus of rupture. The same letter associated with mean values indicate no significant differences between radial positions or among clones based on Tukey's HSD test at 5%.

Table 4. Summary of air-dry density and mechanical properties for the *Eucalyptus* clones in this study and related studies.

Reference	Species	Country	Stand Age	AD (g/cm^3)	MOE$_d$ (GPa)	MOE (GPa)	MOR (MPa)
This study	*Eucalyptus*	Vietnam	6	0.46–0.60	7.85–10.47	6.67–8.98	63.05–84.98
De Melo et al. [26]	*E. camaldulensis*	Brazil	5	0.56		7.01	77.95
Kothiyal and Raturi [27]	*E. tereticornis*	India	5	0.58		7.98	84.80
Duong et al. [17]	*A. auriculiformis*	Vietnam	5	0.50–0.59	8.70–10.95	7.37–9.14	83.81–101.43
Duong et al. [29]	*A. mangium*	Vietnam	5	0.44–0.50	7.73–8.92	7.03–8.23	66.63–84.19

For intrinsic wood properties, clones 5 (0.60 g/cm^3) and 3 (0.56 g/cm^3) had the highest AD, whereas clone 1 had the lowest (0.46 g/cm^3). Similarly, the highest average MOE and MOR values were detected in clone 5 (7.70 GPa and 83.94 MPa, respectively) and 3 (8.98 GPa and 84.98 MPa, respectively), suggesting that clones 5 and 3 might be more appropriate clones than the others we examined for breeding programs focused on improving wood quality of *Eucalyptus* grown in Vietnam. Further studies are required to understand how clonal variation in wood properties is affected by environmental variation and to examine other properties, for example, tension wood [9] affects lumber quality.

Radial position had a significant effect ($p < 0.001$) and had the highest contribution to total variation for SWV$_S$ (55.92%), AD (52.44%), MOE$_d$ (80.15%), MOE (76.92%), and MOR (72.39%) (Table 5). *T-test* results showed that SWV$_S$ mean value and all wood properties in the outer wood were higher than those near the pith in all tested clones, except for AD in clone 5 (Table 3). Table 5 also shows that clone is a highly significant source of variation in SWV$_S$ and wood properties of *Eucalyptus* planted in Vietnam, explaining 40.38, 43.22, 16.47, 19.54, and 24.00% of the total variation of the SWV$_S$, AD, MOE$_d$, MOE, and MOR, respectively. Ramet-to-ramet variation within clone was also a significant source of variation in measured properties, but its contribution was small (approximately 2% of the total variation). The residual effect was responsible for a small proportion (from 0.10% to 0.20%) of the total variation and arises from factors not accounted for in the experimental design (Table 5).

Table 5. Effects of clone, tree, and radial position on stress wave velocity, wood density, and mechanical properties of *Eucalyptus* clones.

Source of Variation	*df*	SWV$_S$		AD		MOE$_d$		MOE		MOR	
		p Value	Var (%)	*p* Value	Var (%)	*p* Value	Var (%)	*p* Value	Var (%)	*p* Value	Var (%)
Clone (C)	5	0.001	40.38	0.001	43.22	0.001	16.47	0.001	19.54	0.001	24.00
Ramet (T)/Clone	24	0.001	2.18	0.001	2.23	0.001	2.33	0.001	2.90	0.001	2.00
Radial position (R)	1	0.001	55.92	0.001	52.44	0.001	80.15	0.001	76.92	0.001	72.39
C × R	5	0.001	0.86	0.001	1.72	0.001	0.63	0.677	0.10	0.001	1.17
T × R	23	0.001	0.46	0.001	0.29	0.001	0.31	0.001	0.39	0.001	0.31
Residuals	333		0.20		0.10		0.12		0.15		0.13

Acoustic velocity is an indicator of wood stiffness and, combined with wood density, is used to calculate MOE$_d$ through the fundamental wave Equation (1). Ilic [30] reported the mean value of dynamic elastic modulus (determined by vibration method) was 29% higher than the corresponding static MOE in *Eucalyptus delegatensis*. De Oliveira et al. [31] found a 17% difference in dynamic elastic modulus (measured using ultrasonic method) and static MOE for *Goupia glabra* and *Hymenaea* sp. In this study, the overall mean value of MOE$_d$ was 8.86 GPa, which was 18.45% higher than that of the static bending MOE (Table 3). Part of the reason for such large differences between the dynamic and static modulus of elasticity comes about from effects of shear in bending and the magnitude of the difference depends on acoustic wave measurement method and the viscoelastic characteristics of the wood, which can vary among species and even within the same tree [26,30].

3.3. Prediction of Static Bending Properties Using Stress Wave Measurements on Standing Trees, Logs, and Small Specimens

Statistical analysis procedures were used to examine relationships of SWV_T and SWV_L to average MOE and MOR for specimens cut from ramets and logs (Table 6). SWV_T had positive correlations with both average MOE and MOR of small specimens for all *Eucalyptus* clones combined. The correlation coefficients were 0.61 (SWV_T and MOE) and 0.53 (SWV_T and MOR). It was apparent that the measurements of stress wave velocity by the same Fakopp device in logs produced better correlations with static properties than in standing trees with relationships of 0.76 for SWV_L and MOE and 0.71 for SWV_L and MOR. These results agree with several studies, utilizing nondestructive techniques on standing trees, or logs, to confirm the relationship between acoustic velocity and mechanical properties for other species [14,17,24,32]. Our results suggest that stress wave velocity measurements of both standing trees and logs can be used to further segregate the Vietnamese *Eucalyptus* plantation resource.

Table 6. Correlations of stress wave velocity measured in standing trees and logs with static bending properties (MOE and MOR) for six *Eucalyptus* clones planted in Vietnam.

Level	Y	X	*n*	Equation	*r*	*p*-Value
Tree level	MOE	SWV_T	30	Y = 0.003X − 1.27	0.61	<0.001
	MOR		30	Y = 0.021X + 2.50	0.53	0.003
Log level	MOE	SWV_L	30	Y = 0.003X − 4.42	0.76	<0.001
	MOR		30	Y = 0.030X − 31.03	0.71	<0.001

Table 7 summarizes relationships of SWV_S, AD, and MOE_d with static properties (MOE and MOR) for individual *Eucalyptus* clones and all clones combined. Significant relationships were observed between SWV_S and MOE (r = 0.63) (Figure 4a), and SWV_S and MOR (r = 0.33) (Figure 4b), although stress wave velocity explained approximately 40% of the variance in weighted MOE and just over 10% of the variance in weighted MOR. For individual clones, better relationships (compared to all clones combined) were found between SWV_S and static properties. Correlation coefficients varied from 0.69 to 0.84 (SWV_S and MOE) and from 0.60 to 0.74 (SWV_S and MOR) (Table 7). Coupled with the good relationships of SWV_T and SWV_L with static properties (Table 6), there were significant relationships between SWV_S and mechanical properties measured destructively in small clear specimens implying that time-of-flight stress wave velocities give a good indication of static bending properties in Vietnamese grown *Eucalyptus* clones.

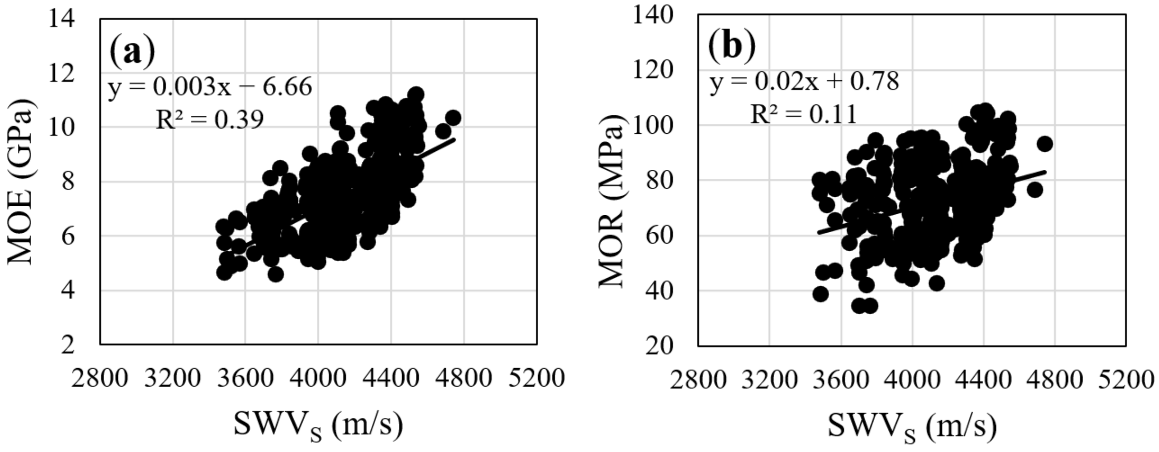

Figure 4. Relationship between stress wave velocity of specimens (SWV_S) and static properties: (**a**) modulus of elasticity (MOE) and (**b**) modulus of rupture (MOR) for all clones.

Table 7. Prediction models of static bending properties (MOR and MOE) based on stress wave velocity of specimens (SWV_S), air-dry density (AD), and dynamic modulus of elasticity (MOE_d) for each *Eucalyptus* clone and all clones combined.

Clone	Variables	MOE		MOR	
		Equation	*r*	Equation	*r*
1	SWV_S	$MOE = 0.004SWV_S - 10.51$	0.83 ***	$MOR = 0.03SWV_S - 57.24$	0.67 ***
	AD	$MOE = 25.46AD - 4.96$	0.85 ***	$MOR = 229.26AD - 41.67$	0.89 ***
	MOE_d	$MOE = 0.76MOE_d + 0.69$	0.92 ***	$MOR = 5.94MOE_d + 16.43$	0.84 ***
2	SWV_S	$MOE = 0.005SWV_S - 15.22$	0.69 ***	$MOR = 0.05SWV_S - 131.10$	0.60 ***
	AD	$MOE = 22.42AD - 43.66$	0.75 ***	$MOR = 248.15AD - 51.40$	0.81 ***
	MOE_d	$MOE = 0.82MOE_d - 0.11$	0.83 ***	$MOR = 8.29MOE_d - 5.17$	0.82 ***
3	SWV_S	$MOE = 0.007SWV_S - 20.79$	0.81 ***	$MOR = 0.06SWV_S - 166.60$	0.74 ***
	AD	$MOE = 23.40AD - 4.03$	0.92 ***	$MOR = 217.08AD - 35.74$	0.93 ***
	MOE_d	$MOE = 0.85MOE_d + 0.03$	0.96 ***	$MOR = 7.65MOE_d + 4.87$	0.93 ***
4	SWV_S	$MOE = 0.006SWV_S - 18.12$	0.79 ***	$MOR = 0.04SWV_S - 79.81$	0.67 ***
	AD	$MOE = 26.76AD - 5.21$	0.88 ***	$MOR = 160.32AD - 8.17$	0.78 ***
	MOE_d	$MOE = 0.88MOE_d - 0.06$	0.92 ***	$MOR = 5.16MOE_d + 23.71$	0.79 ***
5	SWV_S	$MOE = 0.005SWV_S - 10.18$	0.84 ***	$MOR = 0.02SWV_S - 1.68$	0.62 ***
	AD	$MOE = 13.01AD - 0.04$	0.36 **	$MOR = 74.11AD + 39.81$	0.31 *
	MOE_d	$MOE = 0.93MOE_d - 0.60$	0.89 ***	$MOR = 4.61MOE_d + 42.59$	0.68 ***
6	SWV_S	$MOE = 0.004SWV_S - 10.17$	0.82 ***	$MOR = 0.04SWV_S - 10.86$	0.72 ***
	AD	$MOE = 15.15AD - 1.32$	0.63 ***	$MOR = 215.42AD - 47.95$	0.76 ***
	MOE_d	$MOE = 0.74MOE_d + 0.71$	0.88 ***	$MOR = 8.59MOE_d - 3.55$	0.87 ***
Combined	SWV_S	$MOE = 0.003SWV_S - 6.66$	0.63 ***	$MOR = 0.02SWV_S + 0.78$	0.33 ***
	AD	$MOE = 13.93AD + 0.29$	0.64 ***	$MOR = 173.61AD - 17.01$	0.82 ***
	MOE_d	$MOE = 0.85MOE_d - 0.07$	0.93 ***	$MOR = 7.34MOE_d + 7.41$	0.83 ***

Note: ***: $p < 0.001$, **: $p < 0.01$, *: $p < 0.05$.

Density and static properties are known to be related in *Eucalyptus* species, as stated by Ilic [30] and Sharma et al. [33]. The results in this study revealed that AD was significantly correlated with static bending properties measured on small clear specimens, explaining over 40% of the variance in recorded MOE values (Figure 5a) and closer to 70% of the variance in MOR for all clones combined (Figure 5b). Correlation coefficients were also determined between MOE and MOR with AD for each clone (Table 7). The correlations between AD and static bending properties differ among clones with *r* values varying from 0.36 to 0.92 and from 0.31 to 0.93 for AD and MOR. At the specimen level, for all clones, combined correlation coefficients for AD with MOE and MOR were 0.64 ($p < 0.001$) and 0.82 ($p < 0.001$), respectively.

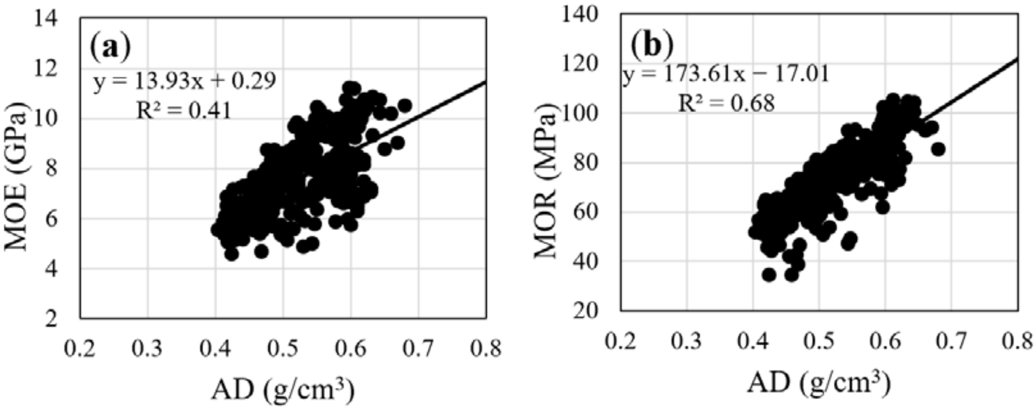

Figure 5. Relationship between air-dry density (SWV_S) and static properties: (**a**) modulus of elasticity (MOE) and (**b**) modulus of rupture (MOR) for all clones.

Table 7 also presents regression analyses that examined the relationship between MOE_d and destructively measured mechanical properties for each clone and all clones combined. The correlation coefficient between MOE_d and MOE ($r = 0.93$, $p < 0.001$) were stronger than that between SWV_S and MOE ($r = 0.63$, $p < 0.001$), as well as between AD and MOE ($r = 0.63$, $p < 0.001$). The coefficient of determination (R^2) increased considerably for MOE when SWV_S and AD of specimens were used together to predict stiffness. Individually, SWV_S and AD explained approximately 40% of the variance in MOE, increasing to 86% (Figure 6a) when SWV_S and AD were used together. Previous reports confirm that dynamic modulus of elasticity is strongly correlated with MOE in other species [32,34–36]. Relationship between MOE_d and MOR for all combined clones were also strong (0.83, $p < 0.001$) and ranged from 0.68 for clone 5 to 0.93 for clone 3 (Table 7). MOE_d explained 68% of the variance in recorded MOR (Figure 6b), similar to the effect of AD on MOR (Figure 5b). Hence, the combination of SWV_S and AD does not improve prediction of bending strength.

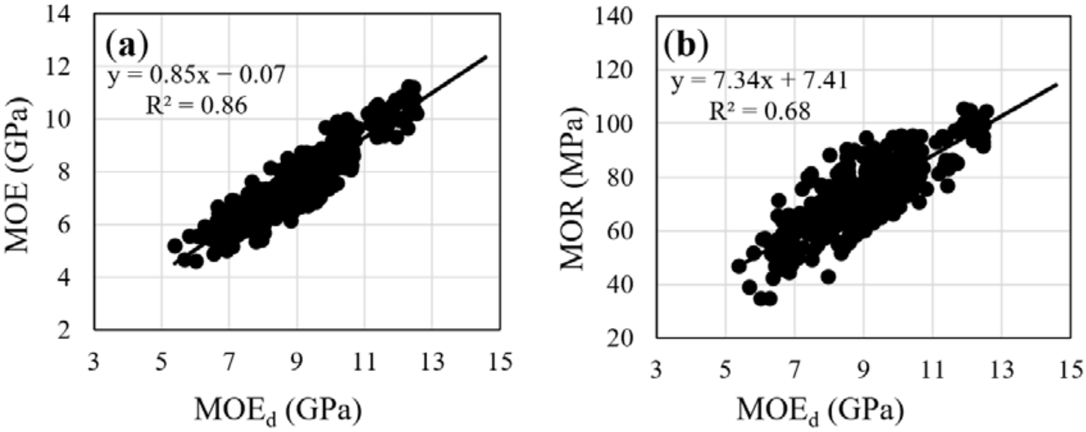

Figure 6. Relationship between dynamic modulus of elasticity (MOE_d) and static properties: (**a**) modulus of elasticity (MOE) and (**b**) modulus of rupture (MOR) for all clones.

4. Conclusions

From this study, it is possible to make the following preliminary conclusions:

- There was a significant difference in density and static properties in radial location and among *Eucalyptus* clones. Clones 3 and 5 had significantly higher AD, MOR, and MOE than other clones. Therefore, clones 3 and 5 might be appropriate for *Eucalyptus* tree breeding programs focused on improving wood quality, specifically for lumber production in the north central region or similar sites of Vietnam.
- SWV_T and SWV_L had positive correlations with both average MOE- and MOR-determined by static bending tests of small specimens. This implies that stress wave velocities measured using time of flight gives a good indication of static bending properties in *Eucalyptus* clones planted in Vietnam.
- At the specimen level, SWV_S and AD were significantly correlated with static bending properties. Improved prediction of stiffness can be achieved when both SWV_S and AD of specimens are used together to calculate dynamic modulus of elasticity (MOE_d), while this combination does not improve predictions of bending strength, compared to using AD alone.

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