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RADIAL AND AMONGCLONAL VARIATIONS OF TRANSVERSE SHRINKAGE AND BASIC DENSITY IN 5-YEAR-OLD*ACACIA AURICULIFORMIS* CLONES PLANTED IN VIETNAM

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ABSTRACT

This study investigated transverse shrinkages and wood density for *Acacia auriculiformis* trees from six clones planted in north-central Vietnam. Radial and among-clonal variations of partial and total shrinkages in tangential (respective to T_n and T) and radial (respective to R_n and R) directions, partial and total coefficient of anisotropy (respective to T_n/R_n and T/R), and basic density (BD) were examined. There were significant differences among clones for R_n and R, but no significant differences were found among clones for T_n and T. The lowest average R_n and R were detected in clones Clt18 and Clt26, suggesting that these clones might be more appropriate for breeding programs focused on improving shrinkage traits for sawn timber production. BD is not a good indicator for predicting transverse shrinkages. In contrasts, stress wave velocity measured in standing trees has the potential to be used as a non-destructive method for predicting the transverse shrinkage of *A. auriculiformis* planted in Vietnam.

KEYWORDS:*Acacia auriculiformis*, clones, wood shrinkage, basic density, non-destructive.

INTRODUCTION

Timber and non-timber processing industries form an important part of the Vietnamese economy; exports from this sector were USD 13.18 billion in 2023. To meet this demand,annually the country must import up to 3-4 million cubic meters of the timber to be processed, including logs from tropical *Acacia* trees (Cam and Huy 2024). In Vietnam,*Acacia* species are widely planted for shortrotation to supply raw material for pulp and particleboard industries (Savero et al. 2023, Van Duong et al. 2023). However, growers may have significant economic advantages if switch to longer-rotation saw-log production (Huong et al. 2020). Therefore, in recent years, the Vietnamese Government has been encouraging tree growers to increase the rotation lengths of plantations and produce sawlogs (Blackburn et al. 2020). *Acacia auriculiformis* is one of the crucial sources of solid wood domestically, and it is preferred for its quality and suitability in various applications. Several studies have been done on the static bending properties of *A. auriculiformis*planted in Vietnam (Hai et al. 2010, Viet et al. 2020, Van Duong et al. 2022). Other characteristics, such as the dimensional stability of *A. auriculiformis*,which is important for solid wood end-use products, haveyet to receive much attention. Consequently, the clones of *A. auriculiformis* must meet specific requirements for different end uses that demand distinct wood properties.

Dimensional instability due to shrinkage or swelling of the cells or fibers is one of the major impediments in the processing and use of timber (Zobel and Van Buijtenen 1989, Wu et al. 2006, Augustina et al. 2023). The axial, radial, and tangential shrinkages, which together account for the volumetric shrinkage, are directed by features of the wood structure. However, radial and tangential shrinkages are of major importance. Typical oven-dry shrinkage values for mediumdensity woods are 2-6% for radial shrinkage and 5-10% for tangential shrinkage. Longitudinal shrinkage of the wood is generally quite small about 0.1 – 0.3% of green condition when oven-dried (Walker 2006). The difference in radial-tangential shrinkage is the cause of most problems that arise during seasoning and drying.

Wood shrinkage and density are the most essential parameters of wood dimensional stability because density is widely acknowledged to reflect shrinkage properties. Van Duong and Matsumura (2018) found strong positive correlations of basic density with radial (r = 0.82) and tangential (r = 0.72) shrinkages in *Melia azedarach*. Similar results are reported for eucalypt species (Wu et al. 2006) and poplar hybrid crosses (Pliura et al. 2005). However, many exceptions have been noted. Shupe et al. (1995b) reported no significant correlation between wood density and shrinkage in a single cottonwood tree. These results suggest that the magnitude of the effects of wood density on shrinkage depends on the wood species.

A cheaper and more rapid means of measuring shrinkage is needed than wood blocks used in traditional methods.Several studies suggest that non-destructive methods may be used to assess dimensional stability (Dundar et al. 2013,2016, Van Duong and Matsumura 2018, De Melo et al. 2021). For example, Dundar et al. (2013) reported that ultrasonic velocity was a significant predictor of transverse shrinkages and therefore has good potential to be used as a field method to the evaluate dimensional stability of *Piceasitchensis* and *Tsuga heterophylla* woods. Van Duong and Matsumura (2018) found statistically significant, but weak correlations between stress wave velocity measured on log and radial (R^2 = 0.22) and tangential (R^2 = 0.20) shrinkages measured on clear small specimens from relative logs of *Melia azedarach*. Based on their findings, acoustic technology is a promising method that could be adapted for rapid shrinkage measurements on wood.

The main objective of this study was to provide information on radial and among-clonal variations in transverse shrinkage and basic density of *A. auriculiformis* clones planted in north-central Vietnam under identical conditions. The relationship between basic density and transverse shrinkage was examined. In addition, the potential of stress wave velocity measured on a standing tree as a rapid and nondestructive method to predict the dimensional stability of *A. auriculiformis* was also discussed.

MATERIAL AND METHODS

Materials

The materials for the study were collected from six*A. auriculiformis*clonal trials (Clt7, Clt18, Clt19, Clt25, Clt26, Clt57)established by the Vietnamese Academy of Forest Sciences. These are clones that have been recognized by the Vietnam Ministry of Agriculture and Rural Development as national and technologically advanced varieties (Vo et al. 2019). The trial sites are located in Cam Hieu commune, Cam Lo district, Quang Tri province, north-central Vietnam (16°45'60"N and 107°01'12"E). A total of 30 ramets (5 per clone) were used in the present study. A detailed description of the trial forest and sample ramets was reported in a previous paper (Van Duong et al. 2022). Stem diameter (DBH) at 1.3m above the ground, tree height (TH), and stress wave velocity of standing tree (SWV_T) were measured for each clone, as presented in Tab. 1. The SWV_T was measured using a Fakopp Microsecond Timer for each tree (Serial No.: FN-12/2020, Fakopp Enterprise Bt., Hungary) with start and stop sensors at heights of 1.5 m and 0.5 m, respectively. After felling, a cross-sectional disc 100 mm thick was collected from each ramet at 1.5 m from the ground to measure the selected wood properties.

From each disc, eight specimens 20 mm (radial) × 20 mm (tangential) × 30 mm (longitudinal) were carefully cut from parts near the pith (R1) and near the bark (R2) on both sides (north and south) to examine the basic density (BD) and transverse shrinkage (4 specimens near pith and bark, respectively). Due to the small average radius at breast height of the 30 ramets (approximately 60 mm), these specimens were carefully cut from areas close to the pith and bark. This approach was intended to ensure a representative sample for analyzing the radial variation in wood properties. The total number of small clear wood specimens was 240 (40 specimens for each clone).

Tab. 1: Mean values and standard deviations of stem diameter and tree height for each clone (Van Duong et al.2022).

Clone	**Code**	***n***	**DBH (cm)**	**TH (m)**	**SWV_T (m/s)**
Clt7	1	5	11.28 ± 0.53	13.20 ± 0.39	3609 ± 85
Clt18	2	5	12.23 ± 0.74	12.91 ± 0.29	3339 ± 101
Clt19	3	5	10.83 ± 0.84	12.40 ± 1.80	3291 ± 74
Clt25	4	5	11.68 ± 0.85	13.20 ± 0.68	3347 ± 45
Clt26	5	5	13.72 ± 0.61	13.49 ± 1.67	3353 ± 153
Clt57	6	5	11.01 ± 0.48	12.70 ± 1.63	3561 ± 106

Note: *n* = number of sampled ramets; DBH = diameter at breast height (1.3 m above the ground); TH = tree height; SWV_T =stress wave velocity of standing tree.

Transverse shrinkage and basic density

Specimens' preparation and measurement of transverse shrinkage were designated as ISO13061-13:2017. The specimens for measurement of shrinkage were soaked in distilled water until saturated. The dimensions in the tangential and radial directions were measured with a digital micrometer CD-S20C (minimum scale: 0.01) at the mid-point on each axis, which was marked for re-measurement. The specimens were conditioned in a room at a temperature of 20°C and a relative humidity of 60% for eight weeks to minimize the negative influence of drying stress on the shrinkage. The specimens were then oven-dried at 103 ± 2°C until constant oven-dry weight, and each dimension was re-measured in tangential and radial directions.

The basic density was calculated as the ratio of oven-dry weight to green volume. The dimensional differences of specimens after saturation and either airdrying or oven-drying were used to estimate the partial or total percent shrinkage in the tangential and radial directions of wood. Partial shrinkage (100 × [saturated – air-dry dimension]/saturated dimension) was estimated in tangential (T_n) and radial (R_n) dimensions, and these values were used to calculate the partial coefficient of anisotropy (T_n/R_n). Total shrinkage (100 × [saturated – oven-dry dimension]/saturated dimension) was also estimated in tangential (T) and radial (R) dimensions, and these values were used to calculate the total coefficient of anisotropy (T/R).

Data analysis

The mean values of each clone were calculated by averaging the values obtained from near the pith and the bark for each clone. The difference in T_n, R_n, T_n/R_n, T, R, T/R, and BD between the two radial positions was examined using a *T-test*. A one-way analysis of variance test was applied to evaluate the differences among clones in transverse shrinkage properties and BD, followed by Tukey's HSD test with the level of significant differences at $P< 0.05$.All analyses were conducted using R software version 4.0.0. (Version 4.0.0; RStudio, Boston, MA, USA).

RESULTS AND DISCUSSION

Radial and among-clonal variations of transverse shrinkage and basic density

Radial and among-clonal variation for transverse shrinkage (T_n, R_n, T_n/R_n, T, R, T/R) and BD for the six *A. auriculiformis*clones are summarized in Tab. 2. The overall mean values for partial and total shrinkage in the tangential direction were 2.43% and 4.40%, resp. In the radial direction, the overall mean values were 0.81% for partial shrinkage and 1.66% for total shrinkage. This result was compatible with those of Tonouewa et al. (2020), who reported 5% for tangential shrinkage and 2% for radial shrinkage of 7-year-old *A. auriculiformis* in West Africa. On the other hand, Chomchran et al. (1986) reported lower values for transverse shrinkages (resp. values for T and R were 2.6% and 1.3%) for 13-year-old *A. auriculiformis* planted in Thailand. Meanwhile, Hai et al. (2010) reported higher values of partial and total shrinkage for 5,5-year-old *A. auriculiformis*clones in southern Vietnam (respective values for T_n, T, R_n, and R were 2.64%, 5.92%, 1.64%, and 3.23%). The different reports of transverse shrinkage of the same species could be attributed to age and environmental factors.

Understanding the pattern of radial variation of shrinkage is important, especially in young trees that contain a significant amount of juvenile wood (Shupe et al. 1995b). In this study, the radial position had a significant effect ($P< 0.05$) on variation for shrinkage in the tangential direction, both in partial and total shrinkage. The within-clone trends of T_n showed similarities with the T trends. *T-test* results showed that T_n and T mean values in the outer wood were higher than those near the pith in all tested clones. In contrast, no significant difference was found between inner and outer wood from pith both in R_n and R, except for clone 1 (Tab. 2)

Tab. 2: Average values of wood shrinkage and basic density for six different Acacia auriculiformis clones planted in Vietnam.

Property	Position	*n*	Clone						Mean
			1	**2**	**3**	**4**	**5**	**6**	
T_n (%)	R1	120	1.66^{y}± 0.25	1.57^{y}± 0.34	1.94^{y}± 0.40	1.62^{y}± 0.27	2.05^{y}± 0.53	1.78^{y}± 0.43	1.77 ± 0.41
	R2	120	3.41^{x}± 0.35	2.63^{x}± 0.32	2.98^{x}± 0.29	3.30^{x}± 0.19	3.08^{x}± 0.40	3.18^{x}± 0.39	3.10 ± 0.41
	Average	**240**	**2.53 ± 0.94^{a}**	**2.10 ± 0.63^{a}**	**2.46 ± 0.63^{a}**	**2.46 ± 0.88^{a}**	**2.57 ± 0.70^{a}**	**2.48 ± 0.82^{a}**	**2.43 ± 0.78**
R_n (%)	R1	120	0.78^{y}± 0.16	0.72^{x}± 0.11	0.78^{x}± 0.21	0.80^{x}± 0.20	0.72^{x}± 0.12	0.89^{x}± 0.12	0.79 ± 0.16
	R2	120	0.92^{x}± 0.17	0.76^{x}± 0.14	0.82^{x}± 0.13	0.90^{x}± 0.17	0.73^{x}± 0.21	0.90^{x}± 0.16	0.84 ± 0.18
	Average	**240**	**0.85 ± 0.18^{a}**	**0.74 ± 0.13^{b}**	**0.80 ± 0.17^{ab}**	**0.86 ± 0.18^{a}**	**0.73 ± 0.17^{b}**	**0.89 ± 0.14^{a}**	**0.81 ± 0.17**
T_n/R_n	R1	120	2.24^{y}± 0.68	2.21^{y}± 0.57	2.69^{y}± 0.97	2.09^{y}± 0.64	2.95^{y}± 1.00	2.01^{y}± 0.42	2.37 ± 0.80
	R2	120	3.80^{x}± 0.75	3.57^{x}± 0.65	3.72^{x}± 0.59	3.82^{x}± 0.85	4.48^{x}± 1.12	3.60^{x}± 0.47	3.83 ± 0.81
	Average	**240**	**3.02 ± 1.06^{b}**	**2.89 ± 0.91^{b}**	**3.21 ± 0.95^{ab}**	**2.95 ± 1.15^{b}**	**3.72 ± 1.30^{a}**	**2.80 ± 0.92^{b}**	**3.10 ± 1.09**
T (%)	R1	120	3.37^{y}± 0.35	3.12^{y}± 0.49	3.60^{y}± 0.65	3.30^{y}± 0.25	3.69^{y}± 0.65	3.47^{y}± 0.48	3.43 ± 0.53
	R2	120	5.62^{x}± 0.51	4.78^{x}± 0.52	5.18^{x}± 0.42	5.61^{x}± 0.44	5.45^{x}± 0.76	5.56^{x}± 0.84	5.37 ± 0.67
	Average	**240**	**4.50 ± 1.22^{a}**	**3.95 ± 0.98^{a}**	**4.39 ± 0.97^{a}**	**4.45 ± 1.24^{a}**	**4.57 ± 1.13^{a}**	**4.51 ± 1.25^{a}**	**4.40 ± 1.14**
R (%)	R1	120	1.58^{y}± 0.24	1.55^{x}± 0.19	1.60^{x}± 0.28	1.67^{x}± 0.29	1.58^{x}± 0.19	1.75^{x}± 0.12	1.62 ± 0.23
	R2	120	1.77^{x}± 0.17	1.59^{x}± 0.22	1.76^{x}± 0.22	1.72^{x}± 0.26	1.59^{x}± 0.37	1.76^{x}± 0.25	1.70 ± 0.26
	Average	**240**	**1.68 ± 0.23^{ab}**	**1.57 ± 0.20^{b}**	**1.68 ± 0.27^{ab}**	**1.70 ± 0.27^{ab}**	**1.59 ± 0.29^{b}**	**1.76 ± 0.20^{a}**	**1.66 ± 0.25**
T/R	R1	120	2.19^{y}± 0.45	2.04^{y}± 0.41	2.34^{y}± 0.61	2.05^{y}± 0.51	2.37^{y}± 0.51	1.99^{y}± 0.30	2.16 ± 0.49
	R2	120	3.19^{x}± 0.33	3.02^{x}± 0.30	2.96^{x}± 0.32	3.31^{x}± 0.42	3.52^{x}± 0.54	3.16^{x}± 0.38	3.19 ± 0.42
	Average	**240**	**2.69 ± 0.64^{a}**	**2.53 ± 0.61^{a}**	**2.65 ± 0.57^{a}**	**2.68 ± 0.78^{a}**	**2.95 ± 0.78^{a}**	**2.58 ± 0.68^{a}**	**2.68 ± 0.69**
BD (g/cm^3)	R1	120	0.49^{x}± 0.02	0.46^{y}± 0.02	0.44^{x}± 0.03	0.48^{x}± 0.03	0.41^{y}± 0.02	0.51^{x}± 0.03	0.47 ± 0.04
	R2	120	0.49^{x}± 0.01	0.50^{x}± 0.02	0.45^{x}± 0.02	0.49^{x}± 0.04	0.45^{x}± 0.02	0.51^{x}± 0.02	0.48 ± 0.03
	Average	**240**	**0.49 ± 0.02^{b}**	**0.48^{b}± 0.03**	**0.44^{c}± 0.03**	**0.49^{b}± 0.03**	**0.43^{c}± 0.03**	**0.51 ± 0.03^{a}**	**0.47 ± 0.04**

Note: Mean values are followed by standard deviation; *n* = number of wood specimens; R1 = near the pith; R2 = near the bark; T_n = partial tangential shrinkage; R_n = partial radial shrinkage; T_n/R_n = partial coefficient of anisotropy; T = total tangential shrinkage; R = total radial shrinkage; T/R= total coefficient of anisotropy; BD = basic density. Different letters (x - y) within a column and (a - c) within a line indicate significant differences between heights at a 95% confidence level.

The results of ANOVA revealed significant differences among clones for R_n and R, but no significant differences were found among clones for T_n and T (Tab. 2). The highest R_n and R were detected in clone 6 (respective values for R_n and R were 0.89% and 1.76%), whereas the lowest R_n and R were seenin clone 2 (corresponding to 0.74% and 1.57%) and 5 (corresponding to 0.73% and 1.59%). Coupled with the low R_n and R for clones 2 and 5, there was no significant difference in radial shrinkage between positions near the pith and bark. This implies that clones 2 and 5 have promise for *A. auriculiformis* tree breeding programs focused on improving shrinkage traits for sawn timber production on similar sites in this region of Vietnam. Further research must be done to test whether site conditions affect its properties.

The differential radial-tangential shrinkage is one of the primary factors contributing to shape distortion both during the seasoning process of lumber and throughout its final use. In this study, the overall mean ratio of tangential to radial shrinkage (coefficient of anisotropy) was 3.10 for partial shrinkage and 2.68 for total shrinkage (Tab. 2). This result was consistent with the findings ofTonouewa et al. (2020) for *A. auriculiformis* in West Africa (T/R = 2.6). In all studied clones, T_n/R_n and T/R increased radially. There were statistically significant ($P< 0.01$) differences in T_n/R_n and T/R between near the pith and the bark positions for all clones (Tab. 2). This pattern indicates that *A. auriculiformis* clones planted in north-central Vietnam tend to produce wood with larger shape distortion in the outer wood region.

The overall mean of BD among clones was 0.47 g/cm^3. There were significant ($P< 0.001$) differences in BD among clones. The lowest and highest BD values were observed in clones 5 (0.43 g/cm^3) and 6 (0.51 g/cm^3), respectively.In the radial direction, a significant difference was found in BD between positions near the pith and bark in clones 2 and 5. In contrast, no significant difference was found between the inner and outer wood from the pith for the other clones. The radial and among-clonal variations of BD in this study were consistent with results of air-dry density obtained in the previous study for the same *A. auriculiformis* clones (Van Duong et al. 2022).

Relationship between shrinkage and basic density

The results of correlation analysis for the transverse and BD are presented in Tab. 3, and Fig. 1, and Fig. 2. There was a statistically significant ($P< 0.05$) but weak correlation between radial shrinkage and basic density (respective value for R_n and BD was 0.23, R and BD was 0.19). Still, no statistically significant correlations were found between BD and tangential shrinkages, as well as BD and coefficient of anisotropy in partial and total shrinkages (Tab. 3). Hai et al. (2010) reported similar results in *A. auriculiformis* clones planted in southern Vietnam. Density is widely acknowledged to reflect shrinkage property, but the degree of correlation is highly dependent on species. Wu et al. (2006) reported good positive correlations of BD with T (r = 0.66) and R (r = 0.64) in three species of eucalypts grown in China. Similar results were also obtained in other hardwood species, such as *Melia azedarach* (Van Duong and Matsumura 2018) and *Tamarixaphylla* (Sadegn et al. 2012). In contrast, no significant correlation was found between wood density and shrinkage in *Liriodendron tulipifera* (Shupe et al. 1995a) or *Tectona grandis* (Solorzano et al. 2012).

Tab. 3: Correlation coefficients between transverse shrinkage and basic density.

Variables	**T_n**	**R_n**	**T_n/R_n**	**T**	**R**	**T/R**	**BD**
T_n	1.00						
R_n	0.25^{***}	1.00					
T_n/R_n	0.73^{***}	-0.43^{***}	1.00				
T	0.95^{***}	0.26^{***}	0.68^{***}	1.00			
R	0.24^{***}	0.67^{***}	-0.23^{***}	0.30^{***}	1.00		
T/R	0.80^{***}	-0.15^{*}	0.84^{***}	0.80^{***}	-0.31^{***}	1.00	
BD	0.03^{ns}	0.23^{***}	-0.13^{ns}	0.06^{ns}	0.19^{*}	-0.02^{ns}	1.00
Note: ns = no significance at 0.05 level; $^{*}P< 0.05$; $^{***}P< 0.001$.							

All total shrinkage traits had good positive correlations with partial shrinkage traits in corresponding directions. The correlations between T_n and T, R_n and R, and T_n/R_n and T/R were 0.95, 0.67, and 0.84, respectively (Tab. 3). This means the total shrinkage would be a good indicator for predicting partial shrinkage (the target trait). This approach will lower the expenses, time, and technology needed for testing shrinkage by eliminating the requirement to dry wood in controlled temperature and humidity environments (Hai et al. 2010).

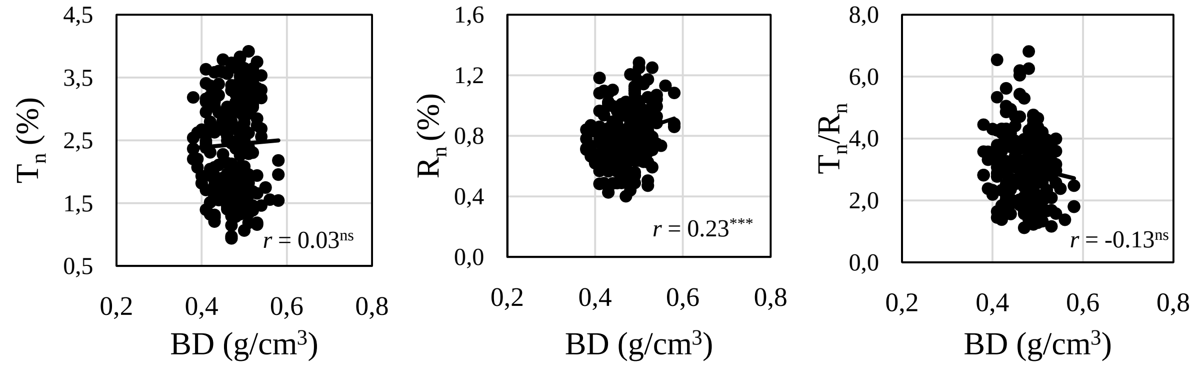

*Fig. 1: Relationships between basic density (BD) and partial transverse shrinkage (T_n, R_n, and T_n/R_n).Note: ns = no significance at 0.05 level; ***P < 0.001.*

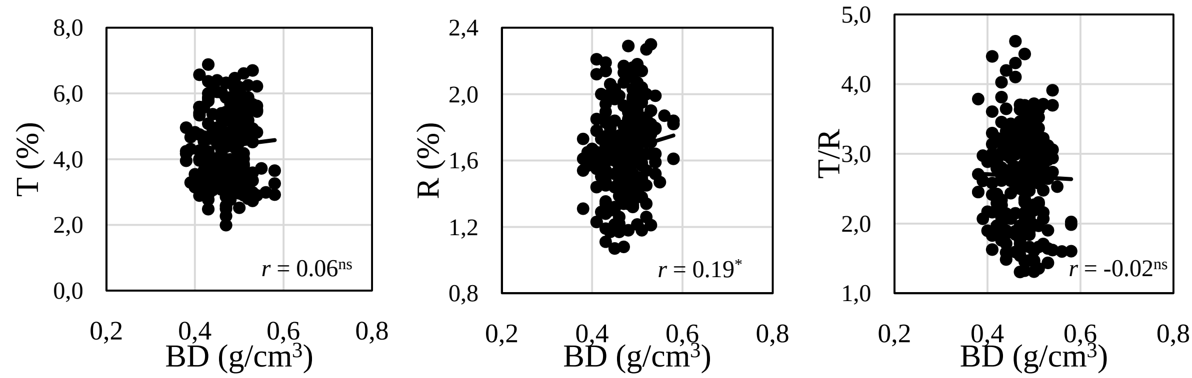

*Fig. 2: Relationships between basic density (BD) and total transverse shrinkage (T, R, and T/R).Note: ns = no significance at 0.05 level; *P < 0.05.*

Prediction of transverse shrinkage from stress wave velocity

The results of linear regression analysis for transverse shrinkages and stress wave velocity measured on standing trees are presented in Figs. 3 and 4. The tangential and radial shrinkages increased linearly with increasing SWV_T. The relations of SWV_T with T_n, T, R_n, and R for combined clones with the values of correlation coefficient (r) are 0.46, 0.42 (Fig.3), 0.42, and 0.35 (Fig.4), respectively. In contrasts, no significant relationship was detected between SWV_T and the anisotropycoefficient. Until now, there is little information regarding to predict the dimensional stability of *A. auriculiformis* wood based on acoustic velocity measured on a standing tree. Van Duong and Matsumura (2018) reported that the correlation coefficients of stress wave velocity of log with T and R were 0.47 and 0.45 in *Melia azedarach*, respectively. The correlation coefficients obtained in this study were moderate and low for both partial and total shrinkages. However, these results indicate sufficient potential for acoustic wave measurement in standing trees to be used as a non-destructive method for predicting the transverse shrinkage of *A. auriculiformis* planted in Vietnam.

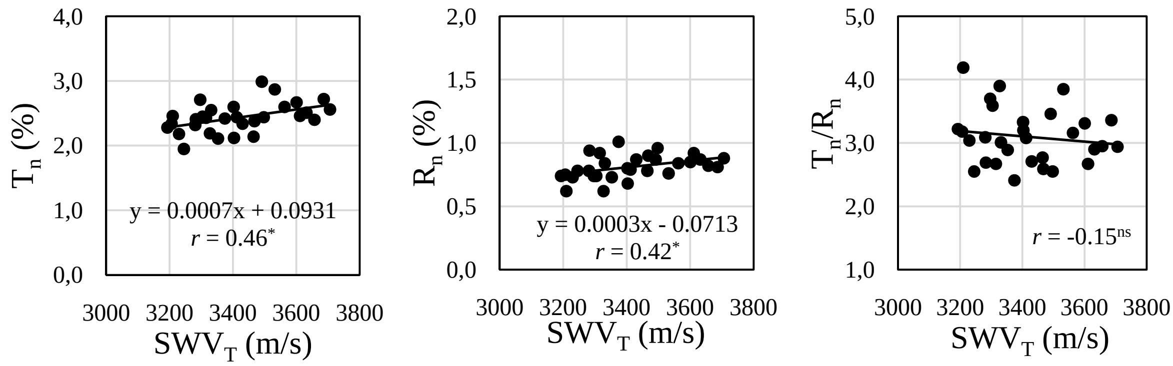

Fig. 3: Relationships between stress wave velocities measured on standing trees (SWV_T) and partial transverse shrinkage (T_n, R_n, and T_n/R_n).

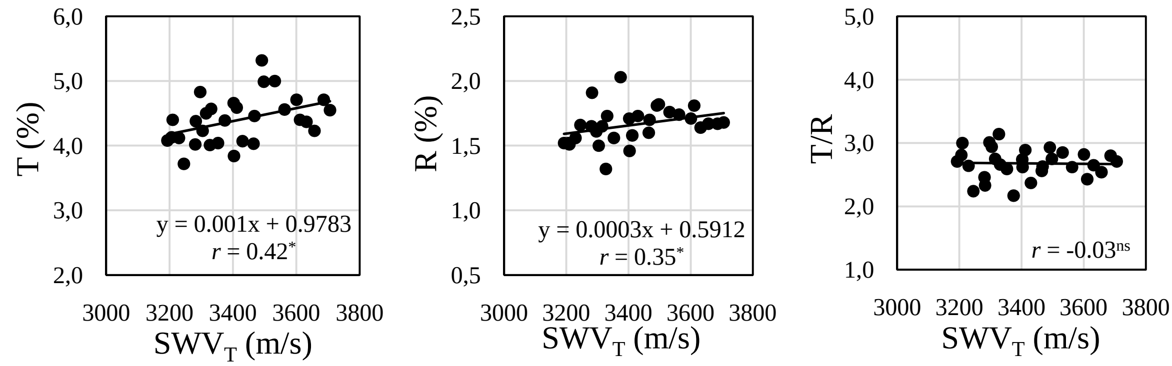

*Fig. 4: Relationships between stress wave velocities measured on standing trees (SWV_T) and total transverse shrinkage (T, R, and T/R). Note: ns = no significance at 0.05 level; *P < 0.05.*

CONCLUSIONS

There were significant differences among clones for R_n and R but no significant differences were found among clones for T_n and T. Coupled with no significant difference in radial shrinkage between near the pith and the bark, clones 2 and 5 had smaller R_n and R than the other clones examined (respective R_n and R values for clone 2 were 0.74% and 1.57%, respectively; for clone 5 were 0.73% and 1.59%, respectively). Therefore, clones 2 and 5 might be selected for *A. auriculiformis* tree breeding programs focused on improving shrinkage traits for sawn timber production on similar sites in Vietnam.

Regarding the relationships of SWV_T and transverse shrinkage, the increase of SWV_T may result in a significant increase in T_n, T, R_n, and R. The correlation coefficients of SWV_T with T_n, T, R_n, and R were 0.46, 0.42, 0.42, and 0.35, respectively. Therefore, acoustic wave measurement in standing trees of *A. auriculiformis* is a highly promising method for tree breeders to sort trees with large transverse shrinkage.

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