Effects of Annual Ring Number and Width on Ultrasonic Waves in Some Softwood Species

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The effect of annual ring number and width on the longitudinal (P) and transverse (S) ultrasonic wave velocities in the radial direction of black pine, Scots pine, Turkish red pine, and cedar softwoods was evaluated in this study. Annual rings were evaluated using high-resolution images captured with a Lumix camera. The 2.25 MHz P and 1 MHz S wave frequencies were propagated through the radial direction of small clear samples. An increase in ring number caused different changes in the P and S wave velocities. Only Scots pine and cedar presented continuous decreases in P and S wave velocities with the increase in annual rings. On the contrary, V_R of Red pine slightly decreased and surpassed the initial value when the ring numbers increased from 5 to 10 and 15, respectively. Furthermore, the greatest decrease (4%) in the velocities was observed for V_{RL} of Red pine. According to one-way ANOVA results, significant relations were only observed for V_R *vs*. ring number of Black pine and cedar. R^2 values ranged from 0.0001 (Red pine V_R) to 0.18 (Cedar V_R) for ring number and 0.0002 (Cedar V_R) to 0.44 (Scots pine V_R) for ring width. Furthermore, ANOVA results for linear regression analysis showed that V_R of Scots pine and V_R, V_{RL}, V_{RT} of Red pine can be statistically significantly predicted by the ring widths.

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INTRODUCTION

Ultrasonic testing is an evaluation method that is relatively less laboratory-dependent than other methods and that can be applied in various fields. Prominent properties of this type of testing include mobility and compatibility. However, interpretation of the ultrasonic signal is not easy, and an experienced user is needed for using the tools in manual mode. Also, the reproducibility of ultrasonic evaluation seems limited in manual mode. Therefore, operator-independent automated systems reduce the errors caused by misreading by the experienced or inexperienced user and improve the signal-to-noise ratio (Gros 1997). Interpretation of signals in wood science becomes more complicated due to the complex structure of wood material that presents different properties through the essential axis and planes. The anisotropic and inhomogeneous material structure of wood greatly attenuates ultrasound due to scattering from the inhomogeneity variations in the microstructure (Berndt and Johnson 1995). Therefore, an ultrasonic beam attenuates due to variation in composition, density, and porosity of the material (Gros 1997). Furthermore, these properties change due to environmental conditions and cause variations within the species that are much more complex than anisotropy (Brancheriau *et al.* 2012). The cellular microstructure of wood and the nanostructure of the cell walls control the elastic properties. Furthermore, the properties of wood are maximized in the longitudinal (L) direction (Ansell 2015). The same is true for ultrasonic wave velocities (UWV) in wood, and according to Dackermann *et al.* (2014), radial and tangential wave velocities are generally about a third of the longitudinal wave. Similar behavior is true for shear or transverse wave velocities, and transverse wave velocities of wood are remarkably slower than the longitudinal waves. These significant differences occur because of the longitudinally aligned anatomical elements such as fibers and tracheid, and radially aligned wood rays in growth rings. However, such structural elements are not observable through the tangential direction. When the polar orthotropic nature of wood is taken into consideration, the propagation of ultrasonic waves encounters these variations. Furthermore, micro-fibril angle and the length of the anatomical elements have influences on variations. For example, a small cell wall layer is responsible for higher acoustic wave velocities (Bergander and Salmén 2000). More comprehensive data for the propagation and distribution properties of longitudinal and transverse ultrasound waves in wood and wood-based materials are provided by Bucur (2006).

Changes in environmental factors may have essential effects on the anatomical properties of wood. One of the essential variations in wood structure is the annual rings (ARs) due to environmental factors in normal growth or engineered growth by sylvicultural practices. Tree-rings enclose the history of all experiences or developments that take place in the surrounding area within the tree stem. According to Carrer (2011), tree-rings are a valuable source of information due to the characteristics they have earned year by year. Many studies have evaluated tree-ring-related issues, and the fundamentals of the tree-ring research and evaluation are thoroughly presented by Schweingruber (1988) and Speer (2012). A hand lens with a scale is the simplest optical instrument for measuring the tree-rings. However, advanced tools, hardware, and software are the leading development for the evaluation of tree-ring and it's effects on the properties. For example, Jackson *et al.* (2009) evaluated the ring-growth patterns of many wood specimens by terahertz time-domain reflectometry. Perlin *et al.* (2019) conducted an ultrasonic tomography investigation of timber slices through the tangential and radial directions regarding the growth ring direction. Mori *et al.* (2019) developed a non-destructive RW measurement technique and evaluated the effectiveness over the archaeologically excavated waterlogged wood. Adamopolous *et al.* (2009) determined the relationship between the ring-width (RW) and stem height for *Pinus brutia* using LINTAB and TSAP-Win. Trouillier *et al.* (2018) used optical scans and CooRecorder for RW measurements and CDendro for cross-dating of white spruce. Shishkova and Panayotov (2013) used CooRecorder and CDendro to measure and cross-date the tree-widths of *Pinus nigra*, respectively.

Knapic *et al.* (2007) investigated the relation between RW, the number of rings, density, and cambial age properties of oak wood. Kharrat *et al.* (2019) evaluated the RW, density, and modulus of elasticity (MOE) variations for black spruce and Jack pine woods using UWV measurement in terms of 5, 10, 15, and 20 annual ring numbers (ARNs) from the pith. They stated that the correlation between density and dynamic MOE is positive and statistically significant in rings. Dackermann *et al.* (2016) reported that AR acts as a barrier against waves and decreases the velocity of waves. Effects of inter and intra-tree (ring) variations were evaluated before. However, a comparison between the trees should be made over the same number of AR instead of similar size or diameter because results tend to be similar (Bendtsen 1978). From this point of view, figuring out the influence of AR on the ultrasonic wave by the same number instead of using the same sample size was aimed in this study. Consequently, this study tried to determine the effect of ARN and annual ring width (ARW) on the longitudinal and transverse UWV in the radial direction of four different softwood species in terms of the same number of rings.

EXPERIMENTAL

Materials and Methods

Black pine (*Pinus nigra* Arnold.), Scots pine (*Pinus sylvestris* L.), Turkish red pine (*Pinus brutia* Ten.), and cedar (*Cedrus libani* A. Rich.) woods were used in this study. Samples for each species were prepared with at least 5, 10, and 15 ARs. As seen in Figs. 1 and 2, samples were prepared according to the ARN instead of a certain dimension through the radial direction. Therefore, the dimensions of the samples in radial direction were different not only within the species but also between the species. The tangential and longitudinal dimensions were the minimum of 20 millimeters due to the diameter of the transverse transducers.

As can be seen in Fig. 1, predetermined cutting lines were marked on the laths by considering the start and finish points of AR. The laths were cut using a newly-sharped circular saw blade. Samples with improper or false rings and rings with compression wood were not tested. All the samples were prepared using only sapwood sections of the planks. Planks were prepared from the sections following the breast height of the logs. Furthermore, all the samples were cut from the same logs to prevent the probable variations dependent on the sampling. A total of 240 samples (20 for each ARN group) were tested.

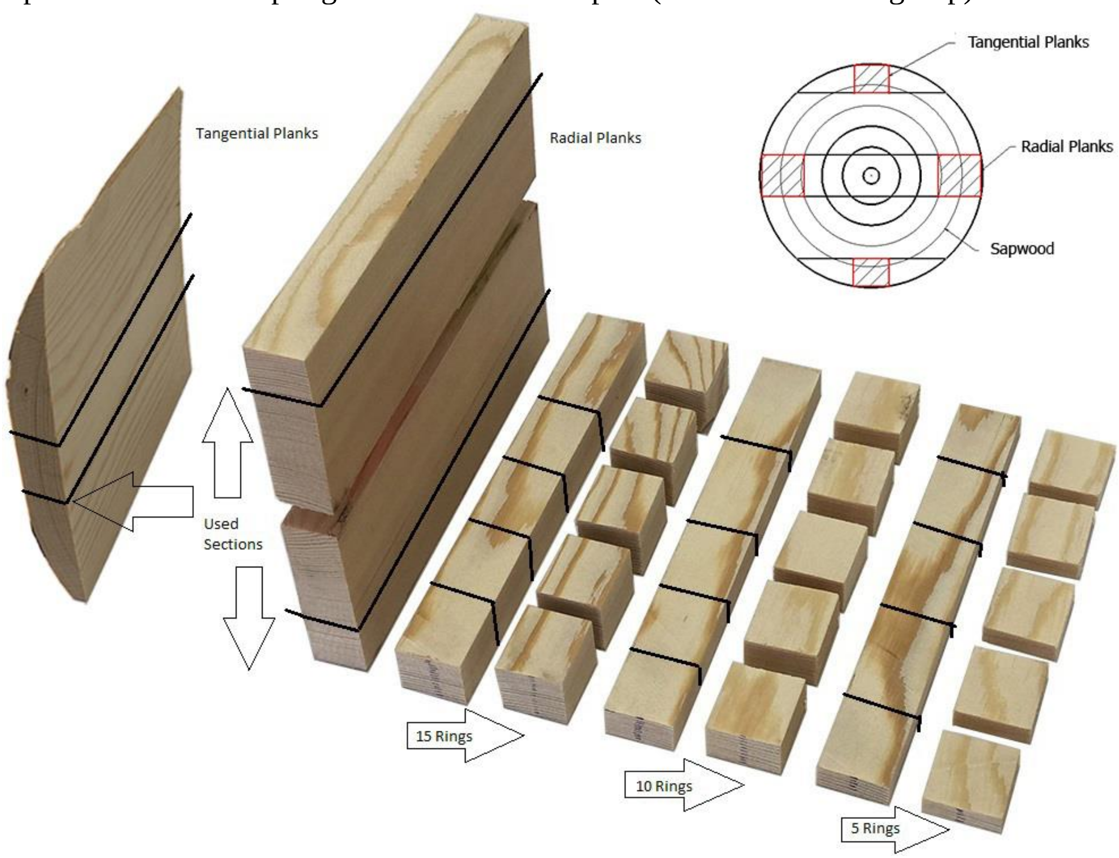

Fig. 1. Sample preparation steps

Annual ring width (ARW) measurement was performed by image analysis and digital caliper. High-resolution images of the cross-section of the samples were taken using a Lumix GX1 camera and G macro 30 mm F/2.8 lens (Panasonic, Matsushita Electronics, Osaka, Japan). CooRecorder and CDendro (Cybis Elektronik and Data AB, Saltsjöbaden, Sweden) software were used to identify and point the AR borders for growth ring measurements, as seen in Fig. 2.

An Olympus Epoch 650 flaw detector (Olympus, Waltham, MA, USA) was used to measure the time of flight values in micro-second. Relatively high frequencies such as 1 Megahertz (MHz) can be used for the small (around 100 mm) specimens (Krause *et al*. 2015). Bucur and Kazemi-Najafi (2011) reported that 2.25 MHz transducer frequency provides greater energy and penetration into the material. Furthermore, Gonçalves *et al*. (2011, 2014), Hering *et al*. (2012), Vázquez *et al*. (2015), Niemz *et al*. (2017), Bachtiar *et al*. (2017), and Luis Gómez-Royuela *et al*. (2021) are some of the recent studies performed elastic characterization of wood using these central frequencies. Therefore, the effect of AR on UWV in the radial direction has been evaluated using longitudinal (2.25 MHz) and transverse (1 MHz) waves. Longitudinal wave velocity in the radial direction (V_R), and transverse or shear wave velocities in the Radial direction and Longitudinal (V_{RL}) or Tangential (V_{RT}) polarizations were calculated using the transmitting time of ultrasound waves and dimensions of the samples through the radial direction.

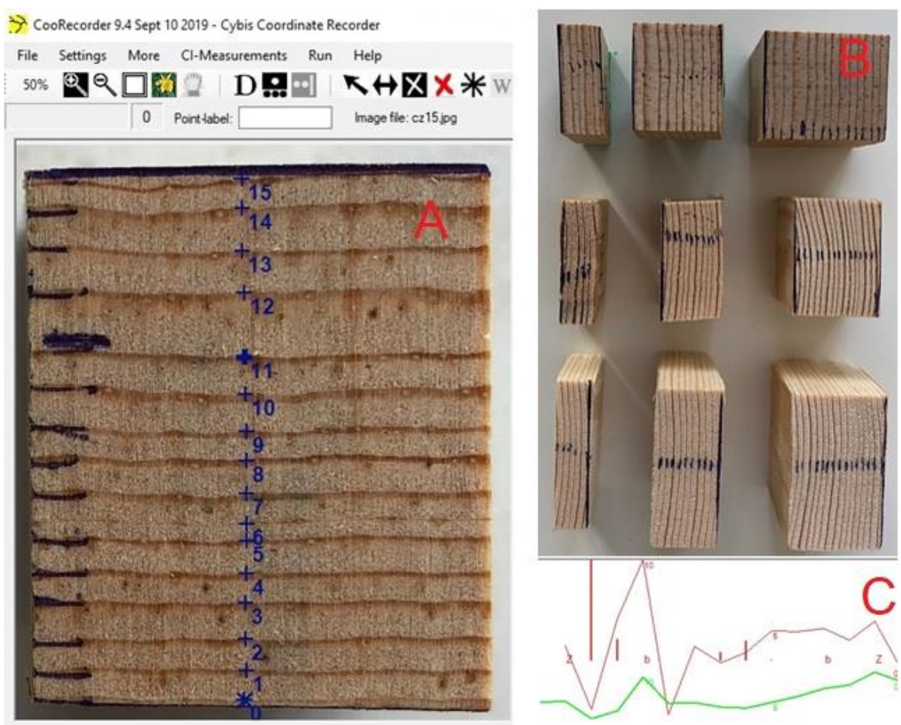

Fig. 2. CooRecorder ring border pointing and RW for red pine (A), radial sections, and AR of the samples (B), and CDendro Plot details for cedar wood (C)

Defect-free samples were conditioned at 65% relative humidity and 20 ± 1 °C temperature. Densities were determined according to TS 2472 (2005) standard by stereo-metric method (dimension and weigh measurement using a digital caliper and precision scale, respectively).

One-way Analysis of Variance (ANOVA) was performed to interpret the effect of

ARNs on velocities. Duncan's multiple range (DMR) test was conducted to figure out the differences between the mean values of ARN groups. The confidence interval was 95%. The coefficients of determination (R^2) by linear regression analysis were calculated to evaluate how differences in UWV can be expressed by ARW and ARN.

RESULTS AND DISCUSSION

The average values of ARW, density and UWV are presented in Table 1. The widths of the annual tree-ring strictly depend on the growth conditions. Temperature and precipitation are the responsible factors for the variations in tree-ring width (Dogan and Kose 2019). In general, widths are positively correlated with the amount of summer precipitation (Haneca *et al.* 2009), and it's expected that location and environmental factors may make great variations in the ring properties. As can be seen in the table, variations for the ARW ranged from 7.7 to 17.6%. Reported variations for ARW were 20.4% (Mederski *et al.* 2013), 42.3% (Fabisiak and Fabisiak 2021), 15.3% (total chronology from 1958-2016) (Özel *et al.* 2021), and 60.5% (Büyüksari *et al.* 2017) for Scots pine, 40.8% (total chronology from 1970 to 2011) (Kantarci *et al.* 2013), 17.8 to 35.2% (Doğan and Köse 2015) for black pine, 39.2% (Adamopoulos *et al.* 2009) for red pine (*Pinus brutia* Ten.), and 60.9% (Öktem and Sözen 1992) for *Cedrus libani*. When compared to the reported data, it's thought that relatively fewer variations for ARW were obtained due to sample preparations because samples were cut from the outer section of the matching planks, as mentioned in the experimental.

Variations in the ARW are to be expected due to climate changes. As noted by Köse *et al.* (2012), year-by-year alterations in environmental factors cause discrepancies in tree-ring widths, and in the literature, great varieties of ARW were reported for tested species. For example, variations of approximately 0.25 to 1.8 mm (Kemalpaşa Mountain) and from 1 to 6 mm (Karabelen Mountain) were observed for *Pinus brutia* Ten through 1942 to 1998 period (Tolunay 2003). Therefore, great variations in ARW are possible not only due to the growth conditions and region but also by the periods. Therefore, ARWs can be in accordance with the literature or not due to lots of affecting factors. However, as can be seen in Table 1, ARW averages of Scotch pine wood ranged from 1.26 to 1.37 mm, which are in accordance with 1.34 mm reported by Büyüksarı *et al.* (2017) and in the range of 0.79 to 2.6 mm and 0.37 to 3.91 mm reported by Dündar (2005) and Sensuła *et al.* (2017), respectively. Similar harmonies are valid for black pine such as 0.11 to 4.82 mm (from 1744 to 2011 – Hodul Mountain) (Kantarci *et al*. 2013), and cedar woods such as 2.45 to 4.11 mm (Akkemik 2003).

According to results shown in Table 1, all longitudinal and transverse wave velocities were decreased when ARNs were increased from five to ten. However, V_R of red pine, V_{RL} of black pine, and V_{RT} of red pine were increased when ARN was increased from 10 to 15. However, almost all increased values were below the average of the initial values except V_R of red pine. The V_R of red pine slightly surpassed (0.1%) the initial value, but it was just 2 m/s and can be regarded as negligible. Also, V_{RT} of red pine and cedar for 10 and 15 rings were almost equal. Therefore, constant but various decreases in all velocities by the increase in ARN were observed only for Scots pine and cedar.

The maximum decrease (-4.0%) in the velocity was seen in the transverse ultrasonic wave of red pine. The changes in longitudinal wave velocities with the increase in ARN ranged from -3.7% (black pine, 15 rings) to +0.1% (red pine, 15 rings). Decreases in V_{RL}

ranged from -4% (red pine, 15 rings) to -0.8 (red pine, 10 rings). Decreases in V_{RT} ranged from -3.7% (black pine, 15 rings) to -0.5 (Scots pine, 10 rings). The tendencies of V_{RL} and V_{RT} for red pine and Scots pine were nearly the same. Moreover, velocities decreased more specifically following the ten AR, except V_{RL} for black pine.

Table 1. Average ARW, Density, UWV Values of the Species

Species	ARN	Sample Size		ARW (mm)	Density (kg/m³)	V_R (m/s)	V_{RL} (m/s)	V_{RT} (m/s)
Scots pine	5	20	Avg	1.37	512	1625	1068	691
			Std.D.	0.20	22.01	88.96	86.08	50.21
			CoV (%)	14.77	4.30	5.47	8.06	7.26
	10	20	Avg	1.29	517	1605 (-1.3)*	1060 (-0.8)	688 (-0.5)
			Std.D.	0.10	23.83	88.94	98.65	43.37
			CoV (%)	7.74	4.61	5.54	9.31	6.30
	15	20	Avg	1.26	516	1589 (-2.2)	1047 (-2.0)	673 (-2.6)
			Std.D.	0.18	30.36	80.42	77.32	53.20
			CoV (%)	13.93	5.88	5.06	7.38	7.90
Red pine	5	20	Avg	1.20	551	1967	1215	723
			Std.D.	0.16	11.70	62.01	95.03	40.55
			CoV (%)	13.61	2.12	3.15	7.82	5.61
	10	20	Avg	1.13	544	1953 (-0.7)	1205 (-0.8)	717 (-0.9)
			Std.D.	0.17	10.16	81.44	89.82	52.82
			CoV (%)	15.26	1.87	4.17	7.45	7.37
	15	20	Avg	1.17	542	1969 **(+0.1)**	1166 (-4.0)	717 (-0.8)
			Std.D.	0.21	12.91	117.11	100.93	40.03
			CoV (%)	17.60	2.38	5.95	8.65	5.58
Black pine	5	20	Avg	1.49	560	1863	1224	640
			Std.D.	0.40	11.65	94.94	72.32	44.19
			CoV (%)	16.02	2.08	5.10	5.91	6.90
	10	20	Avg	1.53	547	1816 (-2.6)	1179 (-3.7)	623 (-2.7)
			Std.D.	0.22	22.52	77.47	84.51	33.47
			CoV (%)	14.45	4.11	4.27	7.17	5.38
	15	20	Avg	1.56	543	1794 (-3.7)	1200 (-1.9)	617 (-3.7)
			Std.D.	0.18	18.77	42.80	95.07	34.57
			CoV (%)	11.57	3.46	2.39	7.92	5.60
Cedar	5	20	Avg	3.21	498	1861	1210	1076
			Std.D.	0.28	21.25	38.79	52.00	81.36
			CoV (%)	8.85	4.27	2.08	4.30	7.56
	10	20	Avg	3.23	501	1825 (-2.0)	1190 (-1.6)	1053 (-2.1)
			Std.D.	0.36	16.05	51.52	68.12	92.99
			CoV (%)	11.03	3.20	2.82	5.73	8.83
	15	20	Avg	2.93	500	1808 (-2.9)	1180 (-2.5)	1052 (-2.2)
			Std.D.	0.45	13.96	49.72	87.21	92.66
			CoV (%)	15.35	2.79	2.75	7.39	8.81

Note: Avg (Average), Std.D. (Standard deviation), CoV (Coefficient of Variation). *Values in parenthesis are the % differences to five ARs values

The reported V_R, V_{RL}, and V_{RT} values for the evaluated species are presented in Table 2. Some of the velocities were in harmony, while others were not. However, as reported by Yılmaz Aydın and Küçükköse (2020), ultrasound propagation is a reliable non-destructive test method for the characterization of wood stiffness.

Table 2. UWV in the Radial Direction

Species	UWV (m/s)		
	V_R	V_{RL}	V_{RT}
Scots pine	1713 (Akar 2017)	1105 (Akar 2017) , 1863[a] (Martinez *et al.* 2010)	590 (Akar 2017) , 1520[b] (Martinez *et al.* 2010)
Red pine	2261 (Güntekin et al. 2015a; b)	1408 (Aydın and Ciritcioglu 2018)	666 (Aydın and Ciritcioglu 2018)
Black Pine	1973 (Güntekin and Yılmaz Aydin 2016), 2128 (Aydın and Yılmaz Aydın 2020)	1280 (Aydın and Yılmaz Aydın 2018), 1370 (Aydın and Yılmaz Aydın 2020)	423 (Aydın and Yılmaz Aydın 2018), 547 (Güntekin and Yılmaz Aydin 2016), 743 (Aydın and Yılmaz Aydın 2020)
Cedar	2261 (Güntekin et al. 2015a; b)	-	1449[c] (Hasegawa *et al.* 2016), 1680[d] (Hasegawa *et al.* 2016)

[a,b] Transversal ultrasonic velocity in radial and tangential directions obtained by Sylvatest Duo 22kHz, respectively, [c,d] Japanese cedar values for non-contact and contact type measurements, respectively.

The ANOVA results for ARN are presented in Table 3, and changes in the means of UWV due to an increase in ARN were statistically significant only for V_R of black pine and cedar woods. According to Duncan's multiple range test classifications (Table 4), there were no statistically significant differences between the means of UWV and ARN except V_R for cedar and black pine species. Furthermore, the mean values of V_R for 10 and 15 rings were statistically the same.

Generally, a high R^2 value indicates better prediction of the variable. The values closer to 1 reveal that the association is greater, but do not express the statistical significance. However, according to the results of regression analysis seen through Figs. 3 to 6, a maximum of 44% of the data could be predicted by the ARW.

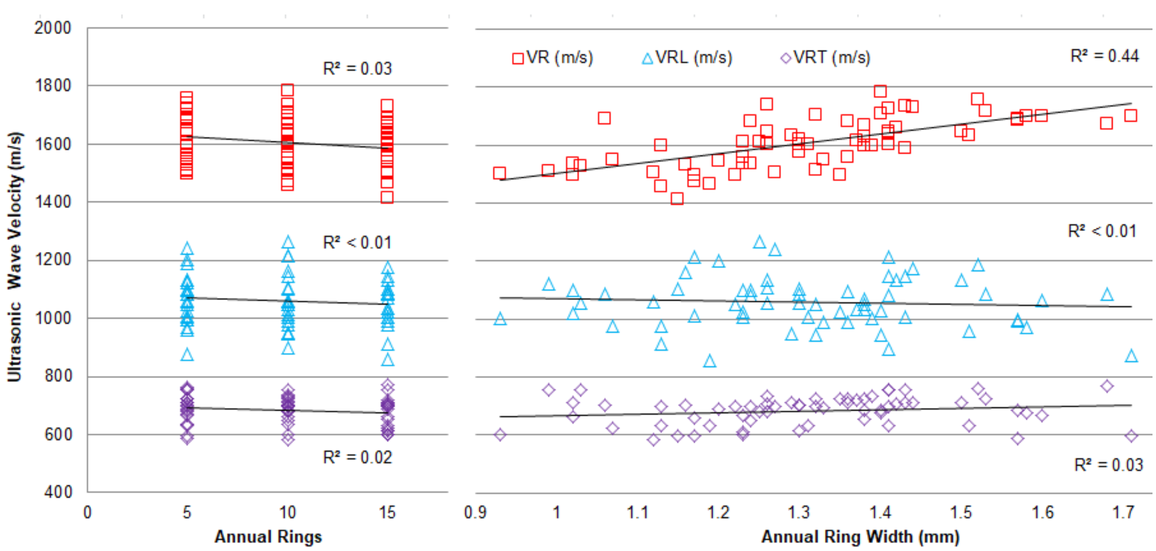

Fig. 3. The relationship between UWV and ARN or ARW for Scots pine

Table 3. ANOVA Results for ARN

One-way ANOVA for ARN								
Velocities	Scots Pine		Red Pine		Black Pine		Cedar	
	F	Sig.	F	Sig.	F	Sig.	F	Sig.
V_R	0.947	0.394	0.173	0.842	4.446	0.016	6.716	0.002
V_{RL}	0.304	0.739	1.455	0.242	1.430	0.248	0.926	0.402
V_{RT}	0.804	0.452	0.137	0.872	2.085	0.134	0.449	0.640

Table 4. Duncan Homogeneity Groups of Ultrasonic Velocities According to ARN

Species	N	V_R			V_{RL}		V_{RT}	
		ARN	1*		ARN	1*	ARN	1*
Scots pine	20	15	1588.75		15	1047.25	15	673.25
	20	10	1604.67		10	1059.76	10	688.19
	20	5	1625.27		5	1068.36	5	691.41
		Sig.	.202		Sig.	.469	Sig.	.264
Red pine	N	ARN	1*		ARN	1*	ARN	1*
	20	10	1953.25		15	1166.45	10	716.50
	20	5	1966.50		10	1205.45	15	717.45
	20	15	1968.65		5	1215.00	5	723.35
		Sig.	.614		Sig.	.134	Sig.	.653
Black pine	N	ARN	1*	2*	ARN	1*	ARN	1*
	20	15	1794.35		10	1179.10	15	616.85
	20	10	1815.65		15	1200.40	10	622.70
	20	5		1863.35	5	1224.25	5	640.25
		Sig.	.373	1.000	Sig.	.116	Sig.	.068
Cedar	N	ARN	1*	2*	ARN	1*	ARN	1*
	20	15	1807.75		15	1179.75	15	1052.25
	20	10	1824.60		10	1189.75	10	1052.55
	20	5		1861.05	5	1209.60	5	1075.55
		Sig.	.262	1.000	Sig.	.213	Sig.	.442

N: sample size**,** *Subset for alpha = 0.05

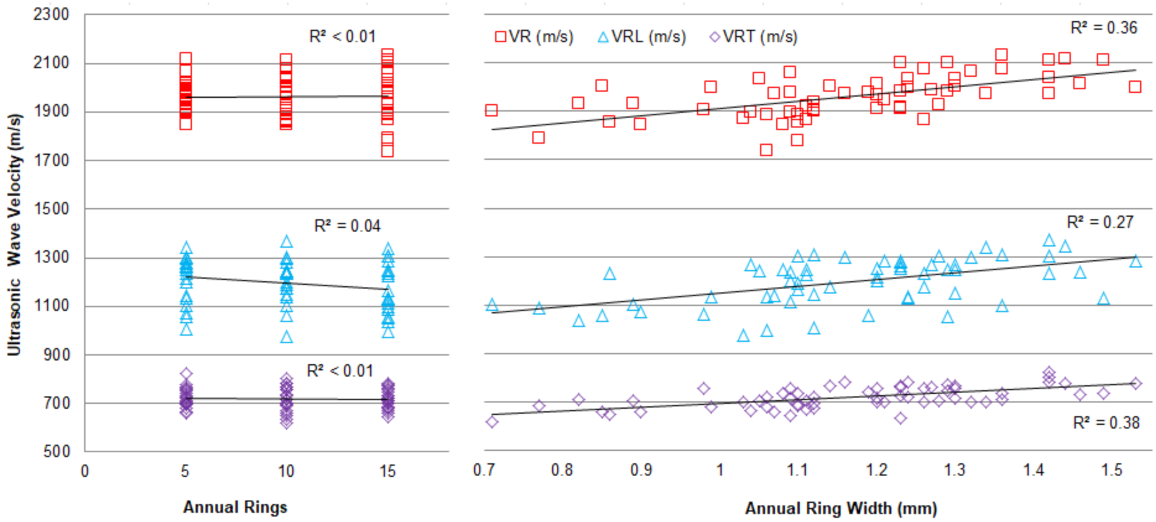

Fig. 4. The relationship between UWV and ARN or ARW for Red pine

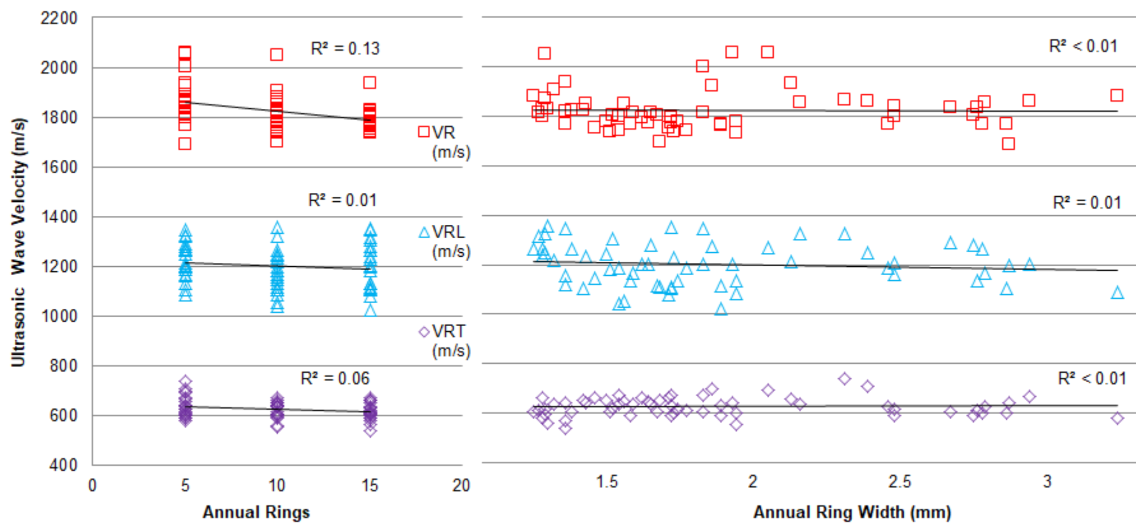

Fig. 5. The relationship between UWV and ARN or ARW for Black pine

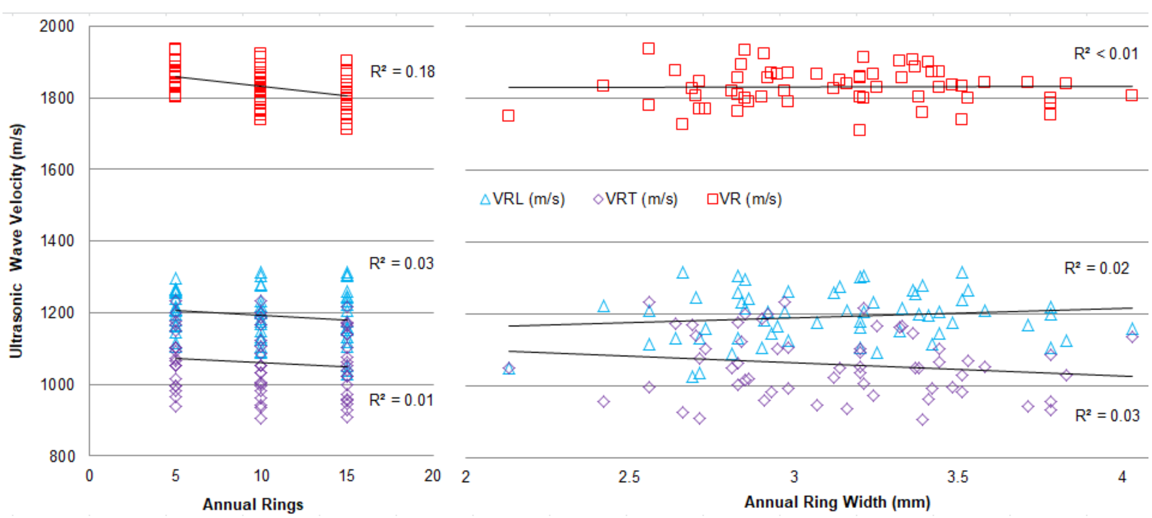

Fig. 6. The relationship between UWV and ARN or ARW for Cedar

According to ANOVA results of linear regression (Table 5), only V_R of Scots pine, and V_R, V_{RL}, and V_{RT} of Red pine could be significantly (P<0.05) predicted by ARW. However, as highlighted before, not even half of the dependent variable can be predicted by ARW. Therefore, in general, models did not statistically significantly predict the dependent variables.

Table 5. ANOVA Results for ARW

Linear Regression ANOVA for ARW								
Velocities	Scots Pine		Red Pine		Black Pine		Cedar	
	F	Sig.	F	Sig.	F	Sig.	F	Sig.
V_R	48.450	0.000	32.211	0.000	0.031	0.861	0.010	0.922
V_{RL}	0.427	0.516	21.232	0.000	0.713	0.402	1.300	0.259
V_{RT}	1.962	0.166	35.585	0.000	0.159	0.691	1.624	0.208

It is unclear that the decrease tendency and severity in velocities (Table 1) are related to ARN, because only Scots pine and cedar woods presented consistent decreases with the increase in ARN. However, these decreases in these two species were not the highest among all. When the whole results were taken into consideration, the ARN and ARW are not the variables that can be associated to make a general expression for the variation of the longitudinal and transverse UWV in the radial direction of softwoods.

Measuring ARW using image analysis illustrates the amount of the latewood (LW) and earlywood (EW) that can be detected by the high-resolution images for high readability (Norell 2009). Capturing images by a digital camera is a fast method of illustration (Norell 2011), and, according to Maes *et al.* (2017), image analysis programs enable users to detect the ring boundaries manually or automatically. In this study, rings of the softwoods were characterized by high-resolution images and evaluated by computer software over the manually determined ring boundaries.

The differences between V_{TR} and V_{RT} are around 10 to 15% for the softwoods with pronounced AR structure (Bucur 1988). However, in this study, only V_{RL} and V_{RT} were measured, and such a comparison was not possible.

Yeh *et al.* (2007) evaluated the effects of detection types on the longitudinal UWV of Japanese cedar and Chinese fir with 9.3±4.3 and 8.8±3.7 mm ARW, respectively. However, they did not investigate the relationship between the ARW and UWV that might provide a comparison opportunity with this study.

Lots of wood quality characteristics are tightly related to the ARW (Blass and Sandhaas 2017), and density is one of the most important determinants of wood characteristics. For example, density and mechanical features are oppositely proportional to the ARW for coniferous (Bektas *et al.* 2003). Furthermore, studies generally investigated the relationship between density and ARW. According to Baar *et al.* (2012), velocity and density are dependent variables for the acoustic properties of wood. Density is the second main variable that influences the ultrasound velocity (Calegari *et al.* 2011). Furthermore, density is one of the essential factors that influences the UWV in solids (Tomppo 2013). However, there is no consensus on the effect of density on the UWV in wood. For example, positive (Baar *et al.* 2012; de Oliveira and Sales 2006; Yılmaz Aydın and Aydın 2018a,b,c), neutral (Ilic 2003; Mishiro 1996; Peng *et al.* 2016), and negative (Bucur and Chivers 1991; Hasegawa *et al.* 2011) influences were reported. As can be seen in Table 1, variations in the densities were not extremely high and ranged from 1.87 to 5.88. Furthermore, means were in harmony with the reported values.

Density differences between the denser LW and less dense EW due to structural properties such as thick or thin-walled cells are one of the responsible factors for property changes, respectively (Zisi 2015). According to Feeney *et al.* (1998), density alterations within the AR are composed of denser LW, and velocity variation within the wood species occurs due to less dense EW. Furthermore, EW share in softwoods is typically five times higher than LW, and this causes significant changes in the stiffness of wood (Zisi 2015). Also, length of tracheid varies in EW and LW (Schubert 2007). In addition, repetitive or cyclic formation of the EW and LW structures in a ring from pith to bark compose a periodic structure that produces bands that allow or block the waves (McIntyre and Woodhouse 1986). This phenomenon was also mentioned by Bucur *et al.* (1994) and (Feeney *et al.* 1998). Moreover, wave propagation through radial and tangential directions is complicated due to stop bands caused by inhomogeneity (Bucur 2003; Tippner *et al.* 2013). Sonic band gaps may be raised due to inhomogeneity caused by a periodic array of annual rings as little as five (James *et al.* 1995), and a strong potential scattering source within the material along the radial direction is provided by a sharp impedance step between EW and LW (Feeney *et al.* 1998). Band filtering alteration due to interaction of microstructure and wavelength (Bucur 2006) is another important issue for the ultrasonic wave propagation in solid wood. Furthermore, although higher frequencies provide acceptable results, measurements significantly vary from sample to sample with variations in ring spacing and other physical properties of wood (McIntyre and Woodhouse 1986). As mentioned in the experimental section, interaction between the frequency of the longitudinal wave and ARW in terms of the pass and stop bands was not evaluated. Indeed, using wide-range frequencies may provide valuable data for comparisons. However, neither density variations within and between the rings nor propagation of different frequencies were the main motivations of this study, and the issue needs to be addressed in a future study.

High-attenuation materials such as wood (Tiitta *et al.* 2020) make measurements and evaluation complicated due to their complex orthotropic nature. According to Saadatnia *et al.* (2015), successful evaluation of wood properties becomes more difficult when the age and diameter of a tree increase because of increased inhomogeneity by adding annual growth rings. This development produces mature wood that has longer elements, thicker walls, as well as higher density (Saadatnia *et al.* 2015).

According to Hasegawa *et al.* (2011) wave velocity in softwood increases from pith to bark, and fiber orientation, wall thickness, and microfibril angle are the three essential factors that influence the acoustic properties of wood. However, annual ring curvature (ARC) is just as influential as when waves propagate through the tangential direction. Various studies dealt with the effect of ARC or inclination on ultrasonic wave propagation. For example, Jordan *et al.* (1998) highlighted the influences of ARC and repetition of the AR on the wave propagation in tangential and radial directions, respectively. As can be seen in Fig. 1 and Table 1, samples used in this study were prepared from outer parts of the sapwood sections of laths to minimize the effect of ARC on UWV and also to obtain lesser variations, respectively.

Bucur (2006) reported that V_{LL} and V_{TT} in LW of spruce were 13.14% and 38.23% higher than EW, respectively. Furthermore, both values were lower than solid wood (a complete annual ring), but the V_{TT} of LW (-2.2%) was closer to that of solid wood. The author reported that V_{LL} of spruce and curly maple were reduced with the increase in ARW.

However, ARW and ARC have no influence on the V_{RT} of spruce since the direction of propagation is radial. On the contrary, the effect of the AR on the V_{TR} of spruce is evident. For this study, the maximum decrease in UWV was 4%, and according to ANOVA results (except longitudinal wave velocity V_R) results agree with this expression.

Kránitz *et al.* (2014) correlated the ARW of aged Norway spruce to dynamic elastic moduli and shear moduli using 2.25 MHz longitudinal and 1 MHz transverse ultrasonic waves. Contrary to the results of this study, the authors reported that ARW significantly affected the data of the samples, and changes in the velocity were associated with changes in cell wall structure due to aging.

The complex structure of wood anatomy plays an essential role in the propagation of ultrasonic waves through the axes. Ray and tracheid are two main tissues that form the structure of conifers, and rays extend along the radial direction of the wood. Besides, resin ducts (not present in some conifer species) elongate through radial and longitudinal directions. Therefore, radial and tangential diameters of cell and lumens, radial and tangential thickness of double walls, and cross-sectional areas of lumen, wall, and cell (Cuny *et al.* 2014) properties can be assumed as the essential responsible factors that influence the UWV in the radial direction of the wood. Furthermore, rays and resin ducts may influence the refraction, reflection, diffraction, scattering, and attenuation for the propagation of the ultrasonic wave in wood. Also, many evergreen gymnosperms present anatomical characteristics within the ARs that separate the EW (relatively large diameters tracheids) from the neighboring LW (dense, small-diameter tracheids) tissues (Szejner *et al.* 2016). These cyclic alterations in sequenced ARs may also influence wave propagation.

CONCLUSIONS

1. There is a decreasing tendency in the ultrasonic wave (UWV) velocities with the increase in annual ring number (ARN). However, this tendency is not stable within and between the species. For example, only UWV of Scots pine and cedar were gradually decreased with the increase in ARN. Furthermore, the longitudinal wave velocity of red pine was decreased, and it scarcely any surpassed the initial value with the increase in ARN. Duncan's test results showed that an increase in ARN did not cause statistically significant differences between the average values of velocities except cedar and black pine woods. However, these differences were not observed when ARN increased from 10 to 15.
2. Except for V_R of Scots pine, and V_R, V_{RL}, and V_{RT} of Red pine, the regression models explained that there were no statistically significant relations between independent and dependent variables due to negligible percent of the variance in the response variable can be explained by the explanatory variables. Therefore, a general assessment of the barrier effect of ARW against the UWV may be inaccurate.
3. When opposite outcomes of the ARW and ARN effects on the UWV (particularly for V_R,) for species are taken into consideration, no meaningful expression can be made, and it’s thought that these diffractions might have occurred casually. The reasons for these behaviors in the longitudinal wave propagation should be determined by further investigations.

4. The current study was limited to evaluating the effects of the same number of annual rings using contact-type transducers propagating certain frequencies through small clear samples in the direct propagation method. However, different propagation methods such as air-coupled, pulse-echo, etc., frequencies such as kHz, transducers, and tools, and larger sample sizes through the radial direction and more annual rings can be used to provide valuable data for comparison.

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