Influence of Growth Ring Number and Width on Elastic Constants of Poplar

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The objective of this work was to evaluate the effect of growth ring number (specimens including 2, 4, and 6 rings from the bark) and growth ring width on elastic constants in the radial direction of *Populus* x *canadensis*, which has not been revealed before. The longitudinal (2.25 MHz) and transverse (1 MHz) ultrasonic waves were propagated to calculate the longitudinal (V_{RR}) and shear (V_{RL}, V_{LR}, V_{TR}, and V_{RT}) wave velocities and used to determine the elasticity modulus (E_R), and shear moduli (G_{RL} and G_{RT}). The average growth ring widths of specimens including 2, 4, and 6 rings were 17.0 mm, 17.8 mm, and 18.2 mm, respectively. According to the results, only V_{RL} steadily increased with increased ring number, while other velocities fluctuated. The same fluctuations were observed for moduli except for G_{LR}, which constantly increased with ring number. The influence of ring number on velocity was statistically significant only for V_{RL} and V_{RT}. However, all moduli were significantly affected by ring number. Linear regression statistics revealed that there were significant relations between the ring width and density, V_{RL}, V_{LR}, V_{RT}, G_{RL}, and G_{RT}.

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Keywords: Annual ring number; Annual ring width; Ultrasonic wave velocity; Elasticity modulus; Shear modulus

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INTRODUCTION

Poplar is an important hardwood species. Its outstanding traits are low density and diffuse-porous and short fibers with small-celled structures. Because of its good machining, bonding, and finishing properties (Balatinecz and Kretschmann 2001), various industrial fields, such as veneer (veneering, package, plywood, and matches), packing (pallet, chest, package), furniture (sawn-timber, generally utilized elements or goods for interior applications, *etc.*), timber chipping (pulping, wood-based engineered products, *etc.*), and construction (timber from log sawing, generally utilized to build roofs) use poplar wood (Birler 2014). Such a wide range of utilization brings poplar wood to the forefront either for commercial or scientific applications. One of the notable commercial applications involves plantation forestry because of the fast-growing ability, which makes the logs shortly available in the market with cheaper prices compared to other hardwood species. Providing logs in a short time provides sustainable consumption of resources. It is important because the demand for timber sources remarkably increases daily. Additionally, a considerable amount of the new inventory will be supplied by the plantations of fast-growing trees, including poplars (Balatinecz *et al.* 2001). However, the quality and mechanical properties of wood obtained from fast-growing trees generally are lower and weaker when compared to natural trees (Liu *et al*. 2019). However, some modification applications can be easily employed to overcome such disadvantages.

When compared to many other fast-growing species, one of the notable distinct qualities of poplar wood is the growth rings (GRs), where the growth-ring width (GRW) is bigger, and the latewood (LW) section of a GR is smaller (Birler 2014). Furthermore, earlywood (EW) and LW sections in a ring can be easily definable. This is because there is a distinctness in surface pattern between the LW (cells and cell walls are commonly small and thick, respectively) and the EW of the following period (cells and cell walls are commonly big and slim, respectively) (Wheeler 2001). Structural properties have significant influences on the wood properties. Thus, Dackermann *et al.* (2016) reported that ultrasonic wave velocity (UWV) decreases due to GR, which functions as a barrier against the propagated wave. For a homogeneous and highly porous structure, such as wood, there are many factors that affect wave propagation. Reflection, refraction, absorption, scattering, and attenuation are some of the phenomena ultrasound encounters while propagating through the wood. Because of the orthotropic nature of wood, such phenomena can be remarkably influenced by the propagation direction and polarization. In this manner, Aydın (2022) evaluated the barrier function of GR on pine (Scots, red, and black) and cedar woods using 1 MHz transverse and 2.25 MHz longitudinal ultrasonic waves. It was stated that UWV tends to decrease while the growth-ring number (GRN) increases. However, except in some cases, neither GRN nor GRW had statistically significant influences on UWV. Even if this is the case for UWV, no study revealed the influence of AR properties on the elastic properties of poplar wood. However, the following are studies that dealt with different aspects of GR-related property evaluation. Roig *et al.* (2008) determined the density of the 12- to 19-year-old poplar clones using X-ray densitometry and correlated it with GRW properties. The influence of climate circumstances on the GRW for *Populus ussuriensis* Kom (Gou and Chen 2011), Canadian poplar (*Populus* x *canadensis* Moench) (Ziemiańska and Kalbarczyk 2018), and *Populus* hybrids in Latvia (Šēnhofa *et al*. 2016), and length and temperature of the day on the ring properties of *Populus alba* L. (Baba *et al.* 2022) were evaluated relative to the interaction with mechanical properties.

Lang *et al.* (2002, 2003), Roohnia *et al.* (2010), Casado *et al.* (2010), Ettelaei *et al.* (2019), Virgen-Cobos *et al.* (2022), Papandrea *et al.* (2022), Zhang and Lu (2014), Rescalvo *et al.* (2020), Hajihassani *et al.* (2018), Özkan *et al.* (2020), Narasimhamurthy *et al.* (2017), Aydın *et al.* (2007), Monteior *et al.* (2019), Guo *et al.* (2011), and Sözbir *et al.* (2019) dynamically and/or statically determined the E_L of different poplar species as solid wood (unmodified or modified), standing trees, or engineered products prepared from *Populus* x *canadensis*. A few studies considered the shear modulus or full (twelve) elastic constants. Roohnia *et al.* (2010) dynamically calculated the G_{LR} and G_{LT} of *Populus deltoides*. Longo *et al.* (2018) determined the elasticity (E_R, E_T, E_L) and shear (G_{TL}, G_{RL}, G_{RT}) moduli of *Populus deltoides* using Resonant Ultrasound Spectroscopy (RUS) and Ultrasonic (US) testing (2.25 MHz) methods. Full (twelve) elastic constants for poplar were predicted only by Zahed *et al.* (2020) for OSB made from *Populus deltoides* and Zahedi *et al.* (2022) for *Populus deltoides*.

As seen in the abovementioned studies, even though there are six moduli (three elasticity and three shear) for wood, the E_L is a commonly determined elastic constant. It is meaningful when the preparation direction of wooden elements in construction is taken into consideration. Furthermore, determining the pure shear modulus is a difficult task that requires special tools. However, both elastic constants are required to perform non-linear real-like numerical analyses to design safe structures using computer-aided engineering applications. Furthermore, the influence of radial variations on elastic constants needs to be clarified for numerical applications. Moreover, providing not only GR-related elasticity and shear moduli in the radial direction but reliable input parameters for three-dimensional finite element analysis are crucial issues that should also be clarified. Therefore, this study aimed to elucidate the influence of GRW and GRN on the longitudinal UWV through radial direction (V_{RR}) and transverse UWV through radial direction and longitudinal and tangential polarizations (V_{RL}, V_{LR}, V_{RT}, and V_{TR}), and E_R, G_{RL}, and G_{RT} modulus that have not been presented before for *Populus* x *canadensis*.

EXPERIMENTAL

Populus x *canadensis* was used for specimen preparation. Two poplar logs were obtained from the plantation located in the Atabey, Isparta, Türkiye. The elevation and the coordinates of the plantation site are 1150 m and 37°57’03’’N 30°38’19’’E, respectively. Logs (from the breast height) were plain-sawn. Radially cut laths (Fig. 1) were divided into two from the pith, and heartwood (HW) sections were removed. Laths were planed to obtain smooth surfaces of approximately 20 mm thickness. As can be seen in the figure, ring borders were marked on the sapwood (SW) section to obtain samples (20 for each property and 10 per log) with 2, 4, and 6 GRs. Rings were counted and marked from the bark side to the pith side to prevent variations in ring properties. Therefore, the radial lengths of the specimens differed from each other, while the longitudinal and tangential dimension was around 2 × 2 cm. The radial to tangential angle was almost 90° to eliminate the effect of ring inclination.

Specimens were acclimatized at 20 ± 1 °C and 65% relative humidity (RH) using a chamber (Memmert Gmbh+Co. KG, Schwabach, Germany) until their weight became constant. At the end of the acclimatization, the density of the samples was determined according to the TS 2472 (2005) standard. To minimize or eliminate the density variations, all samples were matched in terms of the section and height of the pieces seen in Fig. 1. Furthermore, samples that had lower and upper bound density values were not taken into consideration.

The L, R, and T lengths of the specimens were measured using a digital caliper. Three measurements for each direction (nearby the endpoints and midpoint) were taken and the average length was calculated using arithmetic means of the measurements. The GRWs were calculated by dividing the average length of the R direction by GRN. To ensure the exact start and finish border of GR, the surface of the specimens was also sanded using sandpapers.

Ultrasound propagation was performed using an Olympus EPOCH 650 (Olympus, Waltham, MA, USA) digital ultrasonic flaw detector. The contact type A133S-RM and V153-RM (Panametrics-NDT, Waltham, MA, USA) transducers with 2.25 MHz (Pressure-P or longitudinal) and 1 MHz (Shear-S or transverse) central frequencies were used for wave propagation in direct mode to measure transmission time in µs. To reduce the noise and ensure the proper contact between transducers and the specimen, Olympus B2 Glycerin and SWC2 gel (Chemtrec, Waltham, MA, USA) were used. The longitudinal wave propagated through the R direction without polarization to calculate the V_{RR}. The transverse wave propagated through the R direction with L and T polarizations to calculate the V_{RL} and V_{RT}, respectively. For shear moduli determination, V_{LR} and V_{TR} were also measured.

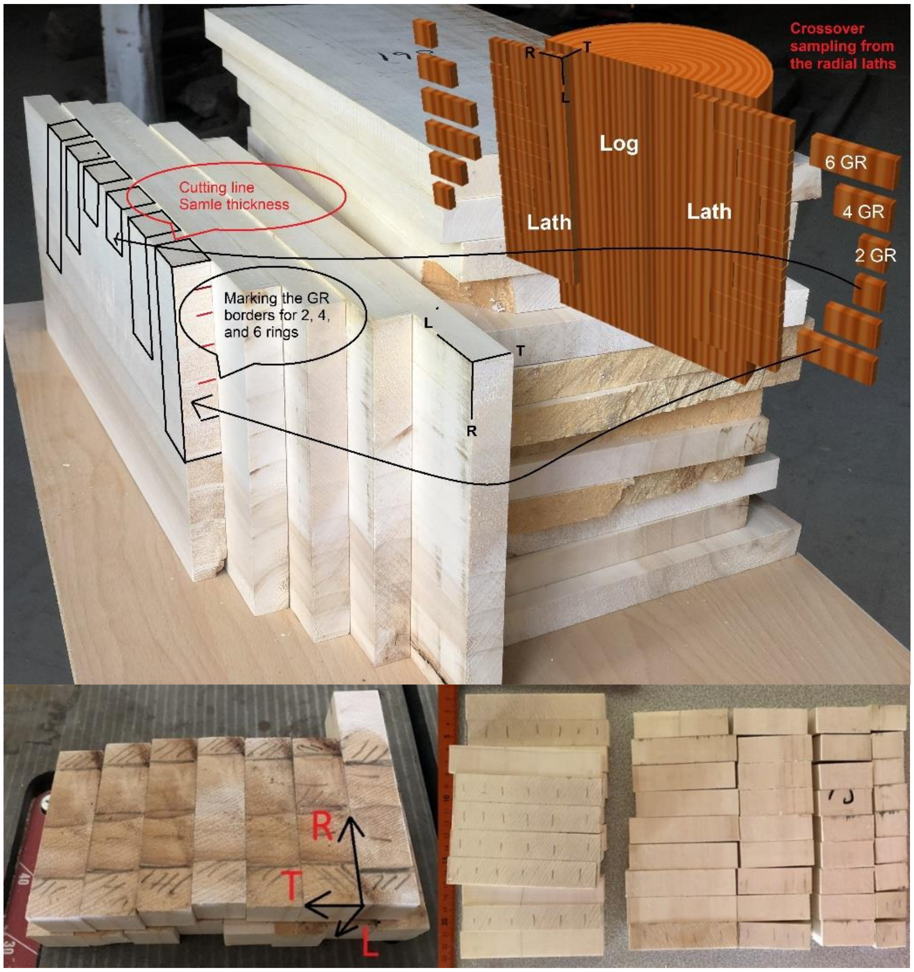

Fig. 1. Radially cut laths and sample preparation details

Because of the different and longer sizes in the R direction, three different (nearby the endpoints and midpoint) measurements were taken and then averaged, particularly for V_{LR} and V_{TR}. Consequently, dynamic elasticity modulus in the R direction (E_R) and shear moduli in RL and RT planes (G_{LR} and G_{RT}) were calculated using Eq. 1 and Eq. 2, respectively,

$$E_R = \rho V_{RR}^2 10^{-6} \quad (1)$$

where E_R is the elasticity modulus (MPa) in the R direction, ρ is density (kg/m^3), and V_{RR} is the longitudinal UWV (m/s) in the R direction without polarization,

$$G_{ij} = \rho \left(\frac{V_{ij}+V_{ji}}{2}\right)^2 10^{-6} \quad (2)$$

where G_{ij} is the shear modulus (MPa) in IJ planes, ρ is density (kg/m^3), and V_{ij} is the transverse UWV (m s^{-1}) in I direction and J polarization (LR, RL, RT, and TR).

For the transverse wave, the V_{IJ} is not equal to V_{JI}, and the average of these two velocities was taken into consideration while calculating the shear modulus in the IJ plane. The objective was to discover the influence of GRN and GRW on the velocity and moduli predicted using velocities. Therefore, shear moduli were also calculated by assuming V_{IJ} is equal to V_{JI} to comprehend the diffraction not only between the V_{IJ} and V_{JI} but also the moduli values.

The One-Way ANOVA test was conducted to interpret the influence of GRN on physical and mechanical properties and UWV. Significant differences between the means were found using Duncan's multiple range test (DMRT). Linear regression statistics were presented to evaluate the influence of GRW on the properties and to express how the properties were successfully predicted by GRW.

RESULTS AND DISCUSSION

Physical Properties

The means for the physical properties are presented in Table 1. The means of GRW ranged from 17 to 18.2 mm, and the average GRW of all the groups was 17.7 mm. Ziemiańska and Kalbarczyk (2018) reported 5.37 mm GRW for SW of the *Populus* x *canadensis* Moench, which is around 3.3 times lower than the average GRW of this study. Remarkably lower averages (6.63 mm and 8.3 mm) were also reported by Ziemiańska *et al.* (2020), including both SW and HW. In contrast, higher means, 19.8 mm (Erten and Önal 1995), 27.8 mm (LeBlanc *et al.* 2020), 28.6 and 28.8 mm (Šēnhofa *et al*. 2016), and 45 to 55 mm (DeBell *et al*. 2002), were also reported for different poplar species. There are many reasons for such high diffraction within the same species. The most important factor that influences the GRW is the climate, and precipitation and temperature have effects on width (Bozkurt and Erdin 1989a). Conversely, such remarkable differences can be meaningfully explained by sampling because the width of the growth ring can be dramatically changed. For example, Zhang *et al.* (2022) reported around 1.2 cm GRW for the first ring from the pith of hybrid clone of I-69 (*P. deltoides*) and I-45 (*P. euramericana*) clones. It increased to around 1.75 cm at the 4th ring and decreased to 0.3 cm at the 12th ring. Therefore, it is not easy to exactly compare or weigh the means because the parameters are not identical.

Density is one of the essential determinants for classifying wood. According to the means, *P. canadensis* met the requirement for European strength classes C24 (350 kg/m^3), and it can be used for structural purposes. The density of the samples ranged from 335 to 373 kg/m^3, and the average of all the samples was 348 kg/m^3. Flórez *et al.* (2014) observed a 310 to 450 kg/m^3 basic density range for *P. canadensis*. Further, 365 kg/m^3 (Zhang *et al.* 2017), 405.6 kg/m^3 (Hodoušek *et al.* 2017), 464 kg/m^3 (Villasante *et al.* 2021), and 529 kg/m^3 (Niklas and Spatz 2010) density means were reported for *P. canadensis*. Either averaged or the separate means of the 2, 4, and 6 ring groups are comparable to that of the literature. However, Birler (2014) reported 400 to 450 kg/m^3 air-dry density for exotic poplar wood cultivated in Türkiye, which is at least 13% higher than the maximum average density of this study. In contrast, the lower bound for the means of this study was around 3.3% higher than those of Aydın *et al.* (2007) reported for poplar. Because the *P. canadensis* is a naturally occurring hybrid of *P. deltoides* and *P. nigra*, the following densities of 390 kg/m^3 (Zahedi *et al.* 2020), 460 kg/m^3 (Hajihassani *et al.* 2018), 375 and 387 kg/m^3 (Altınok *et al.* 2009), 410 kg/m^3 (Bozkurt and Erdin 1989b), 420 kg/m^3 (Keleş 2021), 425 kg/m^3 (varied from 346 to 523) (Monteiro *et al.* 2019), and 450 kg/m^3 (Suleman 2015) should be taken into consideration.

In this study, the UWV ranged from 1607 to 1850 m/s and 504 to 1588 m/s for P and S waves, respectively. In the literature, only Zahedi *et al.* (2022) reported V_{RR}, V_{LR}, V_{RL}, V_{RT}, and V_{TR} values for poplar wood. As shown in Table 2, these values are comparable with the results of this study. Furthermore, when UWVs were averaged within the GRN groups, these values and differences from the reported data become 1746, 1486, 1548, 544, and 513 m/s, and -5.6%, 8.5%, 23.9%, -18.8%, and 21.1%, respectively. In this regard, diffractions are at reasonable levels.

Table 1. Descriptive and Statistics for Physical Properties

Properties	GRN Groups	Descriptives		ANOVA	
		Mean*	Std. Dev.	F	Sig. (P < 0.05)
GRW (mm)	2 Rings	17.0 [a]	0.44	0.639	0.5317
	4 Rings	17.8 [a] (5.2)**	0.34		
	6 Rings	18.2 [a] (7.2)	0.02		
Density (kg/m³)	2 Rings	353.9 [a]	13.29	5.422	0.0073
	4 Rings	344.7 [b] (-2.6)	4.31		
	6 Rings	346.8 [b] (-2.0)	6.85		
V_{RR} (m/s)	2 Rings	1781.8 [ab]	355.40	3.092	0.0539
	4 Rings	1850.1 [a] (3.8)	310.21		
	6 Rings	1607.1 [b] (-9.8)	108.89		
V_{LR} (m/s)	2 Rings	1463.2 [a]	77.07	1.855	0.1667
	4 Rings	1501.2 [a] (2.6)	65.71		
	6 Rings	1494.3 [a] (2.1)	46.34		
V_{RL} (m/s)	2 Rings	1490.6 [b]	84.02	10.340	0.0002
	4 Rings	1566.5 [a] (5.1)	66.35		
	6 Rings	1588.1 [a] (6.5)	42.02		
V_{RT} (m/s)	2 Rings	535.6 [b]	31.03	8.269	0.0008
	4 Rings	531.7 [b] (-0.7)	25.36		
	6 Rings	564.7 [a] (5.4)	14.76		
V_{TR} (m/s)	2 Rings	512.0 [a]	34.58	1.705	0.1917
	4 Rings	504.3 [a] (-1.5)	21.66		
	6 Rings	522.4 [a] (2.0)	28.47		
*Duncan's Homogeneity Groups, **values in the parenthesis are % difference from the 2 GRN					

Table 2. Reported UWV for Poplar Related to Radial Direction Only

Species (Wood or Wood-based Product)	Density (kg/m³)	UW Frequency (Longitudinal/Transverse)	UWV (m/s)					Ref.
			V_{RR}	V_{LR}	V_{RL}	V_{RT}	V_{TR}	
Populus deltoides (OSB)	760	100 kHz/250 kHz	3390	1800	1670	750	830	(Zahedi *et al*. 2020)
Populus deltoides (Solid Wood)	390	100 kHz/250 kHz	1850	1370	1250	670	650	(Zahedi *et al*. 2022)

Influence of AR properties on physical properties

As can be seen in Table 1, GRW means presented insignificant differences, which was essential for its influence evaluation on the physical and mechanical properties. Lars *et al*. (2005) stated that when the GRW is widening, the density of wood decreases. However, DeBell *et al.* (2002) reported that there is no significant correlation between GRW and density. Furthermore, the width of the rings is not identical every year and causes variations in density. For example, the density of Scots pine (with 2 to 7 rings) increased when the GRN increased to 23 but sequentially decreased when the GRN increased to 49 (Krauss and Kudela 2011). Ištok *et al.* (2016) reported 0.65 and 0.549 R^2 values between density and GRN (3 to 18 from pith) for I-214 and S1-8 poplar clones, respectively. The authors also stated that there is a negative correlation between density and GRW. As shown in Table 1, the mean density of 2 GRN presented significant differences and according to linear regression statistics (Table 3), there is a weak (0.309 R^2) but significant adverse relationship between GRW and density. This may influence the wave velocities which is one of the basic determinants for mechanical property calculation (Eqs. 1 and 2). This is because UWV is directly related to the elastic moduli and density of a solid material (Stegemann *et al.* 2016). However, Krauss and Kudela (2011) revealed that the velocity of a longitudinal ultrasonic wave propagated through the L direction of wood (V_{LL}) does not linearly increase or decrease with the increase in GRN. Furthermore, Hasegawa *et al*. (2011) reported that there is no change in V_{RR} when the distance from the pith increases. In this study, except for V_{RL}, neither longitudinal nor transverse ultrasonic waves presented stable increase or decrease tendencies against GRN. Therefore, the barrier effect of GRN on UWV was not proved because as shown in Table 1, V_{RL} did not drop with the increase in GRN. In contrast, 5.1% and 6.5% increases were observed when GRN increased from 2 to 4 and 6, respectively. Furthermore, V_{LR}, V_{RT}, and V_{TR} for 6 GRN were higher than those of 2 GRN.

According to the ANOVA results seen in Table 1, significant differences in the UWV means were only observed for V_{RL} and V_{RT}. However, the homogeneity groups between the velocities were not the same. Therefore, it is not possible to say that increase in GRN influences the UWV in the same manner, but the V_{RR} was the most negatively affected UWV by the GRN while V_{RL} was positive.

According to linear regression statistics (Table 3) and models (Fig. 2), there were positive and negative relationships between GRW *vs.* UWVs. As illustrated in Fig. 2, considering the coefficients, when GRW tended to increase, density and V_{RT} increased while others decrease. But, except for V_{RR} and V_{TR}, the relationships were found to be significant. The R^2 values ranged from 0.012 (V_{TR}) to 0.644 (V_{RL}). Therefore, models can explain a maximum of 64.4% variability of the response data around its average.

Table 3. Linear Regression Statistics for GRW

Statistics		Density	V_{RR}	V_{LR}	V_{RL}	V_{RT}	V_{TR}
Pearson Correlation	GRW	-0.55583	0.16442	0.75457	0.80261	-0.39039	0.11055
	Sig. (1-tailed)	0.00001	0.11515	0.00000	0.00000	0.00161	0.21085
Model Summary	R^2	0.30895	0.02704	0.56937	0.64419	0.15241	0.01222
ANOVA	F	23.69442	1.47267	70.07577	95.95445	9.52987	0.65572
	Sig. (P<0.05)	0.00000	0.23000	0.00000	0.00000	0.00300	0.42200
Coefficients	t	-4.86769	1.21354	8.37113	9.79563	-3.08705	0.80976
	Sig. (P<0.05)	0.00001	0.23031	0.00000	0.00000	0.00321	0.42170

Density vs. UWVs

Even if it is not prominent as in the T direction due to ray cells being aligned in the R direction, wave refraction occurs for ultrasonic waves while passing a GR. This is because of the sequential but nonhomogeneous formation of the EW and LW that causes density diffraction. As a result, the wave attenuates by losing its energy, and attenuation causes velocity alterations. However, the influence of density on UWV in wood is controversial because there are opposite conclusions.

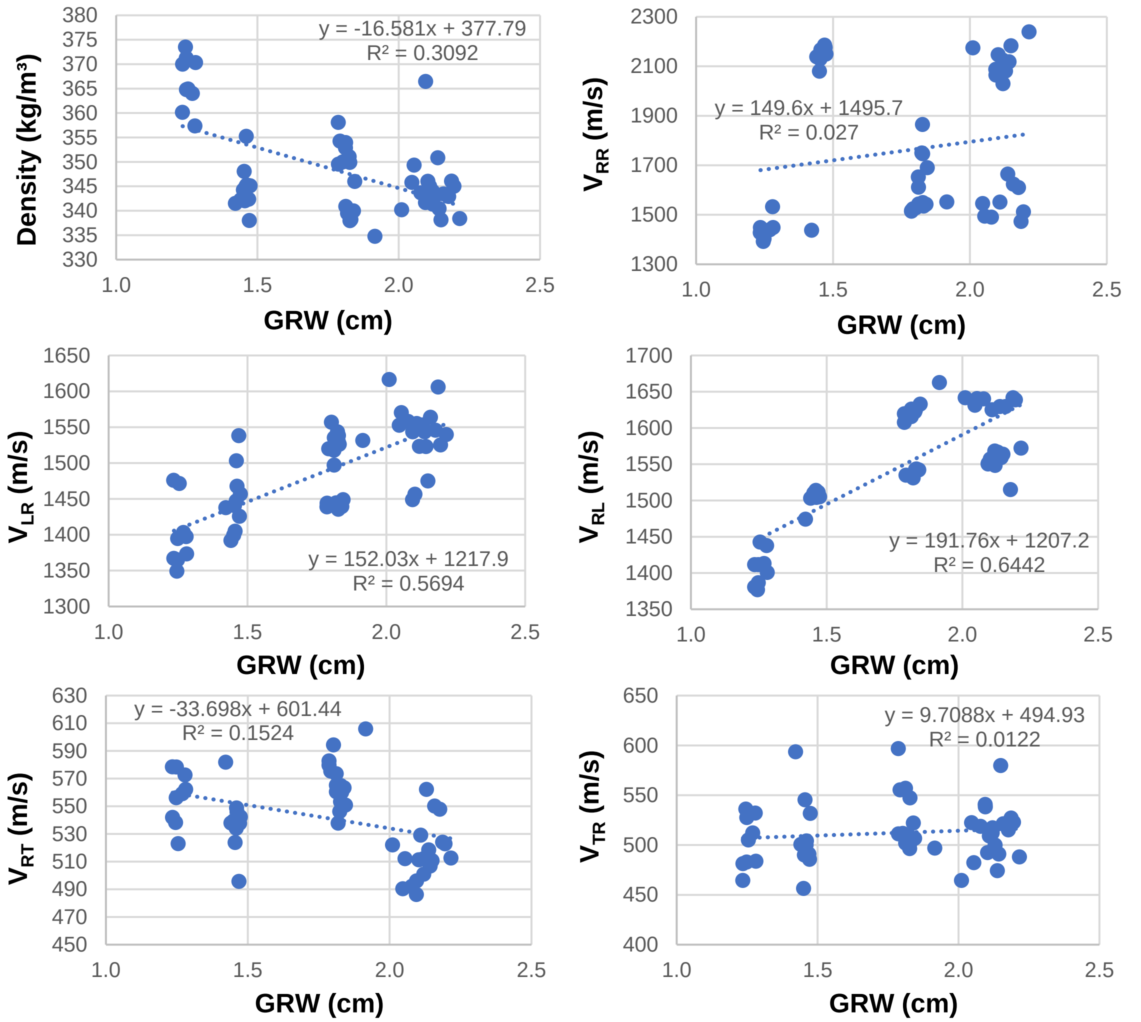

Fig. 2. Linear regression models and coefficients of determination for physical properties

For example, positive values have been reported for V_{LL} of different softwood and hardwood species (de Oliveira and Sales 2006; Baar *et al.* 2012), negative for V_{LL} of 11 Australian hardwoods (R:0.647) (Bucur and Chivers 1991), significant negative for V_{LL}, while insignificant positive for V_{RR} and V_{TT} for Japanese cedar (Hasegawa *et al.* 2011). On the other hand, Hasegawa *et al.* (2011) also reported statistically significant negative for V_{LL} and insignificant negative V_{RR} and V_{TT} for Japanese cypress. Furthermore, neutral conclusions for V_{LL} *vs.* density were expressed by Mishiro (1996) and Ilic (2003). De Oliveira and Sales (2006) reported 0.8 to 0.88 R^2 between V_{LL} and density for Caribbean pine, lemon-scented gum, rose gum, goupie, and courbaril species. A positive relation and 0.84 to 0.89 R^2 between V_{LL} *vs.* density were also reported by Yılmaz Aydın and Aydın (2018a) for cedar. However, a weak (0.146 and 0.29 R^2) and negative relationship between V_{LL} *vs.* density was also reported by Krauss and Kudela (2011) for Scots pine and Liu *et al.* (2019). In this study, R^2 values between UWV *vs.* density (Fig. 3) ranged from 0.000 (V_{TR}) to 0.331 (V_{RL}).

Indeed, there can be several factors (such as microfibril angle-MFA, the slope of grain, *etc.*) that cause variations in UWVs other than density. The proper positioning of the transducer for measuring can reduce or eliminate the influence of anatomical alterations such as tracheid length or MFA (Hasegawa *et al.* 2011). However, quantification of such issues requires both orthotropic material knowledge and expertise in technological equipment usage. For instance, there is a positive strong relationship (R 0.85 and 0.91) between V_{LL} and tracheid length, while there is a negative strong relationship (R 0.82 and 0.9) between V_{LL} and MFA (Hasegawa *et al.* 2011). Furthermore, V_{LL} varies from pith to bark (Bucur 2006). Conversely, V_{RR} has no correlations with tracheid length, MFA, and density (Hasegawa *et al*. 2011). Therefore, as Baar *et al.* (2012) expressed, it is not easy to find a direct effect of density on velocity that reflects the opposite conclusions.

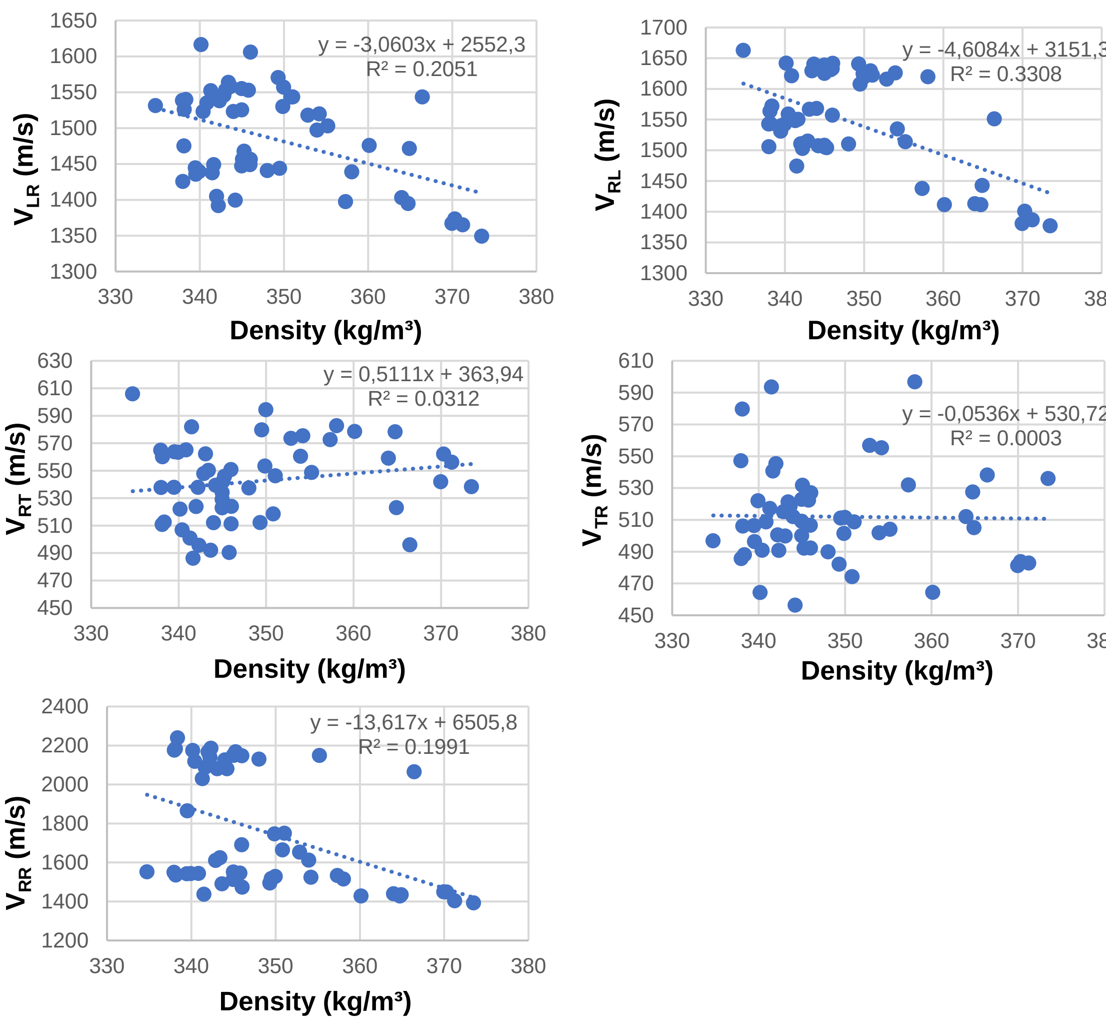

Fig. 3. Linear regression models and coefficients of determination for density vs UWVs

Mechanical Properties

The means for the mechanical properties are presented in Table 4. The E_R ranged from 705 to 1696 MPa. As shown in Table 5, reported E_R values range from 700 to 1900 MPa. The upper bound reaches 5 GPa for the OSB produced using *P. deltoides*. However, the E_R of *P. deltoides* solid wood without any modification is 900 MPa, which was predicted using the US. It is the same with the literature data reported by Longo *et al.* (2018). As shown in Table 4, the E_R means of this study are in the range of the reported values. When considering the unavailable dynamic E_R values in the literature for *Populus* x *canadensis*, this study can contribute to the literature by providing comparable data.

Table 4. Descriptives and Statistics for Mechanical Properties

Properties	GRN Groups	Descriptives		ANOVA	
		Mean*	Std. Dev.	F	Sig. (P < 0.05)
E_R (MPa)	2 Rings	1153.2 [a]	414.96	3.657	0.0326
	4 Rings	1211.4 [a] (5.0)**	394.44		
	6 Rings	899.4 [b] (-22.0)	125.59		
G_{LR} (MPa)	2 Rings	771.6 [b]	61.50	3.888	0.0267
	4 Rings	812.3 [a] (5.3)	67.53		
	6 Rings	824.4 [a] (6.8)	45.79		
G_{RT} (MPa)	2 Rings	97.3 [ab]	9.66	6.819	0.0023
	4 Rings	92.5 [b] (-4.9)	5.29		
	6 Rings	102.6 [a] (5.5)	8.60		
G_{LR} (MPa) ($V_{RL}= V_{LR}$)	2 Rings	785.9 [b] [1.9]	65.67	8.608	0.0006
	4 Rings	847.3 [a] (7.8) [4.3]	72.62		
	6 Rings	875.7 [a] (11.4) [6.2]	57.94		
G_{RT} (MPa) ($V_{RT} = V_{TR}$)	2 Rings	102.0 [b] [4.8]	13.78	6.599	0.0028
	4 Rings	97.6 [b] (-4.3) [5.5]	8.98		
	6 Rings	110.7 [a] (8.5) [7.9]	7.02		

*Duncan's homogeneity groups, **values in the parentheses are % difference from the 2 GRN and the values in brackets are % difference from the shear modulus calculated using $V_{IJ} \neq V_{JI}$ within the GRN groups

Table 5. Reported Moduli for Poplar Species Related to Radial Direction Only

Species	Test	Moduli (MPa)				Ref.
		E_R	G_{LR}	G_{RL}	G_{RT}	
Poplar	-	910	-	915	220	(Zhou *et al.* 2021)
Populus deltoides (OSB)	US	5000	2320	-	470	(Zahedi *et al.* 2020)
Populus deltoides	US	900	700	-	170	(Zahedi *et al.* 2022)
Populus deltoides × *Populus trichocarpa* 'I45-51'	RUS	1500	670	-	170	(Longo *et al.* 2018)
Literature data for Poplar	-	700 to 1200	600 to 1000	-	100-200	(Longo *et al.* 2018)
Populus deltoides × *Populus trichocarpa* 'I45-51'	US	1900	990	-	140	(Longo *et al.* 2018)
Literature data for Poplar	-	900	600 to 1000	-	100-200	(Longo *et al.* 2018)
Liriodendron tulipifera	Tension/Plate tests	872 to 874	1185 to 1324	-	-	(Sliker and Yu 1993)

The shear modulus values in LR and RT planes ranged from 693.8 to 912.2 MPa (705 to 940.1 MPa for $V_{RL} = V_{LR}$) and 83 to 124.5 MPa (80.7 to 123.6 MPa for $V_{RT} = V_{TR}$), respectively. The shear modulus means (Table 4) were in harmony with the reported averages seen in Table 5. When all GRN groups were averaged, the G_{RL} and G_{RT} values were 802.8 and 97.5 MPa ($V_{IJ} \neq V_{JI}$) and 836.3 and 103.5 MPa ($V_{IJ} = V_{JI}$), respectively. The G_{RL} ($V_{IJ} \neq V_{JI}$) of this study was 33.8% higher and 39.4% lower than the lower and upper bounds of reported data (Table 5), while G_{RT} was 2.5% and 55.7% lower, respectively. The G_{RT} is included in the reported range when GRN groups were averaged. However, it is around 53% lower than the reported upper bound. Essentially, even if the species is same, such diffraction is not abnormal for wood materials that present different properties not only between species by species but also due to test methods, growing conditions (climate, elevation, *etc.*), sampling, *etc.*

Influence of AR properties on mechanical properties

As in UWV, E_R did not present linear behavior. Indeed, it increased and then significantly decreased with the increase in GRN. Among the evaluated properties, E_R was the most adversely affected property by GRN increment. The maximum range (-22% to 5%) for the diffraction was observed for E_R. The ANOVA results demonstrated that 6 GRN caused significant diffraction on E_R. The model for GRW *vs.* E_R (Fig. 4) was able to predict only 1.4% of the variables, and according to linear regression results (Table 6) the relationship between E_R *vs.* GRW was found to be insignificant. Dinulică *et al.* (2021) reported a 0.21 R^2 value ($p = 0.03$) for the relationship between E_R *vs.* GRW of Norway spruce. The authors stated that E_R increases with the increase in SW ring width but decreases with LW width irregularity. Vega *et al.* (2020) reported that the dynamic MOE of *Eucalyptus nitens* increased with the increase in rings from the pith and tends to be constant following the outerwood section. It was reported that the density and MFA increased, decreased, and became constant following the outerwood section. Therefore, samples should not include transition sections as in this study.

The G_{LR} constantly increased with the increase in GRN. In contrast, G_{RT} decreased and then surpassed the initial value when GRN increased. The same was true when moduli were calculated using the $V_{IJ} = V_{JI}$ assumption. The G_{LR} was the most positively influenced property by the GRN increment. This advancement was more pronounced when moduli were calculated with the equal velocity assumption. According to ANOVA results (Table 4), GRN had significant influences on the shear moduli calculated using either $V_{IJ} = V_{JI}$ or $V_{IJ} \neq V_{JI}$ assumptions. However, the velocity assumption caused diffraction in the homogeneity grouping of G_{RT}. According to linear regression results seen in Table 6 and Fig. 4, there was a positive and significant relationship between GRW *vs.* G_{LR} and around 55 to 58% of variables can be predicted using GRW. In contrast, a negative weak but significant relationship was observed for GRW *vs.* G_{RT}. As illustrated in Fig. 4, considering the coefficients, when GRW tended to increase, E_R and G_{LR} increased while G_{RT} decreased.

Table 6. Linear Regression Statistics for GRW

Statistics		E_R	G_{LR}	G_{RT}	G_{LR} ($V_{RL}= V_{LR}$)	G_{RT} ($V_{RT} = V_{TR}$)
Pearson Correlation	GRW	0.11627	0.75939	-0.33713	0.74121	-0.49776
	Sig. (1-tailed)	0.19896	0.00000	0.00592	0.00000	0.00006
Model Summary	R^2	0.01352	0.57667	0.11365	0.54939	0.24777
ANOVA	F	0.72629	72.19857	6.79613	64.61844	17.45680
	Sig. (P < 0.05)	0.39800	0.00000	0.01200	0.00000	0.00000
Coefficients	t	0.85223	8.49697	-2.60694	8.03856	-4.17813
	Sig. (P < 0.05)	0.39792	0.00000	0.01184	0.00000	0.00011

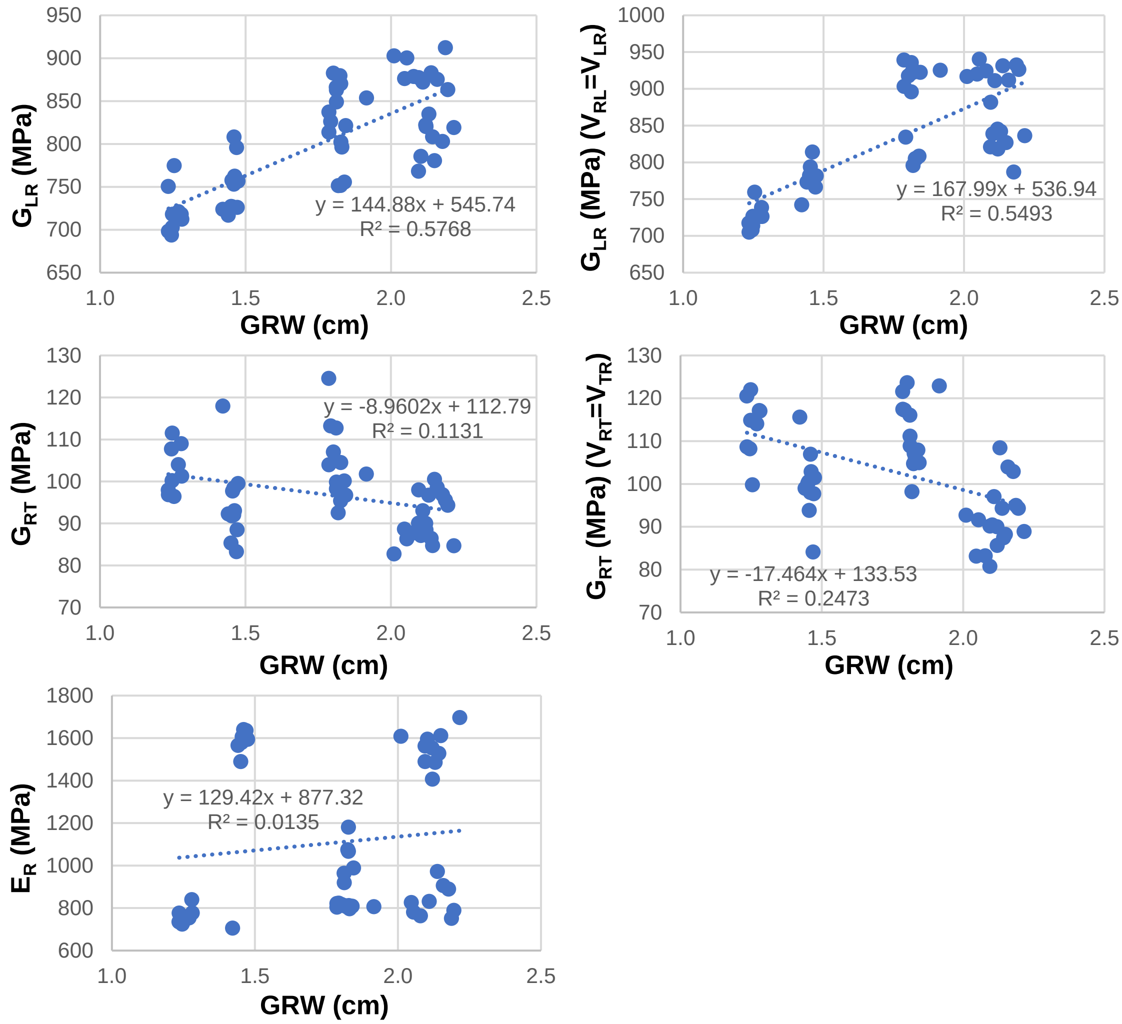

Fig. 4. Linear regression models and coefficients of determination for mechanical properties related to GRW

It is essential to consider that the relationship between the GRW and modulus is not always straightforward. Species, moisture, temperature, grain orientation, density, age of wood, defects, and knots, processing and treatment, load and duration, and orthotropy are some factors that may influence the modulus of wood. However, the specific influence of each factor can vary depending on the type of wood and its individual characteristics. Other than the independent influence, different combinations of these factors with or without GRW can result in complex interactions affecting the modulus of wood.

Density vs. moduli

Slow-growing trees create narrow GRW, and wood becomes denser. In contrast, fast-growing trees create wider GRW, which makes low-density wood. High density and more uniform cell structure provide better stiffness, MOE, and strength. Low density and less uniform cell structure cause reduced stiffness and lower mechanical properties. However, as shown in Fig. 5, the R^2 values between the density and moduli ranged from 0.081 (G_{LR}) to 0.173 (G_{RT} $V_{IJ} = V_{JI}$), and there were adverse relationships between E_R *vs.* density and G_{LR} *vs.* density. Therefore, apart from density, it can be said that combined influences may play a role in the results. For example, if the density increases without a corresponding increase in stiffness (such as interlocked grain, length of the anatomical element, or MFA), the UWV decreases as the density increases. This makes it challenging to relate a direct effect of density on UWV, which is why different studies have reached varying conclusions (Baar *et al.* 2012) either for physical or mechanical properties.

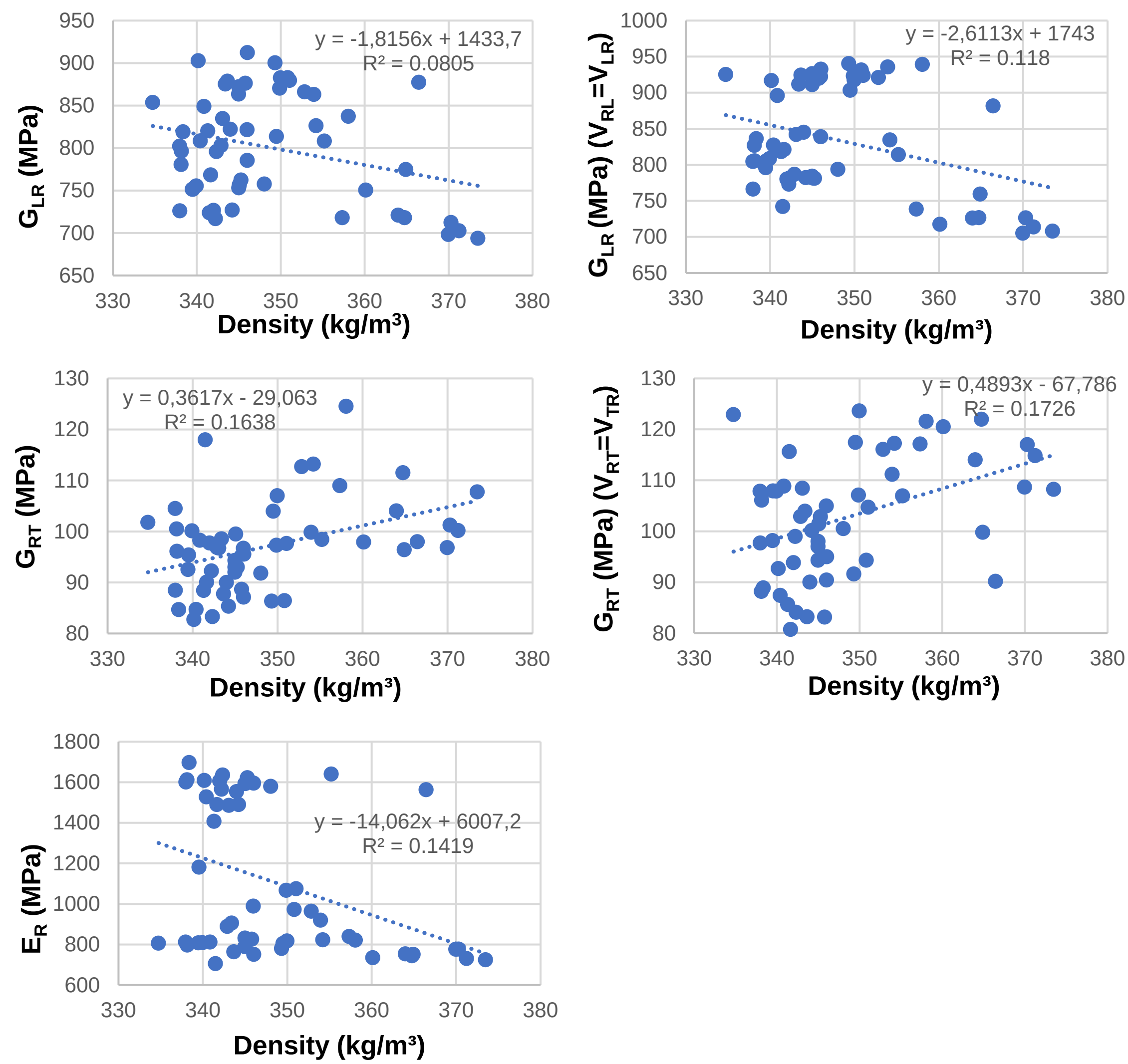

Fig. 5. Linear regression models and coefficients of determination related to density

Propagation length vs. UWV and moduli

Another issue that should be taken into consideration while interpreting the effect of GR on UWV (therefore the dynamically determined mechanical properties) is the propagation length (PL). Strong positive relations (from 0.830 to 0.975 Pearson correlation coefficients) between PL and V_{LL} for Scots pine, black pine, Turkish red pine, and oriental beech were reported by Yilmaz Aydin and Aydin (2018b). Furthermore, the statistically significant ($P < 0.05$) influence of PL on V_{LL} of *Cedrus libani* (Yılmaz Aydın and Aydın 2018a) and *Quercus petraea* L. (Yılmaz Aydın and Aydın 2018c) was reported. However, in this study, the R^2 values between PL and V_{RR}, V_{RL}, V_{LR}, V_{RT}, and V_{TR} were calculated as 0.055, 0.473, 0.163, 0.067, and 0.023, respectively. Furthermore, the R^2 values between PL and E_R, G_{RL}, and G_{RT} are 0.084, 0.297, and 0.015, respectively. Therefore, apart from

V_{RL}, weak correlations between the PL and UWV (and also related moduli) were observed. Common ground between the abovementioned strong and moderate (particularly for V_{RL} and slightly for V_{LR}) relations is the longitudinal direction, but the type of the wave was not the same. According to Bucur (2006) precision of the measurements is related to sample size and accuracy increases with the increase in size. However, when the size increases so much then the noise increases too; therefore finding the exact peak of the wave becomes difficult while arranging the detector parameters such as gain, gate, *etc.*, and the possibility of misreading may increase.

CONCLUSIONS

1. Results revealed that neither longitudinal nor transverse velocities continuously decreased with increased growth-ring number. In contrast, a linear-like increase was observed. Therefore, the growth-ring acting as a barrier against ultrasonic wave velocity expressed in the literature was not verified.
2. According to statistical results, a general expression for the stable influence of growth-ring number or growth-ring width on both longitudinal and transverse ultrasonic wave velocities is senseless. However, both elasticity and shear moduli that were predicted using ultrasonic wave velocities were statistically significantly affected by growth-ring number, while there was no significant influence of growth-ring width on E_R. Therefore, the influence of density on the physical and mechanical properties should be taken into consideration. However, the linear regression models and coefficients of determination between the density and ultrasonic wave velocities or moduli do not support this interaction. Furthermore, there is a contradiction in the influence of density in the literature.
3. This study focused on a limited growth-ring number. This was because samples were prepared only from the sapwood to exclude the influence of heartwood or variations caused by transitions. However, it should be taken into consideration that further investigations using samples including more growth-ring numbers may provide valuable data for an extended comparison.
4. Because of the anatomical formation of wood, there are $V_{LL} > V_{RR} > V_{TT}$ and V_{LR}, V_{LT}, and V_{RT} orders for longitudinal and transverse waves, respectively. One of the main constituents of wood is growth-ring, which consists of earlywood and latewood. Based on the consecutive but irregular formation of earlywood and latewood and therefore the growth-ring, ultrasonic wave velocity either longitudinal or transverse passes through a path with sequentially changed density and elements aligned through the L and R axes. Furthermore, sampling (geometry, sapwood-heartwood or combined, natural or processing faults, invisible inner faults, *etc.*), measurement (positioning, angle of the beam, *etc.*), and user-orientated misreading may influence the property assessment. Therefore, it is not possible to say that other factors independently or in combination do not influence the properties.

REFERENCES CITED

Altınok, M., Özalp, M., and Perçin, O. (2009). "The effects of growing region on mechanic properties of laminated poplar wood (*Populus nigra* L.)," *Ormancılık Dergisi* 5(1), 107-120.

Aydın, M. (2022). "Effects of annual ring number and width on ultrasonic waves in some softwood species," *BioResources* 17(1), 1745-1763. DOI: 10.15376/biores.17.1.1745-1763

Aydın, S., Yardımcı, M. Y., and Ramyar, K. (2007). "Mechanical properties of four timber species commonly used in Turkey," *Turkish Journal of Engineering and Environmental Sciences* 31(1), 19-27.

Baar, J., Tippner, J., and Gryc, V. (2012). "The influence of wood density on longitudinal wave velocity determined by the ultrasound method in comparison to the resonance longitudinal method," *European Journal of Wood and Wood Products* 70(5), 767-769. DOI: 10.1007/s00107-011-0550-2

Baba, K., Kurita, Y., and Mimura, T. (2022). "Experimental study of intra-ring anatomical variation in *Populus alba* L. with respect to changes in temperature and day-length conditions," *Forests* 13(7), article 1151. DOI: 10.3390/f13071151

Balatinecz, J. J., and Kretschmann, D. E. (2001). "Properties and utilization of poplar wood," in: *Poplar Culture in North America,* D. I. Dickmann, J. G. Isebrands, J. E. Eckenwalder, and J. Richardson (eds.), NRC Research Press, Ottawa, Canada, pp. 277–291.

Balatinecz, J. J., Kretschmann, D. E., and Leclercq, A. (2001). "Achievements in the utilization of poplar wood – Guideposts for the future," *The Forestry Chronicle* 77(2), 265–269. DOI: 10.5558/tfc77265-2

Birler, A. S. (2014). *Poplar Cultivation in Turkey*, Ministry of Forestry and Water Affairs, Directorate General of Forestry, Forest Trees Research Institute, İzmit, Türkiye.

Bozkurt, Y., and Erdin, N. (1989a). "Ağaç malzeme kalitesi ve silvikültürel tedbirler [Wood material quality and sylvicultural measures]," *İstanbul University Faculty of Forestry* 39(3), 1-13.

Bozkurt, Y., and Erdin, N. (1989b). *Ticarette Önemli Yabancı Ağaçlar [Important Foreign Trees in Trade]*, Istanbul University Faculty of Forestry, İstanbul, Türkiye.

Bucur, V. (2006). *Acoustics of Wood, The Acoustics of Wood*, Springer-Verlag Berlin Heidelberg, Heidelberg, Germany. DOI: 10.1201/9780203710128

Bucur, V., and Chivers, R. C. (1991). "Acoustic properties and anisotropy of some Australian wood species," *Acustica* 75(1), 69–74.

Casado, M., Acuña, L., Vecilla, D., Relea, E., Basterra, A., Ramón, G., and López, G. (2010). "The influence of size in predicting the elastic modulus of *Populus* x *euramericana* timber using vibration techniques," in: *Structures and Architecture*, P. J. Cruz (ed.), Taylor & Francis, London, UK, pp. 2025-2032.

Dackermann, U., Elsener, R., Li, J., and Crews, K. (2016). "A comparative study of using static and ultrasonic material testing methods to determine the anisotropic material properties of wood," *Construction and Building Materials* 102, 963-976. DOI: 10.1016/j.conbuildmat.2015.07.195

DeBell, D. S., Singleton, R., Harrington, C. A., and Gartner, B. L. (2002). "Wood density and fiber length in young populus stems: Relation to clone, age, growth rate, and pruning," *Wood and Fiber Science* 34(4), 529–539.

Dinulică, F., Bucur, V., Albu, C.-T., Vasilescu, M. M., Curtu, A. L., and Nicolescu, N.-V. (2021). "Relevant phenotypic descriptors of the resonance Norway spruce standing trees for the acoustical quality of wood for musical instruments," *European Journal of Forest Research* 140(1), 105-125. DOI: 10.1007/s10342-020-01318-z

Erten, A. P., and Önal, S. (1995). "Studies on the determination of some physical and mechanical properties of *Populus tremula* wood," *İç Anadolu Ormancılık Araştırma Enstitüsü Teknik Bülten* (79), 51-74.

Ettelaei, A., Layeghi, M., Zarea Hosseinabadi, H., and Ebrahimi, G. (2019). "Prediction of modulus of elasticity of poplar wood using ultrasonic technique by applying empirical correction factors," *Measurement* 135, 392-399. DOI: 10.1016/j.measurement.2018.11.076

Flórez, V., Valenzuela, C., Cancino, J., and Acuña, E. (2014). "Combining taper and basic wood density equations for estimating stem biomass of the *Populus* x *canadensis* I - 488 variety," *Bosque (Valdivia)* 35(1), 17-18. DOI: 10.4067/S0717-92002014000100009

Guo, H., Xu, C., Lin, L., Wang, Q., and Fu, F. (2011). "The composite wood by poplar wood impregnated with Na2SiO3-polyacrylamide hybrid solution," *Science and Engineering of Composite Materials* 18(3), 151-155. DOI: 10.1515/secm.2011.025

Guo, M., and Chen, J. (2011). "Influence of climate factors upon growth ring width of plantation *Populus ussuriensis* Kom on the basis of analyzing growth ring materials," *Procedia Engineering* 15, 4465-4469. DOI: 10.1016/j.proeng.2011.08.839

Hajihassani, R., Mohebby, B., Najafi, S. K., and Navi, P. (2018). "Influence of combined hygro-thermo-mechanical treatment on technical characteristics of poplar wood," *Maderas. Ciencia y Tecnología* 20(1), 117-128. DOI: 10.4067/S0718-221X2018005011001

Hasegawa, M., Takata, M., Matsumura, J., and Oda, K. (2011). "Effect of wood properties on within-tree variation in ultrasonic wave velocity in softwood," *Ultrasonics* 51(3), 296-302. DOI: 10.1016/j.ultras.2010.10.001

Hodoušek, M., Dias, A. M. P. G., Martins, C., Marques, A. F. S., and Böhm, M. (2017). "Comparison of non-destructive methods based on natural frequency for determining the modulus of elasticity of *Cupressus lusitanica* and *Populus* x *canadensis*," *BioResources* 12(1), 270-282. DOI: 10.15376/biores.12.1.270-282

Ilic, J. (2003). "Dynamic MOE of 55 species using small wood beams," *Holz als Roh- und Werkstoff* 61(3), 167-172. DOI: 10.1007/s00107-003-0367-8

Ištok, I., Sedlar, T., Šefc, B., Sinković, T., and Perković, T. (2016). "Physical properties of wood in poplar clones 'I-214' and 'S1-8'," *Drvna Industrija* 67(2), 163-170. DOI: 10.5552/drind.2016.1604

Keleş, S. Ö. (2021). "Variation in morphological and wood cell traits in coppice stems of *Populus nigra* L. and *Salix alba* L.," *Journal of Forest Science* 67(8), 396-407. DOI: 10.17221/208/2020-JFS

Krauss, A., and Kudela, J. (2011). "Ultrasonic wave propagation and young´s modulus of elasticity along the grain of scots pine wood (*Pinus Sylvestris* L.) varying with distance from the pith," *Wood Research* 56(4), 479-488.

Lang, E. M., Bejo, L., Divos, F., Kovacs, Z., and Anderson, R. B. (2003). "Orthotropic strength and elasticity of hardwoods in relation to composite manufacture part III: Orthotropic elasticity of structural veneers," *Wood and Fiber Science* 35(2), 308-320.

Lang, E. M., Bejo, L., Szalai, J., Kovacs, Z., and Anderson, R. B. (2002). "Orthotropic strength and elasticity of hardwoods in relation to composite manufacture. Part II.

Orthotropy of compression strength and elasticity," *Wood and Fiber Science* 34(2), 350-365.
Lars, K., Morling, T., and Owe, M. (2005). "Wood density, annual ring width and latewood content in larch and Scots Pine," *Eurasian Journal of Forest Research* 8(2), 91-96.
LeBlanc, D., Maxwell, J., Pederson, N., Berland, A., and Mandra, T. (2020). "Radial growth responses of tulip poplar (*Liriodendron tulipifera*) to climate in the eastern United States," *Ecosphere* 11(10), article ID e03203. DOI: 10.1002/ecs2.3203
Liu, F., Xu, P., Zhang, H., Guan, C., Feng, D., and Wang, X. (2019). "Use of time-of-flight ultrasound to measure wave speed in poplar seedlings," *Forests* 10(8), article 682. DOI: 10.3390/f10080682
Lui, M. L., Lui, C. F., and Lui, Y. L. (2019). "Physical and mechanical properties of modified poplar wood by heat treatment and impregnation of sodium silicate solution," *Wood Research* 64(1), 145-154.
Longo, R., Laux, D., Pagano, S., Delaunay, T., le Clézio, E., and Arnould, O. (2018). "Elastic characterization of wood by resonant ultrasound spectroscopy (RUS): A comprehensive study," *Wood Science and Technology* 52(2), 383-402. DOI: 10.1007/s00226-017-0980-z
Mishiro, A. (1996). "Effect of density on ultrasonic velocity in wood," *Mokuzai Gakkaishi* 42(9), 887-894.
Monteiro, S. R. S., Martins, C. E. J., Dias, A. M. P. G., and Cruz, H. (2019). "Mechanical characterization of clear wood from Portuguese poplar," *BioResources* 14(4), 9677-9685. DOI: 10.15376/biores.14.4.9677-9685
Narasimhamurthy, U. V. K., Kushwaha, P. K., and Mohanty, B. N. (2017). "Study on anatomical and mechanical properties of plantation grown *Melia dubia* and *Populus deltoids* and its suitability for plywood manufacturing," *International Journal of Engineering and Technical Research (IJETR)* 7(5), 211-214.
Niklas, K. J., and Spatz, H.-C. (2010). "Worldwide correlations of mechanical properties and green wood density," *American Journal of Botany* 97(10), 1587-1594. DOI: 10.3732/ajb.1000150
de Oliveira, F. G. R., and Sales, A. (2006). "Relationship between density and ultrasonic velocity in Brazilian tropical woods," *Bioresource Technology* 97(18), 2443-2446. DOI: 10.1016/j.biortech.2005.04.050
Özkan, U., Aykanat, O., and Ermeydan, M. A. (2020). "Comparison of physical and mechanical properties of densificated pine and poplar wood with beech wood," *Ağaç ve Orman* 1(2), 13-19.
Papandrea, S. F., Cataldo, M. F., Bernardi, B., Zimbalatti, G., and Proto, A. R. (2022). "The predictive accuracy of modulus of elasticity (MOE) in the wood of standing trees and logs," *Forests* 13(8), article 1273. DOI: 10.3390/f13081273
Rescalvo, F. J., Timbolmas, C., Bravo, R., and Gallego, A. (2020). "Experimental and numerical analysis of mixed I-214 poplar/*Pinus sylvestris* laminated timber subjected to bending loadings," *Materials* 13(14), article 3134. DOI: 10.3390/ma13143134
Roig, F. A., Calderón, A., Naves, N., Somoza, A., Lisi, C. S., and Fo, M. T. (2008). "Poplar wood density assessed by X-Ray densitometry: New insights for inferring wood quality," in: *51st International Convention of Society of Wood Science and Technology*, Concepcion, Chile, pp. 1-8.
Roohnia, M., Yavari, A., and Tajdini, A. (2010). "Elastic parameters of poplar wood with end-cracks," *Annals of Forest Science* 67(4), 409-409. DOI: 10.1051/forest/2009129

Šēnhofa, S., Zeps, M., Matisons, R., Smilga, J., Lazdiņa, D., and Jansons, Ā. (2016). "Effect of climatic factors on tree-ring width of *Populus* hybrids in Latvia," *Silva Fennica* 50(1), article ID 1442. DOI: 10.14214/sf.1442
Sliker, A., and Yu, Y. (1993). "Elastic constants for hardwoods measured from plate and tension tests," *Wood and Fiber Science* 25(1), 8-22.
Sözbir, G. D., Bektas, I., and Ak, A. K. (2019). "Influence of combined heat treatment and densification on mechanical properties of poplar wood," *Maderas. Ciencia y Tecnología* 21(4), 481-492. DOI: 10.4067/S0718-221X2019005000405
Stegemann, D., Raj, B., and Bhaduri, A. (2016). "NDT for analysis of microstructures and mechanical properties of metallic materials," in: *Reference Module in Materials Science and Materials Engineering*, Elsevier, Amsterdam, Netherlands, pp. 1-6. DOI: 10.1016/B978-0-12-803581-8.03429-9
Suleman, Y. H. (2015). "Black poplar (*Populus nigra* L.) wood density variation with tree planting spacing," *Tikrit Journal for Agricultural Sciences* 15(3), 14-18.
TS 2472 (2005). "Wood – Determination of density for physical and mechanical tests, wood, sawlogs and sawn timber," Turkish Standards Institution, Ankara, Türkiye.
Vega, M., Hamilton, M., Downes, G., Harrison, P. A., and Potts, B. (2020). "Radial variation in modulus of elasticity, microfibril angle and wood density of veneer logs from plantation-grown *Eucalyptus nitens*," *Annals of Forest Science* 77(3), article 65. DOI: 10.1007/s13595-020-00961-1
Villasante, A., Vignote, S., Fernandez-Serrano, A., and Laina, R. (2021). "Simultaneous treatment with oil heat and densification on physical properties of *Populus × canadensis* wood," *Maderas. Ciencia y Tecnología* 24(5), 1-12. DOI: 10.4067/S0718-221X2022000100405
Virgen-Cobos, G. H., Olvera-Licona, G., Hermoso, E., and Esteban, M. (2022). "Nondestructive techniques for determination of wood mechanical properties of urban trees in Madrid," *Forests* 13(9), article 1381. DOI: 10.3390/f13091381
Wheeler, E. (2001). "Wood: Macroscopic anatomy," in: *Encyclopedia of Materials: Science and Technology*, K. H. Jürgen, Buschow, R. W. Cahn, and P. Veyssiere (eds.), Pergamon, Oxford, UK, pp. 9653-9657. DOI: 10.1016/B0-08-043152-6/01749-6
Yılmaz Aydın, T., and Aydın, M. (2018a). "Relationship between density or propagation length and ultrasonic wave velocity in cedar (*Cedrus libani*) wood," in: *International Science and Technology Conference*, Paris, France, pp. 531-535.
Yılmaz Aydın, T., and Aydın, M. (2018b). "Effect of density and propagation length on ultrasonic longitudinal wave velocity in some important wood species grown in Turkey," *Turkish Journal of Forestry* 19(4), 413-418. DOI: 10.18182/tjf.459005
Yılmaz Aydın, T., and Aydın, M. (2018c). "Relationship between density or propagation length and ultrasonic wave velocity in sessile oak (*Quercus petraea*) wood," in: *4th International Conference on Advances in Mechanical Engineering*, Yıldız Technical University, İstanbul, Türkiye, pp. 1708-1712.
Zahedi, M., Kazemi Najafi, S., Füssl, J., and Elyasi, M. (2022). "Determining elastic constants of poplar wood (*Populus deltoides*) by ultrasonic waves and its application in the finite element analysis," *Wood Material Science & Engineering* 17(6), 668-678. DOI: 10.1080/17480272.2021.1925962
Zahedi, M., Najafi, S. K., Füssl, J., and Elyasi, M. (2020). "Characterization of engineering elastic parameters of oriented strand board (OSB) manufactured from

poplar (*Populus deltoides*) strands using ultrasonic contact pulse transmission," *Drvna Industrija* 71(3), 227-234. DOI: 10.5552/drvind.2020.1908

Zhang, H., and Lu, X. (2014). "Modeling of the elastic properties of laminated strand lumber," *Wood Research* 59(1), 1-10.

Zhang, Y., Fang, S., Tian, Y., Wang, L., and Lv, Y. (2022). "Responses of radial growth, wood density and fiber traits to planting space in poplar plantations at a lowland site," *Journal of Forestry Research*, *Northeast Forestry University* 33(3), 963-976. DOI: 10.1007/S11676-021-01382-0/TABLES/5

Zhang, Y. J., Feng, D. J., and Duo, Y. G. (2017). "Timber physical and mechanical properties of *Populus pyramidalis* Rozier and *Populus* × *canadensis* cv. 'Regenerata," *Journal of West China Forestry Science* 46(4), 35-38.

Zhou, L., Liu, Q., Ma, S., and Han, X. (2021). "Eccentric compression behavior of long poplar columns externally reinforced by BFRP," *Journal of Wood Science* 67(1), article 2. DOI: 10.1186/s10086-020-01934-8

Ziemiańska, M., and Kalbarczyk, R. (2018). "Biometrics of tree-ring widths of (*Populus* x *canadensis* Moench) and their dependence on precipitation and air temperature in south-western Poland," *Wood Research* 63(1), 57-74.

Ziemiańska, M., Kalbarczyk, R., Chen, J.-R., and Dobrzańska, J. (2020). "Climatic signal in a radial growth of Canadian and Maximovich poplars in south-western Poland," *Scientia Agricola* 77(5), article ID e20180151. DOI: 10.1590/1678-992x-2018-0151

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