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VARIATION IN STEM WOOD DENSITY OF JUVENILE *POPULUS SPP.* CLONES

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Abstract
Wood from *Populus spp.* has been widely utilized in Europe for years. Tree stem density is a crucial aspect of understanding wood quality and mechanical properties such as strength. Density patterns are influenced by the genetic traits of clones and environmental conditions. Stem density mostly tends to increase in the direction from the pith to the bark and decrease from the base toward the top. The research aimed to assess the wood density variations of various poplar clones. Empirical material was obtained from a 12-year-old *Populus spp*. plantation in the eastern part of Latvia. In the spring of 2024, 27 clones were analysed using one randomly chosen, healthy tree from each. The analysis involved measuring tree height and determining the variance of weighted stem density in both radial and longitudinal directions. In total, 881 specimens from crosscut discs were analysed. Despite the variation of mean weighted stem density among *Populus spp*. clones, ranging from 291 kg m^{-3} to 382 kg m^{-3} (mean 320.8 kg m^{-3}), no significant differences were found. While previous research has extensively examined variations in poplar wood density along the stem length, our findings indicate that the average density tends to increase towards the upper part of the stem. Although variation of mean wood density within tree stem relative heights is not statistically significant, there is a significant variation (p=0.03) of mean density at different distances from the pith (radial position). Our study shows that the wood density of poplar clones is highest near the pith, then gradually decreases before increasing again closer to the bark.
Keywords: *Populus spp*., clones, weighted stem density, cross-cut discs, relative height.

Introduction

Sustainable forestry management practices, including short-rotation forestry (SRF), play a crucial role in carbon sequestration and biomass production, aligning with both environmental and economic objectives. Among the tree species utilized in SRF, poplar (*Populus spp*.) is recognized for its rapid growth cycle of 10 to 15 years, high productivity, and versatile wood applications, making it an attractive option for plantation forestry also in Latvia (Šēnhofa et al., 2019). Europe's only native poplar species, the black poplar (*Populus nigra*), has a wide distribution, stretching from the Mediterranean to approximately 64° north latitude, covering areas including Denmark and southern Sweden, but excluding the Baltic region (Vanden Broek, 2003). Although poplar is not indigenous to Latvia, forestry regulations permit its use in forest plantations, and it is currently being cultivated in SRF systems. The introduction of poplars in Latvia began in the early 20th century (Saliņš & Smilga, 1960). Experimental studies have demonstrated that various clones, derived from both European and North American species and their interspecific hybrids, exhibit significant economic potential in the region (Jansons et al., 2014; Adler et al., 2021).

Poplar wood is characterized by its lightness and moderate strength. It has excellent workability, making it suitable for veneer production and plywood manufacturing (Goli et al., 2014). However, its low durability requires treatment for outdoor applications (Md Rowson et al., 2021). Its fine grain and ability to take stains and finishes make poplar popular for furniture, cabinetry, and mouldings (Balatinecz et al., 2001). The high cellulose content and ease of pulping make poplar an essential resource for paper production and packaging materials (Boeva-Spiridonova et al., 2007).

Despite the fact that the main purpose of cultivating short-rotation poplar plantations is for biofuel production, this wood has potential applications in higher value-added products such as plywood, wood panel production, the furniture industry, and bio refineries. Therefore, it is very important to study not only the productivity and suitability of various poplar clones potentially grown in Latvia to local growing conditions but also the wood quality, which would allow evaluating the suitability of this wood for different applications.

The aim of this study is to evaluate the wood density of different poplar clones and the variation of stem-wood density in radial and axial directions. The results of the study will be used to make decisions about the suitability of different clones for various wood utilization purposes.

Materials and Methods

The study site is a poplar plantation located in eastern Latvia (56.716861, 27.681861), established in 2013 on former arable land with sandy loam soil. The plantation was designed as a randomized four-block experiment, consisting of 108 different *Populus spp*. clones, with five trees per clone in each block. The trees were planted in rows at a density of 3 × 3 meters using one-year-old containerized seedlings. Initially, the site was fenced, and ground cover vegetation was treated with herbicides. The soil was prepared through ploughing and continuous cultivation before planting.

In May 2024, when the plantation reached 12 years of age, 27 of the most productive clones were selected for further wood property analysis. Only healthy, undamaged trees (without stem or branching defects) were chosen as sample trees for felling. The study included four hybrid groups:

Populus deltoides×P.trichocarpa (DxT) – 'Belg-B10';

P.maximowiczii×P.trichocarpa (MxT) – ‘Lisa (OP42)’, ‘OP24 (LG)’;
Hybrids of *P. trichocarpa* from the Swedish University of Agricultural Sciences ($T×T_{SLU}$) – ‘SLU-15.8’, ‘SLU-1559’, ‘SLU-20.2’, ‘SLU-21.8’, ‘SLU-21.9’, ‘SLU-23.4’, ‘SLU-23.5’, ‘SLU-23.6’, ‘SLU-230’, ‘SLU-25.5’, ‘SLU-25.6’, ‘SLU-26.1’, ‘SLU-27.8’, ‘SLU-44.13’, ‘SLU-59.3’, ‘SLU-66.4’, ‘SLU-72.9’, ‘SLU-722.16’;
Clones from natural *P.trichocarpa* populations (T) – ‘SRF-2’, ‘SRF-20’, ‘SRF-21’, ‘SRF-45’, ‘SRF-47’, ‘SRF-68’.

Each tree stem was divided into sections of different lengths, starting from the base and extending toward the top of the tree. In total, 7 to 8 wooden discs were taken from each tree. The positions of the discs along the stem represented different height levels: 10%, 30%, 50%, 70%, and 90%, as well as at 0.2 m (stump height), 1 m, and 1.3 m above the root collar. All sawn discs were 2 to 3 cm thick. The sample discs were transported to LSFRI Silava for further basic density analysis.

The extraction of the wooden specimens necessary for the study was carried out according to methodology described in Liepiņš et al. (2018). Initially, each cross-sectional disc diameter was measured along two perpendicular directions (diameter with bark). This was followed by the preparation of specimens from cross-sectional wooden discs, as shown in Figure 1. The number of specimens obtained from a single disc depended on its radius. Each specimen had a width of 20 mm.

Not only wooden specimens but also bark specimens were obtained, with the last wooden specimen being debarked. If the last wooden segment was less than 5 mm wide, it was not separated as an individual specimen but combined with the previous one. If the diameter of the analysed cross-sectional disc was less than 2 cm, it was not divided into separate segments - only debarked (resulting in one wood and bark segment). If the cross-sectional diameter was less than 5 mm, the basic density analysis was conducted with the bark. All specimens were assigned an individual code, and it was crucial to avoid including knots and wood defects in them. In total, 668 wood and 213 bark specimens were obtained from 215 cross-cut discs.

Subsequently, all wooden specimens were immersed in water for 24 hours. This was followed by density measurements using Precisa XB 220A scales, equipped with a density measurement set (Precisa, Part No: 350–8556). The specimens were then oven-dried at 103–105 °C for a minimum of five days until a constant weight was reached to calculate basic density. The dry weight was measured immediately after removing the specimens from the oven.

The equation by Liepa (1996) was used to calculate the volume of each sample tree.

The basic density of the wooden specimens was determined by calculating the ratio of the specimen’s dry mass to its green volume.

Figure 1
Preparation of basic density specimens from sample discs

The average density of each cross-sectional disc, based on the wooden and bark specimens and their corresponding areas on the cross-sectional disc, was calculated using equation (1):

$$\rho_{disc} = \frac{S_1 \times a_1 + S_2 \times a_2 + S_n \times a_n + S_b \times a_b}{a_1 + a_2 + a_n + a_b} \quad (1)$$

where ρ_{disc} is cross-sectional wooden disc average basic density, g cm^{-3}; S_1, S_2, S_n are wooden specimen basic density g cm^{-3}; S_b – bark specimen basic density g cm^{-3}; a_1, a_2, a_n is area occupied by wood specimen in a cross-sectional disc cm^2; a_b – area occupied by bark wood specimen in a cross-sectional disc cm^2.

The weighted average formula (Equation 2) was applied to determine the mean density of each sample disc with bark, based on the specimens and their respective areas. The weighted density values from the sample discs were used to illustrate the axial variation in stem density. The density of each stem section was averaged using the values from the cross-sectional discs at both ends of the section, except for the top segments, where the density of the base sample disc was utilized (Liepiņš et al., 2017).

$$Weighted\ Average\ Density = \frac{\sum_{i=1}^{n}(D_i \times V_i)}{\sum_{i=1}^{n} V_i} \quad (2)$$

where D_i – density of wood/bark specimens, g cm^{-3}; V_i – volume of stem section m^3; n – number of different specimens.

The volume of each stem segment (located between two sample discs) was calculated using Smalian’s formula (Equation 3):

$$V_{si} = \frac{l_{si}(g_{1i} + g_{2i})}{2} \quad (3)$$

where V_{si} – volume of stem section, m^3; l_{si} – length of stem section i, cm; g_{1i} – lower surface’s cross-sectional area of an ellipse of section i, mm^2; g_{2i} – upper surface’s cross-sectional area of an ellipse of section i, mm^2; g – cross-sectional area of an ellipse, m^2.

The normality of the data distribution was tested using the Kolmogorov-Smirnov test, which confirmed that the dataset did not follow a normal distribution. Consequently, the Kruskal-Wallis test was employed to determine statistically significant differences between the mean values.

Results and Discussion

This study examines the wood density of various poplar clones at a juvenile age (density data represented in 'Figure 2', with analysis conducted on a single tree per clone. The highest stem density was observed for 'SLU-26.1' - 382 kg m^{-3}, while the lowest was for 'Belg-B10' - 291 kg m^{-3}, indicating moderate variations among the studied clones. While the findings provide initial insights into clone-specific variations in wood density, the limited sample size presents significant constraints on data interpretation. The results may not fully capture intra-clonal variability, as factors such as environmental influences and growth conditions could lead to variations within the same clone (Pliura et al., 2007; Nielsen et al., 2014; Karacic et al., 2021). Additionally, analysing only one tree per clone restricts the ability to draw broader conclusions about the species or to establish statistically robust comparisons. There is a need for multiple density measurements due to significant within-stem variations in basic density based on measurement height and radial position.

The economic and technological feasibility of poplars largely depends on having a reliable feedstock supply and maintaining its quality characteristics. In Sweden, poplar feedstock is combined with other tree species during the pulping process, while its tops and branches serve as fuel in combined heat and power plants (Karacic et al., 2021). Heat and power plants have been promoted to use biomass as an energy source through lower taxes on biomass compared to fossil fuels. Along with the widespread use of firewood for household heating, woody biomass already plays a significant role in the Scandinavian energy sector (Nielsen et al., 2014).

Since the beginning of poplar plantation cultivation, these trees have primarily been used for producing wood for mechanical pulp and plywood. However, in recent years, their use in solid wood products has also been explored (Pliura et al., 2007). Fast-growing species like poplar are widely used for pulp production due to their high cellulose (>50%) and low lignin (<20%) content, ensuring a steady fibre supply for the pulp industry. Additionally, poplars require less bleaching due to their naturally light-coloured wood.

Wood density have outright impact on the fibre elasticity. The characteristics of pulp are closely linked to wood density. Low-density wood produces paper with high sheet density and strong tensile, bursting, and folding properties (Balatinecz & Kretschmann, 2001b; Yadav et al., 2022). In our study, 'Belg-B10', 'SLU-23.5', 'SLU-72.9' and 'Lisa', 'OP42' exhibited lower densities (291, 296, 298, 302 and 303 kg m^{-3}, respectively), making them potentially more suitable for paper and pulp production. In contrast, kraft pulp, used for making strong cardboards and paper, can benefit from higher-density raw material. Adler et al. (2022) highlight the potential for poplar biomass cultivation on marginal lands for the production of biomaterials and biofuels. Poplar wood is also a sustainable raw material for producing cellulose fibres, such as viscose, which is used in textile manufacturing. Fibre production from poplar in Northern Europe could replace 42% of global cotton production while also contributing 5.2 million m^2 of biofuel annually.

Mean density of poplar wood varies widely between clones. While some have low density of around 300 kg m^{-3}, others can reach even 600 kg m^{-3} (Balatinecz et al., 2014). Poplar wood stiffness and bending strength can be compared to species like pine and spruce (Balatinecz & Kretschmann, 2001b). For plywood and veneer production, poplar clones with density of at least 300 kg m^{-3} should be selected (Balatinecz et al., 2014). In the current study, almost all clones met this requirement. However, the following clones exhibited higher density values: 'SLU-26.1', 'SLU-21.9', 'SLU-21.8', 'SLU-1559', with densities, 382, 363, 348, 347 kg m^{-3}, respectively. These characteristics make them more suitable for applications in furniture, construction, and bioenergy.

In Latvia, one of successfully used poplar clones for bioenergy is *P.maximowiczii* × *trichocarpa* known as 'OP42' (*Populus trichocarpa* × *Populus maximowiczii*). Its propagation does not require royalty payments, and it demonstrates promising biomass growth increments under short-rotation forestry management, which maintains high interest in this clone. Liziniewicz (2023) reports that the wood density of 'OP42' clone is around 354 kg m^{-3}, while in our research it was lower – 303 kg m^{-3} ('OP42'), 302 kg m^{-3} ('Lisa').

The mean weighted stem density among different origin groups varies from 270 to 340 kg m^{-3} Figure 3.

The highest mean weighted stem density was observed for TxT group (hybrids of *P.trichocarpa* from Swedish University of Agricultural Sciences) – 325 kg m^{-3}, followed by T group (clones from individuals from natural *P.trichocarpa* populations) – 319 kg m^{-3}, the MxT group (*P.maximowiczii x P.trichocarpa*) – 302 kg m^{-3} and the DxT (*P.deltoides x P.trichocarpa*) - 291 kg m^{-3}. TxT and T groups have the highest stem densities, suggesting that these origin groups produce denser wood. There are no significant differences between the mean densities of different origin groups ($p>0.05$).

Nielsen et al. (2014) reported a high mean stem density of 365 kg m^{-3} for the *P. trichocarpa* x *P. deltoides* origin group in 13-year-old poplar clones. In our study, this specific group was the least represented, with only one clone ('Belg-B10'), which had a weighted stem density of 291 kg m^{-3}.

To improve data interpretation, additional data is needed - either more clones from this origin group or more investigated trees from the 'Belg-B10' clone.

The variation in wood density along the height of the tree must be considered when selecting parts of the tree for different applications.

Figure 2
Weighted stem density of analysed 27 Populus spp. clones (Horizontal line represents mean stem density of all analysed clones)

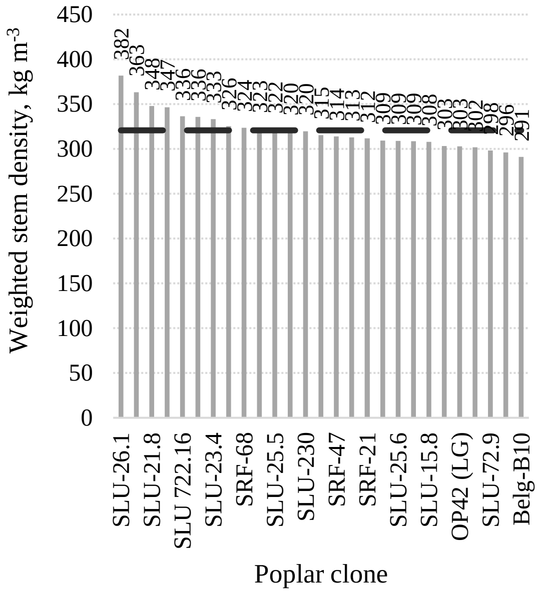
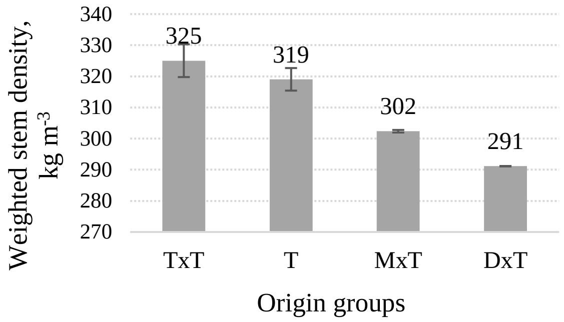


Figure 3
Weighted stem density by origin groups of analysed Populus spp. clones (Whiskers denote ± standard deviation intervals)



The highest density is found at the top of the tree, or 90% height level, 338 kg m^{-3}, while the lowest density occurs in the lower-mid section, or at the 10% and 30% height levels, 316 kg m^{-3} (Figure 4). Although the variation in mean wood density across relative stem heights is not statistically significant (p>0.05), a significant variation (p=0.03) in mean density was found at different distances from the pith (within tne radial position).

This confirms that wood density increases toward the top. The upper parts of the tree are typically exposed to stronger winds and environmental stresses, which may influence their structure, making them denser in some tree species to withstand these forces. Although the variation in mean wood density across relative stem heights is not statistically significant (p>0.05), a significant variation (p=0.03) in mean density was found at different distances from the pith (within the radial position).

Figure 4
Wood density at six relative heights and at stump height (Whiskers denote ± standard deviation intervals. Horizontal line represents the estimated mean of wood density in the entire stem)

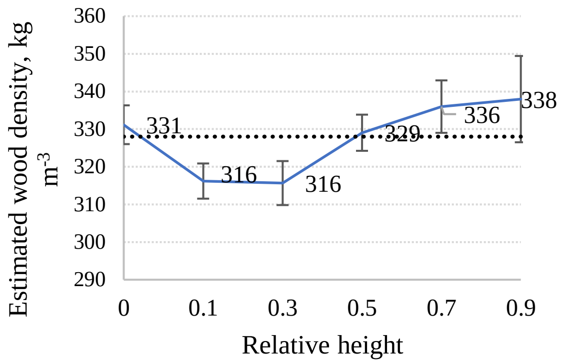
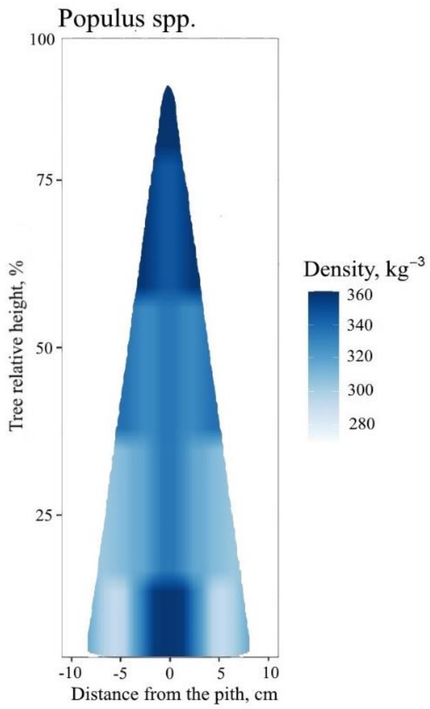


Figure 5
Variation in stemwood density of Populus spp



Ištok et al. (2016) and Kord et al. (2010) report that poplar tree density tends to decrease from the base upwards the stem, and increase from the pith toward the bark. This statement is partially contradictory to the results of the current study. Higher wood density was found in the upper part of poplar trees and at the pith of the stem base, similar to the findings of Pliura et al. (2007) and Taeroe et al. (2015).

A radial density pattern was observed at the stem base level - density decreased from the pith to the bark. However, from the middle of the tree to the top, wood density decreased in the opposite direction, from bark to pith Figure 5. Nevertheless, our study’s findings on radial density variations align with Einspahr et al. (1972), who reported that *P. tremuloides* wood density is highest near the pith, followed by a slight decrease before increasing again closer to the bark. Kord et al.

(2010) also noted that wood density may increase from the pith to the bark as the tree ages, since juvenile wood typically has a lower density than mature wood. A similar tendency is described for axial variation. Wood density varies not only within the tree stem but also due to multiple factors, including tree age, growing density, environmental conditions such as precipitation, temperature. Petráš et al. (2010) confirms that poplar wood density increases with tree age.

For the trees we measured, the stem diameter at breast height (DBH) ranged from 8.6 to 20.3 cm (mean 13.9 cm), while tree height varied from 13.3 to 19.6 m (mean 16.7 m). Tree volume ranged from 0.04 to 0.31 m^3 (mean 0.13 m^3). Liziniewicz (2023) describes a low correlation between diameter and wood density in hybrid aspen and poplars. Similarly, in our study, the correlation between DBH, tree height and wood density was very weak and statistically insignificant.

Conclusions

1. The highest density was recorded for 'SLU-26.1' (382 kg m^{-3}), and the lowest for 'Belg-B10' (291 kg m^{-3}). However, analysing only one tree per clone limits the ability to fully capture intra-clonal variability. Clones with lower density, such as 'Belg-B10' and 'OP42', may be preferable for pulp and paper production due to their impact on fibre elasticity. Meanwhile, higher-density clones like 'SLU-26.1' and 'SLU-21.9' are more suitable for plywood, veneer and solid wood products.
2. Our study reveals that the wood density of poplar clones is highest near the pith, then slightly decreases before increasing again closer to the bark. Despite extensive prior research on poplar wood density variation along the stem, our findings indicate that mean density increases toward the top of the tree. As density variation increases with tree age, it is important to analyse stands of different ages in the future studies and expand the sample size to improve data accuracy.

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