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WOOD DENSITY IN EUROPEAN LARCH (*LARIX DECIDUA* MILL.) FROM SELECTED PROVENANCES GROWN AT THE SIEMIANICE FOREST EXPERIMENTAL STATION

The purpose of this study was to determine variation in the density of wood from different provenances, growing under the same soil and climate conditions. Samples were obtained from an experimental site located at the Siemianice Forest Experimental Station. We analyzed larch wood samples from trees aged 48 years, collected from six different provenances in Poland. Diameter at breast height (DBH) and tree height were used to calculate the parameters for sample trees, from which a 70 cm segment was cut, from breast height upwards (up to 2 m of tree height). Samples with dimensions 20 × 20 × 30 mm were obtained from the material. Sample volume was determined by stereometry. Relative density was determined for 890 samples. The highest wood density was found in trees from Czerniejewo, and the lowest in trees from Rawa Mazowiecka. Analysis of variance, including the mean wood density values of trees, did not demonstrate significant differences between provenances in terms of this characteristic. Mean relative density was higher in larch wood samples from the heartwood zone. The density of samples cut closer to the bark was lower, as the value was affected by the large content of sapwood. A relation was found between the provenances from which the study material was sourced and the relative density of wood.

Keywords: physical properties of wood, genetic variability, coniferous wood, sapwood, hardwood, provenance

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Introduction

Modern forest management faces the difficult task of reconciling higher production with the maintenance of wood quality [Bartoszczuk et al. 2009]. This may be facilitated by provenance research, aiming at identifying populations with the most favorable characteristics within each tree species. Knowledge on the adaptation of trees from various provenances to specific habitat conditions is equally important. Long-term provenance research at experimental sites allows assessment of the adaptation of tree provenances to local climate conditions, which is increasingly important in times of climate change [UNECE/FAO 2011]. Large-scale studies on provenance have been conducted, among other species, on pine [Oleksyn and Fritts 1991; Oleksyn et al. 1993], Douglas fir [Eilmann et al. 2013; Sergent et al. 2014], and larch [Oleksyn and Fritts 1991; Oleksyn et al. 1993; Szeligowski 2001; Wilczyński and Kulej 2013]. For larch, provenance studies have provided valuable findings regarding the spatial variability of the species [Serre 1978; Eckstein and Aniol 1981; Feliksik 1992; Feliksik and Wilczyński 1998a, b; Carrer and Urbinati 2004, 2006; Danek 2009; Wilczyński 2010; Danek and Danek 2011; Koprowski 2012; Bijak 2013; King et al. 2013; Wilczyński et al. 2014; Vitas 2015; Tumenjargal et al. 2020]. Research on variation in the structure of wood from other species indicates a strong impact from genetic factors, as well as from the environment and forestry practices, on the wood forming process [Zobel and Talbert 1984; Zobel and Jett 1995; Vaganov et al. 2006; Schweingruber 2007; Szaban et al. 2014b; Michalec et al. 2020].

Larch is among the most economically valuable coniferous forest-forming tree species in Europe. Its greatest advantages include a high yield of quality wood and rapid growth of wood mass [Büntgen et al. 2005]. Compared with other species, it also has relatively modest habitat requirements. Larch is typically an addition to multi-species tree stands in fresh deciduous forest, fresh mixed forest, and sometimes fresh coniferous forest habitats, enhancing their quality [Chylarecki 2000]. It is found in small, spatially scattered, and isolated areas. In past centuries, larch migration was influenced by artificial spread associated with forest management [Rożkowski et al. 2011]. It is a boreal, highly light-demanding, pioneer species. It is distinguished by rapid growth [Bruchwald and Zasada 2010], high wood quality [Spława-Neyman et al. 1997; Szaban et al. 2013a, 2013b], and high resistance to air pollution [Karolewski and Białobok 1979; Feliksik 1991]. In Poland, two larch subspecies are important for forest formation: the European larch, *Larix decidua* Mill. subsp. *decidua*; and the Polish larch, *Larix decidua* Mill. subsp. *polonica* (Racib.) Domin [Mirek et al. 2002].

Larch wood has a higher density [Petras et al. 2019] and higher resin content in the heartwood than Scots pine or European spruce [Bergstedt and Lyck 2007]. Wagenführ [2007] reports that the density of larch wood varies between 400 and

820 kg·m^{-3}. This significant variation in wood density indicates that population variability between provenances may be expected in the species. Research on wood density is important, as this basic physical property of wood affects most of its strength characteristics, which are fundamental for larch wood buyers.

The purpose of our study was to determine variation in the density of wood from different provenances, growing under the same soil and climate conditions at the Siemianice Forest Experimental Station.

Materials and methods

Material for the study was collected from the Siemianice Forest Experimental Station (E 18°19'46,90", N 51°21'00,12"; Fig. 1). The analysis included European larch wood samples from trees aged 48 years, collected from six different Polish provenances and grown on a common site.

Fig. 1. Experimental site and provenance locations in Poland: 1 – Konstancjewo--Płonne, 2 – Czerniejewo, 3 – Rawa Mazowiecka, 4 – Skarżysko, 5 – Bliżyn, 6 – Krościenko; ⚲ - location of the experimental site at the Siemianice Forest Experimental Station

The experimental site from where the wooden samples were taken was established in 1966 in a fresh mixed-coniferous forest, on podsolic soils with weakly loamy sands. European larch seedlings (*Larix decidua* Mill.) were grown on the site from seeds originating from selected Polish provenances. The area on which the seedlings were planted was flat, uniform in terms of the type of soil, and having the same moisture content throughout the area. The seedlings were

planted in five replications, i.e. each provenance was represented in five plots. The trees were planted with the same spacing, thus the conditions for tree growth were the same for all origins. The analysis included wood from six provenances, growing on the experimental site (Fig. 1). The provenances were numbered as follows:

- Konstancjewo-Płonne – P1,
- Czerniejewo – P2,
- Rawa Mazowiecka – P3,
- Skarżysko – P4,
- Bliżyn – P5,
- Krościenko – P6.

Diameter at breast height (DBH) and tree height were used to calculate the parameters for sample trees, which were then selected at random. From each tree felled for analysis, a 70 cm segment was cut, from breast height upwards (up to 2 m of tree height). Due to the axial variation in density, the segments were collected at the same height from each tree. The northern direction was marked on the segments, as samples were obtained from a board sawn along the north--south axis. Two strips, 700 mm long and with a cross section of 20 × 20 mm, were cut from each board, and then used to prepare classic 20 × 20 × 30 mm samples for density testing in accordance with the ISO 13061-2 standard. Samples from the strip closer to the pith were marked I, and those from the strip farther from the pith were marked II (Fig. 2). Samples with defects (knots, cracks, rot) or with fibers not parallel to the axis of the sample were rejected. From each segment 20 samples were obtained: 10 from wood closer to the pith (I) and 10 from wood farther from the pith (II). An exception was provenance 5, from which only 5 trees were collected, and thus the number of samples per tree was increased to 30 (15 samples from strip I and 15 from strip II).

Sample volume was determined by stereometry. Samples were immersed in distilled water for 48 hours until maximum swell was reached. After drying, the samples were measured using a manual caliper with a precision of 0.05 mm. Subsequently, the samples were dried at 103 ±2°C until no weight loss was recorded, in accordance with Williamson and Wiemann's [2010] guidelines on drying temperature. Dried samples were weighed using Sartorius Basic electronic scales with a precision of 0.01 g. Relative density was calculated using the following formula:

$$\rho = \frac{m_0}{V_{max}}$$

where:
ρ is the relative density [g cm^{-3}],
m_0 is the dry sample weight [g],
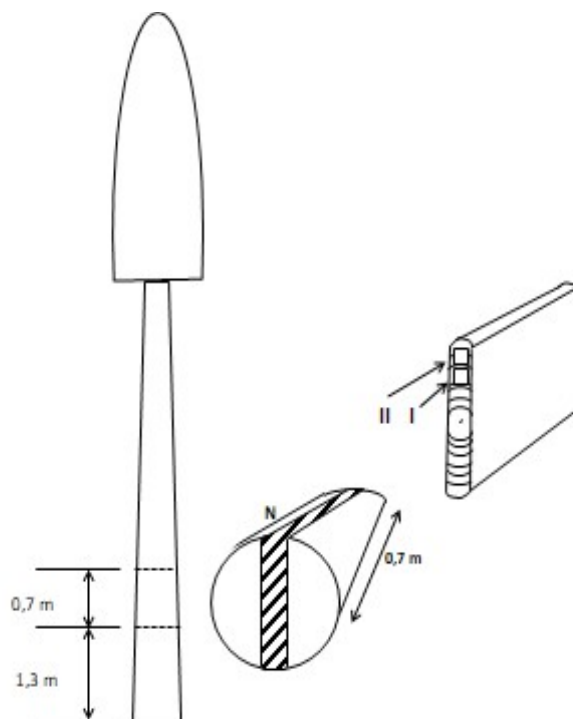V_{max} is the sample volume in the state of maximum swell [cm^3].

Fig. 2. Sampling method for larch wood density testing. N – north. I and II – designation of strips from which the samples were taken

Relative density was determined for 890 samples from 6 provenances. The number of samples per provenance was not equal, and depended on the number of trees collected (Table 1).

Impact of provenance on wood density was analyzed using a model including the random effect of the tree and the number of measurements made (10 or 15 measurements per strip). The analysis of unbalanced data was performed for the linear mixed model using residual/restricted maximum likelihood (REML) analysis. Analysis using the REML algorithm, which estimates the variance components using residual maximum likelihood, provided corrected mean density values for all provenances. To verify hypotheses on the significance of fixed effects, t-tests were performed using the Satterthwaite method [lmerModLmerTest], and the conclusions were confirmed using the likelihood-ratio and permutation tests, which were also used to test the significance of random effects. The same methodology was used to test the radial variation of density, and the impact of distance between the sample and the pith on mean wood density in the studied trees. A significance level of 0.05 was used for inferences. A value of $N = 1000$ was used for the permutation tests.

Analyses were performed using R 3.5.2 software with the lmerTest, lme4, and lattice packages.

Results and discussion

Impact of provenance on the relative density of larch wood

Considering all measurements together for each provenance, and disregarding the effect of the tree and sample location (strip I or II), the highest wood density was found in trees from P2 (0.506 g·cm^{-3}), and the lowest in trees from P3 (0.461 g·cm^{-3}) (Table 1).

Table 1. Measures of position for the relative density of wood from the analyzed provenances

Provenance	N of valid measurements	Minimum	Mean	Median	Maximum	Standard deviation	Variation coefficient
		(g cm^{-3})					(%)
1	140	0.352	0.470	0.470	0.589	0.050	11
2	160	0.394	0.506	0.510	0.624	0.050	10
3	160	0.368	0.461	0.450	0.685	0.051	11
4	140	0.376	0.475	0.468	0.618	0.042	9
5	150	0.379	0.486	0.475	0.629	0.049	10
6	140	0.418	0.497	0.496	0.593	0.032	6

The lowest relative density values were found for a sample from P1 (0.352 g cm^{-3}) and for a sample from P3 (0.368 g·cm^{-3}). The highest relative density values were found for a sample from P3 (0.685 g·cm^{-3}) and for a sample from P5 (0.629 g·cm^{-3}). The highest standard deviation was found for P3 (0.051 g·cm^{-3}). Similar values were also found for two other provenances, P1 and P2, for which the standard deviation was 0.050 g·cm^{-3}. The lowest standard deviation was found for P6 (0.032 g·cm^{-3}). The coefficient of variation was the highest (11%) for P1 and P3 (Table 1).

Analysis of variance including the mean wood density values of trees did not demonstrate significant differences between provenances in terms of this characteristic (p = 0.0788) (Fig. 3).

Findings from our study partly confirm those from previous studies performed at the same experimental site by Spława-Neyman et al. [1997]. These authors determined, among other things, the provenances of larch that produce the highest wood density. Their list of best provenances is similar to that
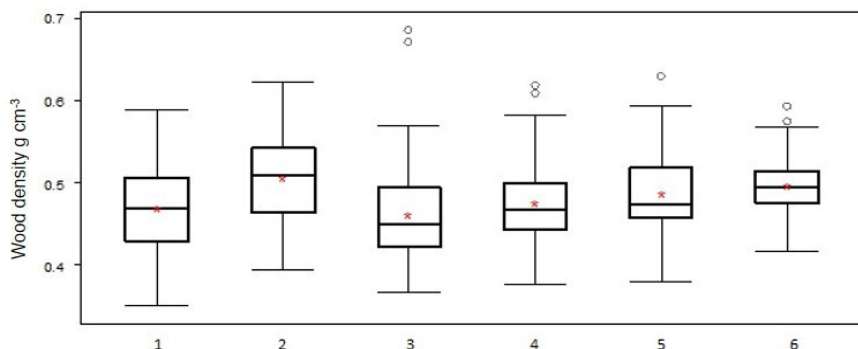
Fig. 3. Distribution of larch wood densities for the studied provenances at the Siemianice Forest Experimental Station (midline of box – median, * – mean, lower border of box – 25th percentile, upper border of box – 75th percentile, upper whisker – largest value within 1.5 times interquartile range above 75th percentile, lower whisker – smallest value within 1.5 times interquartile range below 25th percentile, ° – outlier: value is > 1.5 times and < 3 times interquartile range beyond either border of the box)

established in the present study. Only P1 had a higher place in the wood density ranking. Slightly different results for wood from this site had been presented by Miler and Rzeźnik [1982]. Their rankings for wood density differed from the present ones. Notably, however, those authors collected samples from 12-year-old trees and did not report the number of trees cut from the site.

The present findings also confirmed the rankings in terms of other larch wood characteristics. Szaban et al. [2014a] obtained the same ranking of provenances with respect to modulus of elasticity. The present findings also strictly correspond to those from previous studies in terms of compressive and bending strength [Szaban et al. 2013a, b].

Impact of provenance on the radial variation of relative wood density

Mean relative density was higher in larch wood samples from strips cut closer to the pith (strip I). For all the sampled trees, their mean density was 0.488 g·cm^{-3}. Mean density for samples from the strip cut farther from the pith (II) was 0.475 g·cm^{-3}. The highest density for an individual sample, 0.685 g·cm^{-3}, was found in a sample from strip I. Values calculated for samples from strips cut farther from the pith had a slightly higher spread, with a standard deviation of 0.049 g·cm^{-3}. In both cases (samples from strip I and II) the coefficient of variation was 10% (Table 2).

An initial analysis of these measurements revealed considerable differences in the radial distribution of wood density values between individual trees within a location (Fig. 4).

Table 2. Statistical characteristics for radial variation of relative density

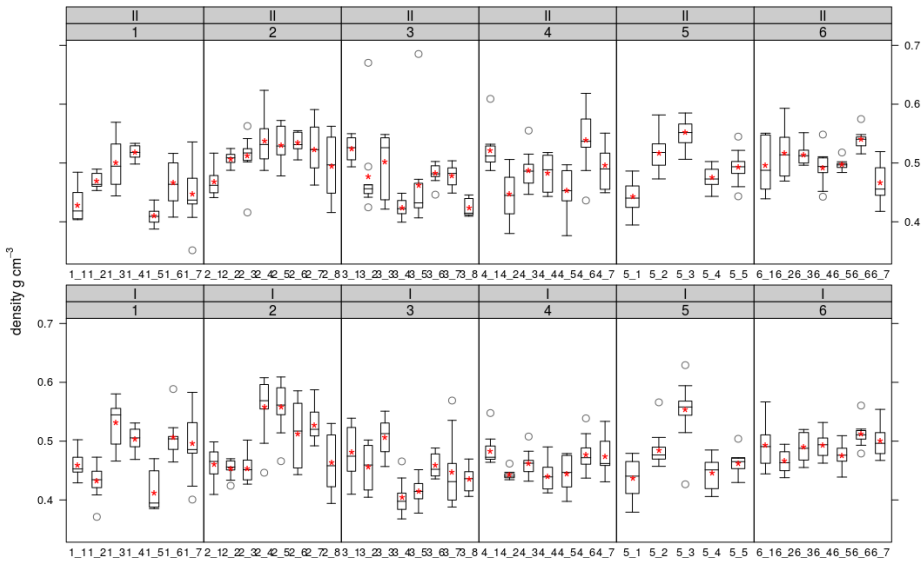| Distance from pith	N of valid measurements	Mean	Minimum	Maximum	Median	Standard deviation	Variation coefficient
				(g·cm⁻³)			(%)
I	445	0.488	0.352	0.685	0.492	0.048	10
II	445	0.475	0.368	0.629	0.469	0.049	10

Fig. 4. Radial variation in the density of larch wood from provenances at the Siemianice Forest Experimental Station (I and II – sample position by distance from pith, in ascending order; 1, 2, 3 – provenance number; 1_1, 1_2, 1_2 – individual trees in a provenance) (midline of box – median, * – mean, lower border of box – 25th percentile, upper border of box – 75th percentile, upper whisker – largest value within 1.5 times interquartile range above 75th percentile, lower whisker – smallest value within 1.5 times interquartile range below 25th percentile, ° – outlier: value is > 1.5 times and < 3 times interquartile range beyond either border of the box)

For samples from strip I, closer to the pith (Fig. 4), the random effect of the tree is $\hat{\sigma}_T^2 = 0.0012$; that is, 52.6% of the total variance (0.0023, the sum of the estimates of the variance component between the trees and the residual variance component) in wood density was associated with the individual tree. This confirms observations made by visual inspection of the above diagram (Fig. 4). The highest density in samples from strip I was found for P2 (0.4980 g·cm⁻³), and the lowest for P3 (0.4504 g·cm⁻³) (Table 3).

Table 3. Mean relative densities of larch wood for the different provenances and positions within the cross-section (strip I – closer to the pith; strip II – farther from the pith)

Provenance	Strip I	Strip II
	Mean wood density (g·cm^{-3})	
1	0.4769	0.4626
2	0.4980	0.5131
3	0.4504	0.4716
4	0.4605	0.4892
5	0.4759	0.4955
6	0.4898	0.5028

Significance tests for fixed effects produced consistent results. None of these tests confirmed a significant difference in wood density between provenances (the p-values for the likelihood-ratio test and permutation test were 0.0838 and 0.0920 respectively). However, the results show that σ_T^2 variance is significantly different from zero, and therefore, the effect of trees should be considered significant (p-values of < 0.05 in both tests).

For samples cut farther from the pith (containing sapwood), variance in density due to the effect of the tree was $\hat{\sigma}_T^2 = 0.0009$ (p-values < 0.05 in both tests), and accounted for 44.2% of total variance (0.0021) in wood density. In this case, the effect of location was statistically significant, as confirmed by all of the tests performed (the p-values for the likelihood-ratio test and permutation test were 0.0262 and 0.0240 respectively). The highest density was found in wood from provenance 2 (0.5131 g·cm^{-3}) and the lowest in wood from provenance 1 (0.4626 g·cm^{-3}). Contrast analysis showed significant differences between locations 1 and 2 (p = 0.0049), 1 and 6 (p = 0.0268), and 2 and 3 (p = 0.0152) (Table 4).

The above analyses were used as a basis for formulating a ranking list of the best provenances, yielding wood with the highest relative density: 1. Czerniejewo (P2), 2. Krościenko (P6), 3. Bliżyn (P5), 4. Skarżysko (P4), 5. Konstancjewo-Tonkowo (P1), 6. Rawa Mazowiecka-Trębaczew (P3).

In all provenances, the mean density of samples cut farther from the pith was lower than that of samples cut closer to the pith. These findings regarding variation in density throughout the cross-section seem inconsistent with the thesis regarding the relationship between wood density and position within the cross-section. Samples used in our study were collected from the peripheral part of the cross-section and from an area between the peripheral layer and the pith.

Table 4. Assessment of difference in mean density between samples cut farther from the pith (strip II) from the different provenances (t-test and Satterthwaite's method were used to evaluate the statistical significance of contrast) (* – statistically significant values)

Prove-nance	1		2		3		4		5	
2	0.0505	0.0049**								
3	0.0090	0.5972	-0.0415	0.0152*						
4	0.0266	0.1357	-0.0239	0.1644	0.0176	0.3041				
5	0.0329	0.0900	-0.0176	0.3445	0.0239	0.2014	0.0063	0.7390		
6	0.0402	0.0268*	-0.0103	0.5447	0.0312	0.0724	0.0136	0.4390	0.0073	0.0702

The density of samples cut closer to the bark is lower, as the value was most likely affected by the large content of sapwood in the sample, while samples cut closer to the pith were composed of heartwood only. The trend of radial variation in wood density, observed in our comparison of wood from different provenances, where density decreases as distance from the pith increases, is likely to become stronger in older trees.

The provenance of the seeding material does have an impact on wood properties, but effects of other factors cannot be excluded. Both the habitat, particularly abandoned agricultural land as opposed to forest stands on standard forest soils [Cukor et al. 2020], and a number of other external factors have a significant impact on tree growth. Initial spacing and forestry practices are major factors. Genes inherited by the trees may predispose them to absorb and use nutrients, affecting the formation of wood, or to react in specific ways to a variety of external factors. The structural variability of individual trees is also large, which affects their further growth and development [Jelonek et al. 2019], giving them the appropriate biosocial standing [Wertz et al. 2020].

An understanding of the variability of larch wood in Poland will enable the selection of populations so as to guarantee the most desirable quality of wood material produced [Szeligowski 2001; Wilczyński and Kulej 2013]. Periodically repeated studies in experimental sites provide data on the properties of wood obtained from trees of specific ages. For this study, trees of pre-felling age were used. One may assume that the wood will continue to exhibit variability, and that other factors will also affect the characteristics of interest in the future. These factors include, for example, variation in the proportions of earlywood and latewood, typical for coniferous tree wood [Wąsik et al. 2020], and differences in peak increment between provenances. Axial variation in wood density is also important: in some conifers it is greater within a single trunk than between individuals from a given stand, as shown in a study on fir wood density [Ochał

et al. 2018]. Therefore, material from valuable and unique experimental sites should be further analyzed in subsequent periods.

Conclusions

- A relation exists between the provenances from which the study material was sourced and the relative density of wood.
- Mean relative density was highest for larch wood from provenance 2 (Czerniejewo), and lowest for wood from provenance 3 (Rawa Mazowiecka).
- Our study provides a basis for formulating a "ranking list" of the best provenances of larch in Poland, yielding wood with the highest density: 1. Czerniejewo (2), 2. Krościenko (6), 3. Bliżyn (5), 4. Skarżysko (4), 5. Konstancjewo-Tomkowo (1), and 6. Rawa Mazowiecka-Trębaczew (3).
- The relative density of larch wood was found to vary depending on its position within the cross-section of the trunk. Wood from the peripheral part, with a high share of sapwood, had lower relative density than wood sampled closer to the pith, which was composed of heartwood.
- Differences in relative density of wood between the studied provenances were found only for samples from the outer layers of the trunk.
- Continued research on provenance is warranted, with a view to selecting the provenances that produce wood material of the highest quality. In times of increasingly visible climate change, new provenance studies should be planned, so as to investigate the adaptive capabilities of trees from various locations.

References

Bartoszczuk P., Budna E., Grzybowska L. [2009]: Leśnictwo 2009. Informacje i opracowania statystyczne (Forestry 2009. Information and statistics). Zakład Wydawnictw Statystycznych, Warszawa

Bergstedt A., Lyck C. [2007]: Larch wood – a literature review. Forest & Landscape Working Papers 23-2007. Forest & Landscape, Denmark

Bijak S. [2013]: Sygnał klimatyczny w przyroście radialnym wybranych iglastych gatunków drzew (Climate signals and radial increment in selected coniferous tree species). Leśne Prace Badawcze 74 [2]: 101-110

Bruchwald A., Zasada M. [2010]: Model wzrostu modrzewia europejskiego (*Larix decidua Mill.*) (European larch (*Larix decidua Mill.*) growth model). Sylwan 9: 615-624

Büntgen U., Esper J., Frank D.C., Nicolussi K., Schmidhalter M. [2005]: A 1052-year tree-ring proxy for Alpine summer temperatures. Climate Dynamics 25: 141-153

Carrer M., Urbinati C. [2004]: Age-dependent tree-ring growth response to climate in *Larix decidua* and *Pinus cembra*. Ecology 85: 730-740

Carrer M., Urbinati C. [2006]: Long-term change in the sensitivity of tree-ring growth to climate forcing in *Larix decidua*. New Phytologist 170: 861-872

Chylarecki H. [2000]: Modrzewie w Polsce. Dynamika wzrostu, rozwój i ekologia wybranych gatunków i ras (Larch in Poland. Growth dynamics, development and

ecology of selected species and breeds). Bogucki Wydawnictwo Naukowe S.C. Warszawa

Cukor J., Zeidler A., Vacek Z., Vacek S., Šimůnek V., Gallo J. [2020]: Comparison of growth and wood quality of Norway spruce and European larch: effect of previous land use. European Journal of Forest Research 139: 459-472

Danek M. [2009]: Wpływ warunków klimatycznych na szerokość przyrostów rocznych modrzewia (*Larix decidua* Mill.) rosnącego w północnej części województwa małopolskiego (Impact of climate conditions on the size of annual increments in larch (*Larix decidua* Mill.) growing in the northern part of the Lesser Poland region). Sylwan 153 [11]: 768-776

Danek M., Danek T. [2011]: Zastosowanie alternatywnych metod przetwarzania danych w analizie dendroklimatologicznej modrzewia *Larix decidua* Mill. z Polski południowej (Use of alternative data processing methods in dendroclimatological analyses of larch (*Larix decidua* Mill.) from southern Poland). Sylwan 155 [3]: 147-158

Eckstein D., Aniol R.W. [1981]: Dendroclimatological reconstruction of the summer temperatures for an alpine region. Mitteilungen der forstlichen Bundesversuchsanstalt Wien 142: 391-398

Eilmann B., de Vries S.M.G., den Ouden J., Mohren G.M.J., Sauren P., Sass--Klaassen U. [2013]: Origin matters! Difference in drought tolerance and productivity of coastal Douglas-fir (*Pseudotsuga menziesii* (Mirb.) provenances. Forest Ecology and Management 302: 133-143

Feliksik E. [1991]: Badania wrażliwości ważniejszych gatunków drzew leśnych na zanieczyszczenia przemysłowe (Study of industrial pollution sensitivity in major forest tree species). Zeszyty Naukowe AR Kraków. Leśnictwo 254 [20]: 353-391

Feliksik E. [1992]: Wpływ warunków klimatycznych na wielkości przyrostów radialnych modrzewia europejskiego (*Larix decidua* Mill.) występującego w Karpatach (Impact of climate conditions on the size of radial increments in European larch (*Larix decidua* Mill.) growing in the Carpathians). Sylwan 136 [5]: 61-67

Feliksik E., Wilczyński S. [1998a]: Wpływ temperatury i opadów na przyrost roczny drewna świerka, sosny i modrzewia występujących w Leśnictwie Pierściec u podnóża Pogórza Wilamowickiego (Impact of temperature and precipitation on annual increments in spruce, pine, and larch trees from the Pierściec Forest District at the foot of the Wilamowice Highlands). Prace Komisji Zagospodarowania Ziem Górskich PAN 44: 77--86

Feliksik E., Wilczyński S. [1998b]: Wpływ warunków termicznych i pluwialnych na przyrost drewna modrzewi (*Larix decidua* Mill.) (Impact of thermal and pluvial conditions on wood growth in larch (*Larix decidua* Mill.)). Sylwan 142 [3]: 85-90

Jelonek T., Tomczak A., Karaszewski Z., Jakubowski M., Arasimowicz-Jelonek M., Grzywiński W., Kopaczyk J., Klimek K. [2019]: The biomechanical formation of trees. Drewno 62: 5-22. DOI: 10.12841/wood.1644-3985.318.05

Karolewski P., Białobok S. [1979]: Wpływ dwutlenku siarki, ozonu, mieszaniny tych gazów i fluorowodoru na uszkodzenie igieł modrzewia europejskiego (Impact of sulfur dioxide, ozone, their mixture, and hydrogen fluoride on needle damage in European larch). Arboretum Kórnickie 24: 297-305

King G.M., Gugerli F., Fonti P., Frank D.C. [2013]: Tree growth response along an elevational gradient: climate or genetics? Oecologia 173 [4]: 1587-1600

Koprowski M. [2012]: Long-term increase of March temperature has no negative impact on tree-rings of European larch (*Larix decidua*) in lowland Poland. Trees 26: 1895-1903

Michalec K., Wąsik R., Barszcz A., Sowa J.M. [2020]: The effect of stand origin on the wood structure of Norway Spruce. Drewno 63 [206]. DOI: 10.12841/wood.1644--3985.256.01

Miler Z., Rzeźnik Z. [1982]: Ocena modrzewia z różnych proweniencji na podstawie własności technicznych drewna (Assessment of technical properties of larch wood from different provenances). Prace Komisji Nauk Rolniczych i Komisji Nauk Leśnych PTPN. Tom LIV: 98-105

Mirek Z., Piękoś-Mirkowa H., Zając A., Zając M. [2002]: Flowering plants and Pteridophytes of Poland. A Checklist. W. Szafer Institute of Botany. Polish Academy of Sciences. Kraków

Ochał W., Wertz B., Grabczyński S., Orzeł S. [2018]: Dokładność określania świeżej masy strzał jodły na podstawie przeliczników wagowo-objętościowych (Accuracy of estimation of silver fir stem mass on the basis of volume-to-weight conversion factors). Sylwan 162 [4]: 277-287

Oleksyn J., Fritts H.C. [1991]: Influence of climatic factors upon tree-rings of *Larix decidua* and *L. decidua × L. kaempferi* from Puławy. Poland. Trees Structure and Function 5: 75-82

Oleksyn J., Fritts H.C., Hughes M.K. [1993]: Tree-ring analysis of different *Pinus sylvestris* provenances, *Quercus robur*, *Larix decidua* and *L. decidua × L. kaempferi* affected by air pollution. Arboretum Kórnickie 38: 89-109

Petras R., Mecko J., Krupova D., Slamka M., Pazitny A. [2019]: Aboveground biomass basic density of softwoods tree species. Wood Research 64 [2]: 205-212

Rożkowski R., Chmura D. J., Chałupka W., Guzicka M. [2011]: Cechy przyrostowe i jakościowe modrzewia polskiego [*Larix decidua subsp. polonica* (Racib.) Domin] z Góry Chełmowej w 37−letnim doświadczeniu rodowym (Growth and quality characteristics of Polish larch [*Larix decidua subsp. polonica* (Racib.) Domin] from Góra Chełmowa in a 37-year-long family study). Sylwan 155 [9]: 599-609

Schweingruber F.H. [2007]: Wood structure and environment. Springer Verlag, Berlin-Heidelberg-New York

Sergent A.S., Bréda N., Sanchez L., Bastei J.C., Rozenberg P. [2014]: Coastal and interior Douglas-fir provenances differ in growth performance and response to drought episodes at adult age. Annal Forest Science 71: 709-720

Serre F. [1978]: The dendroclimatological value of the European larch (*Larix decidua* Mill.) in the French Maritime Alps. Tree-Ring Bull 38: 25-34

Spława-Neyman S., Pazdrowski W., Małecki S., Owczarzak Z. [1997]: Właściwości drewna modrzewi z 21 proweniencji na terenie Polski (Properties of larch wood from 21 provenances in Poland). Prace Instytutu Technologii Drewna 41: 1-22

Szaban J., Jakubowski M., Kowalkowski W. [2014a]: Moduł sprężystości przy zginaniu statycznym wybranych proweniencji modrzewia europejskiego (*Larix decidua Mill.*) (Static modulus of elasticity in selected European larch (*Larix decidua* Mill.) provenances). Studia i Materiały Centrum Edukacji Przyrodniczo-Leśnej 16 2B[39]: 161-170

Szaban J., Kowalkowski W., Jakubowski M. [2013a]: Druckfestigkeit von Längstfasern der europäischen Larche (*Larix decidua* Mill.) verschiedener Provenienzen auf der Versuchsfläche der LZD Siemianice (Compressive strength of European larch (*Larix decidua* Mill.) wood from different provenances grown on an experimental plot located at Siemianice Forest Experimental Station). Annals of Warsaw University of Life Sciences – SGGW Forestry and Wood Technology 84: 213-216

Szaban J., Kowalkowski W., Jakubowski M. [2013b]: Biegefestigkeit vom Holz der europäischen Lärche (*Larix decidua* Mill.) auf der Versuchsfläche der

Forstuntersuchungsanstalt LZD in Siemianice (Bending strength of European larch (*Larix decidua* Mill.) wood from different provenances grown on a plot located at Siemianice Forest Experimental Station). Annals of Warsaw University of Life Sciences – SGGW Forestry and Wood Technology 84: 217-221

Szaban J., Kowalkowski W., Karaszewski Z., Jakubowski M. [2014b]: Effect of tree provenance on basic wood density of Norway spruce (*Picea abies* [L.] Karst) grown on an experimental plot at Siemianice Forest Experimental Station. Drewno 57 [191]: 135--143

Szeligowski H. [2001]: Proweniencyjne różnice w odporności modrzewia europejskiego (*Larix decidua* Mill.) na suszę (Differences in drought resistance between European larch (*Larix decidua* Mill.) provenances). Sylwan 145 [6]: 65-78

Tumenjargal B., Ishiguri F., Aiso H., Takahashi Y., Nezu I., Takashima Y., Baasan B., Chultem G., Ohshima J., Yokota S. [2020]: Physical and mechanical properties of wood and their geographic variations in Larix sibirica trees naturally grown in Mongolia. Scientific Reports 10 [1]: 12936. DOI: 10.1038/s41598-020-69781-7

UNECE/FAO [2011]: The European Forest Sector Outlook Study II, 2010-2030. Geneva. ISSN 1020-2269

Vaganov E.A., Hughes M.K., Shashkin A.V. [2006]: Growth dynamics of conifer tree rings. Springer Nature Switzerland AG. ISBN 978-3-540-31298-7

Vitas A. [2015]: A Dendroclimatological Analysis of European Larch (*Larix decidua* Mill.) from Lithuania. Baltic Forestry 20 [2]: 65-72

Wagenführ R. [2007]: Holzatlas (Wood atlas). Fachbuchverlag. Leipzig im Carl Hauser Verlag: 422-428

Wąsik R., Michalec K., Barszcz A., Mudryk K. [2020]: Variability of selected macrostructure features, density and compression strength along the grain of "Tabórz" Scots pine wood (*Pinus sylvestris* L.). Drewno 63 [205] DOI: 10.12841/wood.1644--3985.D16.11

Wertz B., Bembenek M., Karaszewski Z., Ochał W., Skorupski M., Strzeliński P., Węgiel A., Mederski P.S. [2020]: Impact of Stand Density and Tree Social Status on Aboveground Biomass Allocation of Scots Pine *Pinus sylvestris* L. Forests 11 [7]: 765 doi.org/10.3390/f11070765

Wilczyński S. [2010]: Uwarunkowania przyrostu radialnego wybranych gatunków drzew z Wyżyny Kieleckiej w świetle analiz dendroklimatologicznych (Determinants of radial increment in selected tree species from the Kielce Upland in the light of dendroklimatological analyses). Zeszyty Naukowe UR w Krakowie 464: 34-41

Wilczyński S.B., Kulej M. [2013]: The influence of climate on the radial increment of larches of different provenances on the basis of the experiment in the Carpathian Mountains in Southern Poland. European Journal of Forest Research 132 [5-6]: 919-929

Wilczyński S., Szymański N., Wertz B., Muter E. [2014]: Wpływ wieku na odpowiedź przyrostową drzew na czynnik klimatyczny na przykładzie modrzewia europejskiego (Impact of age on trees' increment response to climate factors, as exemplified by European larch). Studia i Materiały Centrum Edukacji Przyrodniczo Leśnej 40: 256-264

Williamson B.G., Wiemann M.C. [2010]: Measuring wood specific gravity … Correctly. American Journal of Botany 97 [3]: 519-524

Zobel B.J., Jett J.B. [1995]: Wood genetics related to provenance and seed source. Genetics of wood production. Springer Verlag. New York-Berlin: 195-213

Zobel B.J., Talbert J. [1984]: Provenance, seed source, and exotics. Applied forest tree improvement. John Wiley & Sons. ISBN 0471096822

List of standards

ISO 13061-2 Physical and mechanical properties of wood – Test methods for small clear wood specimens. Part 2: Determination of density for physical and mechanical tests

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