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Intraspecific structural signs of curly silver fir (*Abies alba* Mill.) growing in the Ukrainian Carpathians

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Abstract: The aim of this paper is to present the intraspecific differentiation of the curly silver fir (*Abies alba* Mill.) by the wood structure growing in the Ukrainian Carpathians. To find the morphological distinctions by using the silvicultural and biometric methods, 50 silver fir trees with anomalous wavy-relief stemwood formations were investigated. The trees aged from 94 to 132 years were characterised by the diameter at breast height of 32–59 cm. The length of the wave-grained stemwood varied from 6 to 11.5 m. The amplitude of the wood fibre waves varied from 4.4 to 24.1 mm. The smallest values of the amplitude of the wave-grained wood corresponded to the smaller wavelengths. The significant differences in the wood density and annual growth between the silver fir trees with the straight-grained and wave-grained stem wood were determined. The number of annual rings in 1 cm of the curly silver fir was 27.1% lower and 22.7% higher than the same characteristics for the straight-grained stem wood. The obtained linear equation described the relationship between the number of annual rings in 1 cm and the basic wood density of the silver fir with the straight-grained wood. The aesthetic features of the curly silver fir stem wood were discussed in the subject area of a new niche of exclusive wood products.

Keywords: amplitude of wood wave; length of wood wave; wave-grained stemwood; wood structure

Modern forestry combines not only economic and environmental functions, but also natural processes of the intraspecific differentiation of tree species according to the wood properties. To remain competitive in an increasingly globalised timber market, as well as to be successful over the long-term, it is important to take a new niche in the timber market. Purposeful cultivation of tree species with the desired wood properties will allow one to optimally serve the demand in the wood market (Sopushynskyy et al. 2005; Schmidt 2011; Noskowiak et al. 2013). In forestry practice, diagnosing wood with the given properties is a tool for optimising the chain of determining the value of round timber, which provides an increase in the financial income for forestry enterprises (Sopushynskyy 2014).

Phenotypic and genotypic factors cause high variability in the physical-mechanical properties of wood, not only between populations of the same species, but also in individual trees. Variation in an individual is not immediately apparent (Panshin, De Zeeuw 1980), but is the result of a complex system of interrelated factors that modify the physiological processes involved in the wood formation (González-Rodrigo et al. 2013). Silver fir (*Abies alba* Mill.) is one of the most important tree species often distributed on relatively high-elevated areas in European mountains, which are used for producing high

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value sawn timber (Wolf 2003; Mauri et al. 2016). Silver fir holds the second position after the common beech (*Fagus sylvatica* L.) with regard to the area covered and standing volume in the Carpathian Region (Niemtur 2007). Its growth is significantly influenced by environmental factors that determine its structural features and wood quality (Borchert, Friedrich 2011; Kobal et al. 2015). Furthermore, the species is sensitive to changes in the environment and is characterised by different morphological forms of the crown, colour and shape of the needles, colour of the bark, etc. (Zayachuk 2014; Mauri et al. 2016; Dobrowolska et al. 2017).

Environmental challenges in forest management require an understanding of the future changes in the qualitative characteristics of a tree species, which are due to the global climate change (Dobrowolska et al. 2017). The morphological characteristics of the silver fir are quite uniform growing on various sites, despite some differences in certain physiological features, such as late frost resistance (Huber, Kohn 1963) or better drought resilience (Pavari 1951; Lofting 1954). The gene ecology of the silver fir is much more detailed due to the many research works through mutual scientific cooperation between various forest institutions (Konnert, Bergmann 1995; Ballian et al. 2012). The phenotypic signs of trees could significantly indicate the variability in the physical properties of the wood between populations of the same species. The interspecific differentiation of individuals is not immediately obvious, but is the result of a compound system of interrelated ecological factors that affect the physiological processes involved in the wood formation (Panshin, De Zeeuw 1980).

The intraspecific differences of a tree species in terms of its wood properties is an integral part of sustainable forest management, the main task of which is the rational use of stemwood. To better understand the changes in the wood structure of the silver fir and, consequently, its tree growth, forest stands growing in the Ukrainian Carpathians were selected in our research. The scientific reason was to estimate the intraspecific structural distinctions in the stemwood of the species and to show the dimensional characteristics of the anomalous wavy-relief wood formations.

MATERIAL AND METHODS

Investigated area. This research was conducted in the Carpathian Mountains of west Ukraine (25° 13' E, 48°06' N, between 750 to 1 045 m a.s.l.) in 2017 (Figure 1). The dominant silver fir trees were located in humid mixed forest stands, with the estab-

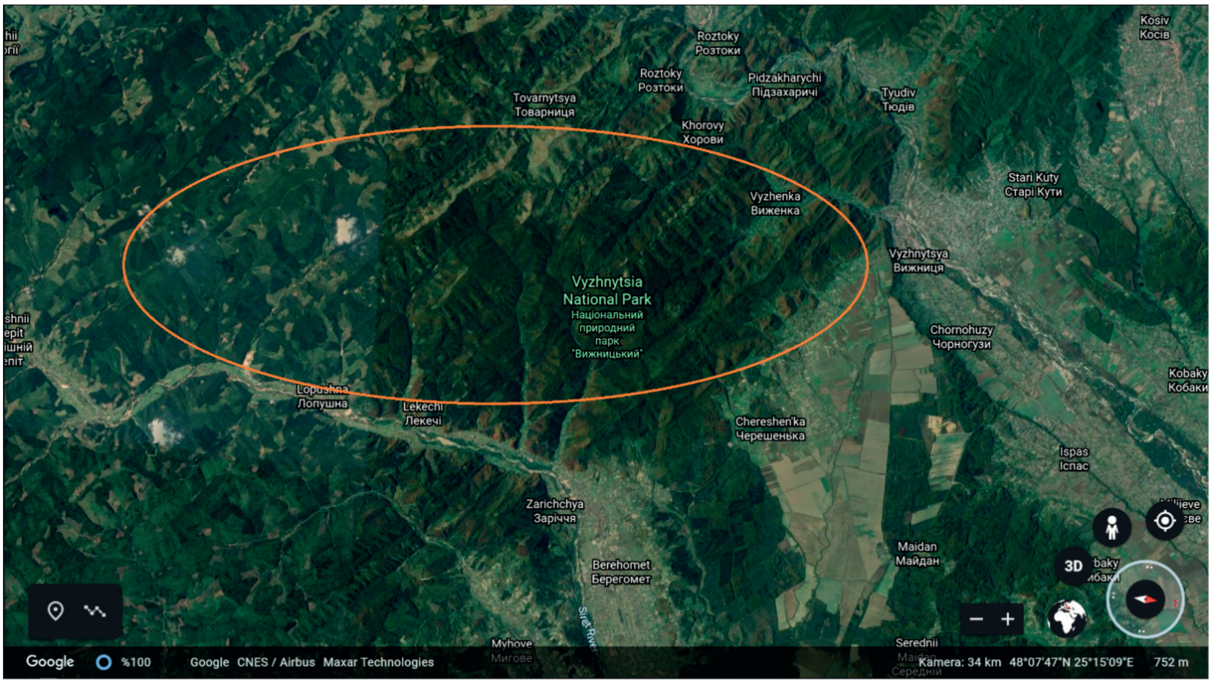

Figure 1. The location of the investigated area (Carpathian Mountains – 25° 13' E, 48°06' N, between 750 to 1 045 m a.s.l.)

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Table 1. The forest and estimated features of the sampling plots of the fir stands

Sampling plots	Stand composition	Age (years)	Number of trees	Stand quality/ stocking	*H* (m)	*D* (cm)	*M* (m^3)
1	5ABA3FAS2PIA	107	30	I/0.8	28	36	540
2	5ABA3PIA2FAS	107	25	I/0.7	28	36	500
3	6ABA2PIA2FAS	117	31	I/0.7	30	46	550
4	6ABA2PIA2FAS + ACP	112	25	I/0.4	30	42	345
5	4ABA3PIA3FAS + ACP	108	25	I/0.4	29	40	349
6	7ABA2FAS1PIA + ACP	118	27	I/0.4	29	44	387
7	6ABA3FAS1PIA + ACP	105	26	I/0.7	30	40	530
8	6ABA3PIA1FAS + ACP	130	26	I/0.4	30	48	330
9	4ABA3PIA3FAS + ACP	118	25	I/0.5	30	44	324
10	6ABA3PIA1FAS + ACP	106	26	I/0.65	29	40	435

ABA – *Abies alba*, PIA – *Picea abies*, FAS – *Fagus sylvatica*, ACP – *Acer pseudoplatanus*, "+" defined as < 5%; I – first class stand quality; *H* – average tree height; *D* – average tree diameter; *M* – timber volume per hectare

lishment of four quadratic sampling plots on a 50 m × 50 m area, and where all the silviculture and dendrometric characteristics were obtained (Table 1). The area included fir stands of the middle mountain belt with an altitude of 600–1 200 m above sea level, which belongs to the natural-geographical district "Bukovynian Carpathians" of the subregion "Pokutsko-Bukovynian Carpathians" region "Outer Fleet Carpathians", which stretches from the northwest to southeast of the Ukrainian Carpathians. The relief was characterised by a strong ruggedness due to the presence of a large number of mountain streams. The main type of soil is forest brown mountain-sand. The living ground cover was represented by *Lamium galeobdolon* (L.) L., *Athyrium filix-femina* (L.) Roth, *Symphytum cordatum* Waldst. & Kit. ex Willd., *Rubus fruticosus* L. and *Vaccinium myrtillus* L., and understory – *Corylus avellana* L., *Lonicera nigra* L., *Daphne mezereum* L., *Spiraea ulmaria* (L.) Maxim. and *Sambucus nigra* L. The mean annual temperature is 4.6 °C and the mean annual sum of the precipitation is equal to 979 mm. The stands grew on the northern, southern, south- and north-eastern exposures of the slopes with steepness from 10° to 25°.

Data collection. A total of 50 trees with wavy-grained stemwood were investigated for the morphological features of the anomalous wavy-relief formations. They were randomly chosen. The diameter was measured by a Codimex manual calliper and the height was measured by a Halgöf EC-II-D electronic clinometer. The volume of the curly stemwood (Vc.w.) was calculated by using multiple tables for determining the volume of round timber depending on the diameter in the upper section, its length and quantity. The biometric characteristics were collected from the felled trees with a focus on acquiring an in-depth understanding of the wavy-grained stemwood structure and its silvicultural potential (Figure 2). The stand quality (growth class) is a taxonomic characteristic (conditional indicator) used to assess the productivity of the stand and the growth rate of the trees. It is determined by the mean height and age of the prevailing forest-forming species or each of the species included in the stand. There are five main stand quality classes denoted by Roman numerals. The most productive forest stands belong to class I, the least productive to class V. If necessary, the number of classes could be increased, highlighting stands with productivity above grade I or below grade V; in these cases, the index designations of the classes Ia and Va, or even Ib and Vb, are used. For plantings of seed and vegetative origin, the stand quality classes are set separately due to the different growth rates at an early age. The stand quality classes may vary with the age of the stand, as well as a result of the transformation of the environmental conditions (drainage, waterlogging, etc.).

To gain understanding about the morphological characteristics of the trees, the dimensional characteristics of the wavy-grained stemwood were measured according the methods developed by Harris (1989). The number of annual rings in 1 cm was measured on a LINTAB 6 measuring tool. The basic wood density was determined as the ratio of the weight of the oven-dry wood versus the volume of the green wood.

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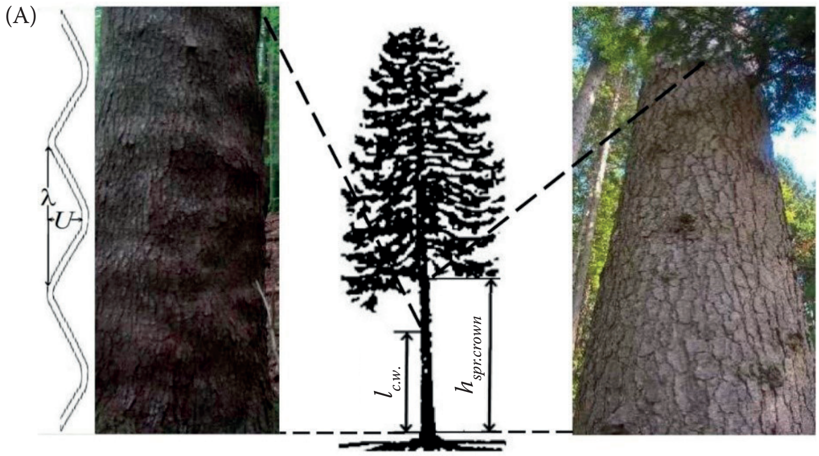

Figure 2. The biometric features of the silver fir with the wavy-grained (A) and straight-grained (B) stemwood: $l_{c.w.}$ – length of the wave-grained stemwood (m); $h_{spr.crown}$ – spring of crown (m); λ – length of the wave (mm); U – amplitude of the wave (mm)

Data analysis. The descriptive statistics were based on the procedure of SPSS 13.0 (IBM, Armonk, USA) and included the number of samples, minimum and maximum value, mean value and its standard deviation, coefficient of variation and accuracy figure. Excel procedures (Microsoft, Redmond, USA) were used for building the linear relationships between the studied variables.

RESULTS AND DISCUSSION

The morphological properties of trees are significant features in the timber's quality, which is mainly influenced by the genetic and environmental factors (Harris 1989). Trees of the Norway spruce (*Picea abies* (L.) Karst.) from the subalpine zone consist of more anomalies. The most common anomalies, disregarding the elevation, are resin ducts, both regular and traumatic (Kaczka et al. 2012). The genetics of the hereditary variation of the silver fir is well characterised by distinctions in the wood structure and reflected by the biometric features of the stemwood (Table 2).

The curly silver fir in the age range from 94 to 132 years was characterised by a height of 25 to 32.5 m and a diameter at breast height of 32–59 cm. The length of the wave-grained stemwood varied from 6 to 11.5 m with a mean value of 8.3 m, which, in technological terms, corresponds to the nominal dimensions to produce sawn timber. The volume of the wave-grained wood ($V_{c.w.}$) in a stem averaged 0.9 m^3. It is obvious that the wave-grained wood of the silver fir is a unique raw material for woodworking enterprises, and products from this wood may occupy a new niche in the furniture industry. The morphological features of the curly silver fir included structural distinctions of anomalous

Table 2. The biometric features of the curly silver fir (*Abies alba*) growing in the Ukrainian Carpathians

Characteristics	Min.	Mean ± SD	Max.	*CV* (%)	*P* (%)
Age (years)	94	112 ± 1.29	132	8.2	1.2
h_{tree} (m)	25	29 ± 0.25	32.5	6.2	0.9
$d_{1.3\ m}$ (cm)	32	44 ± 1.03	59	16.8	2.4
$h_{spr.crown}$ (m)	4.5	7.0 ± 0.18	10	18.5	2.6
$l_{c.w.}$ (m)	6.0	8.3 ± 0.18	11.5	15.6	2.2
$V_{c.w.}$ (m^3)	0.3	0.90 ± 0.06	2.33	51.1	7.2

h_{tree} – height of tree, $d_{1.3\ m}$ – diameter at breast height, $h_{spr.crown}$ – spring of crown, $l_{c.w.}$ – length of the wave-grained stemwood , $V_{c.w.}$ – volume of the wave-grained wood , Min. – minimum; Mean ± SD – mean and its standard deviation; Max. – maximum; *CV* – coefficient of variation; *P* – accuracy figure

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Table 3. The length of the wavy-relief stemwood formations (mm)

Sampling plots	Min.	Mean ± SD	Max.	*CV* (%)	*P* (%)
1	38.1	90.1 ± 3.56	156.1	27.9	3.9
2	40.6	109.3 ± 5.31	179.8	34.4	4.9
3	43.3	82.6 ± 3.56	143.5	30.5	4.3
4	55.6	71.5 ± 1.83	123.8	18.1	2.6
5	55.6	109.2 ± 3.79	172.2	24.6	3.5
6	71.1	108.0 ± 4.02	194.2	26.3	3.7
7	33.7	67.7 ± 3.37	114.0	35.2	5.0
8	57.2	127.6 ± 3.90	174.2	21.6	3.1
9	65.0	136.7 ± 3.68	171.3	19.0	2.7
10	59.9	77.0 ± 1.97	133.3	18.1	2.6
On average	33.7	86.6 ± 1.57	194.2	33.9	1.8

The number of measurements for each sampling plot was equal to 50; Min. – minimum; Mean ± SD – mean and its standard deviation; Max. – maximum; *CV* – coefficient of variation; *P* – accuracy figure

wavy-relief stemwood, the reflection of which was the length and the amplitude of the wave-grained formations (Table 3).

The statistical evaluation of the aesthetic wood characteristics indicated a high variation in the length of the wavy-relief stemwood formations (Table 2). The absolute values of the length of wood wave varied from 33.7 to 194.2 mm with a mean value of 86.6 mm. the curly silver fir aged from 118 to 130 years on sampling plots 8 and 9 were characterised by the highest mean values of 127.6 and 136.7 mm, respectively. The lowest figure was appropriated for a 95-year-old silver fir stand on sampling plot 7 with a mean value of 67.7 mm. The statistics showed that the coefficient of variation of the studied features was within the acceptable limits ($V < 40\%$), and the accuracy index was less than 5%, which confirmed the significance of the research results. The depth of wave-grained formations was also no less of an important indicator of the structural changes in the stemwood (Table 4).

As shown in Table 4, the largest mean value of the amplitude of the wavy-relief stemwood formations was equal to $U = 16.9$ mm. The absolute values of the amplitude of the wood fibre waves varied in the range from 4.4 to 24.1 mm. The tendency to decrease the amplitude of the wood waves was similar to the decline in the length of the grained wood wave. The smallest values of the amplitude of the wave-grained wood were characterised by those

Table 4. The amplitude of the wavy-relief stemwood formations (mm)

Sampling plots	Min.	Mean ± SD	Max.	*CV* (%)	*P* (%)
1	5.2	12.4 ± 0.40	17.6	23.0	3.2
2	4.9	10.5 ± 0.39	16.8	26.4	3.7
3	5.5	9.7 ± 0.33	14.4	23.9	3.4
4	4.4	7.3 ± 0.24	11.2	23.7	3.3
5	6.7	13.7 ± 0.68	22.3	35.3	5.0
6	6.5	13.4 ± 0.59	20.6	31.1	4.4
7	4.5	6.9 ± 0.23	10.3	23.1	3.3
8	6.6	15.2 ± 0.68	23.0	31.8	4.5
9	6.6	16.9 ± 0.70	24.1	29.1	4.1
10	4.8	9.0 ± 0.38	12.9	30.1	4.3
On average	4.4	11.5 ± 0.21	24.1	41.0	1.8

The number of measurements for each sampling plot was equal to 50; Min. – minimum; Mean ± SD – mean and its standard deviation; Max. – maximum; *CV* – coefficient of variation; *P* – accuracy figure

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Table 5. The number of annual rings in 1 cm (N_{rings}) and the basic wood density (ρ_b) of the silver fir with the different stemwood structure

Characteristics	Number of measurements	Min.	Mean ± SD	Max.	*CV* (%)	*P* (%)
Straight-grained wood						
N_{rings} (pieces·cm^{-1})	89	3.5	8.5 ± 0.24	15.0	26.6	2.8
ρ_b (kg·m^{-3})	89	245	317 ± 2.74	408	8.1	0.9
Wave-grained wood						
N_{rings} (pieces·cm^{-1})	50	3.5	6.2 ± 0.22	10.0	25.1	3.6
ρ_b (kg·m^{-3})	50	292	389 ± 7.33	478	13.3	1.9

N_{rings} – number of tree rings in 1 cm; ρ_b – determined as the ratio of the weight of the oven-dried wood and the volume of the green wood; Min – minimum; Mean ± SD – mean and its standard deviation; Max. – maximum; *CV* – coefficient of variation; *P* – accuracy figure

model trees, which were inherent by the smaller wavelengths. In most experiments, the statistical indicators of the amplitude measurements were characterised by a significant figure expressed in the accuracy ($P < 5\%$).

The changes in the properties of the stemwood in the radius and height were advisable associated expediently with the structural arrangement of the wood fibres of the trees. In this context, the distinctions in wood density as an integral indicator of the stemwood quality should be considered as one of the important indicators of the intraspecific variability within the tree species. Because of that, the annual rings and density of the straight-grained and wave-grained stemwood of the silver fir were analysed (Table 5).

The obtained results indicated that the number of annual rings in 1 cm of silver fir with the straight-grained wood ranged from 3.5 to 15 pieces·cm^{-1} with an average value of 8.5 pieces·cm^{-1}. The mean value of the number of annual rings in the trees with wave-grained wood was 27.1% lower than by the trees with straight-grained stemwood. The basic density of the straight-grained wood varied from 245 to 408 kg·m^{-3}. The mean value of the basic wood density of the trees with the wavy-relief stemwood formations was 22.7% higher than the similar indicator of the silver fir trees with the straight-grained wood. It is important to emphasise that the accuracy figures were less than the limit values ($P < 5\%$). In another study carried by Maksymchuk et al. (2017), the following results were determined: The number of annual rings per 1 cm of silver fir with straight-grained wood ranged from 5.0 to 15.0 pieces·cm^{-1} with an average value of 8.8 pieces·cm^{-1} at the breast height and 8.1 pieces·cm^{-1} at the height of 7.0 m. The basic density of the wavy-grained wood varied from 292 to 478 kg·m^{-3}, while the basic density of the straight-grained wood ranged from 256 to 408 kg·m^{-3}.

The basic wood density within the radius of the silver fir varied differently for the straight-grained and wave-grained wood. The wood density increased uniformly from the pith to the bark in the trees with the straight-grained wood and irregularly in the trees with the wave-grained stemwood (Figure 3).

The maximum values of the wood density were typical for the silver fir with mature wood over the last 40 annual increments (Figure 3). The basic wood density of the straight- and wave-grained wood indicated a significant difference over the radius of the stem. The maximum value of the basic wood density reached 478 kg·m^{-3} and it was inherited by the curly silver fir wood, and was 17.2% higher than the identical value for the straight-grained stemwood. Density has traditionally been associated with the various physical-mechanical properties (Lewark 1979; Van Buijtenen 1982; Esteban et al. 2009) and the variation in density is thought to affect the other properties. Studies on the silver fir have shown that this correlation exists, although it can be slight ($R^2 < 50\%$) (Mazet, Nepveu 1991). The behaviour of the various physical-mechanical properties must, therefore, be determined individually in order to identify the factors that affect each property (González-Rodrigo et al. 2013).

The research results showed that the increase in the annual growth of the curly silver fir led to an increase in the basic wood density. The trees with the straight-grained stemwood were characterised by an opposite trend (Figure 4).

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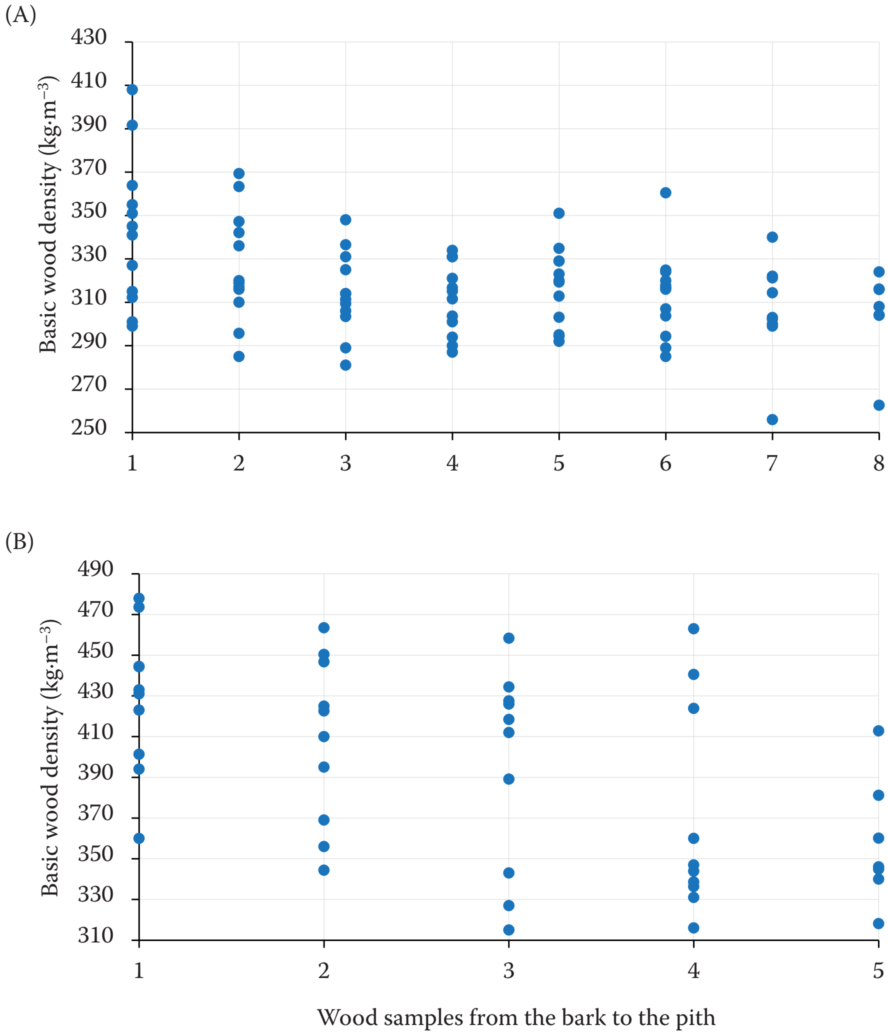

Figure 3. The variability in the base density of the silver fir with the straight-grained (A) and wave-grained (B) stemwood

The increase in the number of annual rings in 1 cm of silver fir with the straight-grained wood caused an increase in the basic wood density, which was described by the first-order equation $\rho_b = 0.07\ N_{rings} - 13.59$ ($R^2 = 0.63$). A similar relationship was found for the Norway spruce thriving in the Ukrainian Carpathians (Sopushynskyy et al. 2017). However, this dependence was not typical for the curly silver fir. To sum up, the differences in the macrostructure and stem phytomass formation of the silver fir encouraged the further anatomical and mechanical studies of stemwood to determine the nature of the origin of the abnormal wood and its properties.

It can be suggested that the structural anomalies of the silver fir stemwood could indicate a substantial fiddle-back figure of wood fibres relative to the axis of the trees and the uniqueness of the wood texture (Figure 5). Previous research on the wood anomaly suggests the need to study the structural changes of the stemwood, which is reflected in the morphological characteristics of the forest tree species (Harris 1989; Ballian et al. 2012; Sopushynskyy 2014).

The aesthetic features of the wood play an important role due to their volumetric and fashionable patterns. The wave-grained wood appearance of the silver fir in furniture design is of marketable importance for customers who are always interested in a new niche of exclusive wood products (Kohl 2009). The decorative properties of the fiddle-back figure wood on the European market (Germany, Austria, Poland, etc.) are highly valued. The price of one m^3 of high-value decorative stemwood varied from 2 286 to 9 960 EUR and depends on many factors, like the offer and demand of the wood market, the length of the wave-grained stemwood, the fiddle-back figure appearance etc. (Sopushynskyy 2014).

The morphological characteristics were crucial for diagnosing groups of individuals of the silver fir

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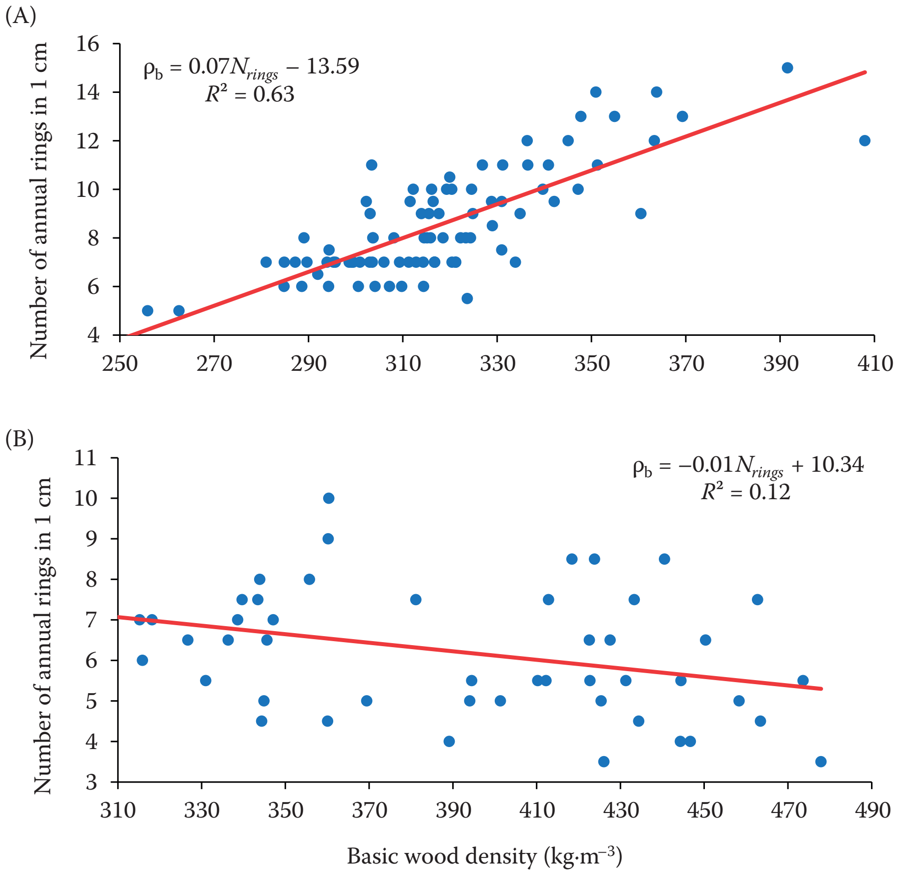

Figure 4. The relationship between the number of annual rings in 1 cm and the basic density of the silver fir with the straight-grained (A) and wave-grained (B) stemwood

Figure 5. The wood texture of the curly silver fir

with the wave-grained stemwood, which differed from the typical representatives on the structural features that were inherent in the intraspecific systematic unit. Thus, the length of the round timber of the curly silver fir varied from 6.0 to 11.5 m. The length of the stemwood wave was in the range from 33.7 to 194.2 mm, and the amplitude of the wavy formations ranged from 4.4 to 24.1 mm. In our opinion, the intraspecific structural signs of the curly silver fir growing in the Ukrainian Carpathians were naturally caused by similar mutations of the same genes. The stemwood of the curly silver fir for the wood processing industry is a unique wood raw material for the production of high-value wood products, and, for forestry, is the basis for the selection of the subspecies/form with a decorative wood structure.

CONCLUSION

Research on the morphological characteristics of the curly silver fir growing in the Ukrainian Carpathians showed there is an intraspecific differen-

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tiation in the wood structure in the humid mixed forest stands.

The aesthetic wood features of the curly silver fir were indicated by the length of the wood wave, which varied from 33.7 to 194.2 mm, with a mean value of 86.6 mm. The individuals aged between 118–130 years were characterised by the highest mean values of 127.6 and 136.7 mm compared to the younger 95-year-old silver fir stand with a mean value of 67.7 mm. The absolute values of the amplitude of the wood fibre waves varied in the range from 4.4 to 24.1 mm, with a mean value of 11.5 mm. The decrease in the amplitude of the wood waves was similar to the declining length of the grained-wood wave. In most experiments, the statistical indicators of the amplitude measurements were characterised by a significant accuracy figure.

The morphological characteristics were crucial for diagnosing the curly silver fir, which differed from the typical representatives of this species. These morphological signs claimed that the change in the structural arrangements of the wood fibres relative to the stem axis of the curly silver fir have a genetic origin. Its structural anomalies substantially indicated about the aesthetic features reflecting the volumetric and fashionable wood patterns. The wave-grained stemwood of the silver fir could be of important commercial interest in a new niche of exclusive wood products.

The significant differences in the wood density and annual growth of the silver fir with the straight-grained and wave-grained stemwood were obtained. The number of the annual rings in 1 cm of curly silver fir was 27.1% lower than in the trees with the straight-grained wood. The mean value of the basic wood density of the curly silver fir was 22.7% higher than the same characteristics for the straight-grained stemwood. The relationship between the number of annual rings in 1 cm and the basic wood density of the silver fir with the straight-grained wood was described by a linear equation.

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