Specific Structural Indexes for Resonance Norway Spruce Wood Used for Violin Manufacturing

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The aim of this study was to assess wood quality using diagnostic keys related to the main traits of trunk architecture in the most important resource of resonance spruce of the Romanian Carpathians. The material sampled from standing and felled trees yielded 568 individual ring series adding up to over 81,000 growth rings. The resonance xylotype was first recognized in felled trees, already designated for violin manufacture, for which a 6-class quality classification system was proposed. This system was extended to the qualitative classification of the standing trees (diameter at breast height larger than 10 cm). The width and regularity of the growth rings, the width of the sapwood and latewood, and the compression wood ratio are the variables that make recognition of trees containing resonance wood possible. Wood with resonance structural value was detected locally along the tree stem, and the best resonance structural quality was found uniformly distributed from 5 to 9 m above the ground and in the external half of the cross-section. Trees having a proper structure for violin fliches, but not yet with an appropriate size (38 cm underbark diameter), accounted for about 7% of the total tree population.

Keywords: Resonance spruce; Structural quality; Qualitative classification; Wood structure

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INTRODUCTION

Resonance wood is highly valuable because of its noble use and the material value of the finished products manufactured from it. The resonance quality is a result of the physical-acoustic properties of the material which express its ability to conserve the original tone of the sound emitted by the transmitted sonic radiation. There are physical, mechanical, acoustic structural, chemical, and morphological markers used to recognize the resonance quality of materials intended for the manufacture of musical instruments (Bucur 2006). The connections between the structure and properties support the notion that by imposing physical-structural conditions on the rough material, many acoustic requirements can be subsequently met. The usefulness of these structural features has been officially recognized since they were introduced in standards as criteria for grading wood intended for musical instruments (Krzysik 1968; SR 1294 1993). The tree-to-tree and individual variability of these markers, which are involved in the identification of resonance spruce, explain the different acoustic performances of musical instruments, which result from the wide scattering of the wood's physical-acoustic parameters (Haines 1979). Their wide variation amplitude, along with various interdependent relations, makes it possible to group these values into qualitative acoustic classes (Beldeanu and Pescarus 1996).

The acoustic field travelling through the wood interacts with all levels of wood's architecture, from the macroscopic (providing the most practically useful markers) to the ultrastructural (providing the most physical-acoustic relevant markers). Woods with a high level of structural organization (*e.g.*, softwoods) allow for better stability of transversal vibrations, unlike hardwoods, which have a very diverse and non-homogeneously organized structure (Bucur 1980a). The architecture at an electronic-microscopic scale seems more relevant in relation to the acoustic performance of the wood as compared to the gross structural features of the wood (Brémaud 2012). The most suggestive acoustic markers are the microfibrillar angle (Ono and Norimoto 1984; Obataya *et al.* 2000; Hori *et al*. 2002; Wessels *et al.* 2011) and the cellulose crystallinity degree (Norimoto *et al.* 1984).

Among the structural macroscopic features, the growth ring width and its radial regularity, the proportion of latewood, and the frequency of indented rings have the greatest differential values. In spruce, for example, the growth ring width is an indicator of the instrument's sonority (Bucur 1983), its connections with the speed of sound, and the loss of vibration (Roohnia *et al*. 2011). This supports its importance in the luthiers' material selection, even if it is empirical. The attention given to this marker is pointed out by its grouping around the value of 1.6 mm for soundboards for guitars and violins (Holz 1984). Very fine textures (growth ring widths of 1.2 mm and below) do not conduct soundwaves as easily (Krzysik 1968) and render a harsh (Hutchins 1978) and throbbing tone (Grapini and Constantinescu 1968). Violin wood with growth ring widths in the 1.2 to 2.0 mm class yield the best results in terms of aesthetics and the regularity and quality of sanding (Beldean and Pescarus 1992). The relevance of the growth ring width in relation to the acoustic markers is statistically perceivable only when considered alongside of other physical markers such as density (Traoré *et al*. 2010) and the proportion of latewood (Ştefănescu 1964). Some authors have considered that the chordophones are not the effect of the narrowness of the growth rings, but rather of their regularity (Ghelmeziu and Beldie 1970). Wood with growth rings in the 0.4 to 0.5 regularity class meets two acoustic requirements: high longitudinal elasticity and minimum participation of the transversal plane to the acoustic invariants (Rocaboy and Bucur 1990). Deviations from regularity cause mutations in the vibrational behavior of the wood material intended for pianos, resulting in three-fold diminishing of the longitudinal elastic modulus and a 32% reduction in sound wave velocity (Bucur 2006).

The proportion of latewood allows for the forecast of the acoustic radiation size (Krzysik 1968) and the figure of merit (Ille 1975). The threshold value most frequently mentioned for this structural marker (25%) corresponds to the lowest admissible acoustic radiation value for soundboards (Krzysik 1968). The increase in the admissible proportion of latewood to 35%, to increase the usage index of resonance spruce (Ille 1975), is regarded with reserve by the luthier community. Experience has proven that striped spruce wood (containing more than 1/4 to 1/3 latewood inside its growth rings) produces stifled sounds with low intensity (Ştefănescu 1964). As an effect of their crystallographic structure (Wellwood *et al*. 1974) and in spite of their much higher density, the sound wave travels more easily through the latewood insertions in the growth ring matrix of the resonance wood (Drelich *et al*. 2003). There is no correlation between the proportion of latewood and the width of the growth ring (Ghelmeziu and Beldie 1970). Consequently, the luthiers' acceptance of material with wider growth rings (Darnton 2009), but at the same time with a low latewood proportion - which, in relation to the density (Bergqvist 1998) yields a lighter material- comes as no surprise.

The structural individuality of resonance wood is an argument for the distinguishing of resonance spruce into intraspecific taxonomic units with xylogenetic character (*i.e.*, xylotype). Naturally, there are limitations to the individual effectiveness of these markers (Brémaud 2012a), and they have diagnostic value only when used synergistically (Brémaud 2012b).

The versatility of the vibratory properties of wood in relation to its structure may have a geographic connotation, currently little known, which would justify the importance of this provenance when selecting rough materials for the manufacture of musical instruments (Darnton 2009). For Romanian violin manufacturers, the main trait used to forecast the wood material's acoustic performance is the growth ring conformation (Albu 2010). The acoustic value of Romanian Carpathian resonance wood (Holz 1967), especially its suitability for piano manufacture (Ege 2009), has been experimentally demonstrated with the aid of acoustic constants, placing it at the top of the geographic provenance list (Bucur 1980b), especially as the density and latewood ratio are concerned (Bucur 1976).

The low frequency of the resonance xylotype in spruce forests (Geambașu 1995) motivated the present study to explore the trees' architecture and its relationship with the requirements of violin makers to determine the spatial distribution of the resource. The main goals were the identification of the structural markers with the highest effectiveness in isolating the resonance xylotype; the grouping of their values in structural quality classes usable on standing trees whilst meeting the requirements of violin manufacturers; locating the structural quality along the radius and axis; the determination of the resonance xylotype frequency; and the assessment of the structural markers' ability to indicate the local spruce provenance.

EXPERIMENTAL

Sampled Area

The field investigations took place in the area with the most important resonance spruce resources known in Romania, located in the Gurghiu Mountains, a subdivision of the Romanian Eastern Carpathians (Fig. 1).

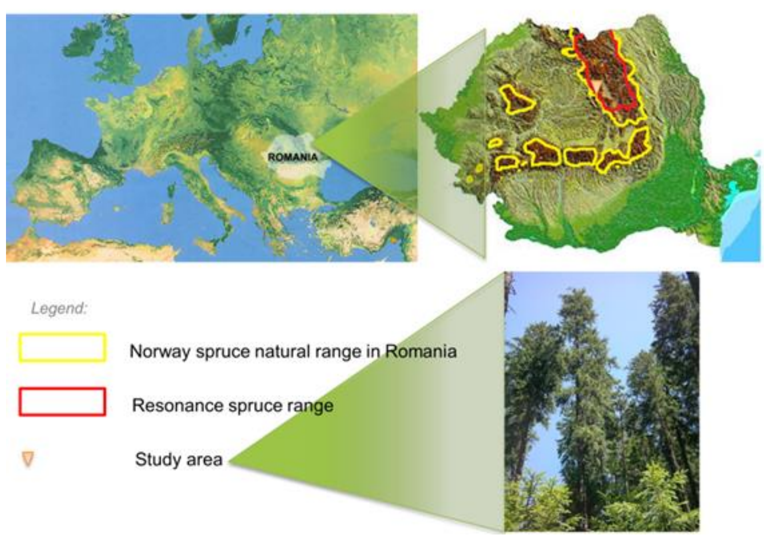

Fig. 1. The geographic location of the study

Its potential, known and appreciated for more than 300 years, has been exploited mostly by foreign luthiers who received the material by the agency of either Italian traders or collectors of the tribute owed by the Romanian provinces to the Ottoman Empire (Vaida 1958).

The two local cores of resonance spruce (Lăpușna and Fâncel, 46°49’N, 25°16’E) are located in the erosion caldera of a recent geologic volcano. The hollow conformation of the relief offers protection from the atmospheric turbulence, which is unfavorable to development of wood acoustic characteristics (Duncker and Spiecker 2008; Dinulică *et al*. 2012). The geological substratum, dominated by andesites with amphiboles, sustains the soil’s ability to store important reserves of easily-accessible water, thus maintaining relatively constant humidity. The stands from which the material were sampled did not vary significantly in terms of their terrain conditions: altitudes ranged from 1,240 to 1,580 m; slopes ranged from 17 to 35°; and expositions were to the NE and NW.

Sampling Design

The sampling was done in stages. In the first stage, the material (discs) was taken from trees felled when harvesting a newly identified resonance spruce resource (FANK sample plot). The pieces were identified and labeled with markings for the cardinal directions, making reconstituting the samples’ position inside the tree and sample plot possible. In this stage, the values of the phenotypic markers used to identify standing resonance spruces (proposed by Pașcovici 1930) were checked by a producer of musical instruments. Ten felled trees were followed through the process of conversion to semi-manufactured violins by the Gliga Company, the largest Romanian producer of bowed string instruments. In the felling area, the trees were sawn into 18 resonance logs with lengths ranging from 8 to 12 m. In the company storehouse, they were sawn into 2-m-long pieces and discs were taken from each end. Sixty-five such discs were used in the present study (Table 1).

Table 1. Sampling in the Established Plots

Sample Plot	Area (m^2)	No. of Sampled Spruce Trees	N Measured Samples		N Rings
LAPUS1	1000	11	47	cores	6,798
LAPUS2	1107	44	66		9,823
LAPUS3	500	7	15		2,068
LAPUS4	2156	61	104		16,036
LAPUS5	500	5	18		3,260
LAPUS6	2256	30	58		8,874
FANK	1000	10	65	discs	34,296

In the next stage, material (80 cores) was harvested from 23 resonance trees as identified using external traits, located in the LAPUS 1, LAPUS 3, and LAPUS 5 sample plots (Table 1). The samples were drawn only from the north direction at heights of 1.3, 3.3, and 5.3 m. For this purpose, an increment borer with a body length of 40 cm and an interior diameter of 5 mm was used.

In the last stage of field work (2009 to 2010), the sample plot networks were thickened with another four plots. In these plots, all spruce trees with diameters of at least 20 cm were examined, and two cores were extracted at 1.30 m from each tree from directions that were varied cyclically. The 20-cm breast height diameter threshold value supposedly marks the appearance of wood with acoustic qualities in the trees' basal section structure (Ștefănescu 1961; Grapini and Constantinescu 1968). The 7-sample plots totaled an area of 8519 m^2. The sampled trees had diameters ranging from 22 to 101 cm, while the heights spanned from 19 to 49.5 m. Several measurements were taken on the freshly drawn samples: the sapwood thickness (SAPT), which cannot be reconstructed after drying; and the position of the compression wood. Out of the 400 cores drawn, only those that maintained their integrity after laboratory seasoning were chosen for further measurements, a total of 308 samples (Table 1). The usable length (without advanced rotting) of the drawn samples ranged from 19.6 to 373.1 mm.

Ring Data Acquisition and Structural Indexes

The samples were seasoned for up to three months in fresh-air dry storage, until equilibrium moisture content was reached. The discs were prepared for measuring by sanding with a belt sander using several different grits of sandpaper. The cores were glued on plywood boards and flattened by sanding. The usable surface of the cores was then scanned, and the growth rings were measured using the WinDENDRO Density 2006c image-analysis system (WinDENDRO 2007). The samples were scanned at resolutions of at least 900 dpi. The entire scan collection consisted of a total of 81,155 growth rings.

The databases resulting from the semi-automatic measurement of the growth rings were loaded with the following primary structural indexes: the total ring width (TRW), the earlywood width (EWW), the latewood width (LWW), the earlywood proportion (EWP), and the latewood proportion (LWP) from TRW. As a result, each growth sample generated 5 chronological series of structural indexes. Additionally, the discs presented the possibility of exploring the variability of these indexes along the circumference of the ring. For this purpose, an orthogonal axis system was employed. It was laid out using the cardinal points (N, E, S, W) with the origin in the marrow.

In order to quantify the regularity of the TRW, four indexes were used, as presented in Table 2.

Table 2. Regularity Indexes from Transversal Ring Records

Structural indexes		Formula	Interpretation
r	Radial irregularity of annual growth	$r = \frac{\max(TRW_i) - \min(TRW_i)}{\text{average}(TRW_i)} \cdot 100\ [\%]$ $i = \overline{1 \dots n}$ n = length of series of rings	*r*=3...130 for Romanian resonance spruce (Ghelmeziu and Beldie1972)
ri	Regularity index	$ri = \frac{\max(TRW_i) - \min(TRW_i)}{\max(TRW_i)}$	*ri* ≤ 0.7 for resonance wood (Rocaboy and Bucur 1990)
R	Circumferential irregularity of annual growth	$R_i = \frac{\max(TRW_{i_k}) - \min(TRW_{i_k})}{\text{average}(TRW_{i_k})} \cdot 100\ [\%]$ R_i- Circumferential irregularity of ring i. TRW_{i_k}- Width of ring i along the direction of k radius (N, S, V, E) of the disc.	Index proposed by the authors
δ	Difference between consecutive growth rings	$\delta_i = \lvert TRW_{i+1} - TRW_i \rvert$ $\delta_i = \lvert TRW_{i+1} - TRW_i \rvert$	In wood with acoustic qualities, $\delta_i \leq 0.5$ mm (Krzysik 1968; Albu 2010)

The radial distribution of the values of these indexes makes it possible to divide the trunk section into several (two to four) zones of growth quality (Fig. 2). The separation of these zones was done graphically by simultaneously following each of the variation curves of TRW, LWP, and δ in correlation with the distance to the pith. The major inflection points mark the boundaries of the growth quality zones (Fig. 2). The D zone is not compulsory and represents the effect of the growth release as the competition pressure decreases by silvicultural interventions. Experience has shown that TRW and δ have the greatest contributions in delimiting the zones. LWP is especially involved in individualizing zone D. Usually, zone C encompasses juvenile wood, zone B represents the transition to mature wood, and zone A is the mature wood itself.

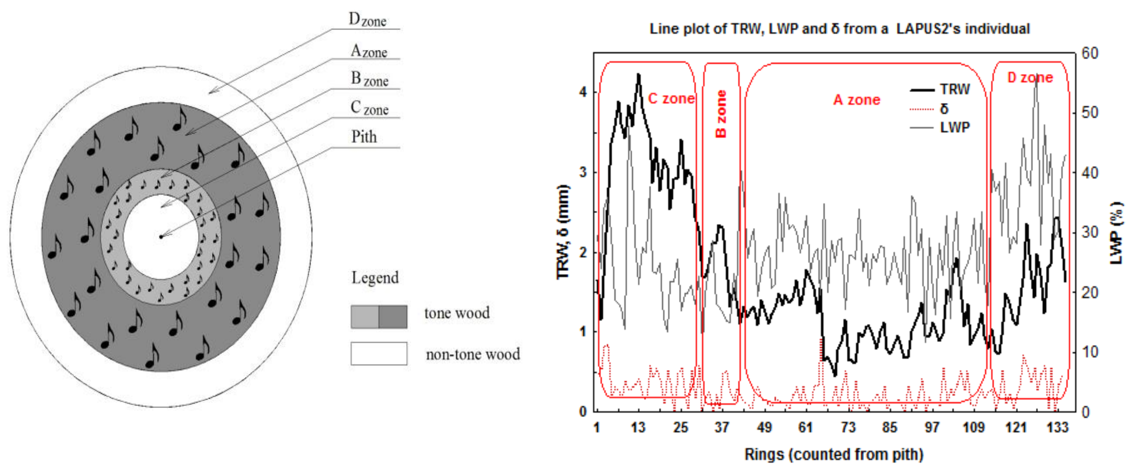

Fig. 2. The acoustic quality zones of the trunk cross section

For a qualitative significance, the growth rings in zones A and B must meet the violin material requirements (Table 3). Thus, zones A and B make up the resonance zone of the cross-section (RES). The compression wood is represented by zones C and D. The appearance of the compression wood delays or interrupts the transition to the wood with acoustic qualities. The structural quality transversal zones have been quantified with the following indexes: absolute length (LAde, LC, LD, LRES), percent length relative to the radius length (PA, PB, PC, PRES), and number of constitutive rings (NRA, NRB, NRC, NRD, NRES). For incompletely sampled cores, the interior quality zone length was estimated using the following formula,

$$LC = \frac{D-b}{2} - LA - LB \ [mm] \qquad (1)$$

where D is the diameter of the tree in the explored section (mm) and b is double the thickness of the bark (mm).

Considering that most of the sampled cores did not contain pith, the tree age was estimated using the following formula,

$$T = n + \left[\frac{\frac{D-b}{2} - L}{TRW\_}\right] \text{[years]} \qquad (2)$$

where L is the real length of the sample without the bark and $TRW\_$ is the average width of the growth rings in the radius segment missing from the sample. The estimation was done using the TRW series from the pair sample (in the case of trees which had two samples drawn). If the pair sample was missing or incomplete, the average TRW series for the stand was used.

After the transition into digital format was completed, the growth rings were also classified according to the structure type as determined by the probable presence of compression wood (Dinulică *et al*. 2012). The individual widths of the growth rings within the compression wood were totaled (CWW) and related to the real radius length (of the core or disc) or the reconstituted one ($\frac{D-b}{2}$), yielding the compression wood ratio (CWP). The size of the sapwood (NOS index) was defined by the number of constitutive growth rings.

All data analyses were performed using STATISTICA 8.0 software (StatSoft 2007).

The Qualitative-Structural Classification of the Material

In Romania, TRW, LWP, and δ are the structural criteria used to select the rough material for the manufacture of musical instruments (SR 1294 1993) and for their qualitative classification (Table 3).

Table 3. Structural Qualitative Features in Violin Manufacturing at Gliga Company (Albu 2010)

Violin Qualitative Assortment	Qualitative-Structural Requirements
Maestro (I Class)	$TRW_i \leq 2.5$ mm; $LWP_i \leq 35\%$; average (LWP_i) ≤ 20%. No more than 7 growth rings with $35 < LWP_i \leq 40\%$ are accepted; $\delta_i \leq 0.6$ mm; average(δ_i) ≤ 0.5 mm. No more than 7 growth rings with $0.6 < \delta_i \leq 0.8$ mm are accepted.
Professional (II Class)	$TRW_i \leq 2.5$ mm; $LWP_i \leq 37\%$; average (LWP_i) ≤ 35%. No more than 7 growth rings with $37 < LWP_i \leq 45\%$ are accepted; $\delta_i \leq 0.8$ mm; average(δ_i) ≤ 0.6 mm. No more than 7 growth rings with $0.8 < \delta_i \leq 1.0$ mm are accepted.
Student (III Class)	$TRW_i \leq 3$ mm; $LWP_i \leq 39\%$; average (LWP_i) ≤ 37%. No more than 7 growth rings with $37 < LWP_i \leq 50\%$ are accepted; $\delta_i \leq 1.0$ mm; average(δ_i) ≤ 0.8 mm. No more than 7 growth rings with cu $1.0 < \delta_i \leq 1.5$ mm are accepted.
Beginner (IV Class)	$TRW_i \leq 3$ mm; $LWP_i \leq 43\%$; average (LWP_i) ≤ 39%. No more than 7 growth rings with cu $43 < LWP_i \leq 55\%$ are accepted; $\delta_i \leq 1.2$ mm; average(δ_i) ≤ 1 mm. No more than 7 growth rings with $1.2 < \delta_i \leq 1.5$ mm are accepted.

The restrictions the manufacturer has imposed on these indexes inspired the creation of a structural classification scale of the material in this study (Table 4). The upper levels of the scale correspond to the qualities of wood required for violins. The requirement to exceed the width of the usual violin semi-finished product (12 to 13 cm) was added to the qualitative restrictions imposed on the material (Table 3). If this width can be provided by the A zone for at least 50% of the wood, then the material belongs to the first acoustic-structural class and Maestro-level violins can be obtained. For trees which did not have enough time to accumulate a resonance zone of at least 12 cm but still exhibit excellent structural-qualitative traits from a young age, quality class No. 5 was proposed. Finally, trees with irregular or large growths; with a significant amount of compression wood in the mature wood; or those unable to accumulate resonance wood during stand rotation cannot provide material with acoustic value (Structural Acoustic Quality SAQ class 6).

Table 4. Proposed Structural-Acoustic Quality Classes

Structural-Acoustic Quality Grade (SAQ)		Integrating Criteria
1	Wood of superior structural quality	1. Satisfying the conditions required of Maestro violin semi-finished products. 2. 0.8 ≤ TRW_i; average (TRW_i) ≥ 1.2. 3. LA +LB ≥ 130 mm; $LA > \frac{LA+LB}{2}$. 4. $ir_{A,\,B} \leq 0.7$
2	Wood of medium structural quality	1. Satisfying the conditions required of Professional violin semi-finished products. 2. Average (TRW_i) ≥ 0.8. 3. LA +LB ≥ 130 mm.
3	Wood of low structural quality	1. Satisfying the conditions required of Student or Beginner violin semi-finished products. 2. Average (TRW_i) ≥ 0.5. 3. LA +LB ≥ 120 mm.
4	Wood with resonance potential	1. 38 ≥ D ≥ 22 cm 2. LA +LB ≥ 50 mm 3. Zones A and B must at least meet the requirements imposed on wood of medium structural quality 4. T ≤ 150 years.
5	Wood partially usable in the manufacture of musical instruments	1. D ≥ 38 cm 2. 50 < LA +LB < 120 mm 3. T > 150 years
6	Wood without structural-acoustic qualities	1. LA+ LB < 50 mm or average (TRW_i) < 0.5 mm

A structural-acoustic quality class was assigned to each growth sample core or disc. In the case of least two radii, an average structural quality class, per tree, was calculated.

RESULTS AND DISCUSSION

The Variability of the Structural Indexes

In order to describe the variability of the analyzed structural characteristics, descriptive statistics of the structural indexes were computed (Table 5, Fig. 3); the sources of variation in these structural variables (Table 6) were identified; and the influence of the factors was quantified by analyzing the variance of the normally-distributed variables against the variability sources identified in the tree.

The growth ring circumferential regularity index (R) was the only measure found to be normally distributed (Table 5). The very narrow growth rings (with TRW < 0.2 mm) accounted for just 2.4% of all rings. The TRW, LWP, δ_i, and LRES values lay in the range of resonance wood. Wood structurally fit for resonance occupied, on average, half of the basal section of the trees. For 44% of total radii, the LRES exceed the minimum value required by violin. Materials that are not suitable for violin (SAQ class 5) are used usually in piano manufacturing, which requires semi-products smaller than 8 cm. For trees of the first three SAQ classes, the waste material in violin, cello, and contrabass manufacturing ranges between 68 and 81% of tree volume (Albu and Dinulica 2014). Trees having a properly structure for violin, but not yet with an appropriate size accounted about 7% of the total tree population. Only 3.6% of the sampled trees met the requirements of the first structural quality class. Trees of the first three SAQ classes offer a musical instruments output ranging from 19 to 32%. Trees without any structural-acoustic value accounted for 12% of all trees.

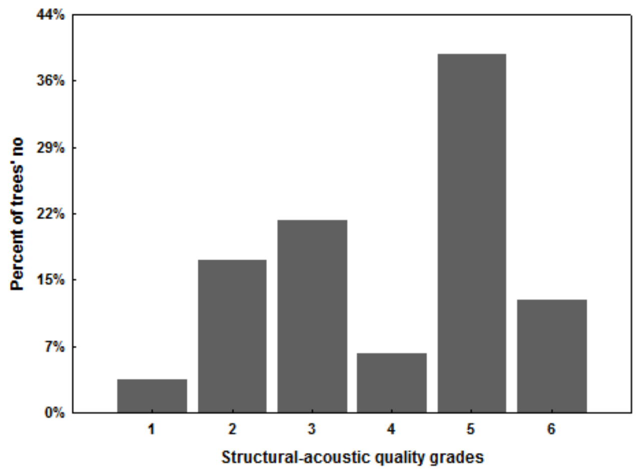

Fig. 3. Structural acoustic quality distribution at breast height

The variability of the experimental values decreased with larger sampling scales: the variation coefficient between the trees basal cross sections were clearly lower than those between its individual rings (Table 5). The variation at ring and zone levels describes the radial variability, whereas the differences between among radii characterizes the tangential variability. The variables involved in the radial distribution of structural quality (LB, LA, LRES) had the strongest dispersion on the tree scale. The ri index had the lowest variability. The ring indexes (TRW, LWW, LWP) corresponded to the radial regularity.

The sampling radius was a source of certain statistical variation for simple ring indexes but not for their regularity. The stability of the LA, LB, and SAQ indexes inside the basal section had very strong influences on the sample quality. The differences between trees were far from the threshold of statistical significance (p<0.05), supporting the hypothesis of the sampling's internal homogeny. Instead, the difference between sample plots and stands was significant, with the exceptions of LA, LB, SAPT, and the indexes of latewood regularity.

The differences between the sample plots were due to the different features of the sampling performed. The selections with exclusively phenotypically resonance tress (LAPUS1, LAPUS3, and LAPUS5) were different from the plots with integral inventorying of adult trees (LAPUS2, LAPUS4, and LAPUS6) when concerning TRW, LWW, and their regularity. This is a first confirmation of changes in value of these indexes as related to the material's structural-acoustic quality.

In order to identify the variants responsible for the change in the variation of the structural values, the Jonckheere-Terpstra (StatSoft 2007) test was applied. Zone D had the same structural features (TRW, r_{TRW}, ri_{TRW}, LWW, r_{LWW}, ri_{LWW}, r_{LWP}, ri_{LWP}, δ_i) as zone C and the same TRW as zone B. The regularity indexes were not different for zone D. The differences between the stands are frequently due to the FANK sample plot.

Table 5. Descriptive Statistics of Spruce Wood Structural Indexes Distributions at Breast Height

Variable	Mean	Median	Min-imum	Max-imum	Coefficient of Variation (%) Between …				*d* (Lilliefors – *p values*) from Kolmogorov-Smirnov Test
					Rings	Zones	Radii	Trees	
TRW (mm)	1.25	1.11	0.03	9.08	60.1	41.8	28.2	23.1	0.086 (<0.01)
EWW (mm)	0.94	0.82	0.00	8.33	64.4				0.098 (<0.001)
LWW (mm)	0.31	0.26	0.01	2.85	64.9	43.6	41.7	30.9	0.103 (<0.001)
EWP (%)	74.15	75.17	1.91	99.22	12.0				0.056 (<0.001)
LWP(%)	25.85	24.83	0.78	98.09	34.4	22.5	17.8	15.5	0.056 (<0.001)
δ_i, mm	0.23	0.15	0.00	5.24	112.4	49.2	31.1	26.5	0.187 (<0.001)
r_{TRW}(%)	135.84	127.69	16.97	528.34		47.8	39.0	33.2	0.072 (<0.001)
ri_{TRW}	0.72	0.75	0.16	0.99		22.7	7.3	6.6	0.082 (<0.001)
r_{LWW}(%)	171.33	164.29	0.67	712.18		45.0	41.8	29.4	0.059 (<0.001)
ri_{LW}	0.79	0.82	0.25	0.99		17.0	5.8	5.2	0.114 (<0.001)
r_{LWP}(%)	123.93	122.65	32.81	432.59		36.1	29.7	20.4	0.084 (<0.001)
ri_{LWP}	0.69	0.72	0.15	0.95		17.0	8.9	7.1	0.098 (<0.001)
LB(mm)	32.16	23.29	0.00	232.87			120.0	97.5	0.202 (<0.001)
LA(mm)	79.48	82.57	0.00	222.46			65.2	53.7	0.102 (<0.001)
LRES(mm)	110.60	122.94	0.00	244.16			54.1	43.7	0.112 (<0.001)
PRES(%)	48.51	54.13	0.00	100.00			54.5	42.1	0.114 (<0.001)
R_{TRW}(%)	48.02	47.12	24.62	74.92				29.5	0.123(>0.2)
R_{LWW}(%)	67.75	65.18	53.45	93.69				17.9	0.143 (>0.2)
R_{LWP}(%)	51.50	52.93	38.18	64.17				17.3	0.245 (p<0.1)
SAPT (mm)	39.99	40.00	3.00	117.40			45.4	39.5	0.077 (<0.001)
NOS	43.28	43.00	10.00	104.00			36.8	31.3	0.059 (<0.001)

Traditionally, the growth ring conformation has been the first criterion in identifying a rough material with acoustic qualities (Spycher *et al.* 2008). The fine texture and associated lower specific weight represent the main traits of the material (Bucur 2006). This would cause some mistrust in TRW's ability to differentiate between the local resonance xylotype. The variability reduction of the structural features in the sampled wood on small sampling scales (Table 5) did not weaken the individuality of the resonance xylotype. Even on a stand scale (with the smallest variation coefficients, see Table 5), a sufficient variability for LB, LA, and LRES ensured the differentiation of trees with structural-acoustic qualities. The internal qualitative-structural homogeneity of the samplings (Table 6) allowed the identification and utilization of the resource.

The generalized narrowness of the growth rings, a characteristic of Carpathian resonance spruce, cannot be first assigned to the site as was previously speculated (Ege 2009). On the contrary, the local spruce population is growing in the species' edaphic and geomorphologic optimum (Albu 2009). It seems, rather, that the stands' vertical and horizontal structuring is responsible for its very modest radial growths. The uneven age structure of the formerly-virgin forests supplies the ideal background (Rădulescu 1969). Opening the canopy, when silvicultural operations are undertaken, stimulates growth but can also cease development of new resonance rings. The later growths will belong to quality zone D, with no acoustic qualities (Fig. 2). However, the resonance trees' ability to restrain their thickness growth even after the canopy has been opened, as shown by the cores collected in this study, is remarkable. On the other hand, tree decline is not favorable for the resources' acoustic quality, neither qualitative (very narrow growth rings, compromising the acoustic value), nor quantitative, by delaying the transition from zone C to zone B or from B to A. The actual xylotype distribution shows similar implications (Fig. 3).

The regularity is the only feature of the growth rings with a unanimously accepted acoustic indicatory value. This has fueled interest in finding an optimal mathematical method to express it (Table 2). Amongst these, ri reflects the structural quality most accurately. Since there are no statistically perceivable differences between the trees (Table 6), the radial regularity of the structure becomes an index of growth rate compatibility. Consequently, those individual trees that correspond to the structural pattern imposed by the acoustic utilization of the material, subscribe to the collective growth processes. The radial homogeneity of the structure, definitive for resonance wood, does not hinder the extremely anisotropic behavior of the physical-acoustic properties (Roohnia *et al*. 2011).

Differential Indexes of Structural-Acoustic Quality

The association between structural variables was explored by means of cluster analysis. The class structure was determined using the k-means (StatSoft 2007) method. The Euclidean approach towards SAQ (Fig. 4) is primarily the natural consequence of the criteria used for the delimitation of SAQ. Therefore, the closeness of TRW, ri_{TRW}, ri_{LWW}, ri_{LWP} and δ_i to SAQ was no surprise (Fig. 4). TRW was the closest variable to SAQ, and the cluster was numerically dominated by regularity indexes. It is also noteworthy that r_i and δ_i were the only regularity indexes in accordance with SAQ.

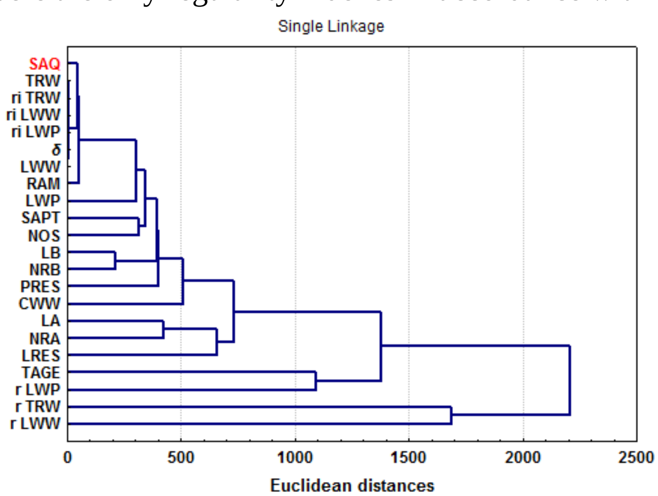

Fig. 4. Dendrogram of the structural variables involved in the analysis

High SAQ's had a larger range of radial regularity, but the central trends were located at lower values (Fig. 5, left). On the contrary, the growth rings of superior quality classes were more closely grouped around the TRW average, with the minimal values exceeding 1 mm. In trees from SAQ 5, LRES insufficiency was caused almost invariably by the small TRW (Fig. 5, right). Surpassing the thickness threshold imposed on the wood used in manufacturing musical instruments was delayed by the difficult growing of the trees. It was not by chance that the trees from SAQ 4 had the lowest TRW.

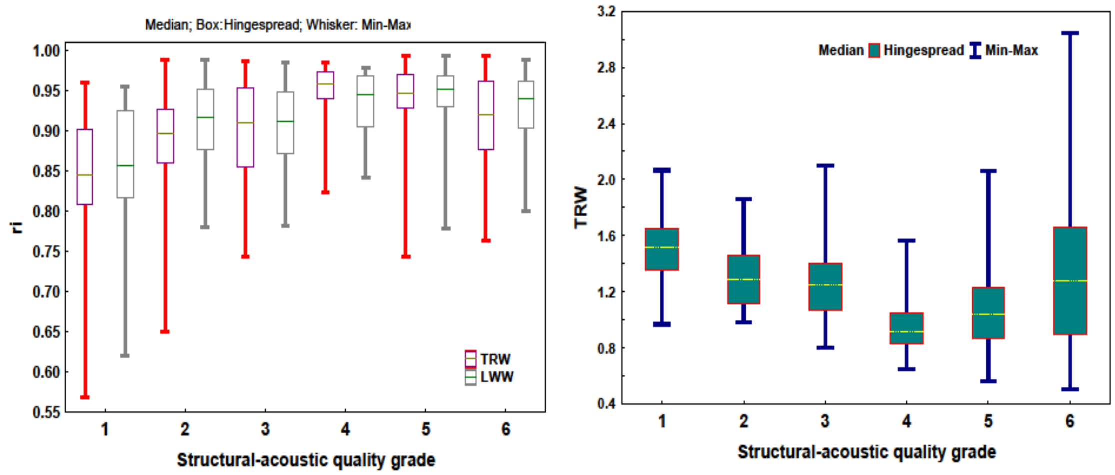

Fig. 5. Stratification of the values of the radial regularity index (left) and of the TRW values (right) in relation to the structural-acoustic quality class of the samples

In the same cluster as SAQ, the radial model is also present: superior SAQs agree with the CBA and CA models only. The dimensions of the zones with structural-acoustic quality (LA, LB, and LRES) are a part of another cluster. The quality-quantity discordance can be inferred. The proximity cluster, at a distance of 300 to 700 Euclidean SAQ units away, is comprised of LWP, NRB, CWW, SAPT, NOS, LB, and PRES. The sapwood was not a criterion for the attribution of SAQ. Its appurtenance to the cluster constituted around SAQ was remarkable. The non-parametric rank test also confirmed the polarization of the SAPT values around SAQ (H=32.51; p< 0.001). SAQ 4 and 5 were the most influential (Fig. 6): the trees with difficulties in bio-accumulating resonance wood (classes 4 and 5) grew slowly, had a narrow sapwood, and were made up by the same number of growth rings as the vigorously growing trees.

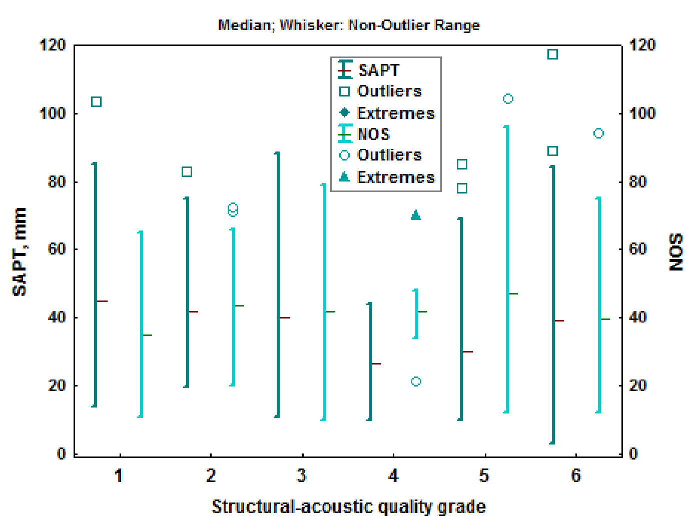

Fig. 6. Stratifying the size of the sapwood in accordance with the sample's structural-acoustic quality class

NOS did not correspond to the SAQ values (*H* from the Kruskal-Wallis 9.79 non-parametric test, p=0.08). Moreover, NOS was constant from one tree to another (χ^2=68.45; p=0.213). The tree age did not affect the value of SAPT or NOS (χ^2=5.69; p=0.46 and χ^2=5.90; p=0.44, respectively). It was inferred that the trees' vitality was sustained until an advanced age: NOS started to regress only after 250 to 300 years of age.

The compression wood was a discriminant of the structural-acoustic quality of the wood material. The depreciatory effect on SAQ also resulted from its position in the dendrogram (Fig. 4). SAQ was more familiar to CWW than to LRES. The presence of compression wood induced substantial modifications in the growth rings' indexes' radial development (p<0.001 in the Kruskal-Wallis test). TRW, especially, was a signal of the defect, but only at the level of the central trend of the distribution. The range of EWP, LWP, and δ_i values did not allow for decisive delimitation of the normal structure defect. LWW was a somewhat more accurate descriptor of CW (LWW was significantly higher in compression wood (0.52 mm) than in normal wood (0.35 mm)). The grouping of CWW values in relation to SAQ is possible. The confirmation came from the Kruskal-Wallis test (H=36.46; p<0.001). The differentiation was made by SAQ 5 and 6, which absorbed most of the CWW values (Fig. 7). The presence of CW in wood for present or future acoustic utilization possibilities (SAQ 1-4) did not restrict LRES below the requirements of violin semi-finished products. In wood with insufficient LRES (SAQ 5), on the other hand, CW was the resonance wood's main competitor, occupying as much as 60% of the radius length (3rd quartile) with extreme values above 80% (Fig. 7). The growth rings in the compression wood accounted for 5.7% of the total measured effective and occupied 8.3% of the total growth ring width. The thickness of latewood is an even more important acoustic descriptor than TRW (Spycher *et al*. 2008). The LWW's linkage to SAQ (Fig. 4) is the discriminatory effect of the absence of compression wood. The defect, also identified in resonance trees (Fig. 7), remained rare in the studied population.

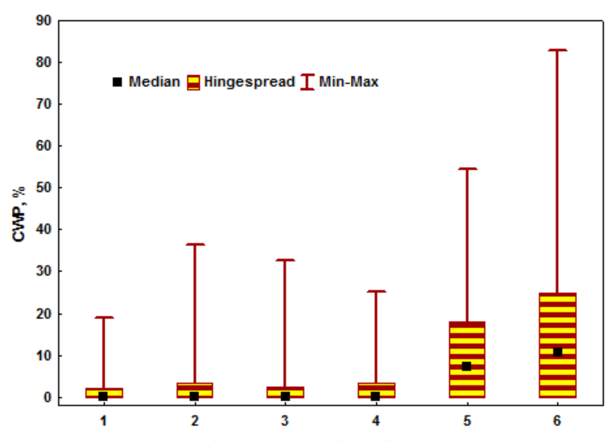

Fig. 7. Distribution of the compression wood relative (CWP) value in relation to the wood's structural-acoustic quality classes (SAQ)

The qualitative classification system proposed (Table 4), in accordance with the present requirements of the Romanian musical instruments producers (Table 3), is more permissive than the traditional prescriptions in matters of lutherie, starting from the first grade (Sonderegger *et al*. 2008). There are two reasons for this: (i) the continuous decrease of the quantity and quality of the resource of resonance spruce requires increases in the wood utilization index *via* the superior utilization of the rough material (Krzysik 1968);

and (ii) the versatility of the extent of the acoustic properties in relation to the architecture of the growth rings allows, between the limits of the correlation field (Ghelmeziu and Beldie 1970; Ille 1975), for the widening of the permitted variation range in each SAQ without significantly affecting the quality of sonic transmission.

Spatial Distribution of the Structural Acoustic Quality

The significance non-parametric tests made it possible to reject the hypothesis of different allocation of structural quality along the basal section circumference (Table 6).

Table 6. Statistical Significance of the Difference between the Experimental Values of Structural-Acoustic Indexes on Different Sampling Scales using the Nonparametric Kruskal-Wallis and Rank Tests

Dependent Variable	Source of Variation						
	Ring	Zone	Radius	Height (distance from the collar)	Tree	Sample Plot	Stand
	p values						
TRW	<0.001	<0.001	0.004	0.26	0.35	0.006	<0.001
r_{TRW}	-	<0.001	0.007	<0.001	0.33	0.002	<0.001
ri_{TRW}	-	<0.001	0.17	<0.001	0.87	0.021	0.002
LWW	<0.001	<0.001	<0.001	0.025	0.57	0.014	<0.001
r_{LWW}	-	<0.001	0.018	<0.001	0.97	0.002	0.04
ri_{LWW}	-	<0.001	0.40	<0.001	0.95	<0.001	<0.001
LWP	<0.001	<0.001	<0.001	<0.001	0.60	0.71	0.01
r_{LWP}	-	<0.001	0.043	<0.001	0.65	0.17	0.1
ri_{LWP}	-	<0.001	0.19	0.0014	0.71	0.97	0.01
δ_i	<0.001	<0.001	0.18	<0.001	0.87	0.67	<0.001
LB	-	-	0.12	<0.001	0.67	0.14	0.07
LA	-	-	0.31	<0.001	0.11	0.09	0.39
LRES	-	-	0.009	<0.001	0.94	0.94	0.002
%RES	-	-	<0.001	<0.001	0.79	0.79	0.001
SAPT	-	-	0.73	-	0.63	0.33	0.13
NOS	-	-	0.46	-	0.88	0.006	0.03
SAQ	-	-	0.10	0.014	0.97	<0.001	<0.001

Some of the structural variables (NOS, CWP, TRW, LWW, ri, LWW, PA, and PRES) closely linked to SAQ (Fig. 4) showed a statistical affinity for some cardinal points. These cardinal points sometimes coincided with the exposition of the terrain in the sample plots (NE, SW). For example, the rings on the NE side were wider (1.6 mm median TRW), and contained more latewood (0.4 mm median LWW) and compression wood (10% median CWP). Consequently, the PRES on this direction was reduced to 40% of the radius length (H=19.04; p=0.044). The SE side of the cross section (upstream from the general direction of the local valley) polarized the highest PA values. In FANK sample plots, the difference between the radii when TRW, LWW, and EWW were concerned was due exclusively to the westward radius.

The referencing of the sample collection directions to the geometry of the terrain (as defined by the contour line and the line of maximum slope) showed a weaker radial regularity of TRW and LWW (z =8.66, p=0.012 and z=2.47, p=0.041, respectively, in the Jonckheere-Terpstra test) and the smaller proportion of the resonance zone (z=2.83, p=0.0163) along the direction of the contour line.

If the inter-radius variations were not convincing, the axial coordinate of the tree architecture was a stable participant in the sampled wood's structure variability (Table 6). The only variable without any statistically perceivable axial variation was TRW. The multiple comparison matrix associated to the Kruskal-Wallis test showed that the differences between the experimental values of the structural variables were owed to the height steps from 11 to 21 m. The parabolic trend of the variations in relation to the height is common (Fig. 8). The variation curves reached their peak between 7 and 15 m above the ground. ri_{TRW}, ri_{LWW}, LWP, r_{LWP}, ri_{LWP}, NRC, and PA exhibited the most favourable resonance values in the 17 to19 m height section. LRES was maximum at the height of 7 m and PRES at 15 to 17 m. Zone A reached its absolute maximum value at 5 m and diminished considerably above 11 m. Zone B reached its widest extent at the height 7 m and disappeared at 19 m. The width of zone C reached 65 mm (the median) at 3 m above the ground and was reduced to 6 mm in the vicinity of the crown. The frequency of the LD values dropped as the height increased, the last appearing at 13 m. At 15 m, the best LWW regularity was recorded. The sections with the widest amplitude of experimental variables were between 7 and 11 m and at 1.30 m.

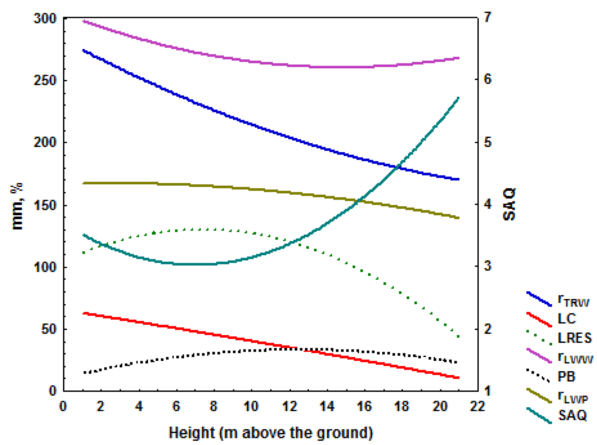

Fig. 8. The fit lines of the axial variations of some structural variables

The axial trend of SAQ was the result of the dynamics of the associated structural variables in relation to the height. The best structural quality (lowest SAQ) was found in the 5 to 9 m height section (Fig. 8), which subsequently met the minimum width required for violin semi-finished products. The total length of stem sections with structural-acoustic qualities (SAQ≤ 3) varied from 5 to 17 m (on average, 11 m) which, in relative values, represented 18 to 57% (on average, 35%) of the tree height. The underbark diameter at the extremity of the resonance structural section varied from 29 to 46 cm (on average, 34.5 cm). In trees with superior SAQ, the section fit for resonance was longer and went up to lower thicknesses (29 cm underbark).

The intra-tree structural directions provide support for the manifestation of this anisotropy. The tangential direction is a source of variation for TRW, LWW, LWP, r, LRES, and PRES (see Table 6; the differences between radii are statistically ensured). There is, for example, a disproportion between the cardinal directions regarding the bioaccumulation of resonance wood. The SE radius contains the widest A-quality zone, explaining some luthiers' preference for the sunny side of the trunk (Schelleng 1982; Kolneder 1998). A different assignment of acoustic quality along the radius stems from the radial distribution of the A, B, C, and D structural zones (Ille 1975). The C zone, which substantially damps sonic vibrations, reached a value of 44 mm (the median). Its length drops and even disappears as the height increases (Fig. 8). There is also a certain restraint towards the sapwood, caused by high internal friction, nevertheless compensated by the high values of the modulus of elasticity (Norimoto *et al*. 1983). The effect is inversely proportional to the width of the rings. This explains the acceptance of very narrow growth rings in top plates for violins manufactured by Romanian producers. The recent market requirements have directed the material with very narrow growth rings towards the Beginner and Student assortments (Table 3). Because of this, the samples with 0.5<TRW < 0.8 mm were placed in SAQ 3. Incidentally, the insufficient growth ring width was the main impediment for placing the SAQ 3 samples in a superior class.

The contribution of the axial direction to the analyzed structural indexes' variability was more solid. The stem section, which provides resonance wood, includes, on average, the first 11 m from the stump. From this, only the section from 5 to 9 m (13% of the stem's length) provided a high structural quality. In the trunk section located above the base log, the annual fluctuations of the radial growth were no longer influenced by the climatic factors (Bouriaud *et al*. 2005). Jablokoff (1963) found that for spruce, the 8 to 16 m height section provided the best structural quality. The axial distribution of tracheid length (Tyrväinen 1995), another structural marker for resonance wood (Beldeanu 2006), emphasized the same height section. Naturally, the other morphologic markers of resonance wood (such as defects) were excluded from this axial distribution of quality. It so appears that Zugliani and Dotta (2009) only identified 8 to 10% of the stem length as fit for manufacturing musical instruments. Inferior structural quality in the butt log was the expected consequence of the stored stresses (from compression, torsion, and traction) and explains the luthiers' reluctance to accept this piece of the trunk (Hutchins 1978). Using the diameter limit for resonance (34 cm underbark) and the average length of the resonance section (11 m), the resonance tree breast height diameter limit was calculated, with the aid of the average diameter decrease factor in the FANK population. The result was 48 cm, bark included. Similarly, it was estimated that for the bioaccumulation of the first 2 m of resonance wood, the tree must exceed the 38 cm overbark diameter.

CONCLUSIONS

1. Based on the current requirements of violin manufacturers, a new classification system of resonance rough material is proposed, which includes tree ring width and regularity along with latewood proportion. Furthermore, wider sapwood and no occurrence of compression wood are distinctive for resonance wood.
2. The proposed system is applicable to both harvested and standing timber and was confirmed in the investigated plot (Fâncel), which provided already raw material for very valuable musical instruments. This system requires an acoustic calibration using appropriate tools, a step that is ongoing.
3. The length of resonance zone of the cross-section that exceeds the minimum value required by violin (120 mm) totaled 44% of total sampled radii. Trees having a properly structure for violin fliches, but not yet with an appropriate size (38 cm underbark diameter), accounted about 7% of the total tree population.

4. Structural quality is cross-section homogeneously distributed. The best resonance zone (A zone) is wider on the uphill radius of a cross-section.
5. Up to 57% of tree length is suitable for acoustical purposes. The best structural resonance rough material could be found from 5 to 9 m above ground.

ACKNOWLEDGEMENTS

We are grateful to both anonymous referees for their valuable inputs and also to Kristen Bretz for the help in pre-editing of our paper. We would like to thank the staff of Gliga Company for the permission and logistic support given during the measurements within the factory.

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Article submitted: July 1, 2015; Peer review completed: September 6, 2015; Revised version received and accepted: September 14, 2015; Published: September 22, 2015.
DOI: 10.15376/biores.10.4.7525-7543