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Creation of density distribution charts in the cross and axial section of a tree trunk – Short Communication

M.F. Lavrov, I.A. Doktorov, G.M. Parnikova

Department of Woodworking Technology and Wooden Constructions, Institute of Engineering & Technology, North-Eastern Federal University in Yakutsk, Yakutsk, Russia

ABSTRACT: The purpose of this paper is to develop a method of constructing density distribution charts in roundwood log based on the density values obtained with a resistograph. The problem of improving the performance properties of structures made of wood and wood-based composite materials and laminated products is particularly relevant for construction in the northern regions. The experience of building in Yakutia shows sufficient reliability and durability of structures made of larch wood, despite the fact that their use is associated with technological challenges: larch planks warp and crack during the drying process; rigidity of wood increases. These disadvantages are caused by the structural features of the wood material; the degree of their intensity is proportional to the index of wood density. This paper presents the methods and results of qualitative research on wood indices obtained in laboratory and field conditions, as well as the authors' methods of graphical representation of density distribution in the cross and axial sections of a tree trunk, which are based on measurements taken via the method of oriented drilling. In the experimental studies, we performed a comparative analysis of the two-dimensional charts of density distribution with the charts of velocity distribution of acoustic pulses produced by a sonic tomograph "Arbotom". The elaborated method of evaluating the quality indicators of forest resources contributes to the expansion of the boundaries of wood-based material utilization, reduces their cost and improves the quality of construction of wooden structures and buildings.

Keywords: quality indicators; *Larix gmelinii*; resistance-drilling; resistograph; densitogram; graphical representation

The density of wood is a more advantageous characteristic than the indicators of wood macrostructure such as the width of the annual ring or the percentage of late wood; it can be used as a factor to determine the quality of wood. Many scientific studies (Poluboyarinov 1976; Ross, Pellerin 1994; Green et al. 2003; Isik, Li 2003; Wang et al. 2003; Howard 2007; Calkins 2009; Fujii et al. 2009; Begunkova et al. 2012a; Rinn 2012) dedicated to wood science emphasize that macrostructure (structural heterogeneity), density and dimensional features are the most tangible wood quality indicators for the identification of high-quality, structurally uniform wood raw materials, and the projection of the stability of physical and mechanical properties of specific products. Increasing requirements for the rational use of wood involve a highly accurate and comprehensive diagnosis of the structure, condition and quality of wood, which allows obtaining reliable data on the state of the wood, its anatomical structure and basic physical and mechanical parameters. As the problem of timely diagnostics of wood quality is very urgent, the purpose of this paper is to improve the diagnostics efficiency through determination of wood density and microstructure parameters by the method of directed drilling.

The use of directed drilling in the evaluation of the qualitative parameters of wood, as well as in the prediction of the operational characteristics of wooden constructions at operated facilities, is presented in the works of Ross and Pellerin (1994), Isik and Li (2003), Wang et al. (2003), Fujii et al. (2009), Rinn (2012), and Lavrov (2015).

MATERIAL AND METHODS

For a qualitative research of *Larix gmelinii* (Ruprecht) Kuzeneva wood, we selected 9 model trees and an experimental trunk with evident structural defects (fibre bending, flexures, taperingness, etc.) of growth in Yakutia.

The Republic of Sakha (Yakutia) is situated in the northeastern part of Russia. This region is characterized by permafrost on the major part of its territory and sharply continental climate when a temperature difference is 100°C (winter temperature can reach –60°C, while in summer it can rise to +40°C).

The selection of sample trees was carried out in accordance with the State Standard procedures (GOST 16483.6-80) in water star weed-cranberry woods near the 25th km of the "Viluy" federal highway. According to GOST 16483.6-80, 9 model trees of the considered species were chosen from among the trees, the diameter of which satisfied the requirements for timber, depending on its purpose (Table 1).

The study of qualitative indicators of *L. gmelinii* wood using the method of directed drilling and pulse tomography was conducted in accordance with the following program (Rinn 2013):

(*i*) sequencing of tests, data analysis to assess the wood quality, and characteristic measurement areas;

(*ii*) measuring of the sound passage velocity with an Arbotom device (Rinntech, Heidelberg, Germany) with 12 pulse sensors in compliance with our method;

(*iii*) measuring with a resistograph (Rinntech, Heidelberg, Germany) in compliance with our method;

(*iv*) bringing the measured values of micro-resistance drilling (resi) to the true values of the indicators;

(*v*) determination of a relationship of the wood basic density obtained by a standard weight method with conventional units of resi.

For the analysis and interpretation of experimental data, there are many types of charts and graphs that are used as tools for the visualization of numerical information, including point, line, plane, volume types. The tables containing the results of the experimental part of research were a source of the numerical data for the charts. The rules of chart making specify that numerical values should be plotted on the vertical axis and categories on the horizontal axis.

Table 1. Characteristics of model trees

Model tree	Age (years)	Diameter at height 1.3 m (cm)	Distance to first encased knot (m)	Tree height (m)	Diameter overbark (cm)
1	201	28.0	2.6	18.3	40.0
2	210	28.6	1.3	18.0	40.5
3	168	28.0	2.8	16.7	34.0
4	184	29.0	3.2	17.2	38.3
5	154	23.2	2.7	15.1	30.3
6	172	27.7	2.4	16.6	35.8
7	212	29.3	3.7	19.0	40.5
8	192	26.7	2.8	17.8	37.3
9	196	29.0	4.0	17.8	39.3

To display the results of the experimental data on the distribution of the basic density by the diameter and height of the trunk, as well as their cross-sections, we chose the following diagrams: (*i*) point diagram – to construct the numerical data on the results of measurements by the method of directed drilling, (*ii*) surface diagram – to predict and design the density distribution in the cross and axial section of the tree trunk.

The step-by-step algorithm of constructing the graph of the basic density distribution was as follows:

(1) Output of the resistogram to the "Decom" software (Rinntech, Heidelberg, Germany), determining the point coordinates for the main measurement zones by the axes (Fig. 1): input and output points for the idle running of the drilling support; input and output points for the zone of wood measurement;

(2) Identification of systematic measurement errors in the units of resi; bringing the available information to the true values of the resi parameters;

(3) Transfer of the measurement data array from conventional units to the units of basic density by using the coupling equation;

(4) Calculation of average density values at the areas of 1 cm;

(5) Construction of wood density distribution graphs by the direction of drilling (north-south, east-west).

The chart presented in Fig. 2 is an informative source to characterize the density distribution by the trunk diameter.

The analysis of the chart allows us:

(*i*) to find the location of the densest wood and the variations of the density values by the trunk diameter;

(*ii*) to identify areas with uniform distribution of density and low-density or damaged wood in the tree trunk;

(*iii*) to determine the average density by the trunk diameter.

With mutually perpendicular combination of basic density distribution graphs (in the north-south and east-west direction), by the diameter of the trunk relative to the drilling direction, we can get surface diagrams of the basic density distribution in MS Excel (Version 2003). These are the assump-

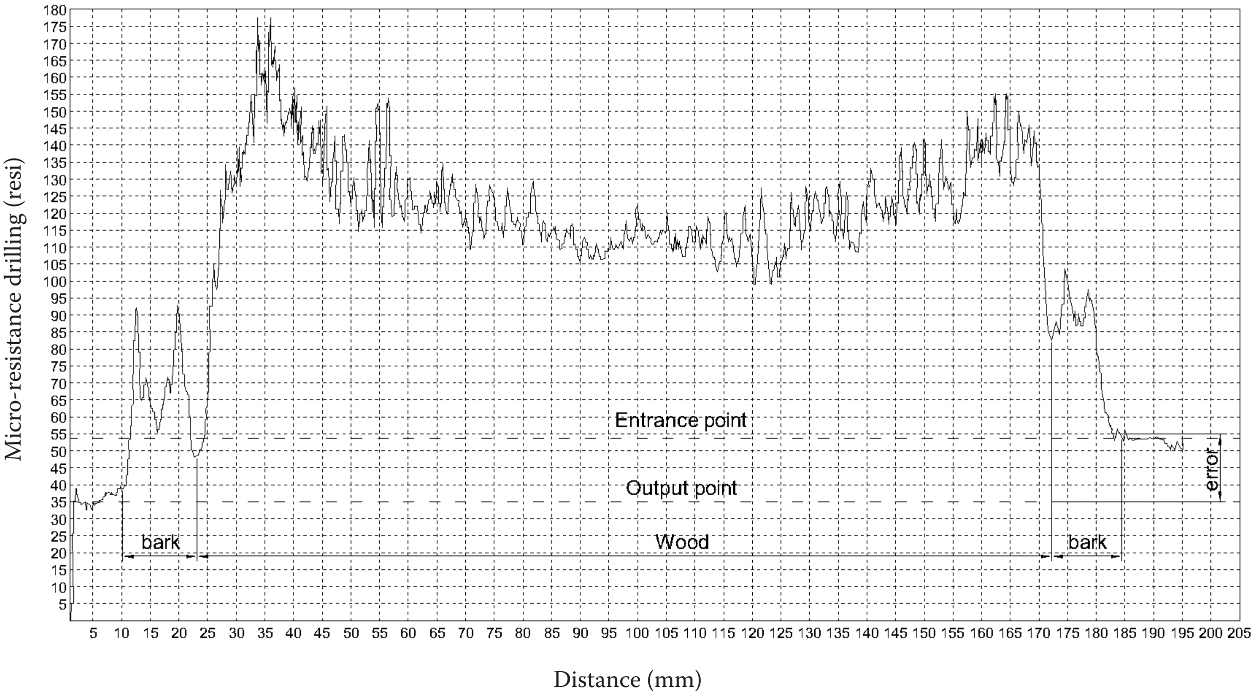

Fig. 1. Resistogram in the "Decom" software (Rinntech, Heidelberg, Germany) and main zones of measurements

tions made for the preparation of surface charts: the cross section of the trunk is circular; the centre of the circle coincides with the cross section of the trunk axis; the changes in the growth ring density around the trunk axis are uniform.

A table that simulates the shape of a trunk section with a division into sections of 1 cm is presented in Fig. 3. There are directions of light which indicate the areas of drilling.

Table 2 shows the identification numbers, where the cells for the main axes (N_i, E_i) contain recorded experimental data on the average density values (for a section with the length of 1 cm) and the cells ($NE_{i,k}$) contain data on density distribution calculated by Eq. 1:

$$NE_{i,k} = E_i - \frac{k}{n+1}(E_i - N_i) \quad (1)$$

where:

$NE_{i,k}$ – calculated data on density distribution,

E_i – average density value in the eastern part (kg·m^{-3}) at the i-th distance (cm) from the central axis,

k – address of the cell at the i-th distance (cm) from the central axis,

n – number of cells at the i-th distance (cm) from the central axis,

N_i – average density value in the northern part (kg·m^{-3}) at the i-th distance (cm) from the central axis.

An example of calculating the data in the cell NE12-9: $N12$ = 588 kg·m^{-3}, $E12$ = 689 kg·m^{-3}, k = 9, n = 15

NE12-9 = 689 kg·m^{-3} – (9/16) × (689 kg·m^{-3} – 588 kg·m^{-3}) = 632 kg·m^{-3}

Average density values of sections in the cross section of 9 model trees with different measuring heights were measured with a resistograph. Then these values were compared with the results of

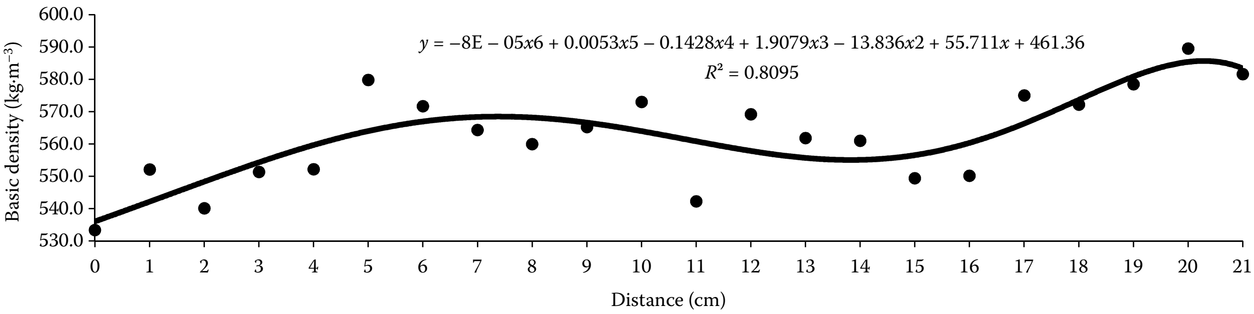

Fig. 2. The chart of the base density distribution

N

													16	16	16	16	16													
											16	16	15	15	15	15	15	16	16											
									16	16	15	15	14	14	14	14	14	15	15	16	16									
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					16	16	15	15	14	14	13	13	12	12	12	12	12	13	13	14	14	15	15	16	16					
				16	15	15	14	14	13	13	12	12	11	11	11	11	11	12	12	13	13	14	14	15	15	16				
				16	15	14	13	13	12	12	11	11	10	10	10	10	10	11	11	12	12	13	13	14	15	16				
			16	15	14	13	12	12	11	11	10	10	9	9	9	9	9	10	10	11	11	12	12	13	14	15	16			
			16	15	14	13	12	11	10	10	9	9	8	8	8	8	8	9	9	10	10	11	12	13	14	15	16			
		16	15	14	13	12	11	10	9	9	8	8	7	7	7	7	7	8	8	9	9	10	11	12	13	14	15	16		
		16	15	14	13	12	11	10	9	8	7	7	6	6	6	6	6	7	7	8	9	10	11	12	13	14	15	16		
	16	15	14	13	12	11	10	9	8	7	6	6	5	5	5	5	5	6	6	7	8	9	10	11	12	13	14	15	16	
	16	15	14	13	12	11	10	9	8	7	6	5	4	4	4	4	4	5	6	7	8	9	10	11	12	13	14	15	16	
16	15	14	13	12	11	10	9	8	7	6	5	4	4	3	3	3	4	4	5	6	7	8	9	10	11	12	13	14	15	16
16	15	14	13	12	11	10	9	8	7	6	5	4	3	3	2	3	3	4	5	6	7	8	9	10	11	12	13	14	15	16
16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
16	15	14	13	12	11	10	9	8	7	6	5	4	3	3	2	3	3	4	5	6	7	8	9	10	11	12	13	14	15	16
16	15	14	13	12	11	10	9	8	7	6	5	4	4	3	3	3	4	4	5	6	7	8	9	10	11	12	13	14	15	16
	16	15	14	13	12	11	10	9	8	7	6	5	4	4	4	4	4	5	6	7	8	9	10	11	12	13	14	15	16	
	16	15	14	13	12	11	10	9	8	7	6	6	5	5	5	5	5	6	6	7	8	9	10	11	12	13	14	15	16	
		16	15	14	13	12	11	10	9	8	7	7	6	6	6	6	6	7	7	8	9	10	11	12	13	14	15	16		
		16	15	14	13	12	11	10	9	9	8	8	7	7	7	7	7	8	8	9	9	10	11	12	13	14	15	16		
			16	15	14	13	12	11	10	10	9	9	8	8	8	8	8	9	9	10	10	11	12	13	14	15	16			
			16	15	14	13	12	12	11	11	10	10	9	9	9	9	9	10	10	11	11	12	12	13	14	15	16			
				16	15	14	13	13	12	12	11	11	10	10	10	10	10	11	11	12	12	13	13	14	15	16				
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													16	16	16	16	16													

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Fig. 3. Table of data on density distribution in the trunk cross section

sound velocity distribution at the same points (Arbotom). Charts created with a resistograph were visually compared with the graphic data generated by Arbotom to establish the correctness of the applied approach as it is known that the sound speed distribution in wood has a high correlation with its density (Pereira-Rollo et al. 2014).

RESULTS AND DISCUSSION

Comprehensive works of leading researchers on the problems of wood science allowed establishing the fact that growing conditions of woody species had some impact on the physical and mechanical properties of wood. The moisture content of larch wood decreases and the strength properties increase as we move from west to east. At the same time, wood density in the oven-dry condition does not differ very much from growing area to growing area (Vihrov, Lobasenok 1963; Poluboyarinov 1976).

In all cases, it has been noted that wood density is inhomogeneous in its degree and in the trunk zone within each tree of any species: e.g. in the oven-dry condition, wood density in the butt has the best parameters and is significantly reduced by the area in the middle height of the trunk. In some cases, a slight increase in wood density can be observed in the crown area (Poluboyarinov 1976). The distribution of wood density in different parts of the tree trunk is due to uneven deposition of growth

Table 2. Tabular form of data

N16	*NE16-20*	*NE16-19*													
N15	*NE15-19*	*NE15-18*	*NE16-18*	*NE16-17*											
N14	*NE14-17*	*NE14-16*	*NE15-17*	*NE15-16*	*NE16-16*	*NE16-15*									
N13	*NE13-16*	*NE13-15*	*NE14-15*	*NE14-14*	*NE15-15*	*NE15-14*	*NE16-14*	*NE16-13*							
N12	*NE12-15*	*NE12-14*	*NE13-14*	*NE13-13*	*NE14-13*	*NE14-12*	*NE15-13*	*NE15-12*	*NE16-12*	*NE16-11*					
N11	*NE11-13*	*NE11-12*	*NE12-13*	*NE12-12*	*NE13-12*	*NE13-11*	*NE14-11*	*NE14-10*	*NE15-11*	*NE15-10*	*NE16-10*				
N10	*NE10-12*	*NE10-11*	*NE11-11*	*NE11-10*	*NE12-11*	*NE12-10*	*NE13-10*	*NE13-9*	*NE14-9*	*NE15-9*	*NE16-9*				
N9	*NE9-11*	*NE9-10*	*NE10-10*	*NE10-9*	*NE11-9*	*NE11-8*	*NE12-9*	*NE12-8*	*NE13-8*	*NE14-8*	*NE15-8*	*NE16-8*			
N8	*NE8-9*	*NE8-8*	*NE9-9*	*NE9-8*	*NE10-8*	*NE10-7*	*NE11-7*	*NE12-7*	*NE13-7*	*NE14-7*	*NE15-7*	*NE16-7*			
N7	*NE7-8*	*NE7-7*	*NE8-7*	*NE8-6*	*NE9-7*	*NE9-6*	*NE10-6*	*NE11-6*	*NE12-6*	*NE13-6*	*NE14-6*	*NE15-6*	*NE16-6*		
N6	*NE6-7*	*NE6-6*	*NE7-6*	*NE7-5*	*NE8-5*	*NE9-5*	*NE10-5*	*NE11-5*	*NE12-5*	*NE13-5*	*NE14-5*	*NE15-5*	*NE16-5*		
N5	*NE5-5*	*NE5-4*	*NE6-5*	*NE6-4*	*NE7-4*	*NE8-4*	*NE9-4*	*NE10-4*	*NE11-4*	*NE12-4*	*NE13-4*	*NE14-4*	*NE15-4*	*NE16-4*	
N4	*NE4-5*	*NE3-4*	*NE5-3*	*NE6-3*	*NE7-3*	*NE8-3*	*NE9-3*	*NE10-3*	*NE11-3*	*NE12-3*	*NE13-3*	*NE14-3*	*NE15-3*	*NE16-3*	
N3	*NE3-2*	*NE3-3*	*NE4-2*	*NE5-2*	*NE6-2*	*NE7-2*	*NE8-2*	*NE9-2*	*NE10-2*	*NE11-2*	*NE12-2*	*NE13-2*	*NE14-2*	*NE15-2*	*NE16-2*
N2	*NE2-1*	*NE3-1*	*NE4-1*	*NE5-1*	*NE6-1*	*NE7-1*	*NE8-1*	*NE9-1*	*NE10-1*	*NE11-1*	*NE12-1*	*NE13-1*	*NE14-1*	*NE15-1*	*NE16-1*
C	*E2*	*E3*	*E4*	*E5*	*E6*	*E7*	*E8*	*E9*	*E10*	*E11*	*E12*	*E13*	*E14*	*E15*	*E16*

N_i – average density value in the northern part (kg·m^{-3}) at the *i*-th distance (cm) from the central axis (C), $NE_{i,k}$ – calculated data on density distribution, E_i – average density value in the eastern part (kg·m^{-3}) at the *i*-th distance (cm) from the central axis

rings and different ratios of early and late wood. In the oven-dry condition, wood density is maximum in the butt part of the trunk; it is caused by the fact that this part of the trunk is a fulcrum bearing the greatest mechanical load. The density increase in these areas of the trunk is connected with increased thickness of cell walls and high content of resins and other extractive substances (Vihrov, Lobasenok 1963; Poluboyarinov 1976; Volynskiy 1983, 2006). It surely creates serious and, in some cases insurmountable, difficulties in finding a kind of wood with uniform properties for important products and designs. The above information can give us sufficient grounds to make a conclusion that density is the most important quality characteristics of wood raw material; this parameter should be considered while using wood as a raw product for a variety of industrial solutions. According to Poluboyarinov (1976), Volynskiy (1983, 2006), Begunkova et al. (2012b), Chubinskii and Tambi (2013), Isaev and Begunkova (2013), and Chubinskii et al. (2015) wood density is most closely correlated with its physical and mechanical properties, unlike other quality characteristics. It can be used as a basic factor for the calculation of the solid content in raw wood and the determination of forest stand weight productivity. The charts of density distribution obtained by the standard weight method are presented in Fig. 4.

Similar charts of density distribution were submitted in works of some Russian and foreign scientists. They used the following methods: sonic tomography (Rinntech 2005; Pereira-Rollo et al. 2014), X-Ray (Rinn et al. 1996), magnetic resonance tomography (MRT) and computer tomog-

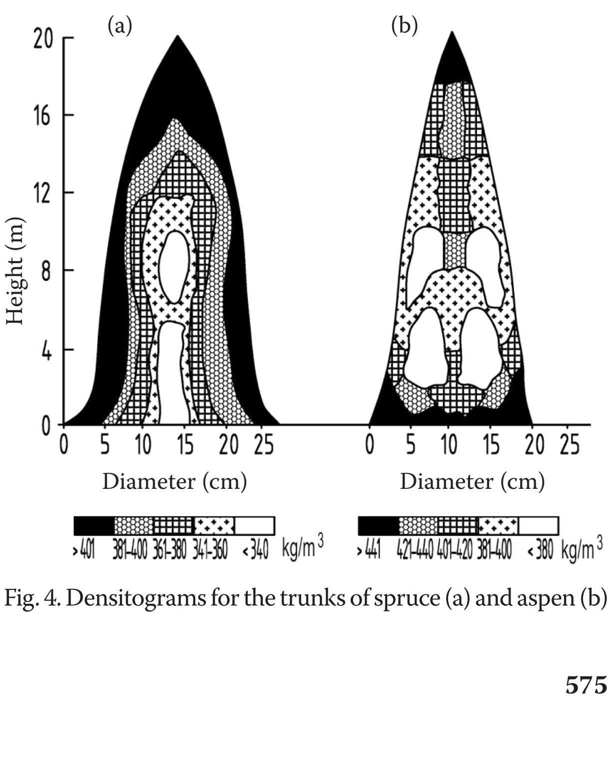

Fig. 4. Densitograms for the trunks of spruce (a) and aspen (b)

raphy (CT) (Chubinskii et al. 2014). The above-mentioned methods have their advantages and shortcomings. The standard weight method does not need any special expensive equipment, but its serious shortcoming is labour input as it is necessary to carry out a large number of laboratory researches on the small standard samples cut from each site of the cross section at different levels on the trunk height (Fig. 4).

Other methods – sonic tomography, MRT, CT, X-Ray – belong to nondestructive methods and they are free of the above-mentioned shortcoming. At the same time it is impossible to assess the density distribution of dry wood by sonic tomography: cracks become natural barriers for sound passage. MRT, CT and X-Ray have other shortcomings: (*i*) high cost of experimental equipment, (*ii*) possibility of carrying out a probe only in laboratory conditions. MRT allows estimating only distribution of moistness and structure of wood. X-Ray is the most accurate method in comparison with others but it is unsafe for the researcher. The presented method of density distribution charts created by means of a resistograph is free of the specified shortcomings and has some advantages: (*i*) rather low cost of equipment, (*ii*) high accuracy of data (Lavrov 2015), (*iii*) mobility of the installation allowing to conduct researches in field conditions of growing trees and wood and in the operated designs as well.

In the experimental studies, we did a comparative analysis of the two-dimensional charts of density distribution in green wood with the charts of ve-

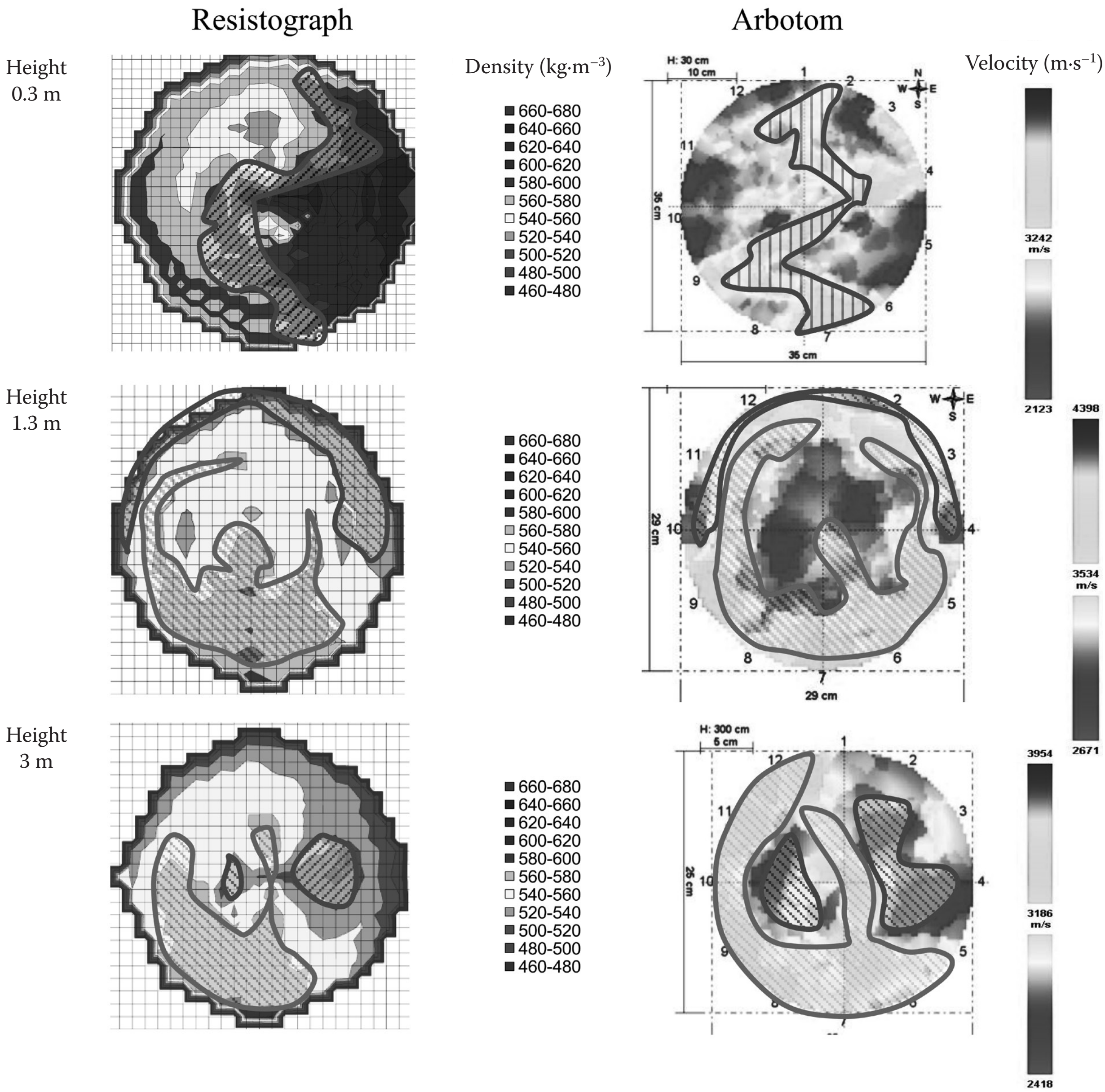

Fig. 5. Comparison of density distribution in the trunk cross section

locity distribution of acoustic pulses produced by a sonic tomograph "Arbotom" (Rinntech 2005). The results are shown in Fig. 5.

Fig. 5 shows that the charts have common trends of density distribution over the cross section of the trunk. To improve the accuracy of the representation of density distribution on the charts, we require additional drilling points in the intermediate directions: from north-west to south-east, from north-east to south-west. The two-dimensional charts of the calculated data on density for the trunk heights are presented in the tabular form in the MS Excel program (Table 3). The data in columns are linked with the density change for the trunk diameter, the data in lines with the height of measurements. If we use the function of inserting a two-dimensional chart in MS Excel, we can get a densitogram of the tree trunk along its height (Fig. 6). Visual representation of this densitogram of a tree trunk depends on the number of measurements along the trunk height (scale spacing).

The proposed practices of constructing density distribution charts allow estimating densities in round crude assortments. Thus, it is possible to

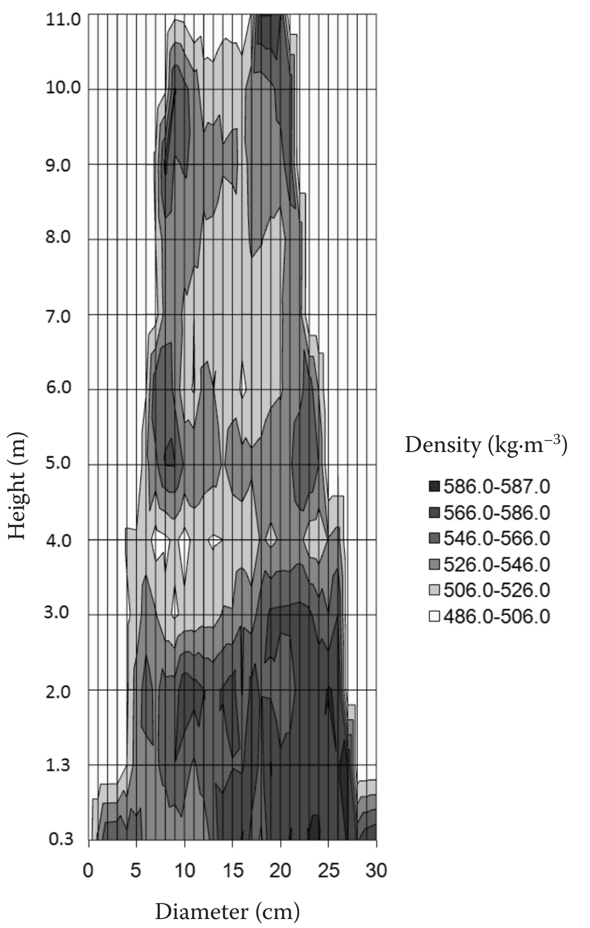

Fig. 6. An example of a densitogram of a tree trunk – drawn up in MS Excel (Version 2003)

Table 3. Data on density distribution (average of all trees in the north-south direction of drilling)

							484.5	501.4	498.9	485.6	493.1	494.6	499.1	496.7	487.6	508.0	609.3	597.1	566.5									
							502.2	567.5	551.3	537.9	514.3	512.4	518.5	520.7	521.0	534.6	533.6	541.4	552.7	560.3								
						510.0	571.0	543.0	548.1	542.0	534.3	540.8	528.6	530.5	522.2	529.2	542.2	536.5	538.7	557.3								
						506.4	536.4	531.5	532.5	536.8	520.8	519.2	510.9	513.7	519.2	528.2	526.7	521.2	516.0	535.9	538.3							
						497.1	533.6	535.5	522.3	506.0	508.7	512.7	524.3	512.6	512.0	519.4	516.7	517.6	523.5	534.1	535.5							
					504.6	561.4	563.9	539.9	512.5	504.0	534.1	526.6	518.3	520.8	502.0	511.1	513.4	520.3	524.1	532.2	538.5	558.1	524.9					
					520.8	541.0	566.5	567.2	543.2	546.1	538.1	534.7	524.3	532.9	534.5	530.1	533.3	543.2	536.9	541.9	563.8	566.2	546.1					
			509.6	509.0	516.7	497.2	501.8	510.2	498.0	511.5	507.8	503.9	505.9	515.1	517.2	507.2	529.8	520.7	528.6	527.1	533.6	512.8	511.0	527.2	534.1			
			501.5	514.3	537.1	527.4	511.2	503.1	510.6	511.6	518.0	518.2	527.5	527.0	541.1	537.2	556.1	569.5	570.6	571.4	572.6	570.0	556.3	546.2	566.2			
			501.7	535.2	554.2	542.1	553.4	554.3	582.2	574.0	566.6	562.2	567.5	575.3	544.3	571.5	564.0	563.2	551.5	552.2	577.4	574.5	580.9	592.1	584.0			
			506.0	537.4	540.6	543.1	552.0	565.3	553.6	543.1	557.8	562.3	559.0	565.0	563.3	578.7	560.2	587.6	570.0	576.6	580.7	578.6	584.0	579.0	585.8	594.4		
530.3	564.7	565.7	552.3	550.1	543.1	529.6	531.1	528.8	537.6	526.6	530.7	555.4	577.3	575.2	597.2	558.6	542.4	581.5	575.3	595.8	578.7	597.7	603.5	576.8	580.4	596.2	563.1	581.1

use them as a theoretical base for developing special software for devices operating in the mode of directed drilling. Creation of density distribution charts in the cross and axial section of a tree trunk, detailed evaluation and regulation of allowable density distribution ranges in the areas of the tree trunk can be among the main criteria in the selection of raw materials for the production of constructional lumber.

CONCLUSIONS

The developed method of drawing up the charts of density distribution in the cross and axial sections of a tree trunk will allow introducing the method of directed drilling in common practice – in the evaluation of both the qualitative indicators of wood in the forests and the elements of wooden constructions at operated facilities. The method of directed drilling can be used for investigating the macrostructure of wood and the biological state of tree trunks almost without breaking its integrity; the method can be applicable for determining the density and mechanical properties of wood. Defining these characteristics in *L. gmelinii* is quite consistent with the principles of scientific studies of wood and the description of its properties. The correlation of the wood macrostructure parameters, its density and strength can be defined based on the identification of the characteristics of the drill-indenter penetration into wood, and the value of its resistance to the advancement of the tool in the formed path. Therefore, development of a mathematical model for the process of drilling and creation of special density distribution charts by the section and height of the tree trunk can provide reliable and reasonable prediction of technical indicators and quality of wood.

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Corresponding author:

Ivan A. Doktorov, Ph.D., North-Eastern Federal University in Yakutsk, Institute of Engineering & Technology, Department of Woodworking Technology and Wooden Constructions, Kuzmina Street 34/1-61, 677000 Yakutsk, Russia; e-mail: allerigor@yandex.ru