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The diameter structure of forests disturbed by the four-eyed fir bark beetle *(Polygraph proximus Blandford)*

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Abstract. This article presents a study of disturbed fir stands in the foothills of the Eastern Sayan. The research was conducted through field surveys on temporary research plots. The data obtained were used to establish the distribution pattern of trees based on natural diameter classes. A comparative analysis of the data was carried out with standard series of distribution of the number of trees of fir forests by Falaleev. The study revealed variations in tree distribution, which could be attributed to dissimilarities in data collection techniques, as well as the condition of the forest stand following pest invasion.

1 Introduction

Assessing the condition of forests requires an understanding of the growth and structure patterns of the forest stand. The study of forest structure dynamics provides the theoretical foundation for developing methods to forest inventory and evaluation of growing and harvesting stock, as well as for assessing forest resource potential [1].

The structure of stands in forest ecosystems refers to the distribution pattern of trees based on their characteristics, which vary over time and space. This pattern is the result of the complex interaction between site conditions, plant community development stage, and the history of exogenous factors' influence [2].

To study the structure of a forest stand, one of the initial methods is to analyze the distribution of trees by diameter classes. The issue of tree stand structure remains relevant for several reasons, despite the abundance of information available on this topic. Firstly, the distribution of trees by diameter is a simple and relatively effective method of describing both an individual element of the plant community and the forest stand as a whole [3]. Data on the diameter structure of a forest stand is crucial for improving and planning forestry activities to enhance the growth and productivity of forest communities' edificators and increase the efficiency of accounting for forest resources [4].

Observations in coniferous stands dominated by fir and spruce have shown that tree characteristics can change significantly over relatively short periods of time. The structure of

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forest stands depends on their age, the biology of the tree species, the origin of the plantations and environmental disasters. Forest structure is not constant, but changes over time [5].

Kuzmichev noted that mixed uneven-aged coniferous stands have a structure that is typical of most mountain forests. Selective cutting is recommended in such forests, which involves thinning trees of all diameter classes proportionally, not just felling the largest trees [6].

Several researchers [7] have concluded that the four-eyed fir bark beetle has a significant impact on the structure of forest stands. A significant difference in tree diameters between those damaged and not damaged by the four-eyed fir bark beetle has been revealed by scientists.

In Siberia, over the past few decades, there has been a noticeable degradation of fir forests due to the invasive four-eyed fir bark beetle (*Polygraph proximus* Blandf.) [8]. The outbreaks of this invasive species have caused large-scale dieback of coniferous forests, particularly the so-called dark coniferous forests that are dominated by Siberian fir, Siberian spruce, and Siberian pine. This phenomenon has been observed in many Siberian regions, including the Krasnoyarsk Krai [9]. Studying the structure of fir stands will enable the determination of the role of invasion in the formation of the growing stock and deadwood stock.

2 Materials and methods

The research was conducted in the foothills of the Eastern Sayan Mountains in Central Siberia. The study area is covered by various types of forests, including mixed, deciduous, and coniferous. The study focused on fir-dominated stands, which are widespread in the research area and cover 35% of the forested land.

The study analyzed 5 fir-dominated stands. 3 circular research plots were placed in each stand, resulting in a total of 15 research plots (Figure 1).

A timber cruising was carried out in every research plot. All measurements were recorded on a field card, including species, diameter, height and health status recorded for each tree. Health status was determined using a 6-point tree life status scale, which categorizes trees as living, dying or dead. Only trees with a diameter of 8 cm or more were measured.

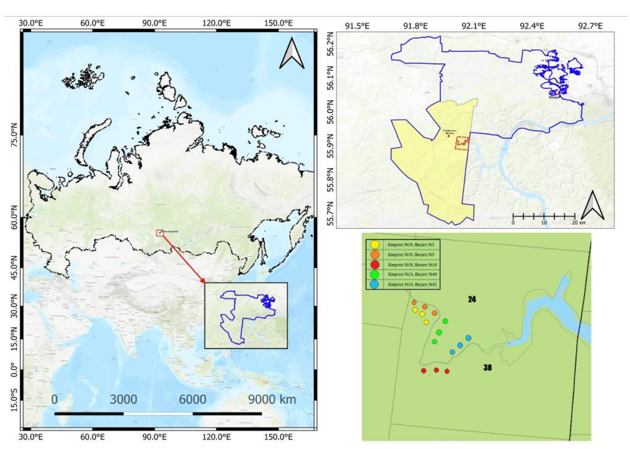

Fig. 1. Study locations.

To characterize the stands (Table 1), the initial data were further processed to obtain indicators such as: basal area, stem volume, average diameter, average height, density, growing stock and deadwood stock.

Table 1. Silvicultural and forest inventory details of the studied forest stands.

Forest compartments	Forest mapping unit	Area ha	Composition	Age, years	Average height m	Average diameter, cm	Bonitet class	Forest type	Density	Growing stock, m3/ha	Deadwood stock, m3/ha
38	2	6,0	9F	140	21.4	18.4	4	F_{fm}	0.32	116	39
			1S	140	19.3	15.7			0.04	12	-
			+P		19.3	16.2			0.02	7	2
			ind B		16.4	12.0			0.004	1	-
									0.38	136	41
38	3	16.0	9F	130	21.5	18.2	4	F_{thf}	0.35	126	44
			1P		19.3	16.2			0.03	8	-
			+B	95	18.3	15.0			0.04	8	-
			ind S	130	18.5	16.0			0.02	6	4
									0.44	148	48
38	10	7.0	6F	140	23.2	20.0	3	F_{fm}	0.33	145	57
			4S	140	24.6	21.6			0.21	91	5
			ind P.	190	23.5	28.0			0.01	6	3
			SP	190	21.4	18.4			0.01	4	-
									0.56	246	65
24	40	24.0	8F	140	22.7	19.6	3	F_{fm}	0.39	161	61
			1S	140	22.7	19.7			0.04	17	-
			1SP	190	19.4	16.0			0.02	4	-
			ind B		21.7	19.1			0.02	10	3
									0.47	192	64
24	42	25.0	7F	130	22.6	19.3	3	F_{thf}	0.35	147	44
			3S	130	21.3	18.9			0.14	53	5
			ind SP.		21.9	16.0			0.01	4	-
			P.		24.4	21.0			-	-	3
			B	100	18.4	16.0			0.01	1	-
									0.51	205	52

Note. F – Siberian fir Abies sibirica Ledeb., SP – Siberian pine Pinus sibirica Du Tour, S – Siberian spruce Picea obovata Ledeb., P – Scots pine Pinus sylvestris L., B – silver birch Betula pendula Roth. Composition: '+' indicates that the following tree species occupies 2.5-5.0% in the total growing stock on the research plot, 'ind' indicates that the following tree species occupies 0.1-2.4% in the total growing stock on the research plot. Bonitet class describes forest productivity (1 is the highest-productivity class and 5 is the lowest-productivity class). Forest type: Ffm – feather moss-dominated fir forest, Fthf – tall herbs/ferns-dominated fir forest.

There are two forest types on the research plots: feather moss-dominated fir forest (F_{fm}) and tall herbs/ferns-dominated fir forest (F_{thf}). The forest stands are mixed. with fir comprising 60-90% of the stand composition. Other species present include Scots pine (*Pinus sylvestris* L.). Siberian spruce (*Picea obovata* Ledeb.). Siberian pine (*Pinus sibirica* Du Tour). and silver birch (*Betula pendula* Roth). The relative density ranges from 0.38 to 0.56. The age of the fir trees ranged from 130 to 140 years. while the age of the Scots pine and Siberian pine was 190 years. The diameter of the trees in the fir stand ranged from 18.2 cm to 20.0 cm.

The forests in the study area are debris-strewn. While the growing stock varied from 136 to 246 m^3/ha. the stock of deadwood (standing dead trees) in the research plots amounted to 41–65 m^3/ha.

3 Results and discussion

The distribution of trees by diameter classes provides an overview of the stand structure. It indicates the contribution of trees in each diameter class to the formation of a forest stand and determines its other related characteristics.

The data obtained from timber cruising on the research plots was used to establish the distribution pattern of trees based on their natural diameter classes.

Analyzing the distribution of trees by natural diameter classes enables comparison and identification of tree measurement patterns in stands comprising trees of different average diameters. The formula used for the breakdown of data into natural diameter classes is as follows:

$$E = \frac{d_i}{d_{av}}, \quad (1)$$

where E – natural diameter class;

di- diameter class. cm;

dav- average diameter of a stand, cm.

Figure 2 and 3 present the distribution of trees by natural diameter classes for both living and dead fir trees.

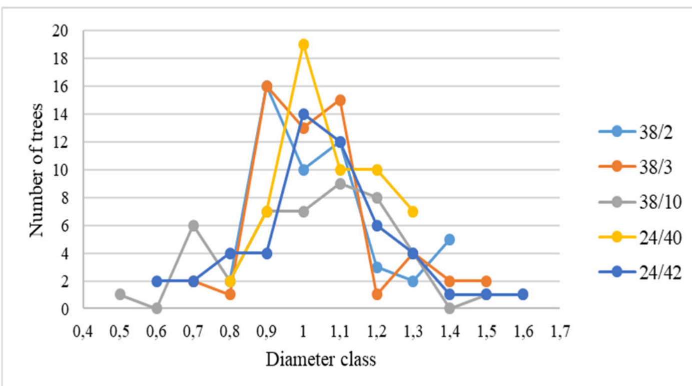

Fig. 2. Relationship between the distribution of trees by diameter classes (living fir trees).

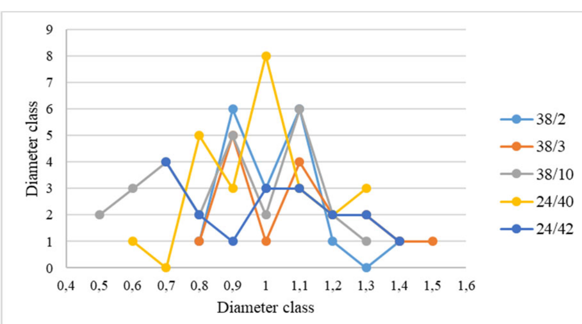

Fig. 3. Relationship between the distribution of trees by diameter classes (dead fir trees).

The distribution of trees is heterogeneous, often displaying two peaks, indicating the presence of trees with different diameters. The maximum number of living fir trees was observed in the 0.9 – 1.1 diameter classes (Figure 2). The deadwood also exhibits variation in tree diameters, with the majority of trees concentrated around the average diameters.

When comparing the diameter structure of living and dead trees, it is observed that the structure of deadwood largely mirrors that of the living trees. Therefore, calculations were only performed for the living fir trees.

To ensure uniformity in the distribution of rows based on forest inventory data (Table 1), the decision was made to combine data into two-centimeter diameter classes. This decision was made due to the heterogeneity of the average diameters of fir (ranging from 18.2 to 20.0 cm), forest stand (ranging from 17.7 to 20.6 cm), and spruce (ranging from 15.7 to 21.5 cm). The resulting series were used for further modeling.

The forest sites were modelled using the percentage of trees in each diameter class. To align the distribution rows, standard functions from the Curve Expert program were utilized. The results showed that the Gaussian Distribution (normal distribution curve) provided the best description of the series.

$$y = ae\wedge\frac{-(x-b)^2}{2c^2}, \tag{2}$$

where y – dependent variable value (number of trees, %);

x - independent variable value (diameter class);

e - base of a natural logarithm;

a - amplitude of the curve reflecting the maximum value of the function;

b - the average value that determines the position of the center of the curve;

c - standard deviation characterizing the spread of data relative to the average value.

Table 2 displays the features of the Gaussian model used to distribute the percentage of trees by natural diameter classes.

Table 2. Parameters of the Gaussian model of tree distribution (%) by natural diameter classes.

Tree species	Average diameter. cm	Equation	Equation coefficients			Statistical adequacy indicators	
			a	b	c	R	μ_{rel}, %
Fir	18	y=a*exp((-(b-x)^2)/(2*c^2))	28.750	0.994	0.128	0.86	± 6.6
	20	y=a*exp((-(b-x)^2)/(2*c^2))	23.648	1.059	0.162	0.97	± 2.5
Spruce	18	y=a*exp((-(b-x)^2)/(2*c^2))	14.338	0.692	0.582	0.58	± 6.0
	20	y=a*exp((-(b-x)^2)/(2*c^2))	30.250	1.438	0.797	0.55	± 13.9
Forest stand	18	y=a*exp((-(b-x)^2)/(2*c^2))	22.688	1.147	0.168	0.96	± 2.7
	20	y=a*exp((-(b-x)^2)/(2*c^2))	22.190	1.069	0.165	0.93	± 3.1

The table shows that the models for the stand as a whole and fir differ significantly from the model for spruce. Spruce is characterized by a low correlation between the experimental and adjusted values (0.55 – 0.58) and fairly high relative errors (±6–13.9%) due to the insufficient number of trees. Additionally, spruce with an average diameter of 20 cm has the shortest distribution series. which explains the high (±13.9%) relative error. At the same time. the coefficients of variation for the stand as a whole and fir varied from 0.86 to 0.97, and the equations' relative error did not exceed 10%.

Figure 4 shows a diagram of the distribution of trees (%) by natural diameter classes.

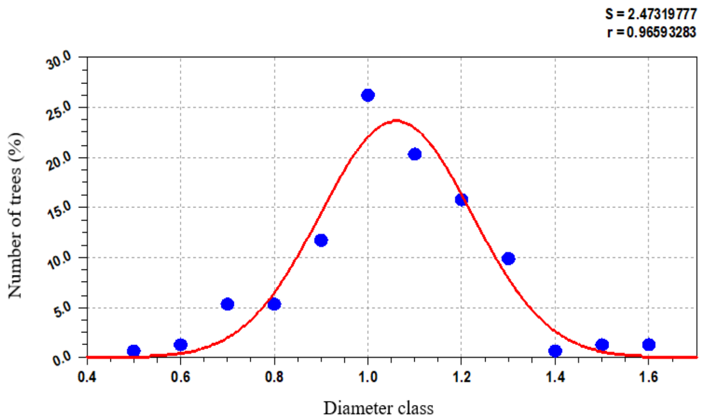

Fig. 4. Aligned series of distribution of trees by natural diameter classes (Gaussian function (fir, Dav = 20 cm)).

The equalized values of the number of trees (%) were calculated based on the obtained equations for the average diameter classes of 18 and 20 cm. according to the natural diameter classes (Table 3).

Table 3. Number of trees (%) by natural diameter classes.

Average diameter . cm	Diameter class													Total
	0.5	**0.6**	**0.7**	**0.8**	**0.9**	**1.0**	**1.1**	**1.2**	**1.3**	**1.4**	**1.5**	**1.6**	**1.7**	
18	0.01	0.12	0.70	2.83	8.08	16.2	22.8	22.6	15.7	7.67	2.64	0.64	0.11	100
20	0.06	0.42	1.96	6.37	14.3	22.2	23.8	17.7	9.09	3.23	0.79	0.14	0.02	100

Following this, a comparative analysis was conducted using standard distribution series to determine the number of trees (%) in fir stands based on diameter classes corresponding to the age stages described by Falaleev (Table 4) [10].

Table 4. The distribution of trees (%) in fir stands by diameter classes depending on their age stages according to Falaleev.

Maturity	Diameter class									
	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
	-	1	1.1	2.6	4.9	7.5	9.7	11.7	13.2	12.6
	Diameter class									
	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2.0
	10.9	8.7	6.1	4.2	2.8	1.5	0.8	0.4	0.2	0.1

Diagrams were constructed to illustrate the differences in the rows based on the relationships between the number of trees (%) and natural diameter classes (Figures 5, 6).

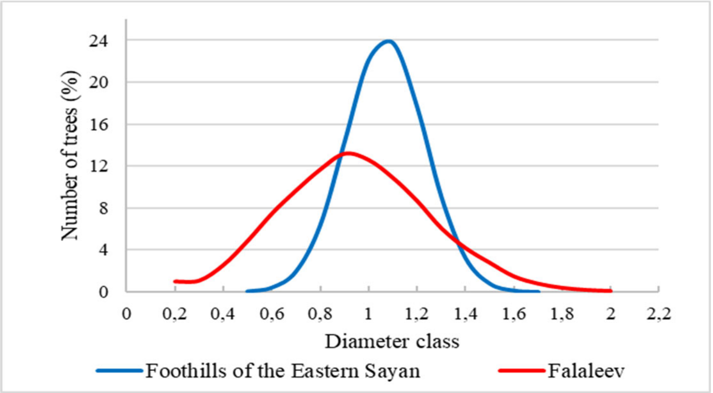

Fig. 5. Distribution of the number of trees in the 18-cm diameter class.

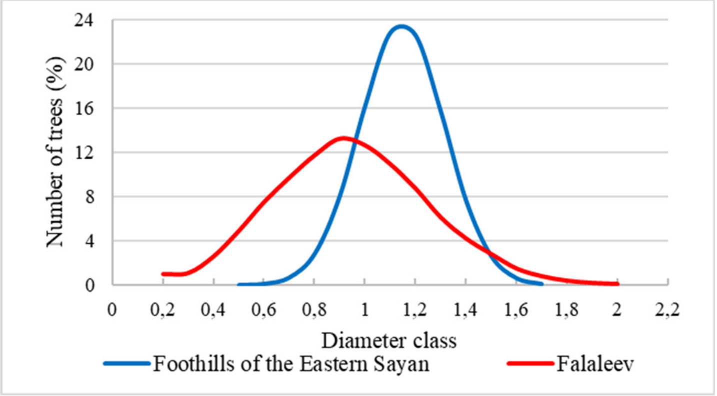

Fig. 6. Distribution of the number of trees in the 20-cm diameter class.

When comparing the distribution of the number of trees in fir stands (%) in the foothills of the Eastern Sayan with Falaleev's data, it appears that the rows exhibit significant differences from each other. A deviation to the right is observed in the resulting disturbed fir trees. For example, based on the obtained data, the highest percentage of trees was observed in the 1.2 diameter class for an average diameter of 18 cm, whereas Falaleev reported the highest percentage in the 0.9 diameter class. Similarly, for an average diameter of 20 cm, the highest percentage of trees was observed in the 1.1 and 0.9 diameter classes, respectively. It should be noted that the distribution series are more compressed compared to Falaleeva's data. Falaleeva's census included trees with a diameter of 4 cm or more, while our census only included trees with a diameter of up to 8 cm. This explains the differences in the left side of the distribution series. The difference on the right-hand side is due to the forest stand's severe damage caused by the four-eyed fir bark beetle. It is important to note that thicker trunks are commonly affected in outbreak areas, while trees with thin trunks are more frequently found in weakened forest communities [7].

4 Conclusion

The study found that the distribution of trees in fir stands in the foothills of the Eastern Sayan varies across natural diameter classes, indicating heterogeneity. The analysis revealed a wide range of structures for both living and dead trees. When comparing the distribution of trees by diameter classes with Falaleev's data, some differences in the forest stand structure were identified. Differences in measurement methods and the state of forest stands may account for these variations. The four-eyed fir bark beetle heavily damages the research plots, particularly large-sized trees, and significantly affects the structure of disturbed forest stands.

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