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RESEARCH ARTICLE

Steepness and types of steepness of structure curves according to volume of aggregates of forest stands of different categories and tree species

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Abstract

Based on data on the structures according to volumes of aggregates of forest stands of different categories – seed-tree coniferous and deciduous, rapidly growing, coppice, and forest plantations, the steepness of the structure curves has been studied while using the new index method for comparing parabolic curves (Petrin, 2021) , and the types of steepness have been determined by a new method – the method of coefficients, and, for comparison, by the method of natural indicators (Douhovnikov, 1966). Comparisons between the coefficients according to types of steepness and the zero natural indicators have showed an inversely proportional relationship with a high degree of correlation.

The curves of the structure indices according to volumes of the particular aggregates of the studied stands according to tree species and stand categories have been compared, and the values of the obtained indices have been analysed. By applying the new coefficients for the types of structure, the values and ranges of the steepness indices of all structure curves according to aggregates of stands have been found. It is concluded that the coefficients for the types of structure, as well as the indices according to steepness, are quite convenient tools for finding the differences in the structures of forest stands and homogeneous aggregates of these.

Key words

aggregates and categories of forest stands, volume structure, steepness indices, structure-type coefficients

Introduction

The curves revealing the growth and structure of even-aged, homogenous aggregates of trees in forests – stands, growing stocks or dendrocoenoses – according to height,

thicknesse and volume have most often parabolic aspects*; these are actually equalized curves (*- this is most often the left-hand-side ascending section of the convex parabola, which seldom exceeds the maximum, i.e. it is a smoothly ascending curve; curves can also be smoothly descending, exponential ones, as in the case of the curves of growth according to form factors). In the study of growth, the steepness of growth curves reveals growth rate, and while investigating structure the steepness of curves shows the rate of increase in the value of a given inventory indicator between the particular levels of thickness. In western literature, the steepness of growth curves is called 'speed of the speed', 'rate of the rate', or trend of growth (Trouillier et al., 2020). In the study of the height structure of a given forest stand, the steepness of height curves shows the rate of increase in heights between the particular levels of thickness. And if we investigate average, model, homogenous aggregates of stands of a given tree species, whose average inventory characteristics are known, as for example the average height or the volume per hectare, we then talk about structure by height or volume of a homogenous aggregate of stands. In the investigating the structures by volume of aggregates of homogenous stands, we may have an average height – levels of the height – instead of increasing levels of thickness on the abscissa. The steeper the structure curve is, the higher the values of the inventory characteristic (the volume per hectare) are for the high levels of the height. Therefore, the steepness and the type of steepness of the curves of the structure of forest stands, or of aggregates of these, are indicators, or parameters, related to their productivity and quantity and quality of wood.

Tomlinson et al. (2014), have found out that the growth rates of coniferous species are higher than those of deciduous ones.

Models have been developed of height curves for different mixed stands with different soil moisture.

Seo et al. (2017), have compared the rates of the growth in breast-height diameter, average height, and volume of stands of three species (*Pinus densiflora*, *P. koraiensis* and *Larix caempferi*) and found out that, under all other conditions equal, the Japanese larch (*Larix kaempferi*) has demonstrated the best rate of the growth in height and volume.

Oddi et al. (2022) have found out about Chilean cedar (*Austrocedrus chilensis*) that it thrives better on moist and cool sites, where there is more carbon in the soil and less oxidation.

In the present paper, we have suggested well-founded and used two new methodological approaches to and parameters of investigating the steepness of structure curves: steepness indices and growth-type coefficients for forest stands or homogenous aggregates of these. So far, structure-curve steepness has been determined through Douhovnikov's (1966) method of natural indicators. This method, however, despite its originality, is labour-intensive and insufficiently precise. This necessitated seeking simpler and more effective methods of determining the aspects of growth curves and structure curves (Petrin, 2021, 2022, 2023a, 2023b), as for particular forest stands and aggregates of these, so for comparative studies of the growth of particular

trees. The steepness and the growth type are most often studied in terms of height, but such studies are also possible in terms of the structure according to the other inventory characteristics as, for example, the average form factors, the volume and the increment.

Materials and Methods

Published data on the structures according to volumes of model aggregates of seed-tree coniferous stands of Scots pine, Austrian pine, Norway spruce, silver fir and Macedonian pine, seed-tree deciduous stands of common beech and common oak and common oak, stands of fast-growing tree species (linden and aspen), coppice stands of beech and oak, and plantations of Scots pine and Austrian pine have been used as a source of the investigation. These are the data on the volume per hectare depending on the average height, which are in the table for determining the volumes of whole growing stocks of trees (Table 1).

We are going to briefly present the contents of the notions: steepness, type of structure, and the indicators of determining these.

The steepness of the structure curve shows the rate of increase (or decrease) in the value of the inventory characteristic (a function) with the increase in the inventory characteristic (an argument) such as the thickness levels of a given stand and the average diameter or average height of an aggregate of homogenous stands. It is determined most easily and conveniently by means of steepness indices (Petrin, 2021). The steepness indices (I_{steep}) are relative numbers, each corresponding to a particular point of the structure curves when the latter are transformed into a relative kind. The indices are reported at the end of the relative curve (q_{xi}), which is obtained by dividing all the values on the ordinate (the volume per ha in this case) by one and the same ordinate value at the beginning of the range on the abscissa.

As one can see in Table 1, the volume structure of an aggregate of forest stands of a given tree species, whose steepness and type of steepness are objects of the present investigation, is investigated within the height-level (HL) range from 10 to 30 metres. The volume curves investigated are converted to the relative expression q_{Hi_V} in terms of one of the initial HLs (for example, H_{α}=12 м), and this occurs by dividing the volumes for the particular height levels (V_{Hn}) by the volume for the fixed initial height level, $V_{H\alpha}$, by means of the equation:

$$q_{Hi} = V_{Hn}/V_{H\alpha} \qquad (1)$$

The value of q_{xi} with a HL=30 m at the end of this same range ($q_{30}=V_{30}/V_{12}$) will be the steepness index of the volume-structure curve for an aggregate of stands composed of the particular tree species:

$$I_{steep}=q_{30} \qquad (2),$$

where I_{steep} – is the steepness index of the volume-structure curve, and the general formula is:

$$I_{steep}=V_{\Omega}/V_{\alpha} \quad (3),$$

where V_{Ω} is the volume of wood per ha at the end of the investigated height range, and V_{α} – the volume at the beginning of this same range.

The type of structure is a particular range within the general range where the indices of all steepness curves for a particular aggregate vary. The structure curves' steepness, as determined through the natural indicators' method (NIs M) invented by Douhovnikov (1966) is the higher the lower the zero natural indicator is. The zero natural indicator is the linear or free coefficient b_0 of the straight line obtained when all the ordinate values for all the relative curves (q_{xi}) of a particular aggregate of stands, obtained in a particular way and called normal numbers, are divided by the same values for the average curve – $q_{x\,av}$.

$$q_{xi}/q_{x\,cp}=ax+ b_0 \quad (3),$$

where x is the level of thickness (or height) of the aggregate i.

a *и* b_0 – coefficients of the straight line;

(b_0 is the zero natural indicator)

The structure-revealing zero natural indicators (ZNIs) are most often obtained with values from 0.2 to 1.9, and in all cases the value of 1 divides the structure curves into structure types.

The present investigation suggests that structure type be determined by using *structure-type coefficients*. The structure-type coefficient is a ratio of the steepness indices for the particular curves of the structure (2) of a given aggregate of stands to their average value- $I_{steep\,av}$. or:

$$C_{type\_i}= I_{steep(x)i}/ I_{steep(x)av} \quad (4)$$

The values of the coefficients for the types are, like the ZNIs, relative numbers of values close to 1, the value that divides the aggregate of curves into types of steepness.

The possible types of structure (or of steepness) are as follows:

Steep type of structure – Type T_{steep}, with which the steepness at the beginning of the curve is slight, but it increases later. This type is characteristic of curves (V_x) having higher indices of steepness (I_{steep}) and, respectively, lower zero natural indicators (ZNIs), b_o, as well as type coefficients, C_{type}, over 1.0.

Inclined type of structure – Type T_{incl}, with which the steepness at the beginning of the curve is higher, but it decreases later. The curves of this type are with lower indices of steepness, higher ZNIs, and structure-type coefficients lower than 1.0.

Average type of structure – Type T_{av}. The curves of this type are characterised by indices of steepness that are average for the aggregate and whose ZNIs and structure-type coefficients have values equal or close to 1.0. At differentiated studies of structure curves, the type T_{av} is not always differentiated.

Table 1. Volumetric table for whole growing stocks of trees according to forest-stand categories and tree species (by Mihov, 2005)

Avera-ge height [m]	Natural seed-tree stands								Rapidly growing		Coppice		Planta-tions	
	Scots pine	Austrian pine	Spruce	Fir	Macedonian pine	Beech	Oak (Wiemenauer)	Oak (Nedyalkov)	Lime	Aspen	Beech	Oak	Scots pine	Austrian pine
	Volumes [m³/ha]													
10	125	163	170	155	188	129	104	147	113	96	137	101	187	221
12	162	205	218	214	254	171	124	188	148	126	169	130	230	271
14	201	250	270	278	324	214	144	229	189	159	202	162	274	320
16	244	297	327	349	397	259	163	272	235	196	234	195	320	370
18	289	348	388	424	471	305	183	315	285	236	266	230	368	420
20	337	402	456	502	545	351	202	358	338	278	299	267	418	469
22	388	459	529	585	617	398	220	401	395	324	331	306	470	519
24	443	519	610	670	685	444	239	443	455	371	363	346	523	569
26	502	582	697	757	749	491	257	484	517	422	396	387	579	619
28	564	648	792	846	807	536	275	524	580	474	428	429	637	669
30	630	717	895	936	856	581	293	563	644	528	460	473	697	719

Results and Discussion

Relationship between the zero natural indicators of volume structures and the structure-type coefficients for aggregates of stands

Table 2 presents the rows of indices of the steepness of the structure-curves by for different aggregates of stands, their respective zero natural indicators (ZNIs) and structure-type coefficients.

Table 1 reveals that the values of the indicators of the type of structure according to volume for the aggregates of stands – the zero natural indicators and the structure-type coefficients – have values about 1.0 and that between them there is an inversely proportional relationship with a very high correlation coefficient – 0.98 – 0.99 and standard deviation 0.26 – 0.27. Lower ZNIs correspond to higher indices of steepness (I_{steep}) and higher structure-type coefficients (C_{type}).

Fig. 1 graphically reveals the rectilinear and inversely proportional relationships between the zero natural indicators and the structure-type coefficients for stand aggregates according to tree species. The rectilinear relationship and the equation pre-

Table 2. Indices of steepness (Isteep), zero natural indicators (ZNIs), structure-type coefficients (Ctype) and correlation coefficients (R) between the structure-type indicators (ZNIs and Ctype) according to categories of stands and tree species

Indicators	Seed-tree forest stands								Average values	Correla-tion coefficients, R: ZNIs÷C_{type} and st.dev.: *p*
	Coniferous					Deciduous				
	Tree species									
	Scots pine	Aust-rian pine	spruce	fir	Macedonian pine	beech	oak, Wiem-enauer	oak, Nedya-lkov		
Indices of steepness – I_{steep}	3.89	3.50	4.11	4.37	3.37	3.40	2.36	2.99	3.50	-
ZNIs	0.78	0.95	0.71	0.62	1.00	0.99	1.73	1.21	1.00	0.98 ; 0.26
C_{type}	1.11	1.00	1.17	1.25	0.96	0.97	0.68	0.86	1.00	
-	Other categories of forest stands								-	-
	Rapidly growing		Coppice		Plantations		-	-		
	Tree species									
	Lime	Aspen	beech	oak	Scots pine	Aust-rian pine	-	-		
Indices of steepness – I_{steep}	4.35	4.19	2.72	3.64	3.03	2.65	-	-	3.43	-
ZNIs	0.60	0.65	1.36	0.85	1.15	1.40	-	-	1.00	0.99; 0.27
C_{type}	1.27	1.22	0.79	1.06	0.88	0.77	-	-	1.00	

sented on the graph make it easy to pass from zero natural indicators to type coefficients and vice versa for all the investigated aggregates of stands according to tree species.

At the same time, the graph reveals that all the three lines – the vertical one on the abscissa's 1.0 (ZNIs), the horizontal one on the ordinate's 1.0 (C_{type}), and the straight one revealing the relationship between them – intercept in ONE point. This means that the division into types of the two indicators (ZNIs and C_{type}) is one and the same in its essence and ranges. All the points (respectively stands) situated above C_{type}=1.0

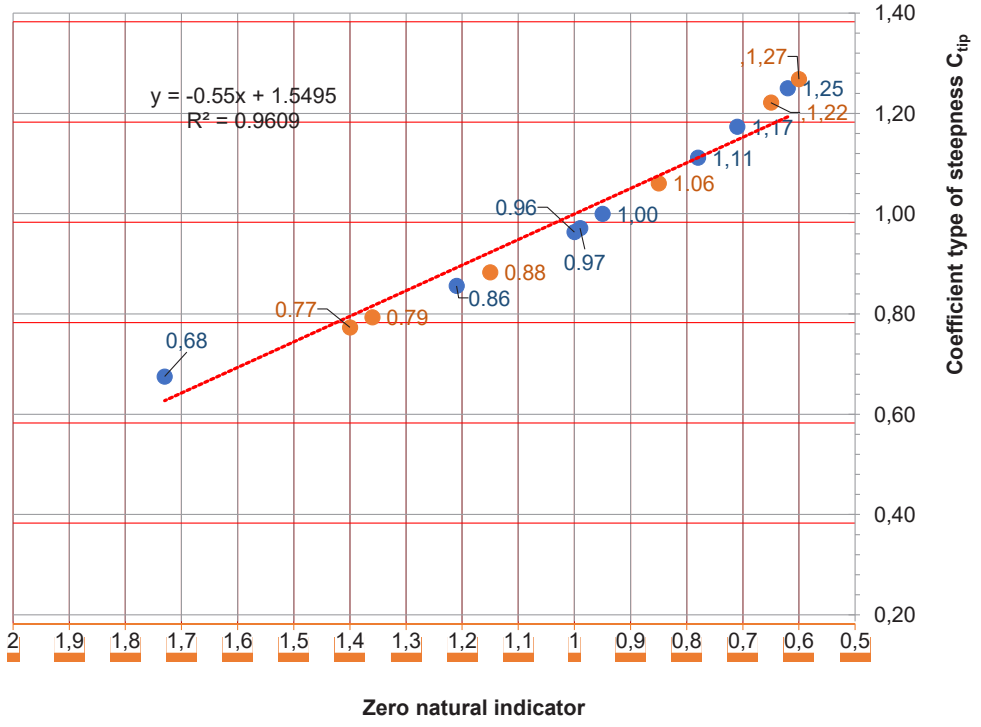

Fig. 1. Relationship between the structure-type coefficients and the zero natural indicators for all aggregates of stands by tree species

are of the steep type, and those below 1.0 are of the inclined type. This same is also the division by ZNIs but along the abscissa – big ZNIs up to 1.0 show the inclined type, and the ones lower than 1.0 – the steep type.

Curves of the indices

Figure 2 presents the index curves of the two investigated aggregates of stand categories according to tree species: 1) seed-tree stands and 2) rapidly growing stands, coppice stands, and plantations. If we analyse the indices of steepness in connection with the biological-and-ecological nature of the investigated tree species, we can find that these indices increase with the increase in the shade tolerance of the tree species, which is related to the increase in soil moisture and can be accompanied by general aggravation of site conditions, i.e. by decrease in stand-quality level (Petrin, 2021, 2022). Thus fir has the highest index of steepness – 4.37, next followed by spruce (4.11), then – by Scots and Austrian pines (3.89 and 3.5) – here the soil factor matters and shade tolerance – these pines, though grow on poor soils, are light-loving, that affect their indices of steepness in the direction of decrease. The indices for Macedonian pine and common beech are almost equal (3.37 and 3.4), and last come the lowest indices for the seed-tree oak (2.36 and 2.99) (Nedyalkov, 1966). The shadier the growth

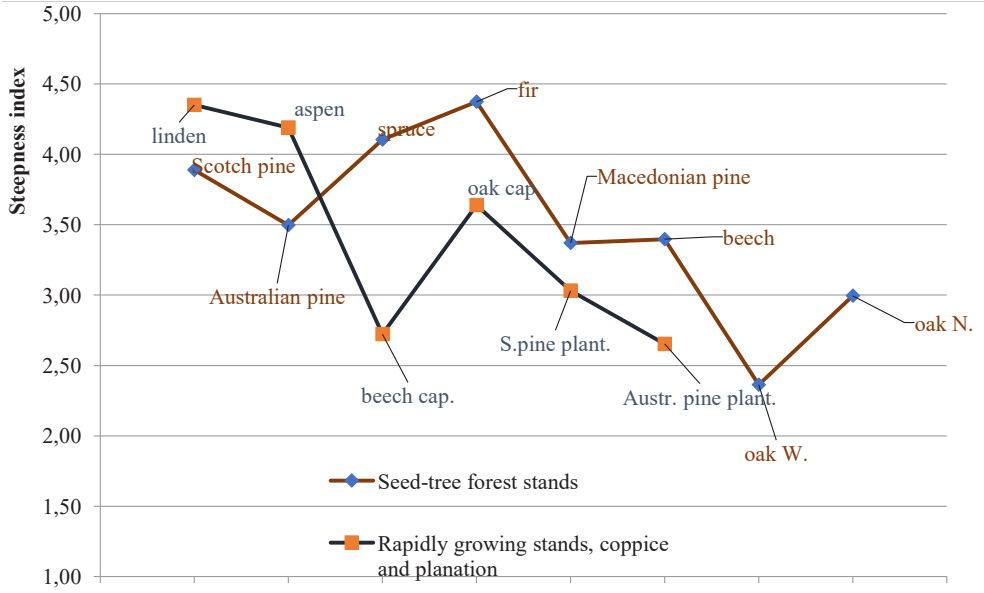

Fig. 2. Curves of the indices according to stand's categories and tree species

conditions are, the steeper the structure curve is. However, for a particular tree species there can also be a combination of opposite factors which make average the structure-curve's steepness as in the case of Macedonian pine and common beech; Macedonian pine is light-demanding but it grows at higher altitudes, at lower temperatures, and the beech, though it is shade-tolerant, grows better at the availability of more light.

Interesting is the situation with the indices for the rapidly growing stands, the coppice ones and the plantations. The rapidly growing ones have the highest indices – lime (4.35) and aspen (4.19) – and they appear only from the steep type of structure (with steepness indices over 3.5), next followed by coppice oak (3.64) – the steep type, next – by Scots pine plantations (3.03), coppice beech – 2.72, and Austrian pine plantations (2.65) – all of them being of the inclined type. With coppice regeneration, as a less favourable variant with a lower energy of growth, the indices generally have lower values. The ways of beech and oak regeneration affect inversely the structure curve – it is steeper with seed-tree beech and slightly inclined with seed-tree oak. This situation is just the opposite with coppice stands. The fact that Scots and Austrian pine plantations have structure curves that are less steep than those for the natural stands of these species is easy to explain with their almost absolutely even age with the respective average height or age. This reduces the range of height grades and makes the structure curve by volume flatter. It is clear that the indices of steepness according to volume per ha of areas under the particular tree species (Fig. 3), which are points on the steepness-index curves, according to stand categories, enable us to make a detailed and profound analysis in connection with the ecological-and-biological peculiarities of tree species, and this assists solving various problems related to volume modelling, tree-species optimisation, etc.

Average relative curves ($q_{x\ av}$) and curves of the indices according to forest-stand categories and tree species

Table 3 and Fig. 3 shows the average relative curves ($q_{Hav)}$ of the structures according to volumes of the investigated aggregates of stands, as calculated by means of Formula 1, and the calculated indices of steepness have been shown too.

The steepest curves are for the rapidly growing tree species (I_{steep}=4.27), next followed by those for the natural coniferous, natural deciduous and coppice stands and the plantations with their respective indices of steepness (I_{steep}): 3.85, 3.54, 3.18 and 2.84.

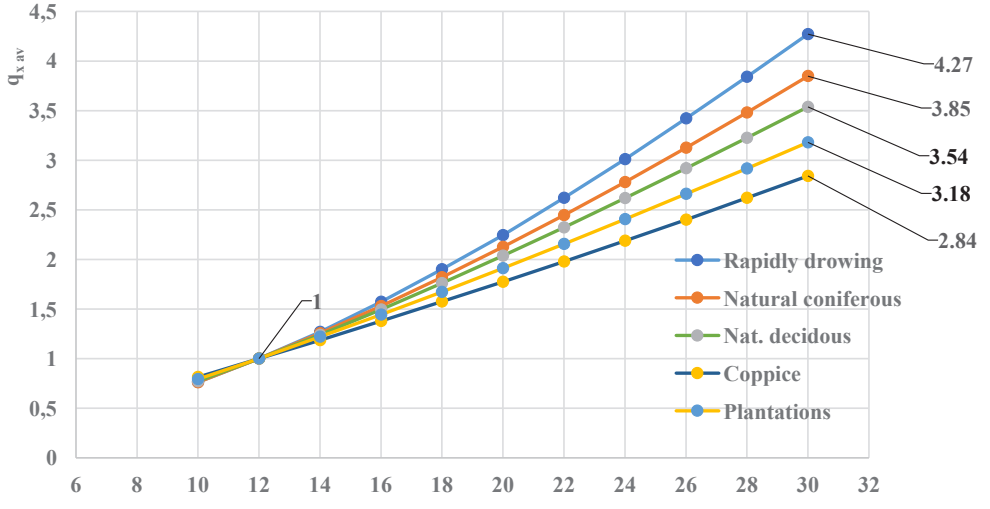

Fig. 3. Average relative curves $q_{x\ av}$ according to stand's categories

Table 3. Average relative curves qx av according to stand's categories

Stand's categories	Height levels, m										
	10	12	14	16	18	20	22	24	26	28	30
Natural coniferous	0.76	1.00	1.25	1.53	1.82	2.12	2.44	2.78	3.12	3.48	3.85
Natural decidous	0.77	1.00	1.24	1.49	1.76	2.04	2.32	2.62	2.92	3.23	3.54
Rapidly growing	0.76	1.00	1.27	1.57	1.90	2.25	2.62	3.01	3.42	3.84	4.27
Coppice	0.79	1.00	1.22	1.44	1.67	1.91	2.16	2.40	2.66	2.92	3.18
Plantations	0.81	1.00	1.19	1.38	1.57	1.77	1.98	2.19	2.40	2.62	2.84

Table 4. Average values and range values of the steepness indices according to growth types and stand categories

Stand categories	Average values of the indices (C_{type}=1)	Structure types	
		Steep (T_{steep}) $C_{tip} \geq 1.0$	Inclined ($T_{inclined}$) $C_{tip} < 1.0$
		Steepness-index ranges	
Seed-tree forest stands	3.5	4.37÷3.5	3.49÷2.36
Rapidly growing, coppice and plantations	3.43	4.19÷3.43	3.42÷2.65
Total	3.47	4.28÷3.47	3.46÷2.5

Index values according to structure types and stand categories

The close rectilinear correlation between the coefficients for type (C_{type}) and the ZNIs (Fig.1), suggests also the availability of a close rectilinear relationship directly between the ZNIs and the steepness indices (I_{steep}) as the coefficients are, by definition, derivative from the indices (Equation 4). And this makes the indices suitable for determining the type of structure without even calculating the coefficients for the type, only proceeding from the index average for the aggregate investigated. Next to the average index, there will be an inclined one and after the average one – a steep type of structure curves.

Table 4 contains the average values and the range values of the steepness indices for two differentiated types of structure – steep and slightly inclined.

One can see in the table that the ranges of the indices as a whole for the steep and slightly inclined types are from 4.28 to 3.47 and from 3.46 to 2.5, respectively, and that the ranges of the indices for the rapidly growing stands, the coppice ones and the plantations, taken together, are narrower than those for the seed-tree stands.

Conclusion

An inversely proportional rectilinear relationship with a high level of correlation exists between the structure-type coefficients and the zero natural indicators, which proves the applicability of the introduced coefficients and indices.

The shadier and moister, or worse, the growth conditions are, the steeper the curve of volume structure is and, for a particular tree species, on a particular site, there can be a combination of opposite environmental factors that make the structure-curve steepness more average.

Coppice regeneration, as less favourable, decreases the steepness of structure curves.

Scots-pine and Austrian-pine plantations have less steep structure curves as compared with the natural stands of these species, which can be explained with their almost absolutely even age and better growth at early age.

Generally, the ranges of the indices for the steep and slightly inclined types are from 4.28 to 3.47 and from 3.46 to 2.5, respectively, as these same indices for the rapidly growing stands, the coppice ones and the plantations taken together are narrower than those for the seed-tree species.

The coefficients of structure-type, as well as the indices for determining the steepness of structure curves, are reliable tools for studying structure curves as of particular stands so of homogenous aggregates of stands.

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