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Growth-rate indices and coefficients of the types of growth in height of coniferous forest stands

Rumen D. Petrin, ✉ lesni4eja2014@gmail.com https://orcid.org/0000-0002-5831-5983

Forest Research Institute in Bulgarian Academy of Sciences, 132, St. Kliment Ohridski Blvd., Sofia, 1756, Bulgaria

Abstract

Based on data about the growth in height of different coniferous tree species, namely Scots and Austrian pines (*Pinus sylvestris* L. and *Pinus nigra* Arnold), Norway spruce (*Picea abies* (L.) Karst.) and silver fir (*Abies alba* Mill.), have their growth rates within the same age range been investigated. New coefficients have been suggested for estimating their types of growth and the suitability of using these coefficients has been proved, as they have been compared with the Douhovnicov's zero natural indicators for the particular curves, and a high level of correlation has been found. The important parametric (qualitative) growth-rate curves, the curves of the normal numbers for the height growth of the four coniferous tree species are presented and analyzed, as well as the index curves. Further on, while applying the new growth-type coefficients, the values and ranges of the growth-rate indices have been found for the tree species investigated. It has been concluded that the growth-type coefficients, as well as the growth-rate indices, are tools quite comfortable and rather suitable for finding differences and similarities between the rates and types of the growth of forest stands.

Keywords: growth rate, growth type, stand-quality level, coniferous stands, tree species

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Индексы темпа роста и коэффициенты типа роста по высоте хвойных лесных насаждений

Румен Димитров Петрин ✉ lesni4eja2014@gmail.com https://orcid.org/0000-0002-5831-5983

Научно-исследовательский институт леса Болгарской академии наук, бул. Климента Охридского, 132, г. София, 1756, Болгария

На основании данных о росте по высоте различных пород хвойных насаждений: сосны обыкновенной (*Pinus sylvestris* L.), сосны черной (*Pinus nigra* J.F.Arnold), ели обыкновенной (*Picea abies* (L.) H. Karst.) и пихты белой (*Abies alba* Mill.) – изучена скорость (или, темп) их роста в одном и том же возрастном интервале. Предло-

жены новые коэффициенты для оценки типа роста и доказана их пригодность к использованию, для чего их сопоставили с нулевыми натуральными показателями Духовникова для отдельных кривых с высокой степенью корреляции. Далее путем применения новых коэффициентов по типу роста были установлены значения и интервалы показателей скорости роста насаждений исследуемых пород. Коэффициенты типа роста, как и индексы темпа роста, являются достаточно удобным инструментом для установления различий и сходства в скорости роста и типе насаждений.

Ключевые слова: индексы темпа роста, коэффициенты типа роста, бонитет, хвойные породы деревьев.

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Introduction

The rates and types of forest stands' growth, available within each stand-quality level, are factors found long ago when studying this growth. The more important inferences from the studies of these matters by different authors have been presented in our dissertation (R. Petrin, 1988) entitled: Regularities of the Growth of Beech Stands and Using These in Forest-Management Planning. These inferences pertain mainly to: the availability of different types of growth of forest stands composed of almost all tree species, the relationship between growth rate and site conditions, and the differences in the productivities of stands of different types – the more productive stands within one and the same stand-quality level are those whose growth type is Ty – the type with an increasing growth rate corresponding to a late climax of increment.

The indicated studies (Davidov, 1977, 1980 and 1984; Douhovnikov and Iliev,1972, Douhovnikov and Bogdanov, 1979, Douhovnikov, 1980; Mihov, 1983, 1984 and 1986 and Petrin, 1988) prove the necessity for composing differentiated growth tables and passing from static to dynamic identification of stand-quality levels, where not only these levels but also the types of growth are identified. Similar findings of different authors have provided the basis of composing growth-rate and stand-quality-level tables differentiated according to growth types as, for example, those for Scots pine, Norway spruce and silver fir (Douhovnikov and Iliev, 1972), beech (Petrin, 1988) etc. Suggested have also been indices for identifying the types of growth of stands in forests (Mihov, 1986; Petrin, 1988 and Mihov and Petrin, 1996), on the basis of their relationship with the zero natural indicators (Douhovnikov, 1966).

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

Yeongwan Seo, Daesung Lee & Jungkee Choi, 2017, have compared the rates of the growth in breast-height diameter, average height, and volume of stands of three species: Pinus densiflora, Pinus koraiensis and Larix caempferi; they have found out that, under all other conditions equal, the Japanese larch (Larix kaempferi /Lk/) has demonstrated the best rate of the growth in height and volume.

Jarosław Socha, Louisa Timinska-Chabanska et al., 2020, have found out for the main forest-forming species in Poland thatthe curves of the stand-quality-level classes of the young and old stands investigated deflect to the utmost extent from their averageaspects.

Facundo J. Oddi, Cecilia Casas 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.

Diego Rodríguez de Prado, Jose Riofrío et al., 2022, have investigated the structures in height of pure and mixed coniferous and deciduous stands and have found thatthe pure coniferous stands reach a higher average height than the mixed ones, and it is just the opposite with the deciduous ones – the mixed ones grow better. Models have been developed of height curves for different mixed stands with different soil moisture.

This paper has been intended to theoretically present and apply into practice two, new methodological approaches, as well as to introduce two, new parameters of growth curves: growth-rate indices (Petrin, 2021) and height-growth-type coefficients for of model forest stands of Scots and Austrian pine, Norway spruce and silver fir. The rates and types of the growth in height are investigated most often as the growth in height is a determining factor of the wood-production process. However, these indicators of the rate and type of growth can also be applied for every other curve of growth or structure of forest stands as all these curves are similar and usually have parabolic shapes.

Materials and Methods

The following published works have been used as sources of data for the investigation:

- Published data on the growth in height and on the stand-quality levels of Scots pine stands (A. Tyurin, Poryazov, Tonchev and Dobrichov, 2004);

- Published data on the growth in height and on the stand-quality levels of Austrian pine stands (C. Nedyalkov, Krustanov and Raykov, 2004);

- Published data on the growth in height and on the stand-quality levels of Norway spruce stands (Nedyalkov, Poryazov, Tonchev and Dobrichov, 2004);

- Published data on the growth in height and on the stand-quality levels of silver fir (Shikov, Poryazov, Tonchev and Dobrichov, 2004).

The work examines model stands of four coniferous tree species, namely: white pine (Pinus sylvestris L.), black pine (Pinus nigra J.F. Arnold), spruce (Picea abies (L.) H. Karst.) and silver fir (Abies alba Mill.). For each tree species, data were used on the course of height growth of one stand from seven Stand-quality level (Ia, I, II, III, IV, V and Va), or a total of 28 stands.

We are going to briefly present the contents of the concepts rate and type of growth and indicators of identifying these.

The rate of growth is the steepness of the curve expressing the growth in height, or in another forest-mensuration characteristic, which shows how quickly height increases with age, and it is estimated by means of growth-rate indices (Petrin, 2021). In Western literature, the steepness of growth curves is called rate of growth, or growth trend (Mario Trouillier et al., 2020).

Growth-rate indices ($I_{gr\,r}$) are relative numbers of the studied growth curves obtained in a certain way. Let us consider the height growth of a forest stand, the growth rate of which is the subject of the present study, and let the average age of height growth be from 20 to 100, 110, and more years. Then, the curve of growth in height for this stand (i) is reduced to a relative expression with respect to the height (H) at an initial age $x=\alpha$, and the curve of normal numbers - q_{xi} is obtained, according to the equation:

$$q_{xi}=H_{xi}/H_{\alpha}, \quad (1)$$

whereH_{xi} is the height at a given age x.

At $\alpha=30$, the equation takes the form:

$$q_{xi}=H_{xi}/H_{30} \quad (2)$$

Then, the value of q_{xi} in 100 years (q_{100}) will be the height-growth rate index ($I_{gr\,r}$) of the stand:

$$I_{gr\,r}=H_{100}/H_{30} \quad (3)$$

Ingeneral, equation (3) can be written in the form:

$$I_{gr\,r}= H_{\Omega}/H_{\alpha} \quad (4),$$

where H_{Ω} is one of the heights at the end of the investigated age range, and H_{α} is the height at the beginning of this age range.

To make it possible to compare, when investigating one or more aggregates of curves, the growth-rate indices have to be calculated within one and the same age range. The best such range is the one 30÷100 years, but it can also be another.

The type of growth, in its turn, is the range that is part of the total range of the growth-rate curves. The rates of growth and the respective types of growth were identified up to now through the natural indicators method (NIM) of Douhovnikov, 1966. With it, the lower the zero natural indicator is the higher the rate of growth is. The zero natural indicators of the growth in height are most often obtained with values from 0.6 to 1.4, and in all situations the value of 1 divides the aggregate of growth curves into types of growth. The zero natural indicator is the linear, or free, coefficient b of the straight line, which is obtained, or which approximates the obtained parabolic curve when all the relative curves (q_x) of the investigated aggregate are divided by their average curve- $q_{x\,av}$:

$$q_x/q_{xav} = ax+b, \quad (5)$$

where x stands for age, and a and b – for the coefficients of the straight line.

In the present study, it has been suggested for the first time to determine the type of growth by means of coefficients for the type of growth. The growth-type coefficient is a ratio of the growth-rate indices (2) for a particular aggregate of stands, or trees, to their average value – $I_{gr\,rav.}$, or:

$$C_t = I_{gr\,r}/I_{gr\,av.} \quad (6)$$

The correlation method and graphical approximation were used to compare the zero natural indicators calculated for each stand and the growth type coefficients.

The possible types of growth are the following ones:

T_{inc} Type – a growth type with an initially low growth rate that later increases – a type of increasing growth with a LATE climax of the increment. To it correspond the curves (H_A) of higher growth-rate indices ($I_{gr\,r}$), of lower zero natural indicators (ZNIs), as well as of coefficients of the K_{tip} type – higher than 1.0.

T_d Type – a growth type with an initially high growth ratethat gradually abates– a type of decreasing growth rate, with an EARLY climax of the increment, where the curves are characterised by lower indices of the growth rate, higher zero natural indicators (ZNIs) and growth-rate coefficients lower than 1.0.

T_{us} Type – usual, or average type, which is not always differentiated. The growth-rate indices for the average type have average values, and the indicators of the types of growth (the zero natural indicators and the growth-type coefficients) have values around 1.

Results and Discussion

1. *Relationship between the growth-rate indices, zero natural indicators and growth-type coefficients for the coniferous tree species*

Table 1 presents the rows of indices of the rates of growth in height, growth-type coefficients and zero natural indicators according to stand-quality levels and tree species.

Table 1

Growth-rate indices ($I_{gr\,r}$), growth-type coefficients (Ct), zero natural indicators and correlation coefficient indicative of growth type

Tree species	Indicators of rate and type of growth	Stand-quality levels								Correlation coefficient (R) Ct÷ ZNIs
		Ia	I	II	III	IV	V	Va	Average indicators	
Scots pine	$I_{gr\,r}$	2.35	2.44	2.47	2.59	2.60	2.78	3.03	2.54	-0.99
	Ct	0.93	0.96	0.97	1.02	1.02	1.09	1.19	1.00	
	ZNI	1.09	1.07	1.05	0.95	0.96	0.89	0.73	1.00	
Austrian pine	$I_{gr\,r}$	-	1.84	1.87	1.97	2.11	2.24	-	2.01	-0.99
	Ct	-	0.91	0.93	1.00	1.05	1.12	-	1.00	
	ZNI	-	1.31	1.23	1.00	0.80	0.64	-	1.00	
	$I_{gr\,r}$	-	3.56	3.90	4.39	4.82	5.00	-	4.33	-0.99

Tree species	Indicators of rate and type of growth	Stand-quality levels								Correlation coefficient (R) Ct÷ ZNIs
		Ia	I	II	III	IV	V	Va	Average indicators	
Norway spruce	Ct	-	0.82	0.90	1.01	1.11	1.15	-	1.00	
	ZNI	-	1.36	1.15	0.97	0.83	0.68	-	1.00	
Silver fire	$I_{gr\,r}$	-	4	4.62	4.66	4.77	5.25	-	4.66	-0.99
	Ct	-	0.86	0.99	1.00	1.02	1.13	-	1.00	
	ZNI	-	1.28	1.02	0.99	0.94	0.77	-	1.00	
Generally	$I_{gr\,r}$	-	2.96	3.22	3.40	3.58	3.82	-	3.38	-0.99
	Ct	-	0.89	0.95	1.01	1.05	1.12	-	1.00	
	ZNI	-	1.25	1.11	0.98	0.88	0.74	-	1.00	

Source: own calculations

One can see in Table 1 that the values of the indicators of the growth type – the growth-type coefficients and the zero natural indicators – coincide around the value of 1, which stands for about Stand-Quality LevelIII. The values of the growth-rate indices within each particular stand-quality level increase with the increase in the shade tolerance of the tree species – from Austrian pine through Scots pine toward Norway spruce and silver fir. This same trend as to an increase is also observed with the decrease in the stand-quality-level class:the growth rate increases within the range of each tree species (TS)and generally for all the tree species. Therefore,the more shady and moist, or worse, the growth conditions are, the steeper the curve of the growth in height is.The coefficient of the correlation R between the zero natural indicators (ZNIs)and Ct is very high – about 1.0.

Figure 1 graphically shows the relationship between these two indicators as the stand-quality-level class becomes lower. The relationship is in a direct ratio and inverse proportion. Therefore, the coefficients for the types of growth are entirely suitable to use for determining the types of growth.

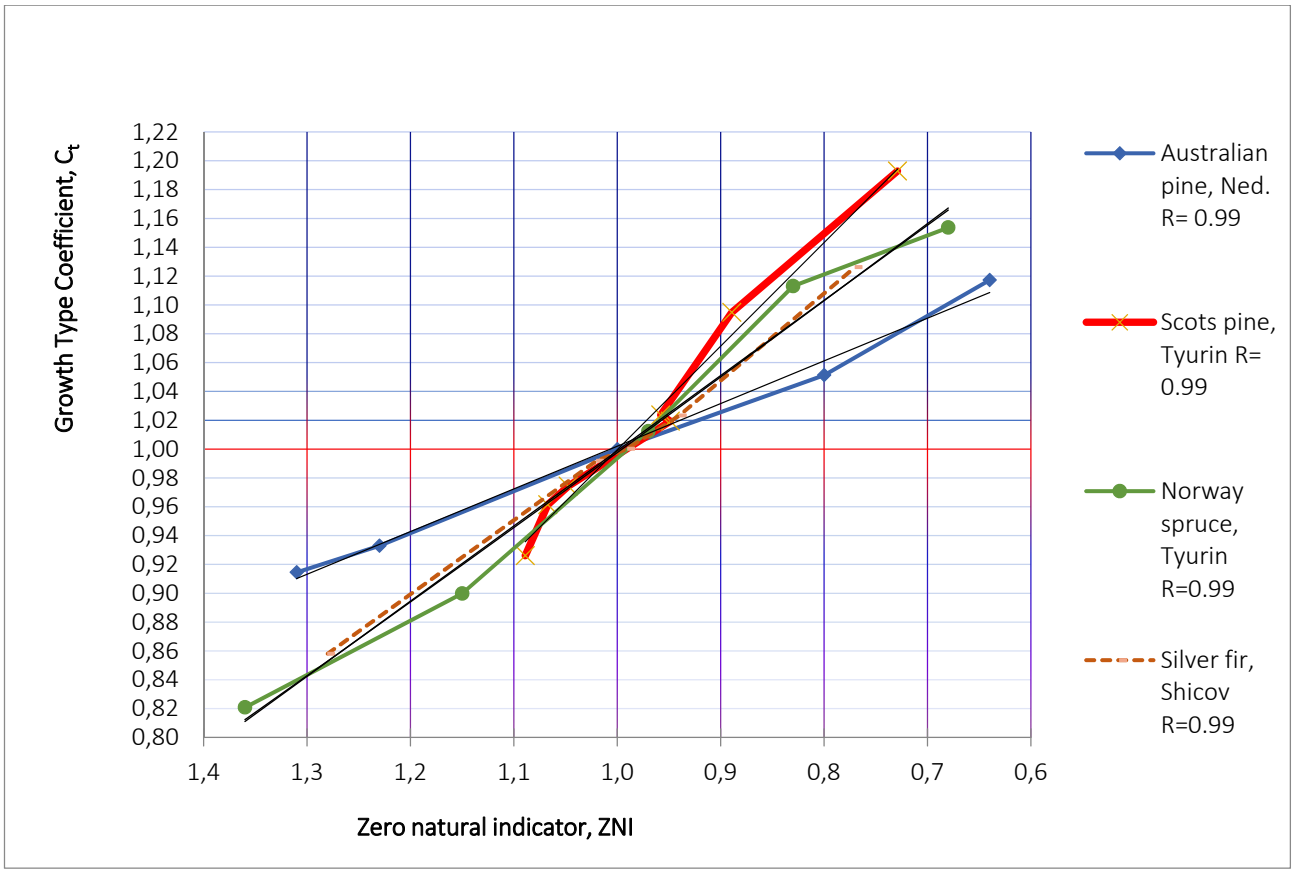

Figure 1. Relashionship between zero natural indicators (ZNi) and height-growth-type coefficients (Ct) for the coniferous tree species with the decrease in stand-quality level

Source: author's composition

The average intervals ofthe zero natural indicators (ZNi) and the growth-type coefficients (Ct) are 1.3÷0.7 and 0.85÷1.15, respectively, and the maximal ones - 1.4÷0.6 and0.8÷1.2.

For each of the ranges of both indicators, their first halves, i.e. up to 1.0, pertain to T_d growth type, and their second ones – to T_{inc} growth type.

2. *Average relative curves (q_{xi}), and index curves of height growth rate*

Table 2 and Figure 2 present the average relative height growth curves (q_{xi}) – also called normal number curves – for tree species (Equation 2), which clearly shows the difference in steepness. They are extremely convenient for comparative qualitative studies of the growth, increment, and structure of forest stands (Douhovnikov, 1966, Mihov, 2005, Petrin, 1988, 2021, 2022).

Table 2

Average relative curves for growth in height ($q_{xi\ av.}$) according to tree species

Tree species	Age, years								
	20	30	40	50	60	70	80	90	100
Scots pine	0.66	1.00	1.33	1.62	1.87	2.09	2.26	2.41	2.54
Austrian pine	0.64	1.00	1.29	1.49	1.65	1.80	1.89	1.95	2.01
Norway spruce	0.54	1.00	1.49	2.08	2.66	3.20	3.64	4.02	4.33
Silver fir	0.51	1.00	1.60	2.32	2.96	3.48	3.95	4.31	4.66

Source: own calculations

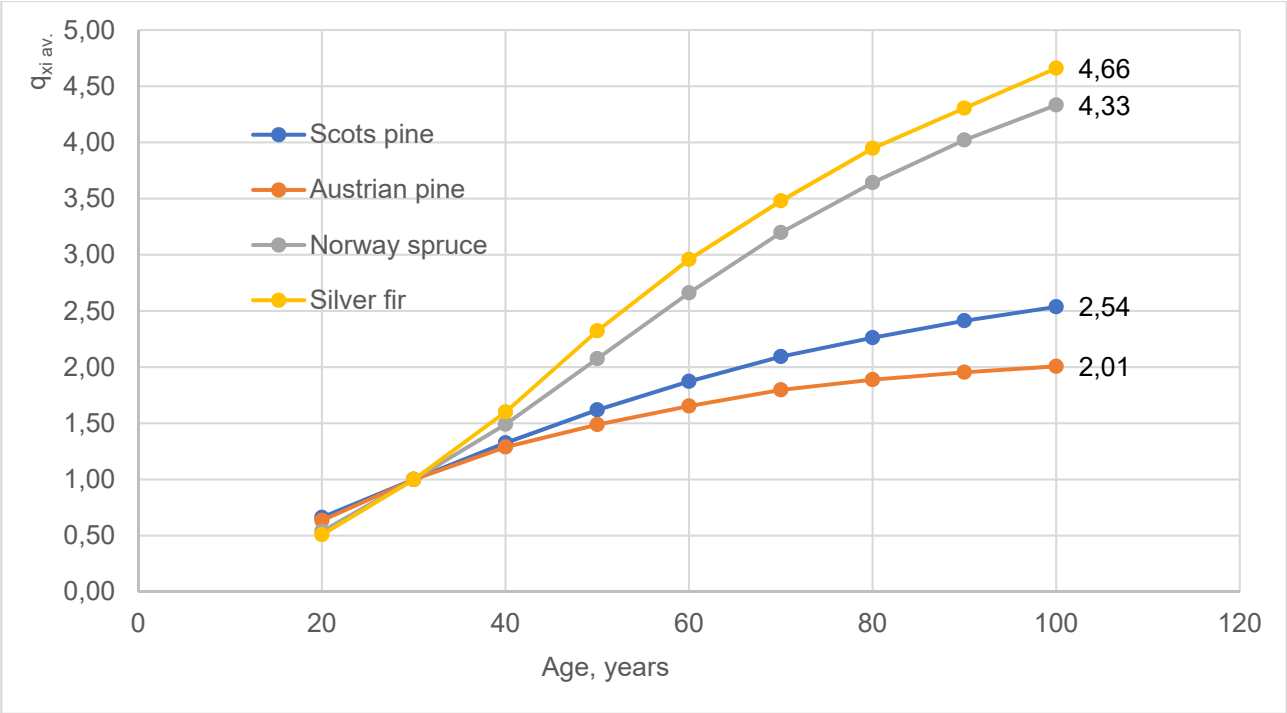

Figure 2. Average relative curves for growth in height ($q_{xiav.}$) according to tree species

Source: author's composition

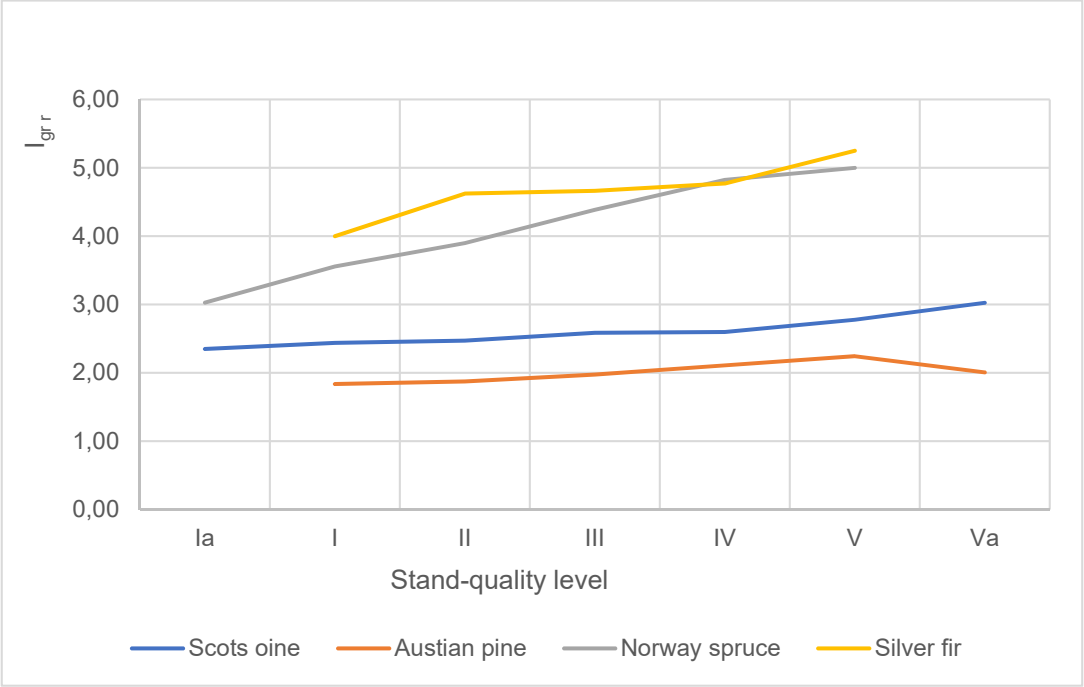

Figure 3. Curves of growth-rate indices according to height and tree species

Source: author's composition

Figure 3 shows the index curves for the growth rate of the four coniferous tree species depending on Stand-quality level.

The location of the index curves in Figure 3, as well as the data from Table 1, make it possible to see the differences in the values of the growth rates of Scots pine, Austrian pine, Norway spruce and Silver fir. As previously found for conifer species (Yeongwan Seo, Daesung Lee & Jungkee Choi, 2017) and broadleaf species (Petrin, 2021), growth rate increases with increasing shade tolerance of tree species.The Silver fir index curve is located at the top, followed by the same one for Norway spruce, Scots pine and Austrian pine. The same tendency towards an increase in growth rate indices is observed when the stand-quality level is lowered, i.e. the growth rate more or less increases for all tree species.

3. *Growth-Rate Index Values for the Coniferous Tree Species according to Growth Types*

Figure 4 shows the growth-rate indices according to tree species with the decrease in the stand-quality-level class depending onthe growth-type coefficients. The indices' straight lines ascend within the stand-quality-level ranges, and the indices according togrowth types have clearly been illustrated. T_{us} Ct = 1.0 from the abscisa does the average index, $I_{gr\ r\ av.}$, correspond.

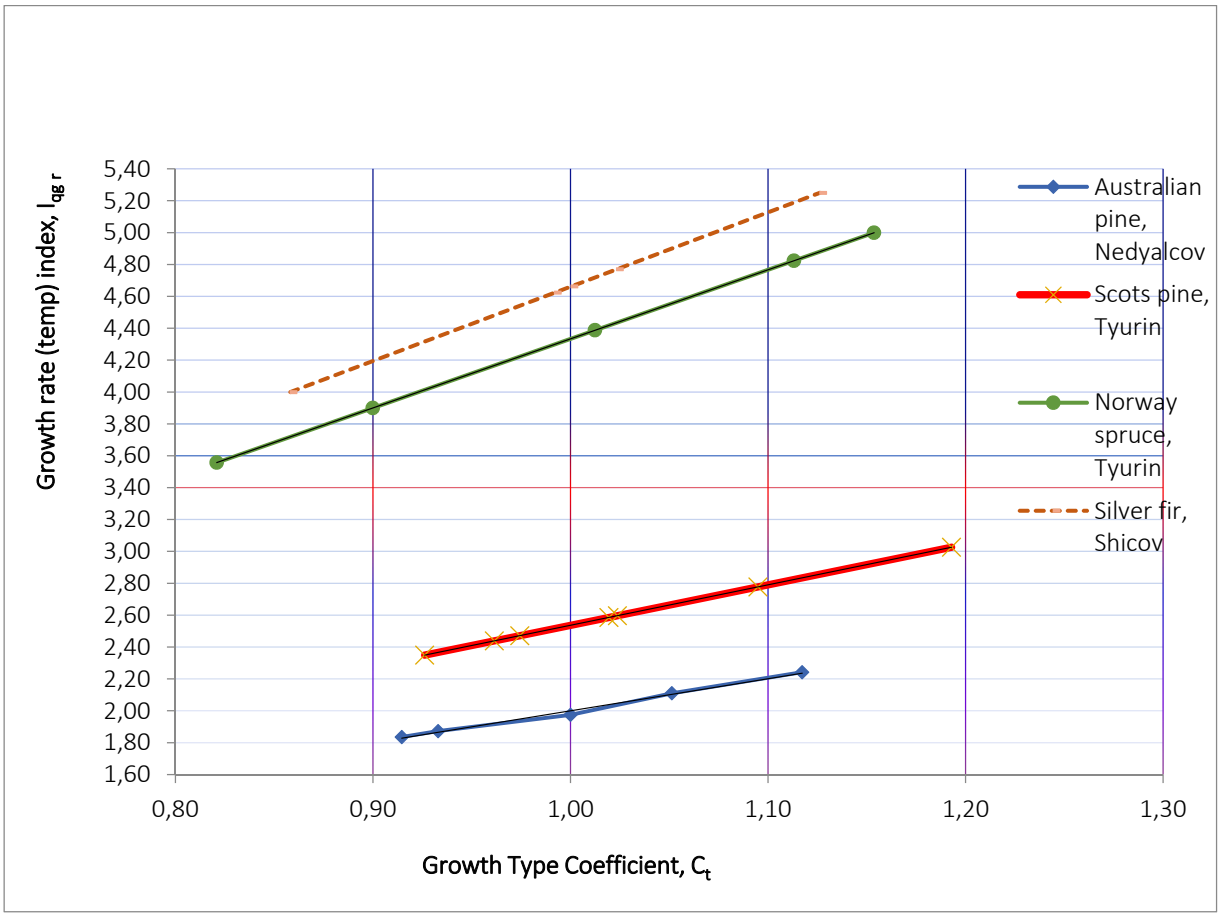

Figure 4. Relationship between the Growth-Type Coefficients for the Coniferous Tree Species (Ct) and the Growth-Rate Indices ($I_{gr\ r}$) with the Decrease in Stand-Quality Level

The ranges of the growth-rate indices according to growth types and their respective average values have been presented in Table 3.

Table 3

Index Ranges and Average Values of the Growth-Rate Indices according to Types of Growth of Coniferous Tree Species with the Decrease in Stand-Quality Level

Tree species	Types of growth			
	T_d (Ct≤1.0)		T_{inc} (Ct≥1.0)	
	Values of Indexes of rate in growth, $I_{gr\,r}$			
	Index range	Average index	Index range	Average index
Austrian pine	1.8÷2.0	1.9	2.0÷2.3	2.15
Scots pine	2.3÷2.6	2.45	2.6÷3	2.8
Norway spruce	3.5÷4.4	3.95	4.4÷5.0	4.7
silver fir	4.0÷4.7	4.35	4.7÷5.3	5
Generally	1.8÷3.4	2.6	3.4÷5.3	4.35

The indices for silver fir and Norway spruce are of the broadest ranges and highest average values, next followed by those for Scots and Austrian pines. The growth curves' steepness decreases with the decrease in the shade tolerance of the tree species.

Generally, the range of the indices forT_d type, with a decreasing rate of the growth in height and an early climax of the increment, is from 1.8 to 3.4, and for Ty type, with an increasing growth rate, the respective range is from 3.4 to 5.3. The average values of the indices are 2.6 and 4.35, respectively.

As a comparison, the growth-rate indices for the two types of growth, T_d and T_{inc}, obtained for deciduous tree species (Petrin, 2022) are, respectively, 2.3 and 2.6, i.e. the curves of the growth of the deciduous tree species are, generally, less steep, especially those of the Ty type.

The following inferences can be made about the investigated model stands of Scots and Austrian pines, Norway spruce and silver fir on the basis of the results presented and analyses made.

Inferences

- There is a narrow co-relationship between the zero natural indicators and the growth-type coefficients.
- The growth-type coefficients are obtained from the growth-rate indices by dividing them by the average index for a particular aggregate of stands, respective curves. And this is their advantage over the zero natural indicators, which require more complex calculations.
- The growth rate increases with the increase in the shade tolerance of the tree species within the range of a particular stand-quality class and also with the decrease in stand-quality level of a particular tree species.
- The ranges of growth-rate and their average values according to growth-types have been found with the Decrease in Stand-Quality Level for the investigated tree species - Scots and Austrian pines, Norway spruce and silver fir.

Conclusion

The growth-type indices, as well as the growth-rate ones, are reliable and effective tools of investigation of the growth of forest stands and particular trees as in height so in every other forest-mensuration parameter.

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Information about the author

✉ *Rumen D. Petrin* – Dr. Sci. (Forestry), Associated Professor, Forest Research Institute in Bulgarian Academy of Sciences, 132, St. Kliment Ohridski Blvd., Sofia, 1756, Bulgaria. ORCID: http://orcid.org/0000-0002-5831-5983, e-mail: lesni4eja2014@gmail.com.

Сведения об авторе

✉*Румен Димитров Петрин* – кандидат (доктор*) с.-х. наук (*по болгарской номенклатуре: образовательная и научная степень «доктор»), доцент, научно-исследовательский институт леса Болгарской академии наук, бул. Климента Охридского, 132, г. София, 1756, Болгария. ORCID: http://orcid.org/0000-0002-5831-5983, e-mail: lesni4eja2014@gmail.com.

✉ – Для контактов | Corresponding author