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VOLUME INCREMENT INDICES OF 5-YEAR INCREMENT PERIODS AND THEIR VARIABILITY IN THE 86-YEAR OLD PINE STAND

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Abstract. In the course of the performed investigations, 4 indices of the volume increment were subjected to basic analysis concerning the main statistical characteristics. The empirical material comprised 94 pine trees derived from an 86-year old pine stand. A complete bole analysis was carried out on cut trees and then, in consecutive 5-year increment periods, 4 indices of the volume increment: C_1, C_2, C_3, C_4 and volume increment intensity as *i*'. Set against the variability of the volume increment intensity *i*', the variability coefficients in the consecutive 5-year increment periods of the volume increment index C_1 were bigger, C_3 and C_4 – comparable and C_2 – smaller than the variability coefficients *i*'. There was no correlation between the mean of two volume increment indices (C_2 and C_3) and the age of trees. The mean of the C_1 index increased with the age of trees. The C_4 mean declined with the increase of tree age. The population of the volume increment intensity *i*' in each increment period was characterised by the distribution which did not differ from the normal distribution. The C_3 index distribution differs for the normal distribution for 1 increment period, of the C_4 – for 2, C_2 – for 6 and of the C_1 – for 12 out of the 15 analysed periods.

Key words: volume increment, volume increment index, pine

INTRODUCTION

The tree stand growth conditions, affected, among others, by the site quality and management method, are best characterised by the current volume increment. The stand volume increment is a very important issue associated with the determination of the amount of the cut as well as the planning of economical and management treatments. It is considered by many as the best indicator of economic effectiveness. However, in spite of its unique importance, it is determined only occasionally. One of the methods of determining the stand current volume increment involves a single backward measurement at the end of the increment period. The notion of 'volume increment

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intensity' has a huge impact on the recognition of the precision and improvement of this group of methods. It was developed and introduced into science in 1954 by Borowski [Borowski 1954] and is defined as the quotient of the current periodical volume increment of the bole without bark and the breast height diameter cross-section area without bark at the end of the increment period. Investigations on the volume increment intensity and, in particular, on the determination of its variability and dependence on different tree traits, constituted the basis for the method proposed by Borowski used for the determination of the current stand volume increment [Borowski 1954, 1958, 1961 a, 1964, 1971, Borowski and Rekosz 1974]. In Poland, investigations on the volume increment intensity in pine stands and, to a smaller degree, also in fir stands were carried out by, among others, Borowski [1954, 1961 a, b], Dudek [1965, 1969], Lemke [1971] and by Remi [1981] in the oak. Borowski's studies [1961 a, 1964] revealed a considerable variability in the volume increment intensity (the mean variability coefficient in the examined stands amounted to 30.5% for the 10-year increment period and 33.0% – for the 5-year increment period). Remi [1981], in the oak stand, reported the variability coefficient of this trait at the level of 33.0% for the 10-year increment period and 35.4% – for the 5-year increment period. Remi also made an attempt to present other indices of the volume increment and to compare the obtained results with the volume increment intensity. Assuming that the breast height diameter shape number at the beginning and end of the increment period is identical (a simplification adopted for short increment periods), then the volume increment is connected with the shape number and the sum of the definite quotient combinations of the breast height diameter cross-section area without bark and the height at the end of the period and their increments. Hence, the idea of employing these quotients to develop volume increment indices, similar to the shape number. Remi suggested the following four indices, which are absolute numbers:

$$C_1 = \frac{Z_v}{Z_g \cdot Z_h}$$

$$C_2 = \frac{Z_v}{Z_g \cdot h}$$

$$C_3 = \frac{Z_v}{g \cdot Z_h}$$

$$C_4 = \frac{Z_v}{g \cdot h}$$

where: Z_v – volume increment,
Z_g – increment of the breast height diameter cross-section area without bark,
Z_h – height increment,
g – breast height diameter cross-section area without bark,
h – height.

In the course of the performed investigations, four indices of volume increment were subjected to the basic analysis from the point of view of the main statistical characteristics. The above analysis was performed in consecutive 5-year increment periods beginning with the period of 11-15 years. The two earlier periods were not taken into consideration because, in the case of some trees, they failed to reach the height of

1.3 m. In addition, the authors investigated if the examined populations of the analysed volume increment indices were in agreement with the theoretical (normal) distribution.

MATERIAL AND METHODS

The empirical material derived from the experimental cut carried out in an 86-year old pure pine stand situated in the Forest Experimental Station in Murowana Goślina. The mean stand height was 19.5 m and the mean breast height diameter – 20.7 cm, while the site index – $II_{,7}$. The experiments were performed on 94 trees on which full analyses of the bole at 5-year increment periods were carried out. This allowed the authors to determine in consecutive 5-year increment periods the following parameters: the volume increment Z_v, increment of the breast height diameter cross-section without bark Z_g, height increment Z_h as well as the height h and the breast height diameter cross-section without bark g. These values were then used to calculate the four volume increment indices. The following basic statistical characteristics were determined for the calculated volume increment indices: the arithmetic mean, standard deviation and the variability coefficient. In addition, the authors also evaluated the distribution normality of the volume increment indices in consecutive 5-year increment periods. In connection with the importance of the volume increment intensity, and despite the lack of information about the breast height diameter cross-section area in bark for consecutive increment periods, the authors decided to calculate the quotient of the bole volume increment without bark and the breast height diameter cross-section area without bark designating it as *i'*. The value calculated in this way was also subjected to statistical analysis and compared with the analysed four indicators.

RESEARCH RESULTS

The performed analyses of four volume increment indices (Tables 2, 3, 4 and 5) as well as the *i'* value (Table 1) revealed distinct differences in this regard of basic statistical characteristics in consecutive 5-year increment periods. The arithmetic mean of the volume increment intensity *i'* (Fig. 1) in the first of the analysed periods from 11-15 years was quite big and increased during the next increment period of 16-20 years reaching its maximum (2.109). In the course of the successive periods, the means decreased, initially quite quickly up the period of 56-60 years. The next increment periods were characterised by small variations in the mean ranging in the interval from 0.997 to 0.950. The variability coefficient *i'* was the smallest in the increment period from 36-40 years (20.90%) and the biggest – in the period from 11-15 years (54.46%). In the case of the remaining increment periods, the variability coefficient ranged from 21.03% to 37.15%. Generally speaking, the arithmetic mean of the C_1 index (Table 2) was found to decrease with the decreasing age of trees (with the only exception of the last increment year 81-85 years) from the highest value of 35.401 – the period 76-80 years to the lowest one of 1.150 – the increment period 11-15 years (Fig. 2). With the exception of one increment period (11-15 years), variability coefficients of the C_1 index were the highest of all the analysed indices and exceeded the value of 33% in all cases. The next

Table 1. Statistical characterization of volume increment intensity *i'* in the 86 year old pine stand in the consecutive 5-year incremental periods
Tabela 1. Statystyczna charakterystyka intensywności przyrostu miąższości *i'* w 86-letnim drzewostanie sosnowym w kolejnych 5-letnich okresach przyrostowych

Indicator Wskaźnik	Min.	Max Maks.	Mean Średnia	Standard deviation Odchylenie standardowe	Variation coefficient Współczynnik zmienności
$i'_{(81-85)}$	0.284	1.668	0.971	0.313	32.28
$i'_{(76-80)}$	0.231	1.787	0.961	0.357	37.15
$i'_{(71-75)}$	0.284	1.641	0.950	0.303	31.85
$i'_{(66-70)}$	0.288	1.750	0.979	0.352	35.92
$i'_{(61-65)}$	0.226	1.874	0.997	0.350	35.10
$i'_{(56-60)}$	0.272	1.679	0.948	0.320	33.70
$i'_{(51-55)}$	0.224	1.989	1.090	0.337	30.93
$i'_{(46-50)}$	0.462	2.180	1.259	0.362	28.74
$i'_{(41-45)}$	0.633	2.972	1.433	0.400	27.90
$i'_{(36-40)}$	0.877	2.559	1.784	0.373	20.90
$i'_{(31-35)}$	0.448	3.236	1.942	0.472	24.28
$i'_{(26-30)}$	0.638	3.088	1.948	0.410	21.03
$i'_{(21-25)}$	0.121	3.664	2.061	0.511	24.78
$i'_{(16-20)}$	0.461	3.418	2.109	0.483	22.89
$i'_{(11-15)}$	0.116	3.619	1.425	0.776	54.46

Table 2. Statistical characterization of volume increment intensity C_1 in the 86 year old pine stand in the consecutive 5-year incremental periods
Tabela 2. Statystyczna charakterystyka wskaźnika przyrostu miąższości C_1 w 86-letnim drzewostanie sosnowym w kolejnych 5-letnich okresach przyrostowych

Indicator Wskaźnik	Min.	Max Maks.	Mean Średnia	Standard deviation Odchylenie standardowe	Variation coefficient Współczynnik zmienności
$C_{1(81-85)}$	10.537	84.331	24.735	13.843	55.96
$C_{1(76-80)}$	8.076	75.327	25.401	12.015	47.30
$C_{1(71-75)}$	5.964	57.816	25.090	9.548	38.05
$C_{1(66-70)}$	8.273	63.033	24.110	10.032	41.61
$C_{1(61-65)}$	10.044	64.932	22.018	10.288	46.73
$C_{1(56-60)}$	9.350	52.160	20.103	8.392	41.74
$C_{1(51-55)}$	3.587	46.944	16.799	6.680	39.77
$C_{1(46-50)}$	6.311	53.006	15.632	6.526	41.75
$C_{1(41-45)}$	4.505	63.601	15.147	6.604	43.60
$C_{1(36-40)}$	2.859	50.800	11.875	6.050	50.95
$C_{1(31-35)}$	1.452	16.888	7.717	2.730	35.37
$C_{1(26-30)}$	1.349	11.210	5.380	1.795	33.37
$C_{1(21-25)}$	1.150	8.211	4.299	1.790	41.64
$C_{1(16-20)}$	0.908	8.101	2.529	1.145	45.25
$C_{1(11-15)}$	0.158	4.407	1.150	0.722	62.78

Table 3. Statistical characterization of volume increment intensity C_2 in the 86 year old pine stand in the consecutive 5-year incremental periods
Tabela 3. Statystyczna charakterystyka wskaźnika przyrostu miąższości C_2 w 86-letnim drzewostanie sosnowym w kolejnych 5-letnich okresach przyrostowych

Indicator Wskaźnik	Min.	Max Maks.	Mean Średnia	Standard deviation Odchylenie standardowe	Variation coefficient Współczynnik zmienności
$C_{2(81\text{-}85)}$	0.415	1.988	0.812	0.245	30.14
$C_{2(76\text{-}80)}$	0.382	1.903	0.807	0.221	27.41
$C_{2(71\text{-}75)}$	0.516	1.676	0.860	0.180	20.90
$C_{2(66\text{-}70)}$	0.377	1.650	0.848	0.185	21.76
$C_{2(61\text{-}65)}$	0.309	1.702	0.836	0.195	23.35
$C_{2(56\text{-}60)}$	0.436	1.795	0.862	0.196	22.68
$C_{2(51\text{-}55)}$	0.160	1.160	0.778	0.152	19.59
$C_{2(46\text{-}50)}$	0.336	1.224	0.767	0.159	20.77
$C_{2(41\text{-}45)}$	0.470	1.252	0.853	0.142	16.67
$C_{2(36\text{-}40)}$	0.463	1.379	0.865	0.145	16.75
$C_{2(31\text{-}35)}$	0.197	1.606	0.863	0.157	18.22
$C_{2(26\text{-}30)}$	0.264	1.300	0.854	0.165	19.37
$C_{2(21\text{-}25)}$	0.266	1.312	0.887	0.205	23.13
$C_{2(16\text{-}20)}$	0.165	1.893	0.715	0.220	30.73
$C_{2(11\text{-}15)}$	0.011	1.305	0.442	0.278	62.93

Table 4. Statistical characterization of volume increment intensity C_3 in the 86 year old pine stand in the consecutive 5-year incremental periods
Tabela 4. Statystyczna charakterystyka wskaźnika przyrostu miąższości C_3 w 86-letnim drzewostanie sosnowym w kolejnych 5-letnich okresach przyrostowych

Indicator Wskaźnik	Min.	Max Maks.	Mean Średnia	Standard deviation Odchylenie standardowe	Variation coefficient Współczynnik zmienności
$C_{3(81\text{-}85)}$	0.520	4.462	1.484	0.633	42.66
$C_{3(76\text{-}80)}$	0.577	3.947	1.558	0.565	36.29
$C_{3(71\text{-}75)}$	0.590	3.224	1.521	0.492	32.32
$C_{3(66\text{-}70)}$	0.513	3.663	1.563	0.567	36.83
$C_{3(61\text{-}65)}$	0.413	3.509	1.531	0.559	36.49
$C_{3(56\text{-}60)}$	0.467	3.000	1.347	0.477	35.46
$C_{3(51\text{-}55)}$	0.337	3.634	1.544	0.541	35.05
$C_{3(46\text{-}50)}$	0.745	3.642	1.745	0.594	34.05
$C_{3(41\text{-}45)}$	0.571	3.334	1.825	0.540	29.62
$C_{3(36\text{-}40)}$	0.644	3.691	1.852	0.633	34.19
$C_{3(31\text{-}35)}$	0.284	3.463	1.505	0.496	32.92
$C_{3(26\text{-}30)}$	0.409	2.703	1.212	0.356	29.40
$C_{3(21\text{-}25)}$	0.293	2.398	1.164	0.394	33.79
$C_{3(16\text{-}20)}$	0.232	2.508	1.139	0.393	34.45
$C_{3(11\text{-}15)}$	0.011	2.887	0.813	0.514	63.30

Table 5. Statistical characterization of volume increment intensity C_4 in the 86 year old pine stand in the consecutive 5-year incremental periods
Tabela 5. Statystyczna charakterystyka wskaźnika przyrostu miąższości C_4 w 86-letnim drzewostanie sosnowym w kolejnych 5-letnich okresach przyrostowych

Indicator Wskaźnik	Min.	Max Maks.	Mean Średnia	Standard deviation Odchylenie standardowe	Variation coefficient Współczynnik zmienności
$C_{4(81-85)}$	0.019	0.076	0.051	0.015	29.78
$C_{4(76-80)}$	0.017	0.089	0.053	0.018	34.17
$C_{4(71-75)}$	0.016	0.085	0.054	0.016	29.30
$C_{4(66-70)}$	0.017	0.105	0.058	0.020	33.89
$C_{4(61-65)}$	0.014	0.105	0.062	0.020	32.06
$C_{4(56-60)}$	0.017	0.115	0.061	0.019	31.76
$C_{4(51-55)}$	0.015	0.126	0.074	0.021	28.25
$C_{4(46-50)}$	0.040	0.168	0.090	0.026	28.46
$C_{4(41-45)}$	0.049	0.218	0.109	0.031	28.67
$C_{4(36-40)}$	0.071	0.220	0.145	0.030	21.03
$C_{4(31-35)}$	0.039	0.380	0.173	0.048	27.75
$C_{4(26-30)}$	0.064	0.390	0.199	0.051	25.83
$C_{4(21-25)}$	0.020	0.697	0.256	0.083	32.56
$C_{4(16-20)}$	0.066	0.890	0.342	0.106	31.02
$C_{4(11-15)}$	0.011	0.987	0.330	0.201	61.09

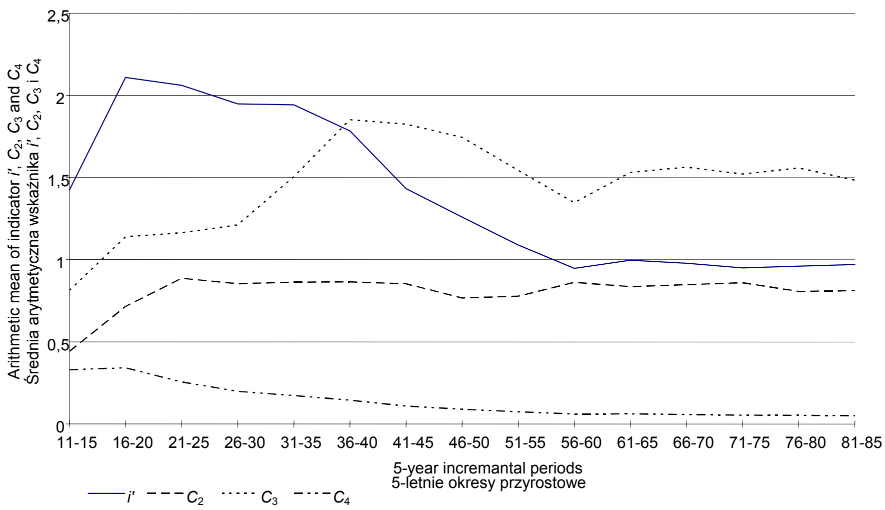

Fig. 1. Arithmetic mean of indicator i', C_2, C_3 and C_4 in the consecutive 5-year incremental periods
Rys. 1. Średnia arytmetyczna wskaźnika i', C_2, C_3 i C_4 w kolejnych 5-letnich okresach przyrostowych

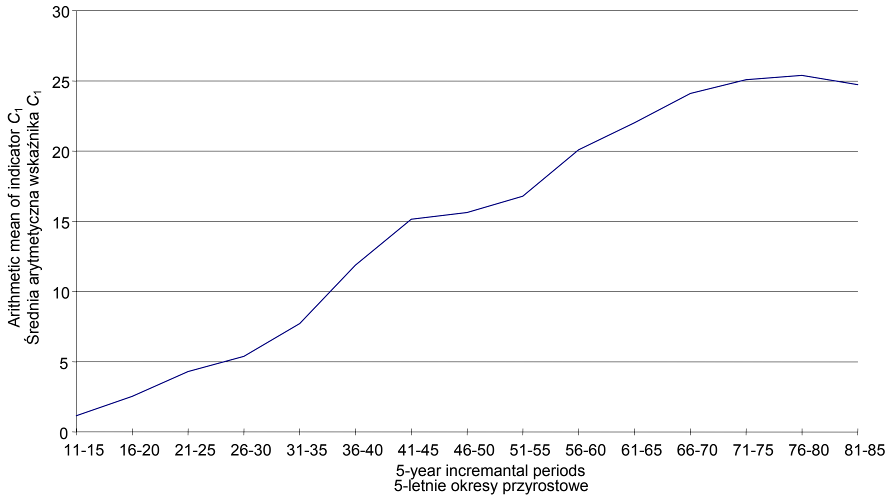

Fig. 2. Arithmetic mean of indicator C_1 in the consecutive 5-year incremental periods
Rys. 2. Średnia arytmetyczna wskaźnika C_1 w kolejnych 5-letnich okresach przyrostowych

index C_2 – was characterised by distinctly lowest values of the variability coefficient (Table 3). The smallest value (16.65%) was observed in the increment period of 36-40 years, while the highest (62.93%) – in the period from 11-15 years (with the exception of this period, the variability coefficient for the remaining periods did not exceed 31%). The arithmetic mean of this index (Fig. 1) was the smallest in the increment period from 11-15 years (0.442) and then increased reaching its maximum in the period of 21-25 tears (0.887). In the next increment periods, means underwent only slight changes in the interval from 0.767 to 0.865 and failed to show any clear connection with the tree age. In the case of the C_3 index (Table 4 and Fig. 1), its arithmetic mean was the lowest in the first of the analysed increment periods (11-15 years) – 0.813, then increased reaching its maximum in the period of 36-40 years (1.852). During the next increment periods, the mean decreased down to the value of 1.347 (period from 56-60) and later increased slightly and in the consecutive periods underwent small variations. The variability coefficients in individual increment periods ranged from 29.40% (the period of 21-25 years) to 63.30% (the period from 11-15 years). The last of the analysed indices – C_4 was characterised (Table 5, Fig. 1), among others, by the fact that the arithmetic mean of this index, once it reached its maximum at the period of 16-20 years (0.342), generally speaking, declined with age down to the value of 0.051 recorded in the last of the analysed increment periods (81-85 years). With the exception of the first increment period, where the variability coefficient reached even 61.09%, it ranged from 21.03% to 34.17% in the remaining periods.

It is quite evident that from among all the analysed indices, the C_2 index was characterised by the smallest variability, whereas the C_1 index – by the highest one.

When selecting mean sample trees, in order to establish the mean value of indices with the assumed standard error of the arithmetic mean and at a definite level of significance, it was necessary to take a great number of measurements. For example, for the general population in the 5-year increment period (76-80 years), at the assumed standard error of ±5% and the level of significance 0.32, it was necessary to take 55 measurements for *i'*, 89 – for C_1, 30 – for C_2, 52 – for C_3 and 46 – for C_4. In the case of the increment period of 41-45 years, it was necessary to take: for *i'* – 31, C_1 – 76, C_2 – 11, C_3 – 35 and for C_4 – 33 measurements.

The above-mentioned numbers characterised properly the discussed issue provided the analysed populations were in accordance with or at least similar to the normal distribution. The evaluation of the conformity of the empirical distribution of the increment indices population with the normal distribution was carried out with the assistance of the W Shapiro-Wilk test. The Shapiro-Wilk test, which is based on the order statistics, is believed to be the strongest for the wide class of alternative distributions. In addition, the test can be applied to samples with sizes $n \leq 50$ and utilises the full information from the sample [Krysicki et al. 2002]. Low values of the W statistics indicate a deviation from normality. Table 6 presents values of the W statistics for the individual volume increment indices. The distributions of the volume increment intensity *i'* in each increment period exhibited distributions which did not differ from the normal distribution. In the case of the C_3 index, its distribution differed from the normal distribution for

Table 6. Assessment of distribution normality for volume increment indicators using the Shapiro-Wilk W-test in the consecutive 5-year incremental periods
Tabela 6. Ocena normalności rozkładów wskaźników przyrostu miąższości testem W Shapiro-Wilka w kolejnych 5-letnich okresach przyrostowych

Shapiro-Wilk W-test in the consecutive 5-year incremental periods Wartość statystyki W w kolejnych 5-letnich okresach przyrostowych	Indicator Wskaźnik				
	i'	C_1	C_2	C_3	C_4
11-15	0.9692	0.8787*	0.9597	0.9399	0.9441
16-20	0.9661	0.8707*	0.8918*	0.9316	0.8359*
21-25	0.9426	0.9724	0.9715	0.9902	0.8495*
26-30	0.9886	0.9842	0.9811	0.9521	0.9256
31-35	0.9869	0.9553	0.8925*	0.9657	0.9394
36-40	0.9847	0.7786*	0.9465	0.9555	0.9834
41-45	0.9485	0.6815*	0.9873	0.9691	0.9321
46-50	0.9822	0.8319*	0.9589	0.9543	0.9599
51-55	0.9929	0.8688*	0.9504	0.9245	0.9878
56-60	0.9907	0.8806*	0.9311	0.9299	0.9922
61-65	0.9890	0.8039*	0.9158	0.9145	0.9912
66-70	0.9802	0.8410*	0.8923*	0.9527	0.9868
71-75	0.9803	0.8994*	0.8931*	0.9778	0.9837
76-80	0.9832	0.8458*	0.7984*	0.9472	0.9781
81-85	0.9779	0.7261*	0.6934*	0.8885*	0.9652

*Distribution differing from the normal distribution.
*Rozkład różniący się od rozkładu normalnego.

one increment period (from 81-85 years), whereas for the C_4 – for two increment periods (from 16-20 and 21-25 years). In the case of the remaining two volume increment indices, considerable discrepancies with the normal distribution were recorded. Out of the fifteen analysed increment periods, the distribution of the C_2 index conformed with the normal distribution nine times, while in the case of the C_1 index – only three times. This situation could have been caused by the actual increment of the height and breast height diameter cross-section area. These traits were taken under consideration when determining the increment indices C_1, C_2, and C_3. It is possible that in the case of some trees, their height and breast height diameter cross-section area increments were seriously disturbed (smaller) and, therefore, the height and breast height diameter cross-section area increments differed from the mean values of this trait leading to the excessive increase of these three increment indices.

CONCLUSIONS

1. Set against the variability of the volume increment intensity *i'* calculated for purposes of this study as the quotient of the bole volume increment without bark and the breast height diameter cross-section area without bark, the variability in consecutive 5-year increment periods of the volume increment index C_1 was greater, C_3 and C_4 – comparable and C_2 – lower than the *i'* variability.

2. No clear correlation was established between values of variability coefficients of all the analysed volume increment indices and the age of trees in the 5-year increment periods. However, it was found that the highest values of variability coefficients of all indices occurred for the first of the analysed periods, from 11 to 15 years.

3. There was no clear regularity and correlation between the arithmetic mean of two volume increment indices (C_2 and C_3) and the age of trees. The arithmetic mean of the C_1 index increased with the age of trees reaching its maximum during the penultimate increment period, only to drop slightly in the last period. In the case of the C_4 index, its arithmetic mean decreased beginning from the second increment period (16-20 years) with the age of trees.

4. The population distribution of the volume increment intensity *i'* in each increment period did not differ from the normal distribution. In the case of the C_3 index, its distribution differed from the normal distribution for one increment period, of C_4 – for two, of C_2 – for six and of the C_1 index – for twelve of the fifteen analysed periods.

5. The analysis of four indices of volume increment indicates small usefulness of the C_1 and C_3 indices for practical purposes, mainly because of their considerable variability. In addition, in the case of these two indices, there is also a serious difficulty when measuring the height increment. The remaining two indices, C_2 (the lowest variability) and C_4 (the smallest labour consumption and the distribution similar to normal in the majority of the increment periods) should undergo further investigations.

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WSKAŹNIKI PRZYROSTU MIĄŻSZOŚCI W 5-LETNICH OKRESACH PRZYROSTOWYCH I ICH ZMIENNOŚĆ W 86-LETNIM DRZEWOSTANIE SOSNOWYM

Streszczenie. W pracy poddano podstawowej analizie cztery wskaźniki przyrostu miąższości pod względem podstawowych charakterystyk statystycznych. Materiałem empirycznym były 94 sosny pochodzące z 86-letniego drzewostanu sosnowego. Na ściętych drzewach wykonano pełną analizę strzały, a następnie obliczono w kolejnych 5-letnich okresach przyrostowych 4 wskaźniki C_1, C_2, C_3 i C_4 oraz intensywność przyrostu miąższości (koncepcja Borowskiego) *i'*. Na tle zmienności intensywności przyrostu miąższości *i'*, współczynniki zmienności w kolejnych 5-letnich okresach przyrostowych wskaźnika C_1 są większe, C_3 i C_4 porównywalne a C_2 mniejsze od współczynników zmienności *i'*. Brak związku pomiędzy średnią arytmetyczną wskaźników C_2 i C_3 a wiekiem drzew. Średnia arytmetyczna wskaźnika C_1 rośnie z wiekiem drzew a wskaźnika C_4 zmniejsza się. Zbiorowość *i'* w każdym okresie przyrostowym posiada rozkład nie różniący się od rozkładu normalnego. W wypadku wskaźnika C_3 jego rozkład różni się od rozkładu normalnego dla jednego okresu przyrostowego, C_4 dwóch, C_2 sześciu a C_1 aż 12 na 15 analizowanych.

Słowa kluczowe: przyrost miąższości, wskaźniki przyrostu miąższości, sosna

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