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Growth and Physiological Resilience of Pine Forests in Ukrainian Polissia

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Abstract. The main prerequisite for this study is the use of forest resources corresponding to the principles of sustainable forest management. The purpose of this study is to figure out the growth characteristics of pine stands and their physiological response to adverse factors. The experimental material (cores) was selected from pine forests of Ukrainian Polissia using Haglöf increment borer at breast height of 1.3 m. The number of annual rings and the parameters of radial increment were found using the ImageJ software. The result was a tree-ring chronology of sample trees. Statistical analysis of the experimental data proved that the radial increment variability decreases with age, and it ranges within 0.99-2.78 mm. The average radial increment value in the data set under study is 1.79 mm. The average number of annual rings of Scots pine (*Pinus sylvestris* L.) trees is 80: the minimum is 61, the maximum is 92. The correlation analysis of experimental data proved that the pairwise correlation coefficients of radial increment (-0.54) and current increment by diameter (-0.53) have an inverse relationship with the age of trees, and diameter at breast height with age – a direct relationship (0.87). The developed mathematical models of the dynamics of the width of the annual ring, the diameter at breast height and the current increment by diameter allow estimating the growth characteristics of Scots pine trees throughout their life. The obtained results were compared with the growth tables of fully stocked (at a relative stocking of 1.0) stands. The adequacy test of the developed mathematical models proved the accuracy of the given patterns and is as follows: for the width dynamics of the annual ring – 0.46; the diameter at breast height – 0.78, and the percentage of current increment by diameter – 0.51. Based on standardisation of individual chronologies by calculating sensitivity coefficients, no significant physiological response was established. Accordingly, the impact of short-term stress reactions is insignificant. The maximum resistance of pine stands to adverse environmental factors is achieved at the age of 50-60 years. This study is important to evaluate the impact of climate change and other adverse factors on the growth of pine stands and forecasting the dynamics of biometric indices. The obtained results can be used by the specialists at IA "Ukrderzhlisproekt" to update biometric indices and substantiate the use of forest resources

Keywords: Scots pine, tree-ring chronology, sensitivity coefficients, current increment by diameter, radial increment

Introduction

The sanitary condition of pine stands in Ukrainian Polissia requires thorough research to establish the cause-and-effect relationships that led to its deterioration. The study of the growth of pine stands in Polissia revealed differences in the parameters of radial increment in areas of intensive economic activity and where such activity was prohibited due to radioactive contamination. Standardisation of individual chronologies and calculation of sensitivity coefficients allow establishing the physiological stability of Scots pine trees in forests [1], i.e., estimating the level to which physiological stress affects the growth and development of the stand. It was found that during the entire period of growth, pine stands undergo physiological stresses, as evidenced by the data from other studies [2; 3].

The growth of trees in a stand is dictated both by the influence of external (microclimatic, soil-hydrological, etc.) factors, and by the physiological features of the tree species. The radial increment of trees depends on the response of the genotype to the amount of precipitation and heat [4] and their distribution during the year. The dynamics of the radial increment of Scots pine trees in various coenopopulations and selection categories of the western

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region showed no significant differences [5]. At the same time, the sensitivity coefficient showed substantial individual variability within the selection categories. Apart from the influence of adverse natural and climatic factors on the growth of trees, it was found that the stability of trees is reduced due to intensive recreational activity [6]. Conducting dendrochronological research requires varied information about natural and anthropogenic factors that can affect tree growth and the variability of indices. A rapid decrease in growth may be associated with interspecific competition [7]. The radial increment value is affected by the thinning of forests both due to planned maintenance felling and sanitary felling [8], as well as the established effect of fires [9].

Climate changes adversely impact the growth and development of pine stands everywhere, not only in Ukraine [10-12]. In contrast to the Forest Steppe, adaptation is much slower in Polissia, leading to massive drying up of stands in large areas [2].

The purpose of this study was to identify the parameters of radial increment, the dynamics by diameter and its current increment. Additionally, it was to establish the physiological resistance of Scots pine trees to adverse factors.

The results of this paper found the physiological stability of Scots pine trees in the region under study. Additionally, mathematical models of the width dynamics of annual ring, diameter at breast height (DBH), and current increment by diameter were developed, which forms the scientific originality of this study.

Materials and Methods

The study was conducted on temporary sample plots in 2020-2021. The wood samples (cores) were selected in pine stands of Ukrainian Polissia, namely: in the State Enterprise "Kamin-Kashyrskyi Forestry" in the Volyn Oblast (22 cores) and in the State Enterprise "Zarichany Forestry" in the Zhytomyr Oblast (22 cores).

The wood samples were selected using a Presler borer (*Haglöf*) at a breast height (1.3 m) [2; 13; 14]. In laboratory conditions, the cores were pasted on a special wooden substrate. Subsequently, the cores were carefully sanded and scanned. For further research, the annual rings of the sample trees were dated and measured with the *ImageJ* software and a special *ObjectJ* plugin (Fig. 1). This provided the results of the tree-ring chronology.

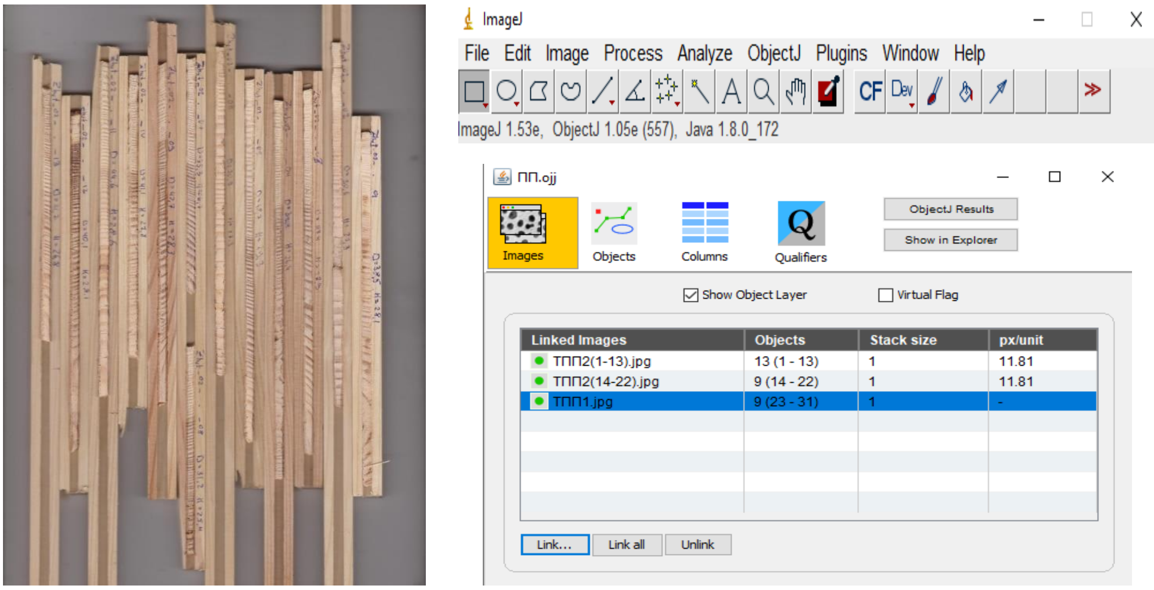

Figure 1. Processing of experimental data using the *ImageJ* programme

The data array obtained through processing of wood samples contained information on the number of annual rings and annual radial increment. The tightness of the relationship between the values under study was established using the correlation analysis [15]. Further research was carried out using the *MS Excel spreadsheet.* The characteristics of the experimental data are presented in the Table 1.

Table 1. Statistical characteristics of experimental data

No.	Number of rings	Mean increment, mm	Standard deviation	No.	Number of rings	Mean increment, mm	Standard deviation
1	76	1.95	2.01	23	89	1.51	0.82
2	85	1.34	1.23	24	78	2.19	0.89
3	78	2.38	2.77	25	90	1.62	0.97
4	80	1.73	1.17	26	77	2.11	1.12
5	83	2.20	1.22	27	85	1.87	0.80
6	69	2.40	2.27	28	78	1.75	0.85
7	72	1.64	1.06	29	86	1.58	1.07
8	77	1.37	0.59	30	89	1.71	0.87

Table 1, Continued

No.	Number of rings	Mean increment, mm	Standard deviation	No.	Number of rings	Mean increment, mm	Standard deviation
9	84	1.91	1.45	31	79	1.42	1.21
10	87	1.65	1.23	32	81	1.66	1.66
11	61	2.78	2.55	33	82	1.75	1.15
12	67	1.86	2.66	34	88	1.97	1.10
13	69	1.86	1.84	35	75	1.50	1.38
14	92	2.02	1.52	36	69	1.43	0.53
15	66	2.78	1.19	37	90	1.71	1.45
16	91	1.86	1.71	38	88	1.50	1.81
17	63	1.75	0.59	39	83	1.71	1.09
18	70	2.05	1.67	40	89	1.75	1.07
19	77	2.37	0.93	41	90	1.65	1.03
20	89	2.00	1.24	42	88	1.65	0.74
21	78	0.99	0.71	43	76	1.14	0.85
22	77	1.77	1.00	44	89	1.51	0.82
Mean:						1.79	1.41

The average radial increment is a variable, as evidenced by the standard deviation. Notably, with increasing age, the variability of radial increment decreases, especially for trees above 80 years old. This trend may indicate the intraspecific competition of trees in the growth process. The radial increment of Scots pine trees ranged within 0.99-2.78 mm, and the mean value was 1.79 mm.

Results and Discussion

To investigate the growth of Scots pine trees, the results of tree-ring chronology were used. Mathematical modelling involved the method of least squares [16], which minimises the sum of squares of the deviation between factual and simulated values. The power equation (1) of the following type was used as a basis:

$$y = a_0 \cdot A^{a_1} \qquad (1)$$

where a_0, a_1 are the equation parameters; A is the age of trees, years.

Based on the results of tree ring dating and correlation analysis, it was established that the pairwise correlation coefficient (r) between annual ring width and age is -0.54. Graphical analysis of experimental data and results of mathematical modelling of the width dynamics of annual ring (Δ_r) (Fig. 2).

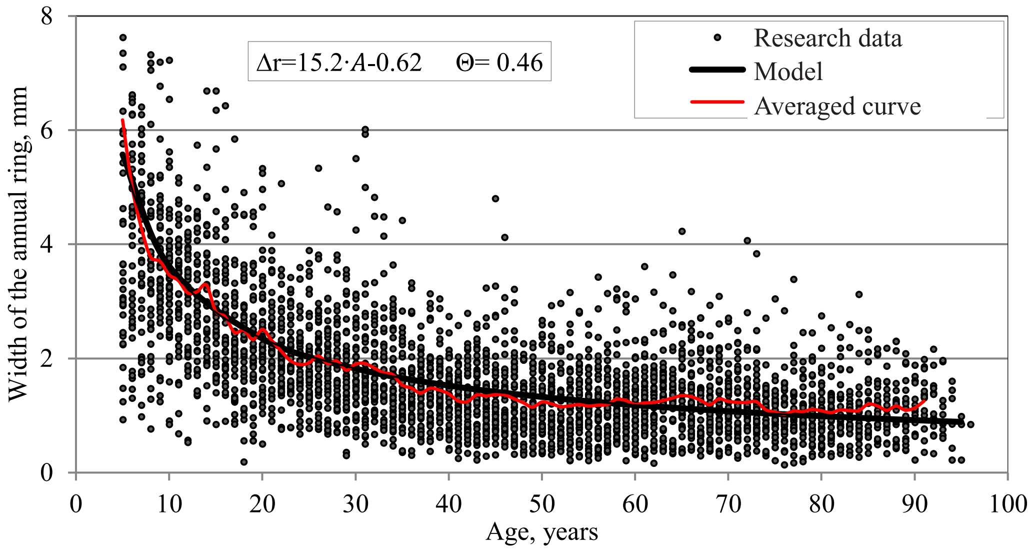

Figure 2. Dynamics of annual ring width of Scots pine trees

The adequacy of the developed mathematical model (2) with experimental data was verified as follows [17]:

$$\Theta = 1 - \frac{(\sum y - \tilde{Y})^2}{(\sum y - \bar{Y})^2} \qquad (2)$$

where Θ is the adequacy of the mathematical model; y are the factual values; $\tilde{Y}$ are the simulated values; $\bar{Y}$ is the arithmetic mean.

The developed mathematical model of the dynamics of the annual growth of trees' trunks (Δ_r) in pine stands adequately describes the established pattern.

Based on the data of annual radial increment of sample trees, the dynamics of DBH (Δd) with age (r=0.87) was established, and the corresponding mathematical model was developed (Fig. 3).

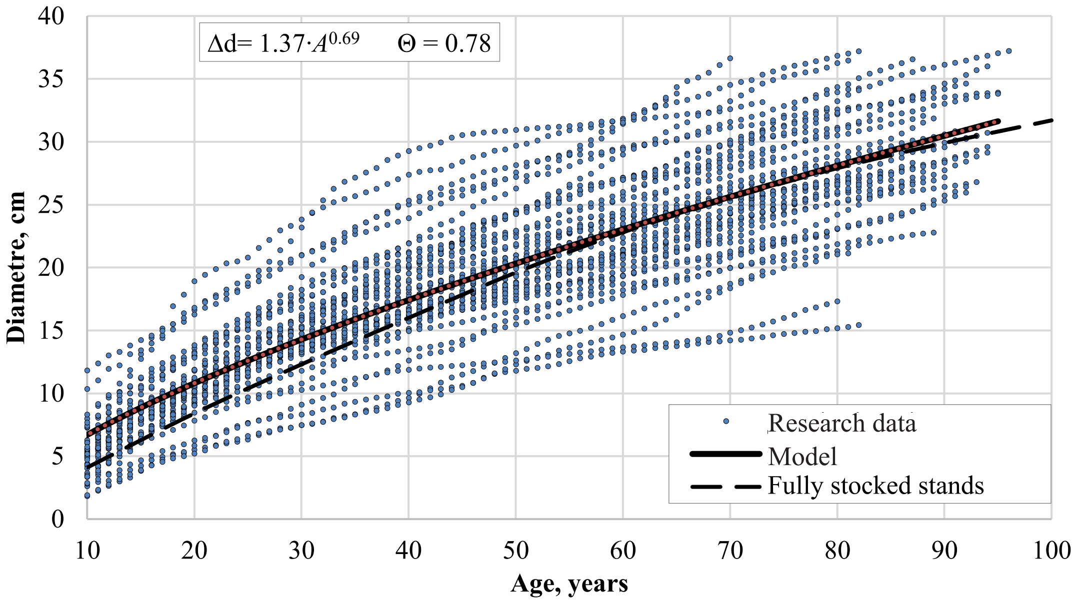

Figure 3. Dynamics of the diameter of Scots pine trees at a height of 1.3 m

The developed mathematical model of the dynamics of DBH (Δ_d) of trees in pine stands adequately describes the established pattern (Θ=0.78). For comparison, Figure 3 shows the dynamics of DBH of fully stocked (with a relative stocking of 1.0) artificial forests of the first (I) site index class [18]. The dynamics of the relative values of the current increment by diameter depending on age (r=-0.53) is established based on factual values and presented in Figure 4.

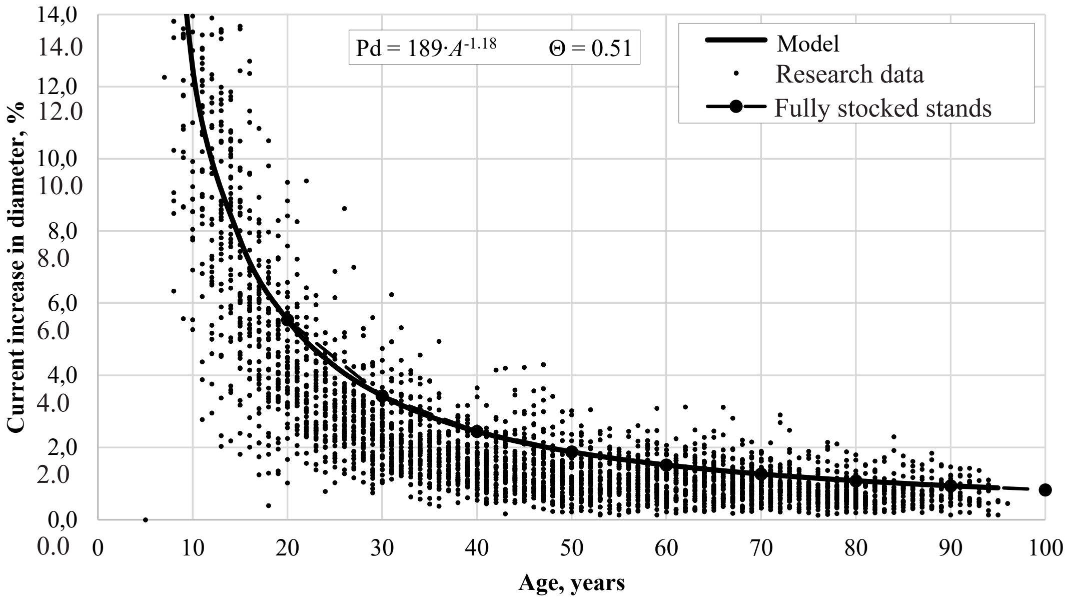

Figure 4. The dynamics of the relative values of the current increase in the diameter of Scots pine trees

The developed mathematical model (P_d) adequately describes the established pattern (Θ=0.51) and, in terms of the nature of the dynamics of changes in the current increment by diameter, is almost identical to fully stocked forests [18].

The study of the physiological stability of pine stands involved the standardisation of individual chronologies through the calculation of sensitivity coefficients ($K_{i(t)}$) as follows [1]:

$$K_{i(t)} = (R_{i(t)} - R_{i(t-1)})/(R_{i(t)} + R_{i(t-1)}) \qquad (3)$$

where $R_{i(t)}$ is the current annual ring width, mm; $R_{i(t-1)}$ is the annual ring width a year ago, mm.

Sensitivity coefficients can vary from −1 to +1. In a steady state, the coefficients approach 0, and an increase in amplitude indicates a decrease in the stability of the stand and the emergence of the probability of exceeding a certain threshold level. Both sharp negative and positive values indicate a decrease in the stand stability (Fig. 5).

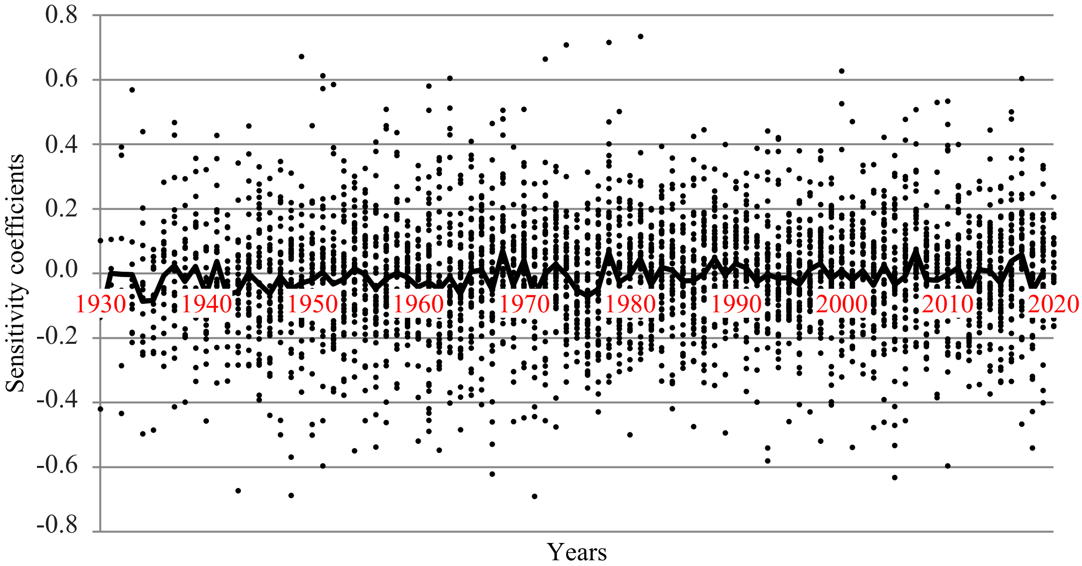

Figure 5. Physiological stability of Scots pine trees

Comparison of the obtained values of the sensitivity coefficients allows evaluating the specific features of the development of trees in the stand. The variation of sensitivity coefficients (Fig. 5) indicates the state of their natural stability in different age periods. No significant physiological reaction was found during the growth and development of Scots pine trees in Ukrainian Polissia. The research results suggest that the effect of short-term stress reactions on the state of physiological stability of pine stands is insignificant; they acquire maximum resistance to adverse environmental factors at the age of 50-60 years and older. A comparison of the results of the study of the physiological stability of pine stands with the data of other authors showed slight differences within the peak periods [1].

Conclusions

The data of the tree-ring chronology and the conducted correlation analysis showed that the pairwise correlation coefficients between the radial increment value and the current increment by diameter have an inverse relationship, and a direct relationship with DBH.

Mathematical modelling provided a model of the width dynamics of the annual ring depending on the age of trees, and the verification of the model proved its adequacy to the experimental data. The mathematical model of the dynamics of DBH of trees adequately describes the established pattern and has substantial differences compared to fully stocked forests, especially up to 60 years of age.

The developed mathematical model of the percentage dynamics in the current increment by diameter of modal (widespread) pine forests is almost identical to the dynamics of this indicator in fully stocked forests and adequately describes the experimental data.

The study of the physiological stability of trees in pine stands did not establish a significant physiological response to natural and climatic factors, and the impact of short-term stress reactions on the growth and development of pine stands in Ukrainian Polissia is insignificant.

At present, the question of finding innovative approaches to substantiating the volume of wood harvesting has matured in Ukraine. The results of this study can be used to further investigate the increment growth of pine stands by volume and develop corresponding recommendations.

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Ріст та фізіологічна стійкість соснових насаджень Українського Полісся

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Анотація. Обґрунтування обсягів використання лісових ресурсів, які б відповідали принципам стійкого ведення лісового господарства є основною передумовою проведення цього дослідження. Мета дослідження полягає у з’ясуванні особливостей росту соснових насаджень та їхньої фізіологічної реакції на несприятливі чинники. Дослідний матеріал (керни) був відібраний у соснових деревостанах Українського Полісся за допомогою приросного бура Haglöf на висоті стовбура дерева 1,3 м. Визначення кількості річних кілець та величини радіального приросту проводилось за допомогою програми ImageJ, що дозволило отримати деревно-кільцеву хронологію модельних дерев. Статистичний аналіз дослідних даних засвідчив, що мінливість радіального приросту з віком зменшується, а його величина знаходиться в межах від 0,99 до 2,78 мм. Середнє значення радіального приросту у досліджуваному масиві даних становить 1,79 мм. Середня кількість річних кілець дерев сосни звичайної (*Pinus sylvestris* L.) становить 80: мінімальна 61, максимальна 92. Проведений кореляційний аналіз дослідних даних засвідчив, що парні коефіцієнти кореляції радіального приросту (-0,54) та поточного приросту за діаметром (-0,53) з віком дерев мають обернений, а діаметра з віком – прямий зв’язок (0,87). Розроблені математичні моделі динаміки ширини річного кільця, діаметра стовбура дерева та поточного приросту за діаметром дозволяють оцінити особливості росту дерев сосни звичайної протягом усього життя. Проведено порівняння отриманих результатів із таблицями ходу росту повних (за відносної повноті 1,0) насаджень. Перевірка розроблених математичних моделей на адекватність засвідчила точність заданих закономірностей та є наступною: для динаміки ширини річного кільця становить 0,46; діаметра стовбурів дерев на висоті 1,3 м – 0,78 та відсотка поточного приросту за діаметром – 0,51. На основі стандартизації індивідуальних хронологій, шляхом розрахунків коефіцієнтів чутливості, не встановлено значної фізіологічної реакції. Відповідно вплив короткотривалих стресових реакцій є несуттєвим. Максимальна стійкість соснових насаджень до неспрятливих чинників середовища досягається у 50-60 річному віці. Дослідження є важливим для оцінювання впливу кліматичних змін та інших несприятливих факторів на ріст соснових насаджень і прогнозування динаміки таксаційних показників. Отримані результати можуть бути використані спеціалістами ВО «Укрдержліспроект» при актуалізації таксаційних показників і обґрунтуванні обсягів використання лісових ресурсів.

Ключові слова: сосна звичайна, деревно-кільцева хронологія, коефіцієнти чутливості, поточний приріст за діаметром, радіальний приріст