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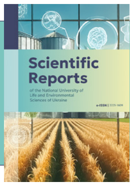

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Radial tree growth in Scots pine stands of Volyn Polissia

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Abstract. This study examines the patterns of radial growth in Scots pine (*Pinus sylvestris* L.) stands within the Volyn Polissia region, with particular reference to the influence of climatic variables. The research aimed to characterise the seasonal structure of climatic sensitivity in Scots pine radial growth and to identify the key climatic factors that drive the interannual variability of tree-ring width. The analysis was based on tree-ring width series obtained from nine temporary sample plots. To remove age-related growth trends, detrending was applied, converting raw measurements into ring-width indices. The relationships between radial growth dynamics and climatic parameters were evaluated through correlation analysis using monthly mean air temperature and total precipitation for both the current and preceding years. The results indicated that the radial growth of Scots pine is most sensitive to temperature conditions during the winter-to-early-spring period of the current year, particularly in February and March. Significant climatic lag effects were also identified: precipitation levels in July and

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August of the previous year positively influence growth in the following year. The analysis confirmed the substantial impact of these climatic factors on interannual growth variability. The absence of significant spatial random effects suggests a coherent common climate signal across the study area. These findings extend current understanding of the seasonal climatic sensitivity of pine stands in Volyn Polissia and can be utilised to assess the resilience of forest ecosystems and to inform adaptive forest management strategies in the face of contemporary climate change

Keywords: *Pinus sylvestris* L.; radial growth dynamics; ring-width indices; climatic factors; dendrochronology

Introduction

The Volyn Polissia is a region characterised by high forest cover and a widespread distribution of Scots pine (*Pinus sylvestris* L.), which is the dominant species in the forest stands of the study area (Fesiuk & Lesnik, 2025). The forests of this region have significant ecological and resource value. Investigating the dynamics of their radial growth enables not only an assessment of the current state of the stands but also the identification of their developmental trends in the context of climate change and forest management.

Tree radial growth is a key indicator that characterises growth processes in forest stands and reflects the interaction between the biological traits of the tree species and external environmental factors. Growth dynamics are directly related to stand productivity, physiological state, and resilience to adverse factors. Furthermore, they determine the potential for providing ecosystem services, particularly carbon sequestration (Bilous *et al.*, 2022; Lesnik *et al.*, 2022).

In modern dendrochronological research, radial growth is considered not only as an indicator of productivity but also as a sensitive archive of climatic information. Tree-ring analysis allows the tracking of interannual growth variability and the identification of the seasonal structure of climatic influence, provided that age-related trends are removed in advance. Applying detrending and converting measurements to ring-width indices (RWI) are necessary prerequisites for the accurate assessment of the climate sensitivity of trees of different ages and from various site conditions (McPartland *et al.*, 2020; Druckenbrod *et al.*, 2024). Recent research by Y. Prokopuk *et al.* (2024) indicates that radial growth sensitivity is primarily driven by precipitation from the dormant season to the early growing season, with site-specific factors such as topography further modulating this response. This finding underscores the need to evaluate the seasonal climate sensitivity of Scots pine (*Pinus sylvestris* L.) in Volyn Polissia, where annual growth fluctuations reflect the complex interplay between environmental change and site-specific conditions.

The significance of local environmental factors is further emphasised by studies focusing on specific forest health issues within the region. For instance, I. Koval & O. Andreeva (2022) analysed changes in the radial growth of Scots pine in epicentres of the pine shoot beetle following clear sanitary felling within the Polissia natural-climatic zone. They found that illuminated areas are characterised by a higher growth sensitivity to hydrothermal conditions, with a negative response to moisture deficits, whereas control plots exhibited a positive correlation with integrated hydrothermal indices. These results indicate a significant impact of microclimatic changes induced by clear-cutting on the growth dynamics of pine stands.

Ukrainian studies have paid considerable attention to determining the response of the main forest-forming tree species in Ukraine to climate change. Specifically, I. Koval *et al.* (2025) examined changes in the radial growth of Japanese larch (*Larix leptolepis* Gord.) under conditions of climate change in the Left-Bank Forest-Steppe of Ukraine. The study developed local chronologies of earlywood, latewood, and total ring width for three periods: 1979-1993, 1994-2008, and 2009-2022. The results showed that, during the third period, the sensitivity of radial growth to climatic fluctuations increased, leading to stand weakening due to rising temperatures. Earlywood was identified as the most sensitive component to climatic change.

Beyond coniferous species, climate sensitivity has also been documented for deciduous stands in the region. I. Ivanyuk & Y. Fuchylo (2020) analysed the impact of meteorological factors on the radial growth of artificial stands of pedunculate oak in the Central Polissia of Ukraine from 1946 to 2018. Optimal values of the hydrothermal coefficient that ensure maximum growth were determined. The study found that oak stands on fresh loamy soils are more sensitive to climatic fluctuations than stands on moist soils.

The patterns observed in Ukraine align with broader European trends regarding the physiological mechanisms of tree growth. For example, a large-scale study by S. Etzold *et al.* (2022), conducted across 47 sites in Switzerland over eight years using automated dendrometers, analysed the daily dynamics of radial stem growth in 160 trees belonging to seven temperate species. The study demonstrated that growth occurs only during a limited number of days within the growing season, with most of these days occurring before the summer solstice. The key driver of annual growth formation is the number of active growth days, whereas the overall length of the growing season is of secondary importance.

While growth duration is a key internal driver, the external regulation of growth by specific meteorological parameters remains equally decisive. This is illustrated by the study of A. Kastridis *et al.* (2022), which analysed the dependence of Greek fir (*Abies borisii-regis* Mattf.) radial growth on climatic factors in the forests of Central Greece over a 60-year period (1961-2020). The results showed that the main growth regulator is precipitation, especially in May-July, while air temperature plays a secondary role. The most negative impact was caused by high June temperatures, which increased evaporation and reduced moisture availability.

Therefore, a review of the scientific literature demonstrates that tree radial growth is a sensitive indicator of the impact of climatic and environmental factors, and in the case of Scots pine, it serves as a key metric of stand resilience and productivity. However, the seasonal structure of the climate sensitivity of radial growth in pine stands within Volyn Polissia, particularly with consideration of climatic lag effects and the removal of age-related trends, remains insufficiently studied. In this regard, the present study aimed to assess the interannual variability of Scots pine radial growth in the stands of Volyn Polissia and to identify the key climatic drivers and seasonal periods that determine growth formation under contemporary climate change conditions.

Materials and Methods

The research was carried out in Scots pine stands during the 2021 and 2023 field seasons within the Kamin-Kashyrske FMU (Branch "Poliskyi Forest Office", SFE "Forests of Ukraine"). In 2021 and 2023, five temporary sample plots were established, and 64 tree cores were extracted in the Dobrenske Forest District. In 2023, four additional sample plots were established in the Nuynivske Forest District, from which 75 tree cores were collected (Fig. 1). To collect wood samples during the field surveys, circular sample plots (CSPs) were established in the most representative areas of the forest subcompartments, following the guidelines of SOU 02.02-37-476:2006 (Ministry of Agrarian Policy of Ukraine, 2006). The plot radius varied depending on stand age, with plot areas ranging from 100 to 500 m^2. Tree diameters at breast height (DBH, 1.3 m) were measured using a tree calliper in two mutually perpendicular directions, and the average value was recorded to the nearest

0.1 cm. The heights of the sample trees were measured using a Haglöf EC-II-D hypsometer. A measuring tape was used to demarcate the plot boundaries (radii).

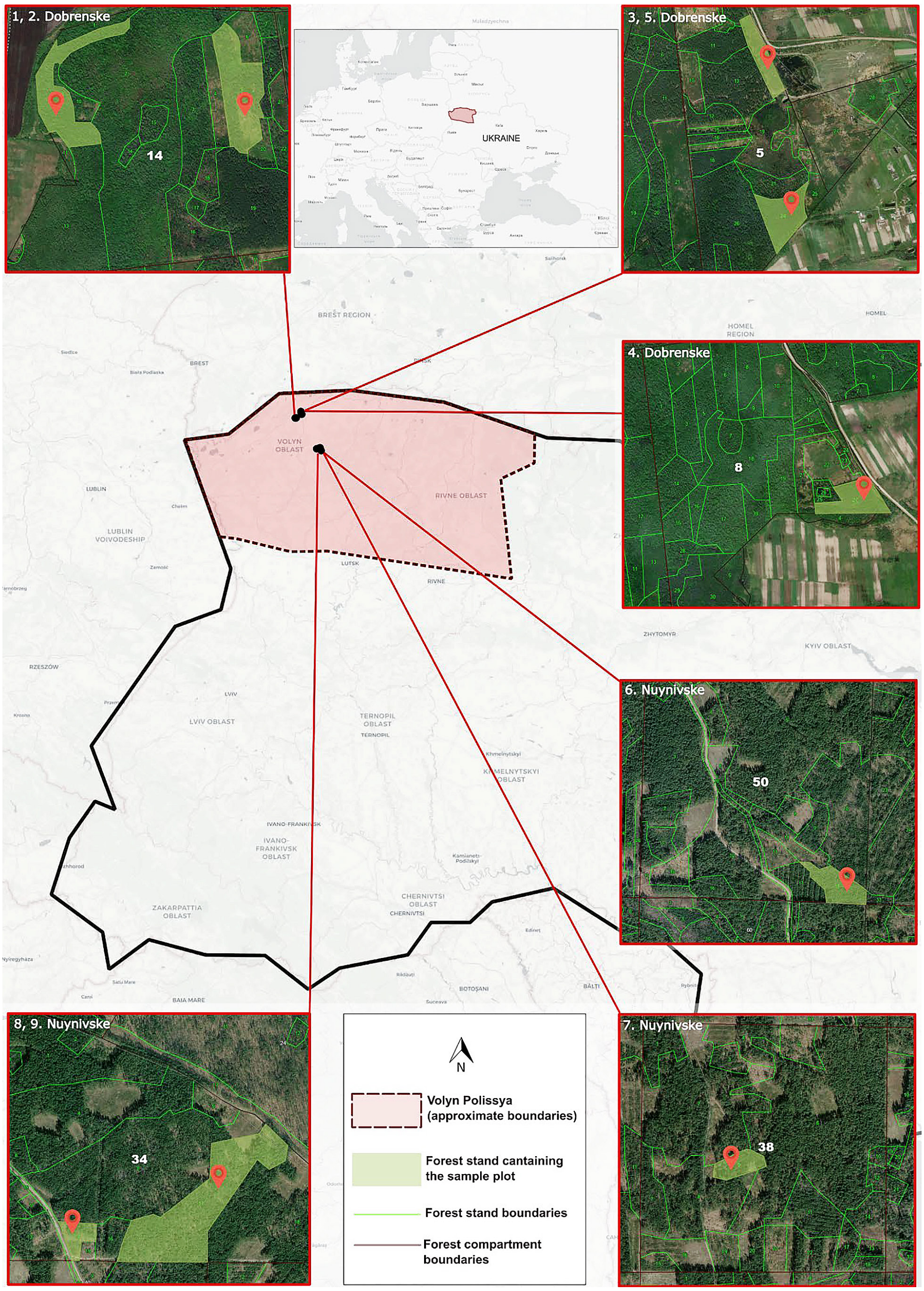

Figure 1. *Location of the temporary sample plots*

Source: compiled by the authors based on the database of the Geoinformation System of Forest Resources Management of Ukraine (Ukrainian State Forest Management Planning Association, n.d.)

Tree cores were extracted from the sample trees at breast height (1.3 m) using a Haglöf increment borer, with boring performed perpendicular to the longitudinal axis of the stem. The extracted cores were mounted on wooden supports for safe transportation and subsequent laboratory preparation, which involved progressively sanding and scanning the samples for tree-ring dating. Each core was uniquely coded to ensure accurate identification of its sampling location. Tree-ring dating and radial growth measurements were performed using ImageJ software equipped with the ObjectJ plugin. Subsequent data processing was conducted using MS Excel. This laboratory processing yielded a comprehensive dataset of annual tree-ring widths. The summary characteristics of the processed dataset are presented in Table 1.

Table 1. *Statistical characteristics of the research data*

No.	Mean increment, mm	Number of rings	Standard deviation	No.	Mean increment, mm	Number of rings	Standard deviation	No.	Mean increment, mm	Number of rings	Standard deviation
1	1.5	89	0.82	48	2.9	41	2.00	95	1.7	61	1.37
2	2.2	78	0.89	49	2.5	43	0.94	96	1.8	66	1.02
3	1.6	90	0.97	50	3.7	21	1.62	97	2.1	66	1.27
4	2.1	77	1.12	51	2.9	20	1.64	98	1.2	66	0.86
5	1.9	85	0.80	52	3.4	20	1.93	99	2.0	68	1.13
6	1.8	78	0.84	53	4.8	20	2.31	100	1.6	58	1.50
7	1.6	86	1.07	54	3.3	19	1.98	101	2.0	63	1.08
8	1.7	89	0.86	55	5.2	20	2.11	102	2.6	50	1.92
9	1.4	79	1.20	56	5.8	18	2.06	103	1.7	61	0.93
10	1.5	79	1.19	57	4.1	21	2.02	104	3.0	66	1.38
11	1.8	82	1.14	58	4.6	18	1.99	105	2.2	64	1.19
12	2.0	88	1.10	59	5.4	18	1.77	106	1.6	66	0.72
13	1.5	75	1.37	60	3.8	21	2.99	17	1.5	63	0.92
14	1.4	69	0.53	61	3.8	21	1.92	108	1.9	59	0.80
15	1.1	90	1.44	62	4.5	20	1.90	109	1.8	61	1.57
16	0.9	87	1.09	63	3.9	17	3.07	110	1.4	52	1.34
17	1.4	83	1.09	64	5.2	20	2.51	111	2.0	64	1.67
18	1.3	89	1.06	65	5.2	17	2.62	112	1.4	67	0.98
19	1.2	90	1.03	66	2.2	19	1.72	113	1.9	59	1.08
20	1.4	88	0.74	67	4.5	19	2.86	114	1.8	64	1.03
21	1.0	76	0.84	68	3.0	17	1.80	115	2.2	66	1.23
22	1.1	88	0.87	69	3.0	16	1.66	116	1.8	61	1.43
23	1.1	90	0.72	70	3.0	17	1.89	117	1.9	62	1.17
24	1.5	81	0.82	71	2.8	19	1.65	118	1.9	60	1.69
25	1.6	71	0.94	72	3.8	18	2.71	119	1.5	50	1.07
26	1.4	81	0.87	73	3.8	20	2.31	120	2.5	58	1.32
27	1.8	95	0.74	74	4.3	21	2.33	121	1.8	60	1.59
28	1.5	97	1.09	75	3.8	18	2.69	122	1.7	59	1.50
29	1.2	92	1.10	76	2.8	19	2.14	123	1.5	64	0.97
30	2.0	93	1.14	77	3.8	19	2.86	124	1.5	81	1.38
31	1.5	98	0.72	78	5.6	18	2.83	125	2.1	81	1.56
32	1.4	97	0.70	79	3.9	17	1.70	126	2.0	83	1.52
33	1.7	87	0.76	80	4.4	17	3.62	127	1.9	77	1.09
34	1.6	98	0.96	81	4.3	18	2.50	128	2.1	83	1.47

Table 1. *Continued*

No.	Mean increment, mm	Number of rings	Standard deviation	No.	Mean increment, mm	Number of rings	Standard deviation	No.	Mean increment, mm	Number of rings	Standard deviation
35	2.2	72	1.04	82	4.8	19	2.35	129	2.2	77	1.29
36	1.3	84	0.60	83	4.6	18	2.43	130	2.3	80	1.00
37	3.7	39	2.31	84	3.6	19	2.08	131	3.2	71	1.35
38	2.5	46	1.46	85	1.7	55	1.01	132	2.5	84	1.93
39	2.5	39	1.41	86	2.5	51	1.62	133	2.1	70	2.22
40	3.1	46	0.95	87	2.5	65	1.54	134	2.4	87	1.66
41	2.7	42	1.97	88	2.6	63	1.61	135	2.5	77	1.68
42	2.3	42	1.47	89	3.6	61	2.34	136	2.3	82	2.12
43	3.4	44	1.07	90	2.3	60	2.10	137	1.8	82	1.66
44	2.6	52	0.82	91	2.4	54	2.21	138	2.0	83	1.23
45	3.0	44	2.04	92	2.1	65	1.71	139	1.5	81	1.60
46	2.8	43	1.20	93	1.9	47	1.43	max	5.8	98	3.6
47	3.2	40	2.41	94	2.1	67	1.40	min	0.9	16	0.5

Source: developed by the authors

All experimental research on plant materials in this study was conducted in accordance with relevant institutional, national, and international guidelines and legislation. The research strictly adheres to the principles of the Convention on Biological Diversity (United Nations, 1992). The dendrochronological sampling was carried out using non-destructive methods (increment borers), ensuring minimal impact on the health of individual trees and the integrity of the forest ecosystem.

To assess the impact of climatic drivers on the annual radial growth of Scots pine, a climate database was compiled, comprising monthly mean air temperatures and total precipitation data from the Kovel meteorological station, the nearest weather station to the study area. The use of data from a single meteorological station is methodologically justified, given the regional scale of the study and the relative climatic homogeneity of the Volyn Polissia. The historical and socio-economic peculiarities of the region – specifically, the inclusion of the territory of the present-day Volyn region within the Volhynian and Polissia Voivodeships of the Second Polish Republic between 1921 and 1939, coupled with the severe infrastructure destruction during the Second World War – resulted in highly fragmented meteorological observations in the first half of the 20th century. Consequently, for subsequent analysis, a complete and continuous climate dataset available from 1946 onwards, obtained from the archival records of the Borys Sreznevsky Central Geophysical Observatory (State Emergency Service of Ukraine, n.d.), was utilised.

To assess the influence of climatic drivers on annual growth formation, climatic variables from both the current year of growth formation and the previous year were used. This approach allowed for the consideration of potential delayed (lag) climatic effects associated with resource accumulation, soil water regimes, and the physiological state of the trees during the previous growing season. The primary processing of the tree-ring width series was performed to remove non-climatic growth trends related to tree age. For this purpose, individual detrending was applied to the radial growth series of each tree using a cubic smoothing spline as a function of age. The smoothing parameter was set at spar = 0.5, which ensured the removal of the long-term age-related trend without loss of interannual growth variability. Following standardisation, ring-width indices were obtained and used in all subsequent analyses of climate sensitivity.

The relationship between radial growth and climatic drivers was evaluated in stages. In the first stage, monthly correlations between the RWI and the climatic variables of air temperature and precipitation were analysed for the months of the current (t) and previous (t-1) years. This approach enabled the identification of critical intra-annual periods with the greatest influence on radial growth formation. To summarise the results of the correlation analysis and visually present the seasonal structure of climate sensitivity, the obtained correlation coefficients were visualised as a heatmap, reflecting the strength and statistical significance of the relationships between the climatic variables and the ring-width indices. All subsequent statistical calculations were performed in the R statistical environment using standard packages.

Results and Discussion

The results of the comprehensive dendroclimatic analysis highlight the environmental context and the specific growth responses of forest stands in the Kamin-Kashyrske FMU. The long-term dynamics of climatic variables (1946-2023) reflect the environmental background of the study region. The calculated air temperature series illustrates both the interannual variability of the mean regime and the intra-annual range between minimum and maximum values (Fig. 2a). Precipitation analysis shows the distribution of annual totals and the relative contribution of different seasons to the water regime (Fig. 2b).

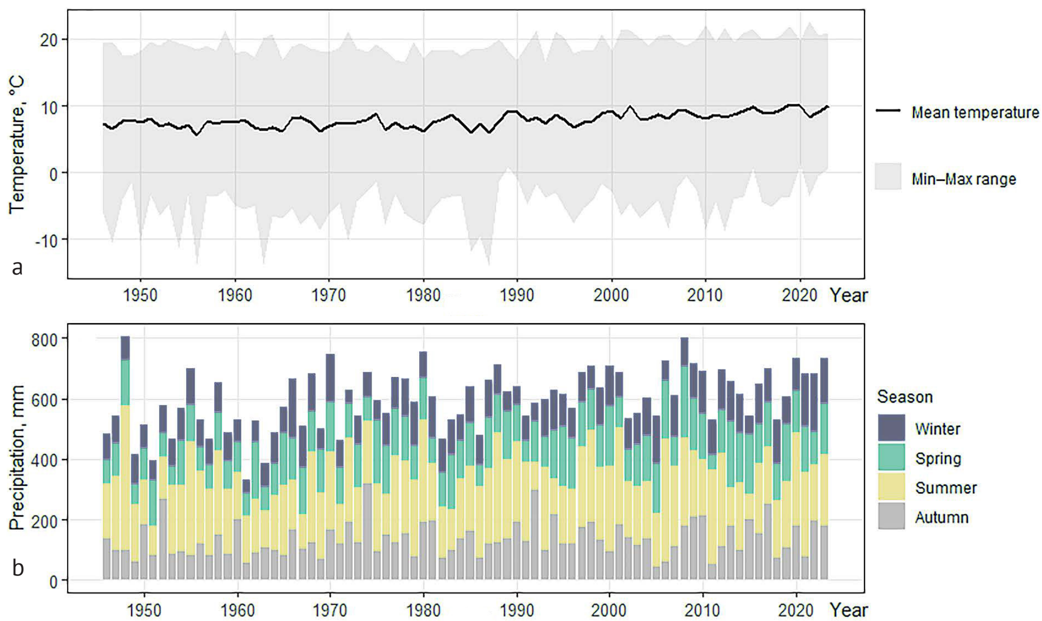

Figure 2. *Long-term characteristics of climatic variables in the study area (1946-2023)*

Note: a – annual minimum, mean, and maximum air temperatures calculated from monthly observations; b – seasonal precipitation

Source: developed by the authors based on the database of the Borys Sreznevsky Central Geophysical Observatory (State Emergency Service of Ukraine, n.d.)

The seasonal structure of climatic conditions is further detailed in the climograph, which visualises the monthly dynamics of temperature and precipitation (Fig. 3). This distribution identifies specific intra-annual periods that potentially act as primary drivers of radial growth formation in the study area. In total, 139 extracted cores were cross-dated, resulting in the measurement of 7,942 tree rings and the determination of their mean width (Table 1). The number of tree rings per core ranged from a minimum of 16 to a maximum of 98. The minimum mean radial growth was 0.9 mm, recorded in tree No. 16 (87 rings), while the maximum was observed in tree No. 56 (18 rings).

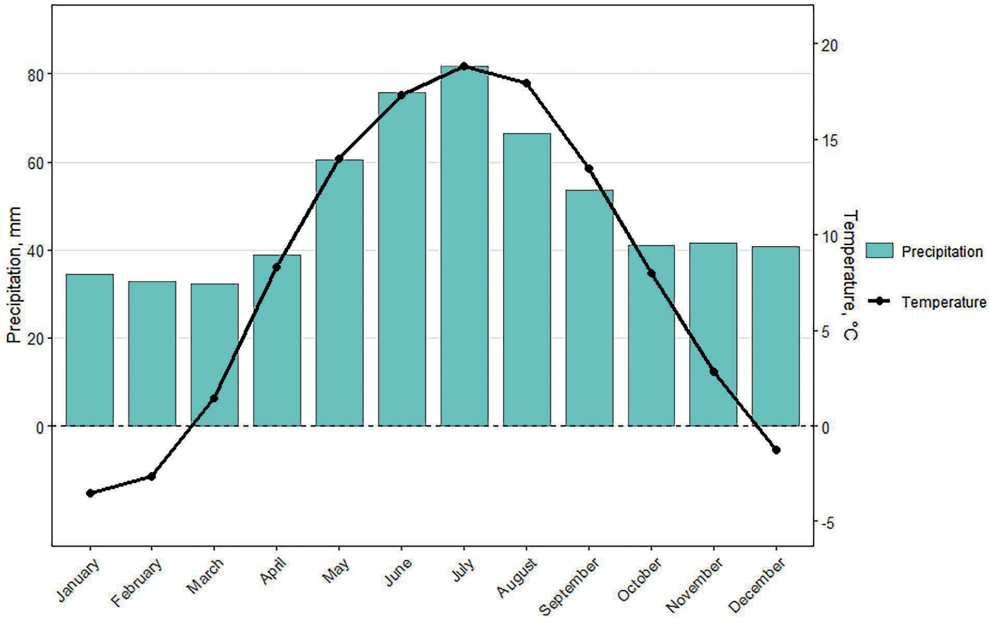

Figure 3. *Long-term monthly mean air temperature and precipitation at the Kovel meteorological station (1946-2023)*

Source: developed by the authors based on the database of the Borys Sreznevsky Central Geophysical Observatory (State Emergency Service of Ukraine, n.d.)

The analysis of individual Scots pine tree-ring chronologies obtained from the nine sample plots indicates a clearly pronounced long-term trend of decreasing radial growth with increasing tree age. The analysis confirms that tree-ring width variability is strictly age-dependent: in young stands, variability is significantly higher due to intensive growth processes, whereas this variability decreases as stand age increases. Such an age-related growth pattern is typical for tree species and can mask interannual growth fluctuations driven by external environmental factors, particularly climate. To isolate the climate-driven interannual variability from this ontogenetic trend, the radial growth series were standardised through detrending. As a result, RWI were calculated for each tree, characterising the relative deviations of growth from the expected age-related baseline. The transition from raw individual tree-ring measurement data to standardised ring-width indices across all sample plots is illustrated in Figure 4. The individual tree-ring chronologies clearly exhibit an age-related trend of decreasing radial growth (Fig. 4a). Following detrending, the ring-width indices for all sample plots (Fig. 4b) fluctuated around a mean of one (RWI ≈ 1), indicating the effective removal of the long-term age-related trend and confirming the validity of the applied standardisation procedure. At the same time, noticeable inter-tree growth variability is observed within each plot, manifested in the differing amplitudes of interannual fluctuations among individual trees.

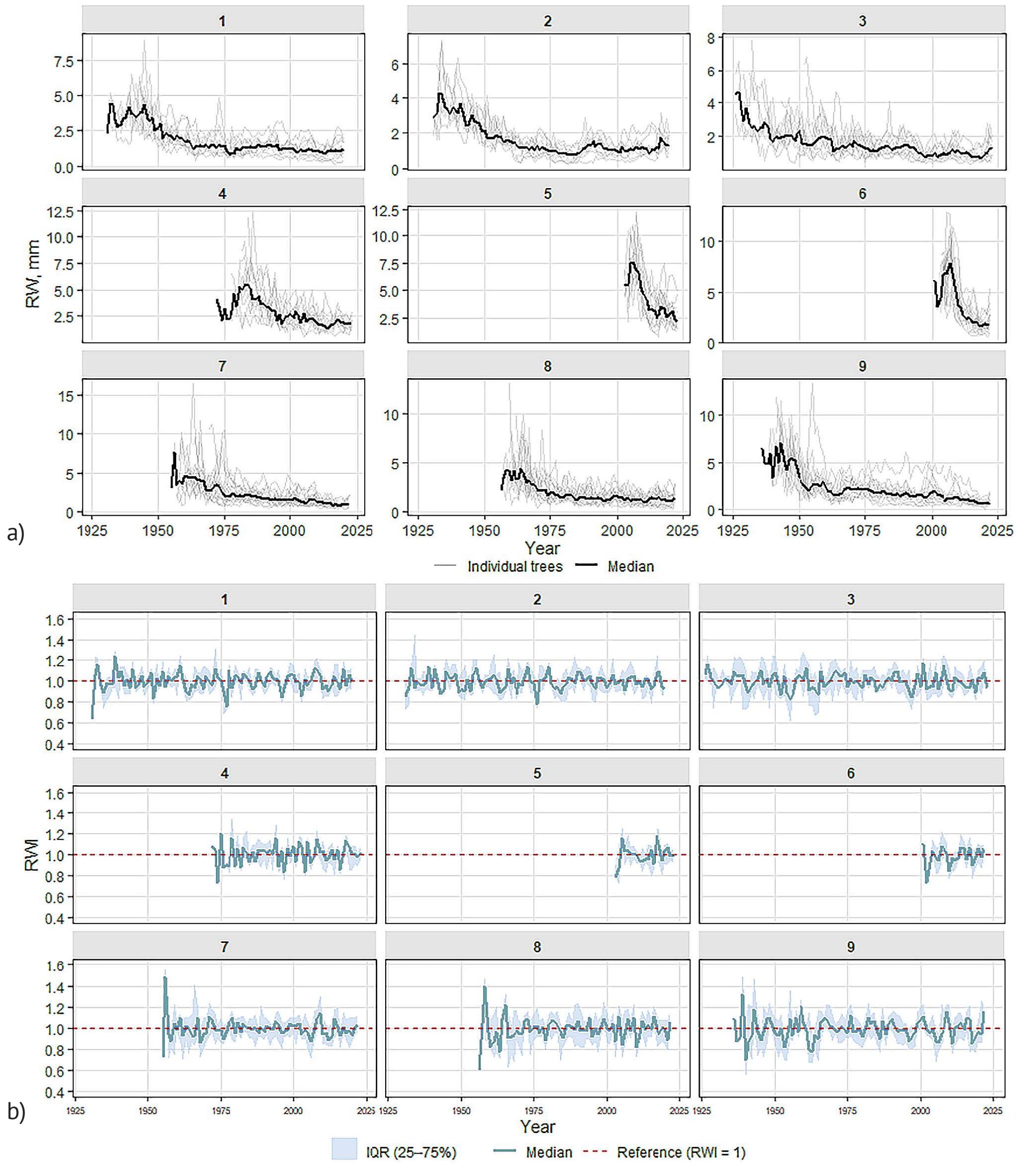

Figure 4. *Individual tree-ring chronologies (a) and standardised ring-width indices (b)*
Source: developed by the authors based on original research data

A comparison of the dynamics of the mean ring-width indices across the sample plots revealed a generally similar pattern of interannual fluctuations, indicating the presence of a common regional growth signal. However, differences in the amplitude and duration of specific phases of enhanced or reduced growth were noted for certain plots, which may be driven by local site conditions. Overall, these results confirm that, following the standardisation of the radial growth series, the RWIs are highly suitable for further analysis of the stands' climate sensitivity, specifically for assessing the relationship between interannual growth variability and climatic drivers of the current and previous years.

To verify the homogeneity of the climate signals, a correlation analysis was conducted between the ring-width indices and climatic variables separately for each of the nine sample plots. The obtained results demonstrate a general coherence in the seasonal structure of climate sensitivity across the sample plot data, despite some differences in statistical significance for specific months. The most stable relationships, in terms of both direction and strength, were observed for air temperature during the winter and early spring of the current year, and for precipitation during the summer months of the previous year. This finding justified the subsequent pooling of data from all sample plots to perform an integrated correlation analysis for the entire dataset of the studied stands.

To assess the seasonal structure of the climate sensitivity of radial growth, monthly correlations between the ring-width indices and the climatic variables of air temperature and precipitation were analysed. The analysis covered the months of the current year of growth formation (t) as well as the previous year (t-1), allowing for the assessment of both direct and delayed (lag) climatic effects. The data from the correlation analysis are presented as a heatmap (Fig. 5).

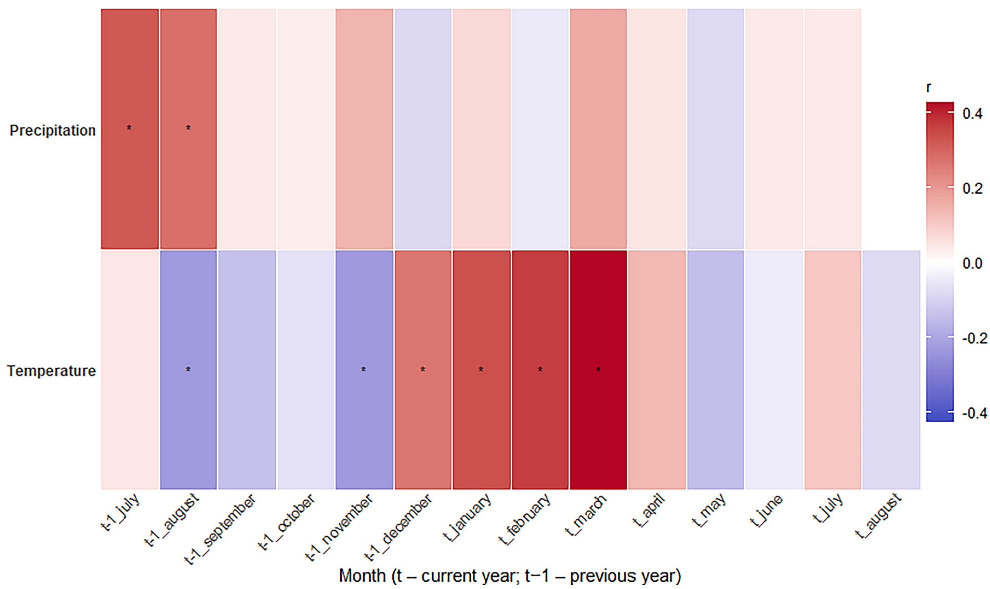

Figure 5. *Correlation analysis of the research data*

Source: developed by the authors based on original research data

The monthly correlation heatmap clearly illustrates the distinct seasonal structure of the climate sensitivity of Scots pine radial growth (Fig. 5). For air temperature, a statistically significant positive correlation with the ring-width indices was established during the winter and early spring of the current year, with maximum correlation coefficients observed from January to March ($r = 0.34$-0.43; $p < 0.01$). During the summer months of the current year, the relationship between temperature and radial growth is weak or absent. For precipitation, a different seasonal impact structure was found: statistically significant positive correlations with the ring-width indices are primarily concentrated in the summer months of the previous year, specifically in July and August ($r = 0.28$-0.32; $p < 0.05$), indicating the presence of delayed (lag) climatic effects. The temperature conditions of the previous year demonstrated both positive and negative correlations depending on the month, reflecting the bidirectional nature of their influence on radial growth formation. Overall, the obtained results confirm the presence of two main types of climate signals in growth formation: the direct impact of temperature conditions at the beginning of the year of growth formation, and the delayed impact of the water regime during the previous growing season. To illustrate the manifestation of the identified climate-growth relationships within the time series, the dynamics of both radial growth and the annual moisture balance were analysed (Fig. 6).

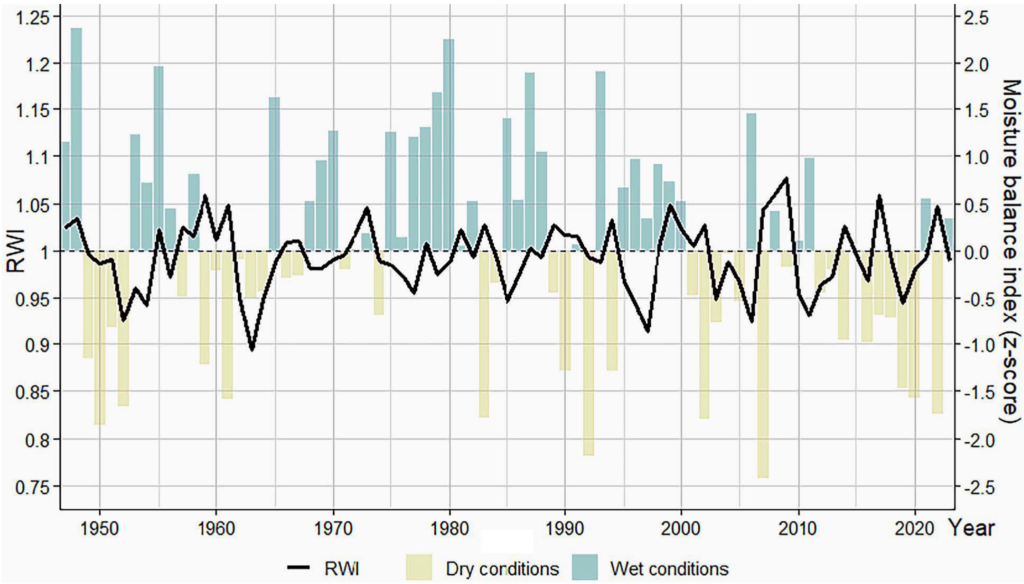

Figure 6. *Relationship between tree radial growth and hydrothermal conditions*

Source: developed by the authors based on original research data and data from the Borys Sreznevsky Central Geophysical Observatory (State Emergency Service of Ukraine, n.d.)

The data analysis (Fig. 6) indicates that negative radial growth anomalies predominantly coincide with years of negative moisture balance, i.e. drought conditions. The most pronounced growth reductions were observed in years when a moisture deficit was combined with elevated temperatures. Since 2000, a clearer synchronisation of negative RWI anomalies with dry periods has been observed, which may indicate the increasing sensitivity of the stands to moisture deficits. The obtained results demonstrate that the radial growth of Scots pine in the stands of the Volyn Polissia is shaped by a combination of long-term ontogenetic processes and seasonally structured climatic drivers. The application of individual detrending and the transition to standardised ring-width indices have enabled the removal of the age-related growth component and facilitated a focus on interannual variability driven by climatic conditions, which is a widely accepted approach in dendroclimatic research.

The identified positive impact of air temperature in February-March of the current year on Scots pine radial growth aligns with the results of numerous dendroclimatic studies, which emphasise the role of thermal conditions at the end of winter and the beginning of the growing season (Koprowski *et al.*, 2012; Janecka *et al.*, 2020; Waszak *et al.*, 2021). Elevated temperatures during this period are critical, as they promote an earlier reduction in soil frost depth. Milder thermal conditions prevent deep soil freezing, which facilitates earlier root water uptake and accelerates the restoration of xylem sap transport in early spring. This, in turn, promotes an earlier resumption of cambial activity and reduces the risk of physiological drought in the early growing season, ultimately ensuring more intensive radial growth.

The positive relationship between precipitation totals in July-August of the previous year and radial growth in the subsequent year indicates the presence of a pronounced lagged climate effect. Sufficient water availability in the second half of the growing season facilitates the accumulation of assimilates and the formation of carbohydrate reserves, which are utilised for growth processes at the beginning of the following year. Similar delayed precipitation effects have been repeatedly noted in dendroclimatic studies (Zeng *et al.*, 2022; Tumajer *et al.*, 2023), which is particularly relevant for pine stands on the sandy and loamy sand soils of the Polissia, where moisture deficit is a primary growth-limiting factor.

The identified sensitivity of Scots pine to shifting hydrothermal conditions in Volyn Polissia aligns with recent studies in adjacent areas. For instance, V. Levchenko *et al.* (2025) demonstrated in the Polissia Nature Reserve that radial growth serves as a primary indicator of both climatic fluctuations and the pathological impact of disease pathogens, which is crucial for assessing forest ecosystem resilience. Furthermore, observations of growth synchronisation with climatic parameters support the conclusions of V.A. Romanenko & S.B. Kovalevskyi (2023) from the Boyarka Forest Research Station. Their retrospective analysis similarly emphasised the importance of monitoring physiological resilience to develop effective forestry adaptation mechanisms for preserving Scots pine stands in Ukraine.

The absence of significant random effects across the sample plots and individual trees indicates the spatial coherence of the climate signal within the study area. This suggests that climatic drivers exert a dominant influence on the interannual variability of radial growth compared with local site conditions. Such spatial coherence of dendroclimatic signals is characteristic of lowland regions with relatively homogeneous climatic conditions (Duchesne *et al.*, 2017). This persistence of the climate signal is further supported by the research of M. Netsvetov *et al.* (2023) in the Chornobyl exclusion zone. Their study demonstrated that even under extreme environmental stressors, such as radiation exposure, pronounced climate signals persist in the growth dynamics of Scots pine.

While the findings emphasise the primary role of climatic drivers, it is important to note that radial growth fluctuations in the region are part of a more complex interaction. As noted by D. Holiaka *et al.* (2026) and V. Myroniuk *et al.* (2026), annual growth dynamics are driven not only by natural factors but also by the intensity of anthropogenic impacts, sanitary conditions, and silvicultural treatments. However, the high spatial coherence of the climate signal observed in this study suggests that under contemporary climate change, these external stressors likely act in synergy with climatic fluctuations (Julio Camarero *et al.,* 2015; Klisz *et al.,* 2023).

The observed synchronisation of negative RWI anomalies with dry periods since 2000 suggests a shift in the stands' adaptive capacity. This trend is likely driven by the increasing intensity and frequency of heatwaves and atmospheric droughts in the 21st century. As temperatures rise, the evaporative demand of the atmosphere increases, meaning that even moderate precipitation deficits now result in more severe physiological stress for the trees than in previous decades. These results are consistent with the findings of A. Debel *et al.* (2021), who analysed Scots pine growth in Bavaria and recorded a significant increase in tree sensitivity to climatic factors over the last few decades. Their study confirms that Scots pine remains one of the most vulnerable European tree species to climate change, with its sensitivity increasing even in relatively moist regions.

In summary, the dendroclimatic analysis of Scots pine stands in Volyn Polissia reveals a robust and spatially coherent climate signal that remains the primary driver of radial growth despite the presence of local environmental stressors. Growth formation depends critically on a specific seasonal window, namely thermal conditions in late winter and moisture availability during the peak of the previous growing season. However, the increasing synchronisation of growth reductions with drought events over the last two decades indicates a potential decline in the adaptive capacity of pine stands. These findings highlight the necessity of integrating seasonally specific climatic responses into forest management strategies to enhance the resilience of Volyn Polissia's forest ecosystems in the face of accelerating climate change.

Conclusions

The study of radial growth in Scots pine stands in the Volyn Polissia, based on tree-ring analysis, has identified several patterns of growth formation under ongoing climate change. The radial growth of Scots pine is characterised by a clearly pronounced age-related decreasing trend, which necessitates the application of detrending for accurate assessment of climate sensitivity. The transition to ring-width indices has allowed the removal of the ontogenetic growth component and enabled a focus on interannual variability driven by external factors. The monthly analysis of climatic variables revealed a distinct seasonal differentiation in the impact of these factors on radial growth formation. The most significant positive impact was exerted by the temperature conditions of the winter and early spring period of the current year, particularly in February and March. The presence of pronounced delayed (lag) climatic effects was also established. Specifically, precipitation totals in July-August of the previous year positively influenced radial growth in the following year, indicating the critical role of water availability at the end of the growing season in forming the resource base for growth. A comparison of the temporal dynamics of the ring-width index with the integrated moisture balance indicator showed that years with reduced growth predominantly coincide with periods of moisture deficit. This confirms the limiting influence of water availability on the formation of interannual radial growth variability and aligns with the results of the correlation analysis. The obtained results emphasise the high sensitivity of the Volyn Polissia pine stands to seasonal and delayed climatic impacts. These findings can be utilised to predict the response of forest ecosystems to further climate change and to justify the implementation of adaptive forest management practices. Future research could be directed towards expanding the range of climatic variables, specifically by incorporating extreme weather events, integrated hydroclimatic indices, and higher-resolution (daily) climate data.

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Conflict of Interest

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Анотація. У статті досліджено особливості формування радіального приросту сосни звичайної (*Pinus sylvestris* L.) у насадженнях Волинського Полісся з урахуванням впливу кліматичних показників. Метою дослідження було визначення сезонної структури кліматичної чутливості радіального приросту сосни звичайної та встановлення ключових кліматичних чинників, що зумовлюють міжрічну мінливість ширини річних кілець. Аналіз базувався на рядах ширини річних кілець, отриманих на дев'яти тимчасових пробних площах. Для усунення вікових тенденцій росту застосовано детрендінг з переходом до індексів радіального приросту. Оцінювання зв'язків між динамікою радіального приросту та кліматичними показниками виконано за допомогою кореляційного аналізу з використанням місячних значень температури повітря та атмосферних опадів поточного і попереднього років. У результаті дослідження встановлено, що радіальний приріст сосни звичайної найбільш чутливо реагує на температурні умови зимово-ранньовесняного періоду поточного року, зокрема у лютому-березні. Виявлено також виражені лагові ефекти клімату: кількість опадів у липні-серпні попереднього року позитивно впливає на приріст у наступному році. Результати аналізу підтвердили суттєвий вплив зазначених кліматичних чинників у формуванні міжрічної мінливості приросту. Відсутність істотних просторових випадкових ефектів свідчить про узгодженість кліматичного сигналу в межах досліджуваної території. Отримані результати розширюють уявлення про сезонну структуру кліматичної чутливості соснових насаджень Волинського Полісся та можуть бути використані для оцінки стійкості лісових екосистем і розроблення адаптивних підходів до ведення лісового господарства в умовах сучасних кліматичних змін

Ключові слова: *Pinus sylvestris* L.; динаміка радіального приросту; показники ширини річних кілець; кліматичні фактори; дендрохронологія