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Dendrochronological assessment of climate risks for the restoration of oak forests in the Ukrainian Polissya

Rostislav Oliynyk
PhD in Physical and Mathematical Sciences, Associate Professor
Taras Shevchenko National University of Kyiv
01033, 60 Volodymyrska Str., Kyiv, Ukraine
https://orcid.org/0000-0002-8675-7009

Roman Vasylyshyn
Doctor of Agricultural Sciences, Professor
National University of Life and Environmental Sciences of Ukraine
03041, 15 Heroiv Oborony Str., Kyiv, Ukraine
https://orcid.org/0000-0002-7268-8911

Olena Pinchevska[*]
Doctor of Technical Sciences, Professor
National University of Life and Environmental Sciences of Ukraine
03041, 15 Heroiv Oborony Str., Kyiv, Ukraine
https://orcid.org/0000-0001-8123-5490

Andiy Spirochkin
PhD in Technical Sciences, Associate Professor
National University of Life and Environmental Sciences of Ukraine
03041, 15 Heroiv Oborony Str., Kyiv, Ukraine
https://orcid.org/0000-0002-2647-3784

Abstract. The deterioration of climatic conditions caused by global warming poses a threat to the sustainable development of forest ecosystems, particularly oak stands, which are an important component of Ukraine's forestry sector. The purpose of the study was to determine the growth responses of *Quercus robur* L. trees to long-term climatic changes leading to increased aridity in the conditions of the Ukrainian Polissya. The gradients of the temperate climate in the locations where *Quercus robur* L. trees grow in Ukraine were analysed, namely the climatic factors (extreme temperatures, precipitation) that affect the growth and development of trees on a monthly and seasonal time scale. The results provide important information on the regional prospects for

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[*]*Corresponding author*

growing oak plantations in Ukraine. Random climatic factors, which act synergistically with systemic factors, negatively affect tree growth, regardless of the characteristics of the forest management system. The influence of climatic conditions on the radial growth of *Quercus robur* L. trees within their natural range was studied. Particular attention was paid to situations where the analysed trees formed rings whose width exceeded the interval – the mean plus or minus the standard deviation ($\bar{R} \pm SD$). Chronologies of climatic signals covering the new reference period 1991-2020 were developed for the studied locations. Simple indices of extreme monthly average air temperatures and monthly precipitation indices were calculated. A climatic analysis was conducted for the years in which anomalies in the growth of *Quercus robur* L. trees were observed, identified by the tree ring width index (TRWI). It has been established that annual precipitation totals and maximum air temperatures in the spring-summer season have a statistically significant impact on radial growth. The constructed polynomial models allow predicting changes in the growth dynamics of *Quercus robur* L. trees for the studied region

Keywords: climate change; climate signals; dendrochronological analysis; tree ring width; ring width index

Introduction

In light of predicted climate change, there is a need to assess the impact of future climate gradients on the growth, development and distribution of tree species. The resilience of species to climate change is of significant importance for forecasting the development of forest management systems (IPCC, 2022). Dendrological research has been conducted mainly in two areas: tree growth dynamics in their natural habitat and their response to climate change, and tree growth characteristics in warm, dry regions that currently exhibit the climatic conditions expected in the future climate for a given locality. However, unfavourable climatic conditions are not the only cause of plant growth disruption, as there are other causes, according to A. Wallraf & S. Wagner (2019). The distribution range of a species is determined not only by climate, as there are a number of systemic factors, including latent ones, that affect the growth of woody plants. The suppression and even displacement of a particular species can occur due to the presence of competing species that are better adapted to the area. The authors A. Wallraf & S. Wagner suggested that any statistical correlations between climatic conditions and growth indicators may be questionable in terms of cause-and-effect relationships.

Nevertheless, M. Steckel *et al.* (2020) believed that climatic gradients, which are entirely random in nature, have both a direct and indirect impact on tree growth and development, as rising temperatures accelerate chemical reactions that release nutrients, enhancing the growth of trees and microbial populations, while reducing humidity and stimulating soil droughts. The impact of climatic stresses on the common oak (*Quercus robur L.*) in the forest-steppe zone of Ukraine, studied by I.M. Koval & A. Bräuning (2024), causes noticeable reactions in the radial growth of trees to climate variations. Depressions in radial tree growth were observed in years with low precipitation and elevated ground temperatures, while maximum growth was observed in years with favourable temperature and humidity conditions for tree growth. A study by R. Puchałka *et al.* (2024)

of *Quercus petraea* within its natural range in northern Poland showed that there is currently a trend towards a decline in the viability of mature trees and a reduction in their radial growth, despite the fact that climatic conditions for this species remain stable. This is evidenced by observations of the species' cambial activity during growing seasons in years with negative and positive water balances. This enabled the authors R. Puchalka *et al.* to compare the phases of wood formation and growth width. They found that in dry years, cambial activity ceased earlier than in wet years, and that precipitation significantly prolonged the duration of cambial activity and contributed to the formation of wide rings. Late spring frosts (LSF) are increasingly being added to the list of anomalies in the modern regional climate.

E. Tonelli *et al.* (2022) investigated the negative impact of late spring frosts on tree productivity and growth in temperate forests. The reduction in growth of trees affected by LSF ranged from 36 to 84%. The negative impact was only observed during the year when LSFs were fixed, with growth recovery occurring within 1-2 years after the event. However, detailed information on how these forests recover after such events is still not available. According to the authors, the increase in the frequency of LSF may, in the long term, threaten the disappearance of certain species, in particular the presence of beech in the high-altitude forests of the Mediterranean. There is a deficit of research on tree growth in conditions that differ significantly from those of their natural habitat. Therefore, the study by D. Moreno-Fernandez *et al.* (2022) on forests in central Spain is extremely relevant, as it can provide insight into how native species will grow in new climatic conditions. The authors of the study connected the process of pine forest dieback observed in 2019 with rapidly changing climatic conditions and drought stress.

The limitation of the mentioned approaches is that the actual adaptation of tree species to climatic conditions has not yet been fully understood. The Polissya region of Ukraine is characterised by a temperate climate, where forest formation has been ongoing for over a millennium. There is a need to predict their productivity in the context of progressive climate change. I. Ivanyuk & T. Ivanyuk (2019) noted that over the last decade, significant fluctuations in the radial growth index of common oak have been observed in the Ukrainian Polissya, indicating the species' response to climatic signals. Despite the relatively high drought resistance of *Quercus robur L.* in its natural range, there is a need for further research into the climatic growth potential of trees of this species and the possibility of expanding their geographical range beyond their natural range.

The problem facing dendroclimatologists today is to correctly identify the climatic signal that has found an accessible response in tree layer data and to distinguish this signal from ground noise. The aim of the study was to investigate the influence of climatic gradients on the radial growth of *Quercus robur L.* trees in the Ukrainian Polissya. To achieve this goal, the following tasks were set: to determine annual anomalies in tree growth by calculating the tree ring width index (TRWI); to calculate climate indices on a monthly/seasonal averaging time scale; to establish a stochastic relationship between radial growth and climate signals.

The scientific novelty lies in determining the possibilities of predicting the growth dynamics of *Quercus robur L.* within its natural range, taking into account regional climate changes caused by global warming.

Materials and Methods

Three locations were studied in Ukrainian Polissya (Korosten – SITE 1; Zhytomyr –

SITE 2; Kyiv – SITE 3 and one in the Left Bank Forest-Steppe zone (Kharkiv – SITE 4), where the most common plantations involve the common oak (*Quercus robur L.)*. The main characteristics of the studied locations are presented in Table 1.

Table 1. Overview of researched sites

Location	Geographical coordinates		Altitude above sea level, m	Climate	Soil types
	Latitude, N	Longitude, E			
SITE1	50.97	28.61	170	Moderately continental	sod-podzolic, sod
SITE2	50.25	28.66	220	Humid moderately continental	sod-podzolic gleyed
SITE3	50.45	30.52	170	Moderately continental	gray podzolised forest
SITE4	50.06	36.35	150	Moderately continental	typical chernozems and podzolised chernozems

Source: developed by the authors

Standardisations of random meteorological series was necessary for statistical comparisons of random variables of different physical nature. For the analysis, a climate signal was used, which is a random variable, Δx, and at any given moment represents a random meteorological quantity (temperature, precipitation), the cantered value of which, x, takes specific values with a certain probability:

$$\Delta x = x - \bar{x}, \tag{1}$$

where $\bar{x}$ – is the climatic norm.

If the cantered values of meteorological variables are stabilised by dispersion, obtain dimensionless standardised values x_{st}:

$$x_{st} = \Delta x / \sigma. \tag{2}$$

In this study, standardised values of extreme monthly average air temperatures and monthly precipitation totals were considered as climate signals. Meteorological information was obtained for all study sites from the Sectoral State Archive of Hydrometeorological Observations of the State Emergency Service of Ukraine (United Hydrometeorological Station Kyiv, n.d.). The study period covered the period from 1931 to 2020 inclusive. The initial meteorological data were taken into account: daily values of maximum/minimum surface air temperature and monthly precipitation totals. The time series of annual tree ring widths at the respective sites were borrowed from scientific works (Procopuk, 2017; Ivanyuk & Fuchylo, 2020; Koval & Bräuning, 2024).

The change in the width of the annual ring, according to the law of tree ring growth, is determined by the following formula, obtained from the equation given in the work (Giraldo & Dell Valle, 2016):

$$TRW = \frac{C_1 e^{-\alpha_1 t} + C_2 e^{-\alpha_2 t}}{3C_3 \sqrt[3]{\rho (C_4 + C_1 e^{-\alpha_1 t} + C_2 e^{-\alpha_2 t})^2}}, \tag{3}$$

where C_1, C_2, C_3, C_4 – some coefficients; α_1, α_2 – positive constants; ρ – wood density.

The appearance of the function of the change in the width of the annual ring as the tree grows is shown in Figure 1.

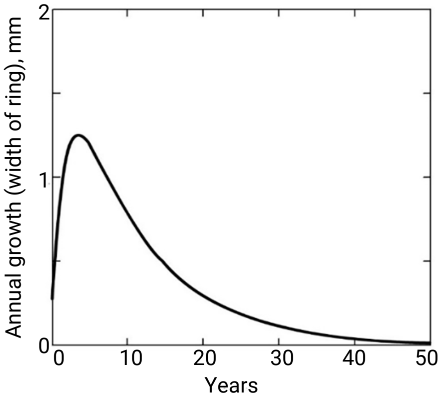


Figure 1. A typical form of the function of the wood ring width (with an increase in the width of wood ring at initial stage)
Source: J.A. Giraldo & J.I. Dell Valle (2016)

Thus, the presented analytical dependence (3) and its graphical interpretation (Fig. 3) describe the general law of tree-ring width variation over time. This relationship forms the theoretical basis for further statistical analysis and standardisation of the obtained dendrochronological series.

Applied statistical analysis of time series of meteorological variables and ring width series was performed using STATISTICA (version 12), which, in particular, allowed for detailed investigation of: graphical representation and analysis of time series behaviour; identification of deterministic components of the series; removal of low- or high-frequency components of the series; random component of the time series; prediction of the behavior of the time series.

Results

The results of calculations for the Zhytomyr region are shown in Figure 2.

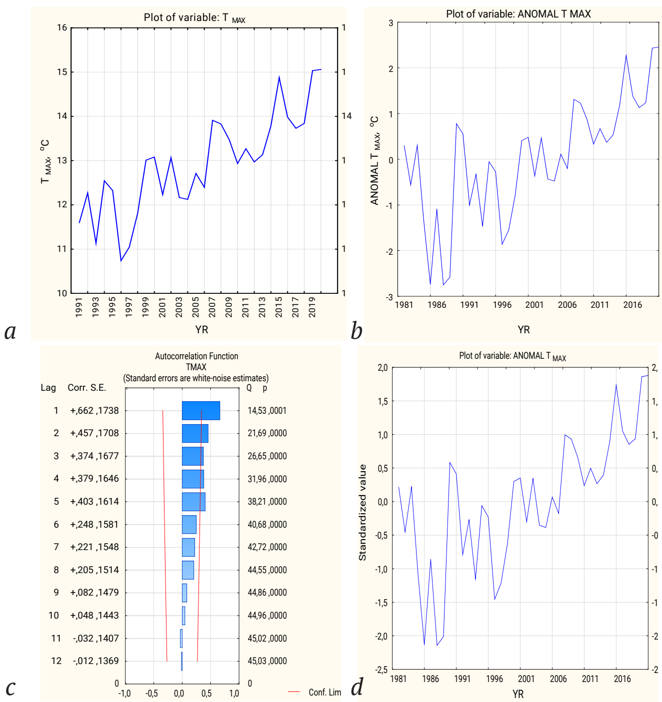
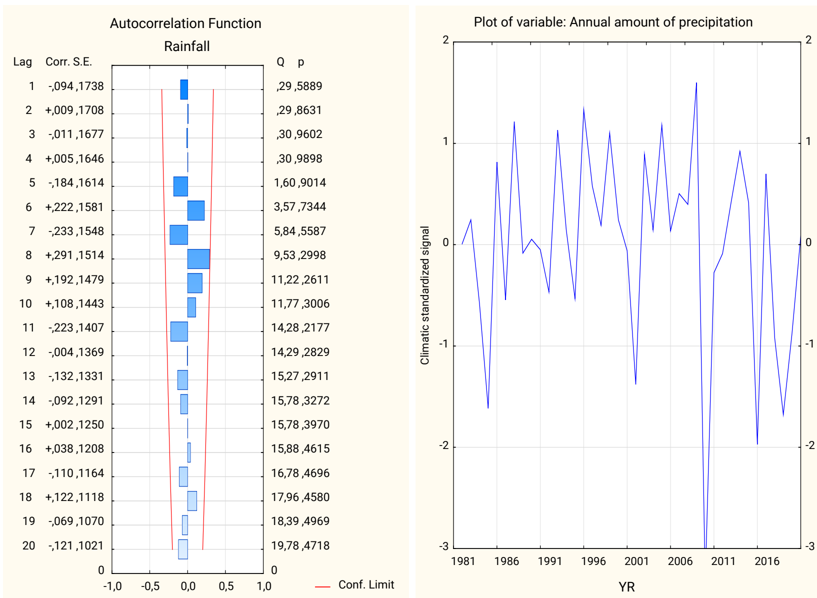


Figure 2. Growth trends of the surface maximum air temperature chronologies (SITE 2)
Note: a – original unprocessed series; b – cantered series; c – autocorrelation function; d – standardised series (climatic signal)
Source: compiled by the authors

The dynamics of annual extreme temperature variability indicate the presence of a linear trend in the random process, which has a steady tendency to increase the maximum temperature (Fig. 2a). Climatological anomalies, according to the recommendations of the World Meteorological Organisation (WMO, n.d.), are determined by centred values relative to the climatic norm (Fig. 2b). The downward trend of the correlation function of the time series of the random component (Fig. 2c) indicates that the process is stationary, i.e., the mean value and variance have become stable, which allows us to move to standardised values of the random component, which acquires the meaning of a climate dimensionless signal (Fig. 2d).

The dynamics of annual precipitation variability for all locations shows a slightly expressed linear downward trend. The tendency towards a decrease in annual precipitation is observed at a level of < 1 mm/yr (Fig. 3). The process proved to be stationary, as evidenced by the downward nature of the correlation function. Therefore, this allows to immediately proceed to the standardisation of the initial series of annual and monthly precipitation totals.



a *b*

Figure 3. Standardised climate signal - annual amounts of precipitation (SITE 2)
Note: a – autocorrelation function rainfall; b – dynamics of climatic standardised signal
Source: compiled by the authors

If examine the width of the ring without taking into account the initial growth phase, the dynamics of the ring width can be satisfactorily approximated by a negative exponential function. Thus, in order to transition to standardised tree ring width index (TRWI) values, it is necessary to decompose the time series, i.e. to convert the non-stationary TRW time series into a stationary one by removing seasonality and trend from it. Depending on the age of the tree, as well as the initial conditions, the trend takes on a slightly different form (Fig. 4), since the dendrological process is non-stationary.

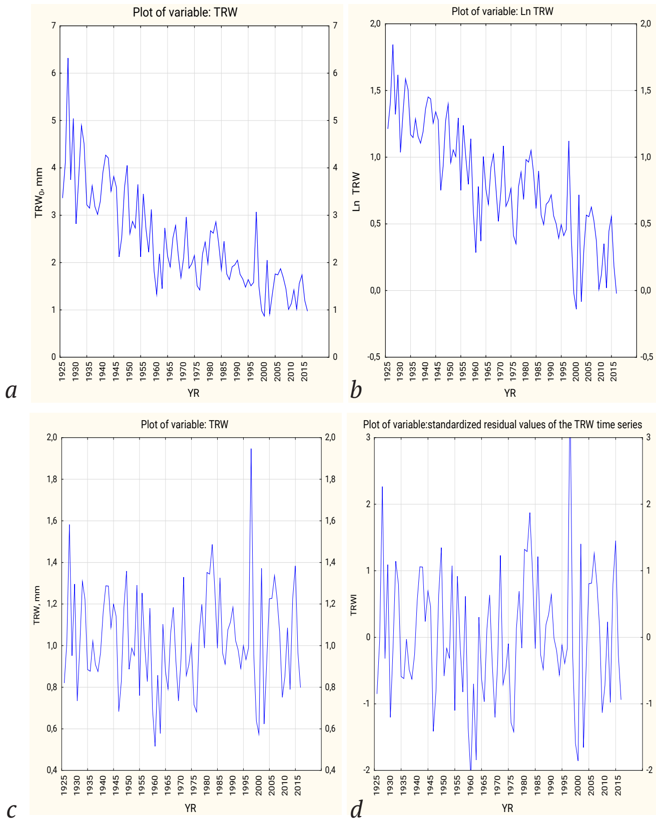


Figure 4. The sequence of standardisation of the width of the wood ring SITE 4
Note: a – original series of data TRW; b – linearisation of the original series by logarithmisation; c – decomposed data series TRW; d – wood ring width index TRWI
Source: compiled by the authors

The study of the correlation function of long TRW series, including the initial growth stage, shows its relative stability. Therefore, there is a need to convert the random process into a stationary mode, i.e. it is necessary to remove the trend. If use the dendrochronological equation (3), a complex task of its parameterisation arises, so applied a statistical approach to remove the trend, which gives satisfactory results provided that the initial sample is sufficient. Since the trend TRW_0 decreases according to the exponential law (Fig 4a), the initial series was logarithmised for its linearisation (Fig. 4b). After removing the linear trend, a new series was formed, the TRW residual series (Fig. 4c), which contains only a random component. The stationarity of the new series allows it to be presented in a standardised form (Fig. 4d) and considered as a series of the TRWI tree ring width index.

Annual climate anomalies and TRWI variations. According to the recommendations of the World Meteorological Organisation (WMO, n.d.), the time lag for recording climate change should be at least 30 years. In order to organise climate information obtained from different locations, it is proposed to select reference periods starting with years ending in a unit. Meteorological data averaged over this period are considered as reference data (climatic norms) against which the climatology of the random process in the studied location is analysed for a fixed reference period. Since the evolutionary cycle of oak forest (*Quercus robur L.*), in particular, is more than a century, the question arises regarding the identification of climate anomalies, namely in relation to the reference period. Unfortunately, climate data for the locations under study have different histories. Nevertheless, it was possible to track the variability of climatic reference indicators (Table 2). The list of regional indicators of climate change includes, first of all, temperature indicators – maximum and minimum air temperatures, which determine the temperature range for a fixed location in a given time interval.

Table 2. General characteristics of test areas

Reference period	Descriptive statistics (maximum temperature. SITE1Winter.sta)						
	Valid N	Mean	Minimum	Maximum	Std.Dev.	Skewness	Kurtosis
1931-1960	78	-1.9	-9.2	5.0	3.24	-0.55	-0.27
1941-1970	66	-1.8	-10.8	5.0	3.11	-0.85	0.96
1951-1980	78	-1.5	-10.8	5.0	2.87	-0.81	1.60
1961-1990	78	-1.2	-10.8	6.1	3.08	-0.59	1.17
1971-2000	90	-0.5	-9.7	6.1	2.95	-0.55	0.77
1981-2010	90	-0.3	-9.7	7.2	3.07	-0.45	0.94
1991-2020	90	0.2	-6.8	7.2	2.92	-0.06	-0.20
2001-2024	69	0.4	-6.6	7.2	2.96	-0.11	-0.24

Source: compiled by the authors by statistical evaluation of primary data of United Hydrometeorological Station Kyiv (n.d.)

Regional responses to global warming, which began in the 1980s, have been ambiguous and unpredictable. Statistical analysis of meteorological data has revealed trends in temperature changes in the lower atmosphere at all sites studied. There is a steady trend towards an increase in both max/maximum temperature and min/minimum temperature, with the latter increasing more noticeably. It should be noted that the empirical distribution of extreme temperatures does not show a tendency towards excess and right-sided asymmetry, but rather approaches the standard Gaussian distribution.

The climatic norms of average annual (average monthly) values of extreme temperatures and annual (monthly) precipitation totals, which were determined for the studied sites, made it possible to identify climatic signals, such as anomalies in temperature and precipitation patterns relative to the climatic norm. Since the random processes under study demonstrate stationarity, by stabilising the centred values of the average annual maximum and minimum air temperatures and annual precipitation totals by dispersion, it is possible to move on to dimensionless standardised indices – IT_{MAX}, IT_{MIN}, IPR. If the corresponding climate index takes on a value $> |\pm 1|$, this means that the meteorological value is outside the interval and such an index is considered a climate signal (Fig. 5, Fig. 6). A climate signal in this format proved to be quite convenient for analysis, since not only the time of the event is identified, but also the relative weight and phase of the signal. It should be noted that the ITMAX, ITMIN and IPR signals contain trend components, since during the reference period under study, the values of climate signals change as a result of both systematic (planetary) and random (regional) factors.

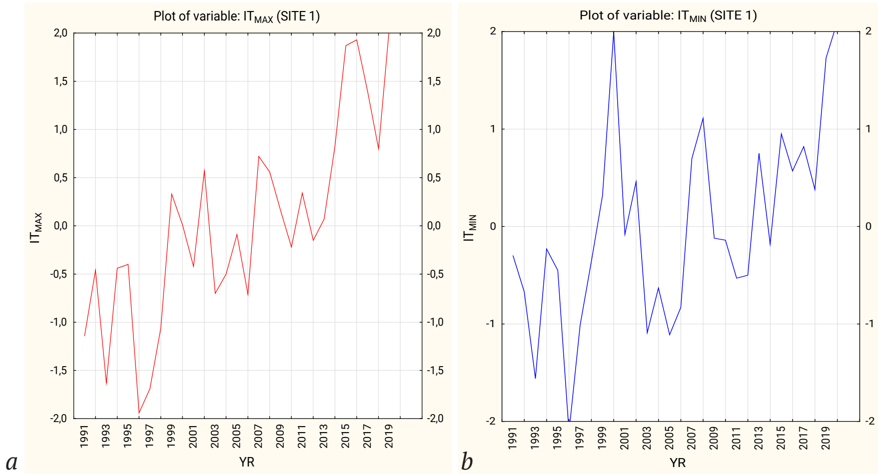


Figure 5. Dynamics of climatic temperature signals (a-ITMAX; b-ITMIN)

Source: compiled by the authors

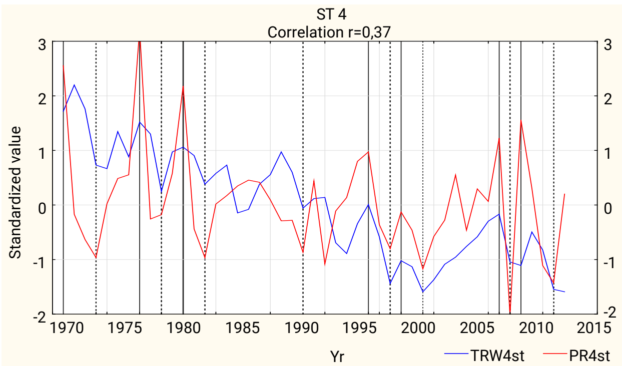


Figure 6. Dynamics of TRWI and IPR series (SITE4)

Source: compiled by the authors

To identify climate signals, input meteorological series data (maximum/minimum monthly average temperature; monthly precipitation totals) were standardised for each year of the reference period at each site. The annual values of climate signals allowed to identify anomalous years and determine the phase of the corresponding signals (Table 3).

Table 3. Anomalous years

SITE 1		SITE 2		SITE 3		SITE 4	
maximum surface air temperature							
*							
1999	1991	2010	1991	1999	1993	2007	1991
2002	1992	2012	1992	2010	1994	2010	1992

Table 3, Continued

SITE 1		SITE 2		SITE 3		SITE 4	
maximum surface air temperature							
2007	1993	2014	1993	2014	1996	2012	1993
2011	1996	2015	1996		1997	2013	1994
2013	1997	2016	1997		1998	2014	1996
2015	1998		1998				1997
2016	2000		2004				2004
			2006				2006
minimum surface air temperature							
1999	1993	2007	1991	1992	1993	1995	1993
2001	1994	2008	1993	2010	1996	1999	1994
2007	1996	2010	1996		2000	2008	1996
2011	1997	2012	1997			2010	1997
2013	2000	2014	2000			2011	2003
2015	2004	2016	2004			2012	2004
	2005					2014	2005
	2006					2016	2009
annual precipitation amounts							
1997	2011	1998	1994	2002	1991	1995	1994
1998	2015	1999	1995	2005	2009	1997	1999
2010		2001	2000	2012	2015	2003	2000
2012		2007	2011	2013		2016	2017
2017		2012	2015				
		2013					
tree ring width							
2010	1996	1991	2002	2001	2003	1997	1999
2011	2000	1992	2003	2006	2009	2001	2000
2012	2001	1993	2004	2007	2010	2006	2002
2013	2002	1997	2016		2011	2014	2009
2014	2003	1998			2012		2012
2015	2004	2010			2015		

Note: * – signal decreases/increases relative to the climatic norm
Source: developed by the authors by analysis of primary of United Hydrometeorological Station Kyiv (n.d.)

Thus, only those years were identified for which the average annual maximum/minimum air temperature and/or annual precipitation in standardised values exceeded ±1, i.e. fell outside the interval . With regard to TRW, the procedure was somewhat more complicated, since the time series were first used to identify the exponential trend, after which the residuals were standardised (Fig. 6). The signal obtained in this way was represented as the tree ring width index (TRWI). Table 3 shows only those cases where TRWI > |1|. Since the probabilistic empirical distributions of the samples are satisfactorily described by the normal law, the Pearson consistency criterion was used to establish a statistical relationship between climate signals and TRWI (Table 4). Climatic and dendrological studies at the study sites allowed to identify climatic signals (ITMAX; ITMIN; IPR) for each year of the reference period (1991-2020) and establish a statistical relationship between them and TRWI, which turned out to be weak to moderate (Table 4). As expected, ITMAX and ITMIN are negatively correlated with TRWI at all sites, while IPR is positively correlated.

Table 4. Pairwise Pearson correlation between TRWI and climatic annual signal

Climatic annual signal	Correlations			
	SITE 1	SITE 2	SITE 3	SITE 4
IT_{MAX}	-0.33	-0.43	-0.45	-0.24
IT_{MIN}	-0.16	-0.31	-0.39	-0.29
IPR	+0.47	+0.35	+0.43	+0.37

Source: developed by the authors

A moderately weak correlation is likely related to noise in the useful signal. While annual precipitation totals, which have a long-term impact on tree growth, still make sense as an annual indicator, temperature indicators at a time interval (year) do not reflect the changing temperature regime during the growing season. As is known, the empirical distribution of annual temperature for a temperate continental climate is bimodal, i.e. the average annual temperature is not the mode of distribution. Thus, a climate history at the level of average monthly values for the years presented in Table 3 is needed to identify seasonal climate effects. Interpreting the response of forest growth to climate change requires an understanding of both the temporal and spatial patterns of seasonal climatic influences on growth, in particular for *Quercus robur L.*

Seasonal climate signals. During the reference period 1991-2020, correlations between annual climate signals and TRWI were found at all sites for each climate variable. The greatest influence on the growth of *Quercus robur L.* is exerted by precipitation ($r = 0.47$; $p < 0.05$) and maximum air temperature ($r = -0.45$; $p < 0.05$), which is consistent with other TRWI studies in temperate climates (Saleh *et al.* 2022). The vegetative activity of oaks begins at temperatures above 4° C, with the optimal temperature range for them varying between t = 15°C and 29°C; the best temperature regime for the active growth phase (t = 21°C-27°C), while dormancy begins at temperatures below t < 10°C. Therefore, seasonal climatology influences the onset and duration of the active vegetation phase. Obviously, the active vegetation of *Quercus robur L.* in a temperate climate occurs in the spring-summer season.

Seasonal climate signals, as noted earlier, represent standardised values of average monthly extreme temperatures and, accordingly, monthly precipitation totals. For SITE1 and SITE4, the study period covered almost a century (1931-2024). A warming trend was observed for all seasons (Fig. 7). In particular, during this period, the average monthly maximum temperature increased by t = 2.2°C, and the average monthly minimum/maximum temperature by t = 2.6°C. The behaviour of seasonal maximum temperature values in different reference periods varied, which complicates the identification of a useful signal.

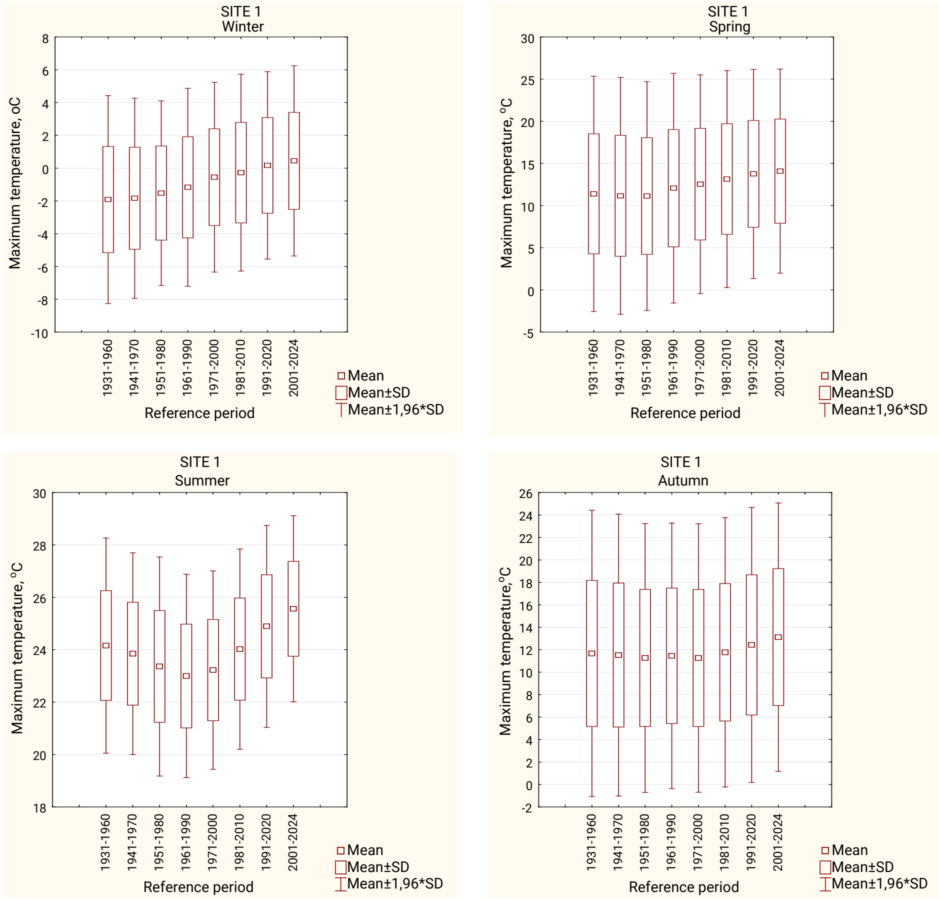


Figure 7. Average seasonal maximum temperatures for different reference periods (SITE 1)
Source: compiled by the authors

There is some ambiguity regarding precipitation. A comparison of seasonal precipitation totals for different reference periods showed: no trend in the winter-spring season; a noticeable negative trend in the summer season, with a 20% reduction in precipitation; a slight decrease in precipitation, about 7%, in the autumn season (Table 5).

Table 5. Seasonal anomalies of the precipitation regime (SITE 4)

Reference period	Climatic rate of monthly precipitation amounts, mm													
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Yr	VegPer.
1971-2000	30.7	29.0	33.5	46.8	49.5	90.0	100.9	65.9	58.5	34.7	43.9	39.0	622.4	386.6
1981-2010	29.3	31.8	36.5	40.4	53.7	82.3	94.0	60.8	56.3	40.6	41.7	35.8	603.2	367.7
1991-2020	31.4	34.0	41.0	38.4	61.2	70.4	82.4	53.4	47.6	42.0	39.9	38.0	579.7	346.8
2001-2024	36.8	36.7	43.3	40.7	59.6	65.1	76.8	49.5	43.5	46.9	38.7	40.8	578.4	335.0

Source: developed by the authors

If evaluate monthly precipitation amounts, there is a noticeable increase in precipitation: Feb (15%), Mar (23%), May (22%), Oct (21%); decrease in precipitation: Apr (18%), Jun (20%), Jul (18%), Aug (19%), Sep (26%), Nov (9%). Monthly precipitation totals in Dec and Jan remained stable. At the same time, the annual precipitation total has a steady downward trend at a rate of about 1 mm *yr $^{-1}$.

This study focuses on the latest reference period of 1991-2020, which, according to the recommendations of the World Meteorological Organisation (WMO, n.d.), is considered the new climate norm for the modern climate. Accordingly, seasonal and monthly climate signals are considered as relative variations with respect to the average values for the last thirty-year reference period. Monthly values of IT_{MAX}, IT_{MIN}, and IPR were determined at all sites, which made it possible to identify anomalous months and seasons that potentially affected tree ring width. Based on monthly precipitation totals, seasonal precipitation indices were formed for which correlation statistical relationships with TRWI were determined (Table 6).

Table 6. Correlation matrix TRWI-IPR SEASON

	IPR WIN	IPR SPR	IPR SUM	IPR AUT
SITE 1	**0.43**	0.12	**0.29**	-0.03
SITE 2	-0.08	**0.26**	**0.32**	-0.05
SITE 3	0.03	**0.28**	**0.26**	0.23
SITE 4	0.04	**0.39**	**0.42**	0.20

Source: developed by the authors

The statistical correlation between TRWI and seasonal climate signals IPR-SEASON (Table 6) was significantly lower at all sites than with annual climate signals, as precipitation can have a cumulative effect on growth. A comparison of the phases of climate signals was carried out separately for the spring, summer and spring-summer seasons. The expected result was a coincidence of the TRWI and IPR phases and a counterphase of TRWI and IT-MAX. However, there are a number of cases where the behaviour of TRWI and the seasonal climate signal is unclear (Table 7). For example, SITE 1: 1991 year. IPR SPR = 1.38; IPR SUM = 0.93; TRWI and 2016 year – IPR SPR = 1.17; IPR SUM = 0.81; TRWI ↑. The behaviour of climate indices is almost the same, but TRWI changes phase. Similarly, SITE 2: 2012 year. IPR SPR = 1.09; IPR SUM = 1.22; TRWI ↓. It was possible to partially explain cases where seasonal precipitation amounts increase and TRWI decreases by using information about IPR for the previous year. Since the temperature and humidity regime determines the effectiveness of the vegetation process, it is necessary to simultaneously use temperature climate signals (Table 7). The synergy of the two factors depends significantly on both the phase of the climatic signals and their seasonality.

$$TRW = 1.143 - 0.308 \cdot IT_{MAX}\, SPR + 0.218 \cdot IT^{2}_{MAX} - 0.010 \cdot IT^{4}_{MAX}. \quad (4)$$

Table 7. Spring-summer seasonal climate indices in years of anomalies TRWI

Seasonal standardised values of maximum and minimum air temperatures											
SITE 1			SITE 2			SITE 3			SITE 4		
YR/ Phase TRWI	*Climatic season*		YR/ Phase TRWI	*Climatic season*		YR/ Phase TRWI	*Climatic season*		YR/ Phase TRWI SPR	*Climatic season*	
	SPR	SUM		SPR	SUM		SPR	SUM		SUM	
1991 ↑	1.38	0.93	1991 ↑	1.03	1.16	2001 ↑	1.28	0.88	1997 ↑	1.61	1.15

Table 7, Continued

Seasonal standardised values of maximum and minimum air temperatures											
SITE 1			SITE 2			SITE 3			SITE 4		
YR/ Phase TRWI	Climatic season		YR/ Phase TRWI	Climatic season		YR/ Phase TRWI	Climatic season		YR/ Phase TRWI SPR	Climatic season	
	SPR	SUM		SPR	SUM		SPR	SUM		SUM	
1992 ↑	1.19	0.59	1993 ↑	0.75	1.37	2003 ↓	0.67	0.88	1999 ↓	0.70	0.62
1993 ↑	0.72	1.39	1994 ↑	1.16	1.37	2006 ↑	1.51	1.21	2000 ↓	1.00	0.46
1997 ↑	0.81	1.69	1997 ↑	0.78	1.65	2007 ↑	0.49	1.47	2001 ↑	1.12	0.97
1998 ↑	1.28	1.50	1998 ↑	1.27	1.19	2009 ↓	0.63	1.23	2002 ↓	0.70	0.99
2002 ↓	0.67	1.05	2000 ↓	1.10	0.50	2010 ↓	0.79	0.77	2009 ↓	1.02	0.69
2003 ↓	0.63	0.91	2003 ↓	0.44	0.81	2011 ↓	0.38	1.71	2012 ↓	0.64	0.87
2004 ↓	0.81	0.89	2004 ↓	0.72	1.12	2012 ↓	1.09	1.22	2014 ↑	0.86	1.40
2010 ↑	0.99	1.15	2015 ↓	0.85	0.37	2015 ↓	0.91	0.34	2016 ↓	0.80	0.42
2016 ↓	1.17	0.81	2016 ↓	1.10	0.52						
Seasonal precipitation standardised values											
SITE 1			SITE 2			SITE 3			SITE 4		
YR/ Phase TRWI	Climatic season		YR/ Phase TRWI	Climatic season		YR/ Phase TRWI	Climatic season		YR/ Phase TRWI SPR	Climatic season	
	SPR	SUM		SPR	SUM		SPR	SUM		SUM	
1991 ↑	1.38	0.93	1991 ↑	1.03	1.16	2001 ↑	1.28	0.88	1997 ↑	1.61	1.15
1992 ↑	1.19	0.59	1993 ↑	0.75	1.37	2003 ↓	0.67	0.88	1999 ↓	0.70	0.62
1993 ↑	0.72	1.39	1994 ↑	1.16	1.37	2006 ↑	1.51	1.21	2000 ↓	1.00	0.46
1997 ↑	0.81	1.69	1997 ↑	0.78	1.65	2007 ↑	0.49	1.47	2001 ↑	1.12	0.97
1998 ↑	1.28	1.50	1998 ↑	1.27	1.19	2009 ↓	0.63	1.23	2002 ↓	0.70	0.99
2002 ↓	0.67	1.05	2000 ↓	1.10	0.50	2010 ↓	0.79	0.77	2009 ↓	1.02	0.69
2003 ↓	0.63	0.91	2003 ↓	0.44	0.81	2011 ↓	0.38	1.71	2012 ↓	0.64	0.87
2004 ↓	0.81	0.89	2004 ↓	0.72	1.12	2012 ↓	1.09	1.22	2014 ↑	0.86	1.40
2010 ↑	0.99	1.15	2015 ↓	0.85	0.37	2015 ↓	0.91	0.34	2016 ↓	0.80	0.42
2016 ↓	1.17	0.81	2016 ↓	1.10	0.52						

Source: developed by the authors

Modelling. The annual change in ring width is a non-stationary process. If consider the early growth period (Fig. 8), the trend appears to be complex. The variability of climatic signals was found to be close to a stationary process, with a linear increasing temperature trend and a decreasing precipitation trend. Nevertheless, such processes can be described by nonlinear regression modelling, namely polynomial models, since the trend-cyclical component of the factors experiences several local extrema. The task of building a model can be significantly simplified if consider separate periods of tree evolution. In particular, as already noted, this study focuses on the period 1991-2020. Since the objects of the study were groups of trees in the age category of over 60 years, the specified period falls on the right wing of the ring width growth curve, which is satisfactorily approximated by an exponential downward law. As noted earlier (Table 4), the correlation between TRWI and the annual IT_{MAX} index at SITE 4 was weak (-0.29). However, when switching to the seasonal time interval, the correlation increased significantly, as it was possible to identify a useful signal (Table 6). The polynomial regression model of TRW by the influencing factor – the average maximum air temperature in the spring season IT_{MAX} SPR (4) – proved to be adequate with statistically significant regression coefficients (Table 8):

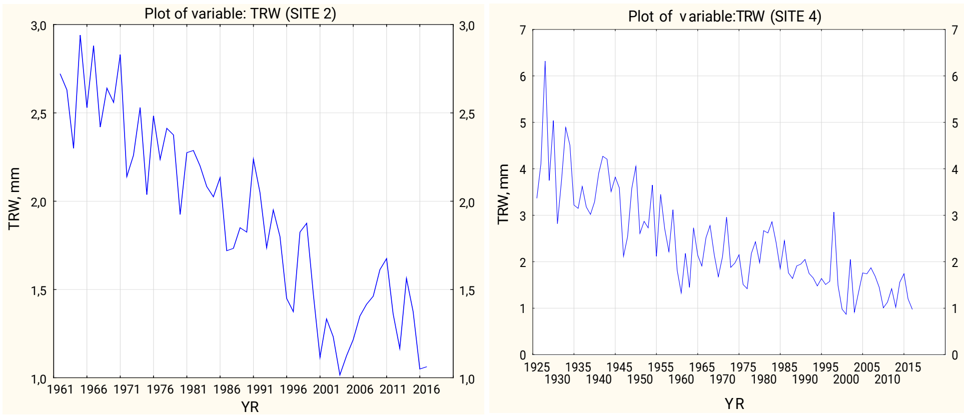


Figure 8. Dynamics of the width of the tree ring
Source: compiled by the authors

Table 8. Regression summary for dependent variable TRW. SITE 4

N = 35	TRW (SITE 4 IT_{MAX} SPRING. sta) R = 0.764; R2 = 0.585; F(3.31) = 6.932; p < 0.0002					
	b*	Std.Err. of b*	b	Std.Err. of b	t (31)	p-value
Intercept			1.142796	0.107829	14.30783	0.000000
IT_{MAX} SPR	-1.01692	0.242777	-0.308296	0.073602	-4.18869	0.000216
IT^2_{MAX} SPR	2.19228	0.621667	0.217752	0.061748	3.52646	0.001335
IT^4_{MAX} SPR	-2.45314	0.667909	-0.010039	0.002733	-3.67287	0.000899

Source: developed by the authors

The results of the analysis (Table 8) show that the multiple correlation between TRW and predictors is strong ($R > 0.75$); the model adequately describes the relationship between response and predictors, and the free term is statistically significant ($p < 0.0000$). Standardised regression coefficients (b*) allow to compare the contributions of each predictor to the prediction of the response. The predictor IT^4_{MAX} SPR has the greatest influence, which has a minus sign in the model, i.e. regardless of the phase of this signal, it is always negative, which ensures a downward trend. Model (4) adequately describes the variations in TRW in the studied interval, and the model curve practically repeats the behaviour of the original series (Fig. 9a).

To analyse the adequacy of the model, examined the residuals, which represent the difference between the actual TRW values and those predicted by the model. Visualisation of the residuals using a histogram shows (Fig. 9b) that the sample density of their distribution is successfully approximated by a normal distribution, which is a sign of the adequacy of the constructed TRW model. The graph of the residuals (Fig. 9c) allows to track their variation throughout the entire time series and ensure that there is no obvious trend. In a correctly selected model, the residuals should approach "white noise": they have no periodic fluctuations, systematic shifts, or strong correlations. The autocorrelation function graph (Fig. 9d) confirms that the residuals are practically 'white noise'.

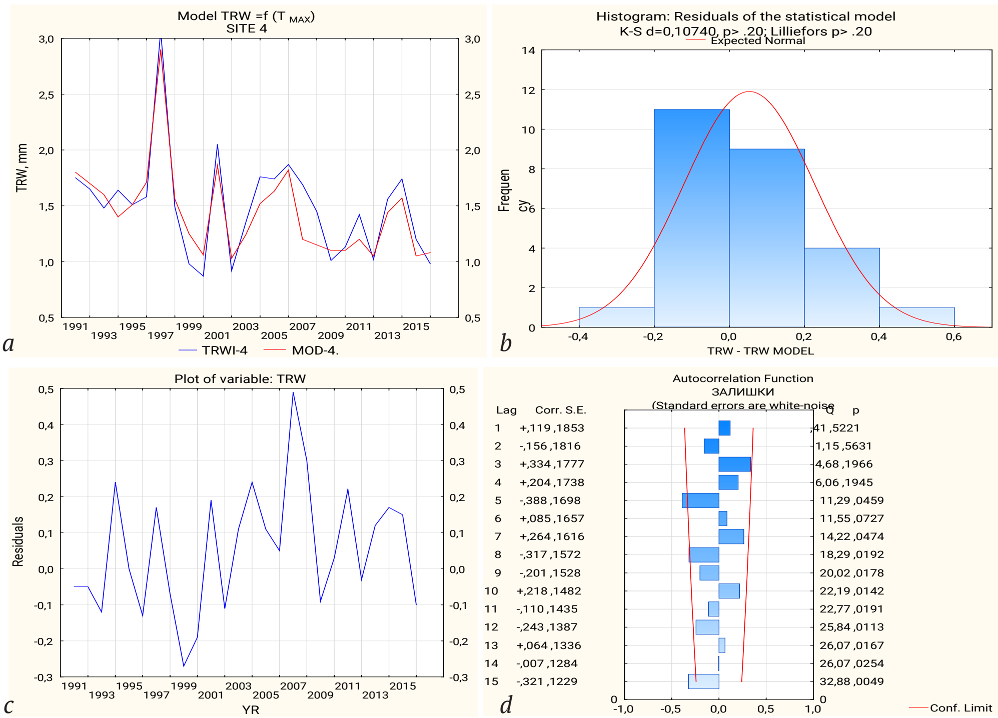


Figure 9. Polynomial model TRW – ITMAX SPR (SITE 4)

Note: a – TRW dynamics; b – empirical law of residual distribution; c – TRW residual dynamics; d – autocorrelation function of residuals

Source: compiled by the authors

It was not possible to develop an adequate polynomial model that would simultaneously combine temperature and humidity characteristics with TRWI, since anomalies in monthly precipitation totals and maximum temperatures were observed in different seasons of the year. However, it was possible to construct an adequate statistical regression model of TRWI-IPR YR. The correlation between the annual precipitation index (IPR YR) and the TRWI response was moderate (Table 4). The clear dependence between the studied series allowed to build an odd-order polynomial model to maintain the phase relationship between the indices. The results of the regression analysis (Table 9) show that the multiple correlation between TRWI and IPR YR is quite strong ($R = 088$); the model adequately describes the relationship between the response and predictors, and the free term is statistically significant ($p < 0.05$).

Table 9. Regression summary for dependent variable TRWI (SITE 2)

N=26	Regression Summary for Dependent Variable: TRWI-2 (SITE 2.sta) R = 0.88; R^2 = 0.78; F (3.22) = 25.65; p <, 00000 ; Std.Error of estimate: 0.50253					
	b*	**Std.Err. of b***	**b**	**Std.Err. of b**	**t(22)**	**p-value**
Intercept			0.048793	0.104385	0.46743	0.044788
IPR	1.71091	0.355526	1.644247	0.341675	4.81232	0.000083
IPR^3	-1.85763	0.867051	-0.806391	0.376384	-2.14247	0.043475
IP^{R5}	1.02733	0.612437	0.149594	0.089179	1.67745	0.107606

Source: developed by the authors

The adequacy of the model is confirmed by the F-test. It should be noted that the predictor IPR5 did not achieve statistical significance, as it did not satisfy the requirement $p < 0.05$. However, its removal from the model worsens the overall picture and adequacy of the model.

$$TRWI = 0.048 + 1.644 \cdot IPR\ YR - 0.806 \cdot \cdot IPR^3\ YR + 0.149 \cdot IPR^5\ YR. \quad (5)$$

Model (5) adequately describes the variations in TRWI in the studied interval (Fig. 10a), with the model curve practically repeating the behaviour of the original series. Analysis of the residuals (Fig. 10b) showed that they are close to 'white noise', i.e. they prove that the studied model is adequate.

The adaptation of forests to global climate change is a matter of debate. There is uncertainty as to whether climate change will increase or decrease forest growth and productivity. In particular, B. Bouslimi *et al.* (2022) and E.A. Boakye *et al.* (2023) argues that high temperatures can cause both an increase and a decrease in wood density, mainly due to their effect on tracheid lignification and cell wall thickening. The width of the rings correlated positively and significantly with the average temperature and annual precipitation, while the density of the rings correlated negatively and significantly with the average temperature and annual precipitation.

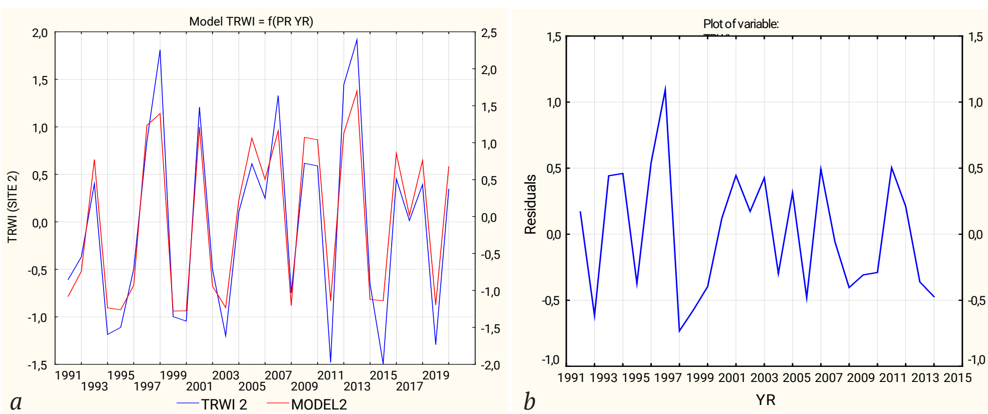


Figure 10. Polynomial model TRWI-IPR YR (SITE 2)
Note: a – TRW dynamics; b –TRW residual dynamics
Source: compiled by the authors

Given that the climate change scenario (IPCC 2022) is likely to be spatially heterogeneous on a regional scale, there is evidence that the response of *Quercus robur L.* to climatic conditions varies geographically, so determining the response of tree species to regional climate change is important for forest prediction and management. The problem with such studies, as noted by D. Perkins *et al*. (2018) and C. Leuschner *et al*. (2023), is that unfavourable climatic conditions are not the only cause of growth degradation, as there are other significant causes, such as soil fertility, groundwater, and competition among species. Therefore, identifying the climatic signal as a controlled predictor against a backdrop of a number of factors, both internal (species, origin, competitive status, age, size) and external (relief, slope, altitude, soil conditions, diversity of plantings, competition between plantings, mixing of species, etc.) is a major problem. It should be noted that the above factors are deterministic, their variability over time is insignificant and predictable, unlike climatic signals, which are stochastic in nature, especially precipitation patterns. The studies by D. Perkins *et al*. and C. Leuschner *et al*. use average annual climate indicators, which, although random, are too smoothed out as a result of averaging, primarily in relation to average annual temperatures. There is also uncertainty regarding annual precipitation totals associated with the cold period – solid precipitation. In current study, the use of climatic temperature signals such as average monthly maximum and minimum temperatures appeared to be much more sensitive seasonal predictors, especially in the spring-summer season.

The use of TRWI as a tree's response to external influences also contains uncertainty due to the construction of the index. Since evolutionary growth, in particular that of *Quercus robur L.*, is a non-stationary process in which a series of local extrema (Fig. 4a) are present against the backdrop of a global maximum (Fig. 3), the interpretation of useful information may depend on the algorithm used to construct the TRWI index. The contrasting seasonal precipitation patterns of Central Polissya did not manifest themselves in the growth responses of *Quercus robur L.*, which is able to withstand droughts thanks to its deep taproot system, which increases access to groundwater, unlike annual precipitation totals. This ensures the relatively high resistance of *Quercus robur L.* to prolonged dry spells in its natural range. The correlations between TRWI and average annual temperatures were, on the contrary, rather weak compared to the correlations at the seasonal level. At all study sites, a negative correlation was found between TRWI and maximum surface air temperature. As expected, the correlation with precipitation was positive, which is consistent with the results presented in studies by A.M. Petriţan *et al*. (2021), Ch. Sun *et al.* (2022), I.M. Koval & A. Bräuning (2024). Spatial-temporal variation in temperature and precipitation fields are the most important factors in regional climate change. Polynomial models constructed separately for temperature climate signals and precipitation appeared to be sufficiently simple and adequate, and their verification showed a decent match with the actual TRWI signal. With reliable climate forecast data, the models obtained can be used both to forecast TRWI and to look into the history of tree development with the relevant historical climate data for a given locality.

Climate warming may lead to a rapid decline in population growth, especially at the edge of the range, and, as a result, to a retreat in the distribution of species in central Ukraine. Therefore, the assessment of long-term growth trends at the edge of the range of *Quercus robur L.* deserves further attention. Significant progress has been made in understanding the factors affecting temperate forest zones. Despite this, researches by A. Gazol *et al.* (2018) and L. DeSoto *et al*. (2020) in this area has focused on the impact of both internal and external factors on the functional state of forests, adaptation methods and the overall carbon balance of forests. The issue of wood quality, against the backdrop of climate challenges, receives significantly less attention. G. Giroud *et al.* (2017) demonstrated that the overall density of wood and its modulus of elasticity increased with temperature and precipitation, regardless of species.

Wood density is a decisive factor in determining wood quality in temperate ecosystems. Climate variables play an important role in shaping wood density, creating challenges for forest managers and stakeholders in the wood processing industry in adapting to climate change. Understanding the impact of both climatic and non-climatic factors on wood density is essential for the development of a sustainable wood processing industry, while effectively minimising negative impacts and optimising economic aspects. Forest managers can use this knowledge to optimise timber production strategies, ensuring long-term environmental sustainability amid ever-changing climate challenges. Wood quality attributes related to wood characteristics are mainly determined by cambium activity (Zhang *et al*., 2020). Among the various attributes, wood density is crucial as it influences strength, durability and manufacturability.

Furthermore, wood density is closely related to its moisture content, which in turn influences its drying schedules. Thus, understanding the impact of climate change on wood density is also important for minimising any negative effects on wood quality, which is a key factor in the success of the woodworking industry.

Conclusions

The conducted study provides insight into the response of *Quercus robur L.* trees to changes in the current climate of the Polissya region of Ukraine. The results show that, given the predicted drier climate in temperate latitudes in the future, the condition of forest ecosystems will be more dependent on annual precipitation totals in both the current and previous years. The relatively high tolerance of oak trees to water shortages is confirmed by the fact that the *Quercus robur L.* trees studied did not show a significant decrease in growth in relatively dry years compared to the trend growth. The powerful root system of mature *Quercus robur L.* trees indicates their potential to cope with moisture deficits and allows them to withstand long periods of dry weather, as evidenced by their growth response. The response of young forests is another matter. Monthly precipitation totals show some stability during the winter season and a certain increase of up to 20% in the spring season; in summer and autumn, there is a noticeable decrease in precipitation, with the annual precipitation total showing a steady downward trend at a rate of about 1 $mm \cdot yr^{-1}$. Assessing the impact of temperature signals throughout the entire period of forest growth is challenging, as there is a steady trend towards higher maximum and minimum temperatures. The average ground-level air temperature has risen significantly since the 1980s at all study sites, by more than 2°C. Moreover, for all seasons, there has been a significant increase in the minimum temperature to 3°C, against a backdrop of relatively stable maximum temperatures, with the exception of the summer season. The climatic history of a forest is determined by its age. Thus, it is advisable to calculate climatic signals based on the age of the forest. Against the backdrop of climatic challenges, the biological development curve of *Quercus robur L.* trees is experiencing an extreme, so these influences may have different effects in the early and late stages of development. TRWI indices at all sites showed a noticeable correlation with seasonal climate signals, in particular with IPR SPR. For sites SITE2 and SITE4, the statistical relationship was strong (0.76-0.88). The transition from annual climate indicators to seasonal climate signals significantly strengthened the statistical relationship with TRWI, as it was possible to partially eliminate noise from the useful signal, which allowed for the construction of adequate statistical polynomial regressioSn models. There is an urgent need to study the response of young forests to climatic temperature challenges, which can be significantly affected even by minimal temperatures.

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Conflict of Interest

None.

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Дендрохронологічна оцінка кліматичних ризиків для відтворення дубових лісів в Українському Поліссі

Ростислав Олійник

Кандидат фізико-математичних наук, доцент
Київський національний університет імені Тараса Шевченка
01033, вул. Володимирська, 60, м. Київ, Україна
https://orcid.org/0000-0002-8675-7009

Роман Василишин

Доктор сільськогосподарських наук, професор
Національний університет біоресурсів і природокористування України
03041, вул. Героїв Оборони 15, м. Київ, Україна
https://orcid.org/0000-0002-7268-8911

Олена Пінчевська

Доктор технічних наук, професор
Національний університет біоресурсів і природокористування України
03041, вул. Героїв Оборони 15, м. Київ, Україна
https://orcid.org/0000-0001-8123-5490

Андрій Спірочкін

Кандидат технічних наук, доцент
Національний університет біоресурсів і природокористування України
03041, вул. Героїв Оборони 15, м. Київ, Україна
https://orcid.org/0000-0002-2647-3784

Анотація. Погіршення кліматичних умов, спричинене глобальним потеплінням, становить загрозу для сталого розвитку лісових екосистем, зокрема дубових насаджень, які є важливою складовою лісового господарства України. Мета дослідження — визначити особливості реакції росту дерев дуба черешчатого (*Quercus robur* L.) на тривалі кліматичні зміни, що призводять до посушливості в умовах Українського Полісся. Проаналізовані градієнти помірного клімату в локаціях зростання дерев *Quercus robur* L. в Україні, а саме кліматичні фактори (екстремальні температури, опади), що впливають на ріст та розвиток дерев в часовому масштабі місяць та сезон. Отримані результати надають важливу інформацію, щодо регіональних перспектив вирощування дубових насаджень на території України. Випадкові кліматичні фактори, які діють синергетично з системними, негативно впливають на ріст дерев, незалежно від особливостей системи управління лісами. Досліджено вплив кліматичних умов на радіальний приріст дерев *Quercus robur* L. в межах його природного ареалу. Особливу увагу приділено ситуаціям, коли аналізовані дерева утворювали кільця ширина яких виходила за межі інтервалу – середнє плюс-мінус середнє квадратичне відхилення ($\bar{R} \pm SD$). Розроблені хронології кліматичних сигналів, що охоплюють новий референтний період 1991-2020 рр. для досліджуваних локацій. Розраховані прості індекси екстремальних середньомісячних температур повітря та індекси місячних сум опадів. Проведений кліматичний аналіз років, в які спостерігалися аномалії росту дерев *Quercus robur* L., що ідентифікувалися індексом ширини кільця TRWI. Встановлено, що статистично значимий вплив на радіальний приріст мають річні суми опадів та максимальні температури повітря у весняно-літній сезон. Побудовані поліноміальні моделі дозволяють передбачити зміни в динаміці росту дерев *Quercus robur* L., для досліджуваного регіону

Ключові слова: зміна клімату; кліматичні сигнали; дендрохронологічний аналіз; ширина кільця дерева; індекс ширини кільця