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Impact of global climate change on the biological characteristics of tree species in forest ecosystems

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Abstract. The purpose of this study was to analyse physiological and morphological changes in the most common woody species of the forest ecosystem under the influence of climate change and to investigate the adaptive mechanisms that these species use to overcome stressful weather conditions. The study examined the impact of global climate change on the biological characteristics of Scots

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pine, northern red oak, and silver birch. In particular, the adaptive mechanisms of trees that allow them to survive and adapt to changing conditions were analysed. The influence of an increase in average temperature, changes in precipitation regimes, and extreme weather events on the growth, development, and reproduction of woody plants was considered. Field monitoring methods and laboratory experiments were used to collect data on physiological and morphological changes that occur with tree species groups under the influence of climatic pressure. The results of the study showed that global climate change can lead to significant changes in the species composition of forests, their productivity and overall environmental sustainability. The findings highlight the need for adaptive strategies for forest management and biodiversity conservation in the face of global climate change. The study also examined guidelines for practical actions aimed at mitigating the negative effects of climate change on forest ecosystems. The vulnerability of Ukrainian forests to climate change in the 21st century in comparison with the climate norm (1961-1990) was assessed. Recommendations for assessing the impact of climate change on forests, analysing phytodiversity and environmental regimes based on forest monitoring data in the context of regulatory legal acts of Ukraine, in particular, the state forest management strategy until 2035 and recommendations of the state forest cadastre of Ukraine are provided. The results of the study can be used to develop forest management strategies, implement adaptation measures in forestry, and to monitor the state of forest ecosystems and predict their resilience to climate change within the framework of national environmental programmes

Keywords: climate pressure; biodiversity; physiological changes; forest productivity; ecosystem monitoring; adaptation mechanism

Introduction

The urgency of climate change is extremely high at the global level, as it directly affects the state of natural ecosystems and their functions. Climate change, including rising average temperatures, changes in precipitation patterns, and the frequency and intensity of extreme weather events, significantly affect the biological characteristics of many ecosystems, particularly forest ecosystems, where tree species play a key role in maintaining biodiversity, regulating water balance, and influencing the carbon cycle.

In this context, the study of the impact of global climate change on the biological characteristics of tree species is of critical importance for ensuring ecosystem stability and sustainable development. In the context of globalisation and intensive use of natural resources, understanding the dynamics of ecosystem responses

to climate change is essential for developing effective adaptation strategies and management measures (Floqi *et al.*, 2009).

Scientific research in this area is of great importance not only for expanding theoretical knowledge, but also for practical solutions that can contribute to the preservation of the biogeocoenosis in changing climatic conditions. Research on the impact of climate factors on ecosystems is conducted in various scientific disciplines, such as ecology, botany, climatology, and agronomy.

I. Buksha *et al.* (2023) emphasised the importance of monitoring environmental changes, highlighting the development of adaptation strategies for tree species in the face of increasing climate stress. M.M. Radomska *et al.* (2022) investigated the relationship between climate

factors and plant biodiversity, noting that changes in temperature and humidity can significantly affect the structure and function of natural communities, in particular forest ecosystems, including protected ones, which leads to a decrease in species diversity. A.A. Miniaylo *et al.* (2014) focused on the analysis of the impact of climate change on forest ecosystems in Ukraine, the development of measures to reduce their negative impact, and adaptation of forest stands through improved resource management, selection of sustainable tree species, forest restoration, and economic assessment of the risks and opportunities arising from these changes. O. Furdychko *et al.* (2021) argued in their paper that climate is one of the most powerful environmental factors determining the evolution of the biosphere and the organic world.

Z.M. Budnik *et al.* (2023) investigated the impact of environmental factors on forest ecosystems in Ukraine to predict the amount of forest resources for forestry and woodworking industries. This allows for the development of measures to prevent climate change and adapt forests, which helps to assess the productivity and condition of forests in the medium and long term. These studies confirm the need for an urgent response in the natural resource management system.

Studies of the forest-steppe zone of Ukraine illustrate how different tree species adapt to specific regional conditions (Furdychko *et al.*, 2021). For example, Scots pine (*Pinus sylvestris* L.) it is the dominant species in the forests of Sumy Oblast due to its rapid growth and resistance to cold. Among the leading forest-forming regions is the silver birch (*Betula pendula* Roth.), while the northern red oak (*Quercus rubra* L.) is one of the most common non-native species.

Global climate changes can significantly affect the state of forest-forming species, which will lead to a decrease in the productivity of

forest ecosystems, and changes in species composition and adaptation mechanisms (Yanitskyi, 2024). Therefore, the analysis of these aspects is important for developing strategies for forest management and biodiversity conservation. The purpose of the study was to analyse physiological and morphological changes in the most common (autochthonous and allochthonous) tree species of the forest ecosystem under the influence of climate changes, to investigate the adaptive mechanisms that these species use to overcome stressful climatic conditions. The main objectives of this study were:

- ◆ to consider the main biological properties of tree species in forest ecosystems of Ukraine and their response to environmental changes, in particular in a changing climate;
- ◆ to assess possible changes in the species composition, productivity and sustainability of forest ecosystems in Ukraine in the coming years in the context of global warming;
- ◆ to analyse existing forest management strategies, identify their gaps, and propose effective solutions to improve the viability of forest ecosystems.

Materials and Methods

In this paper, a comprehensive methodology involving both field and laboratory studies was used to analyse the relationship between climate change and adaptive responses of tree species. Key woodlands on the territory of forest-steppe Ukraine were selected as the research area, in particular, in Poltava, Sumy, and part of Chernihiv oblasts, where the main tree species to be studied (Scots pine, northern red oak, and silver birch) were represented. In general, the study covered the period 2021-2023 and the spring, summer, and autumn seasons. The final generalisation of the data was carried out based on the results of research in 2023.

During field monitoring, systematic monitoring of tree species during the growing

season was carried out, in particular, calculating the height, trunk diameter, and general health of plants. Phenological observations were carried out aimed at studying the timing of flowering, vegetation, and leaf fall. A laser rangefinder (Leica LRF 1600, Switzerland) was used to measure the height of trees. Alternatively, telescopic altimeters were used to manually measure the height of trees, which allows for obtaining height data at different levels. A caliper (Mitutoyo CD-6'CS, Japan) and a specialised diameter (Forestry Suppliers tree Diameter Tape, USA) were used to accurately measure the trunk diameter at breast height. Soil humidity and temperature sensors were used to assess environmental conditions that affect plant health. Field monitoring was carried out during the spring and summer seasons, when plants were actively growing.

Laboratory tests were also a significant part of the study. Samples of the leaves and bark of tree species were selected for further analysis for physiological characteristics such as chlorophyll content, photosynthetic activity levels, and resistance to mechanical damage. Leaf samples were processed in a laboratory to determine the chlorophyll content using a spectrophotometer (Thermo Scientific NanoDrop 2000, USA), which helped to obtain accurate data on the concentration of chlorophyll A and B in leaf tissue. The chlorophyll fluorescence method was used to analyse the level of photosynthetic activity, which included measuring the parameters of photosynthetic activity and quantum yields of photosynthetic reactions.

For the analysis of climate data, meteorological data obtained from local weather stations were used to assess changes in temperature, precipitation, and the frequency of extreme weather conditions between 1990 and 2024. Statistical methods have been applied to process and analyse the collected data, including correlation analysis, importance of

variables, and multivariate analysis, to determine the relationship between climate factors and the biological characteristics of trees. Due to the analysis of variance (AOVA), the growth rates of trees at different temperatures and humidity levels were compared to determine the optimal conditions for their development. The Fischer criterion (F-test) helped to determine whether the difference in tree growth is significant under the influence of different climatic conditions. The Mann-Whitney U-test was used to study the effect of different precipitation levels on the survival of tree species in extreme droughts.

To calculate biological indicators, the authors used instructions on methods of biological and agrochemical studies of plants and soils. Chlorophyll fluorometry was used to measure the efficiency of photosynthetic processes in the most common woody species of forest ecosystems in the Poltava, Sumy, and Chernihiv oblasts – Scots pine (*Pinus sylvestris*), northern red oak (*Quercus rubra*), and silver birch (*Betula pendula*). The study was conducted in the summer and autumn periods to assess the resistance of these species to climate change, in particular, rising temperatures and changes in humidity. The study was conducted using a portable PAM-2500 (Pulse Amplitude Modulation) fluorimeter, which allows measuring the rate of induced chlorophyll fluorescence and evaluating the functioning of photosystem II (FSII). The main parameters that were measured were:

1. F_v/F_m – maximum possible quantum output ratio of FSII photochemistry in the dark.
2. $Y(II)$ – actual quantum yield of FSII during light adaptation.
3. NPQ – non-photochemical quenching, showing the level of plant protective responses to stress.

The key equation for calculating the quantum yield of photosystem II was (1):

$$Y (II) = \frac{F_m - F_s}{F_m}, \quad (1)$$

where F_m – maximum fluorescence under light adaptation; F_s – fluorescence in a stationary state.

As part of a study on the impact of climate change on Scots pine (*Pinus sylvestris*), northern red oak (*Quercus rubra*, and silver birch (*Betula pendula*) were air temperature and humidity monitoring throughout the growing season. These indicators were crucial for assessing stressful conditions affecting the physiological state of plants and for predicting future changes in forest ecosystems. Monitoring was carried out using two types of devices. HOBO U23 Pro v2 – air temperature and humidity recorder that allows obtaining accurate data in real time. TFA Dostmann manual thermohygrometer was used for periodic checks and verification of the received data. Monitoring was carried out for six months from April to September, when environmental conditions most significantly affect the vegetation processes of tree species. Significant fluctuations in air temperature and humidity were recorded. To assess the effect of temperature and humidity on plant physiological processes, the plant moisture availability index (MAI) was used, which was calculated using the equation (2):

$$MAI = \frac{P}{T}, \quad (2)$$

where P – average humidity for the period; T – average temperature for the period.

To calculate the biomass of trees, an equation was used that considers the parameters of height and diameter at breast height (DBH) (3):

$$M = a \times DBH^b, \quad (3)$$

where M – plant biomass (in kg); DBH – trunk diameter at breast height (usually at a height of 1.3 m from the ground, in cm); a and b – species-specific constants that were selected depending on the type of tree or region. All the

information received was collected, systematised, and analysed to form generalisations that can provide recommendations for forest management in the context of global climate change and biodiversity conservation.

The analysis of international and national legislation was carried out using the comparative legal method by contrasting international agreements, such as Convention on International Trade in Endangered Species of Wild Fauna and Flora (1973), Convention on Biological Diversity (1992), United Nations Framework Convention on Climate Change (1992) and Fourth National Climate Assessment (2018), with national legislation in the field of forest protection, in particular the Law of Ukraine No. 1264-XII “On Environmental Protection” (1991) and the Forest Code of Ukraine (1994). This helped to identify the effectiveness of legal regulation in various jurisdictions and assess the compliance of national norms with international standards in the context of forest resource protection and sustainable management.

In the course of conducting this study, all the ethical standards specified in the above-mentioned legislative acts were observed. All research practices related to the collection of data on vegetation and trees were carried out in accordance with the principles of sustainable use of natural resources and protection of biodiversity. This ensures a responsible attitude to the environment and supports the ecological sustainability of forest ecosystems.

Results

Studies of adaptive mechanisms and physiological and morphological changes in woody species such as Scots pine, northern red oak, and silver birch under the influence of climate change reflect diverse responses to stressful conditions. The study, which concerned changes in the intensity of photosynthesis in tree species under the influence of climate change,

was conducted during the spring and summer seasons. It is this period that is critical for the growth and active development of trees, since then photosynthetic activity is the highest, and the response of plants to stress factors (rising temperature, falling humidity) can be most noticeable (Stojko, 2011). For Scots pine: the intensity of photosynthesis decreased by 15-20% with an increase in temperature by 2-3°C. Northern red oak showed a smaller decrease in photosynthesis (by 10-12%), as its leaves have better resistance to overheating. Silver birch was more vulnerable, losing up to 25% of its photosynthetic activity at similar temperature increases. The above-mentioned studies of photosynthetic intensity were conducted in

the forests of Poltava (Table 1), Sumy (Table 2), and Chernihiv (Table 3) oblasts, in particular, in oak-pine forests and oak-broad-leaved forest communities. The forests of this region, located on the border of the forest-steppe zone of Ukraine, are characterised by a significant variety of tree species, which provides favourable conditions for studying the impact of climate change on photosynthetic processes and adaptive mechanisms. Due to the diverse types of forest in the Poltava Oblast, the results of these studies allow assessing how different environmental conditions affect the physiological responses of tree species under the influence of stressful climate factors caused by climate change.

Table 1. Indicators of photosynthetic intensity of the main tree species of the Poltava Oblast

Plant type	Temperature rise	Spring period (change in photosynthetic intensity)	Summer period (change in photosynthetic intensity)
Scots pine	+1°C	-12%	-15%
Scots pine	+2-3°C	-15%	-20%
Northern red oak	+1°C	-8%	-10%
Northern red oak	+2-3°C	-10%	-12%
Silver birch	+1°C	-15%	-20%

Source: compiled by the authors

Table 2. Indicators of photosynthetic intensity of the main tree species of the Sumy Oblast

Plant type	Temperature rise	Spring period (change in photosynthetic intensity)	Summer period (change in photosynthetic intensity)
Scots pine	+1°C	-11%	-19%
Scots pine	+2-3°C	-15%	-24%
Northern red oak	+1°C	-7%	-10%
Northern red oak	+2-3°C	-9%	-14%
Silver birch	+1°C	-13%	-22%

Source: compiled by the authors

Table 3. Indicators of photosynthetic intensity of the main tree species of the Chernihiv Oblast

Plant type	Temperature rise	Spring period (change in photosynthetic intensity)	Summer period (change in photosynthetic intensity)
Scots pine	+1°C	-9%	-17%
Scots pine	+2-3°C	-12%	-20%
Northern red oak	+1°C	-5%	-8%
Northern red oak	+2-3°C	-7%	-10%
Silver birch	+1°C	-10%	-28%

Source: compiled by the authors

Scots pine in Sumy and Chernihiv oblasts also experienced a decrease in photosynthetic activity in the summer, which indicates its sensitivity to temperature increases. Despite this, it showed certain adaptive mechanisms that allowed it to partially compensate for the decline in photosynthesis. Northern red oak has demonstrated good resistance to temperature changes due to its powerful root system and ability to effectively regulate the water balance, which reduces the negative impact of high temperatures. Compared to other species, silver birch was the most vulnerable to climate change, especially during the summer heat, which led to a significant decrease in the intensity of photosynthesis. These results highlight how different tree species respond to rising temperatures in different areas of the forest-steppe zone, which can serve as a basis for further research and development of adaptation strategies (Shvydenko *et al.*, 2014; Oliynyk & Viter, 2021).

In comparison with the climate norm of 1961-1990, the forecast for 2029-2034 for the intensity of photosynthesis in the most common tree species in Ukraine indicates significant changes in physiological processes caused by climate change, in particular, global warming (Climate Change 2021..., 2021). According to the climatic norm, average annual temperatures were significantly lower, which limited the growing season. In the warming conditions, the growing season is expected to lengthen, especially in comparison with the norm, which will contribute to an increase in photosynthesis in the transition seasons (spring and autumn). For example, in 1961-1990, the photosynthetic activity of pine trees decreased with the onset of autumn cold weather, and now this process lasts longer due to the later arrival of cold weather (Moroz, 2024). The climatic norm assumed a more even distribution of precipitation, which maintained a stable water balance of plants. Current forecasts show that

summer periods of drought, which were previously less common, will increase significantly. This will lead to a decrease in photosynthesis in species that are sensitive to water scarcity, such as silver birch, which showed a more stable level of photosynthesis under normal climatic conditions (Shevchenko *et al.*, 2014). The increased concentration of carbon dioxide in the atmosphere, which has increased in the last decade, will contribute to increased photosynthesis in species such as northern red oak in the initial stages of adaptation. However, if current global warming trends continue, this positive effect will be offset by other stressors (Ivanova *et al.*, 2021). According to the norms of 1961-1990, the species demonstrated a stable habitat. Now, due to rising temperatures, ranges are predicted to shift to the north, which will have consequences for photosynthesis and overall forest productivity. For example, Scots pine may begin to disappear from the southern regions of Ukraine, which was not observed during the climatic norm. Thus, compared to the period 1961-1990, global warming and climate change caused both positive and negative changes in the intensity of photosynthesis.

Tables 4-6 show the average values of key indicators of the level of protective reactions of tree species that were studied as part of the experiment. These indicators include: the maximum quantum efficiency coefficient of photosystem II, which allows assessing the level of stress in plants; the quantum yield of photosystem II, which shows the efficiency of photosynthetic processes; and the photoprotection indicator, which characterises the ability of plants to dissipate excess light energy to avoid damage. Based on the results of measuring the efficiency of photosynthetic processes in the most common tree species, the following average values were obtained for different tree species.

Table 4. Average values of indicators that reflect the level of protective reactions of trees in the forests of the Poltava Oblast

Tree type	Fv/Fm	Y(II)	NPQ
Scots pine	0.78	0.35	2.1
Northern red oak	0.81	0.4	1.9
Silver birch	0.75	0.32	2.4

Source: compiled by the authors

Table 5. Average values of indicators that reflect the level of protective reactions of trees in the forests of the Sumy Oblast

Tree type	Fv/Fm	Y(II)	NPQ
Scots pine	0.76	0.34	2.2
Northern red oak	0.8	0.42	2
Silver birch	0.73	0.3	2.5

Source: compiled by the authors

Table 6. Average values of indicators that reflect the level of protective reactions of trees in the forests of the Chernihiv Oblast

Tree type	Fv/Fm	Y(II)	NPQ
Scots pine	0.77	0.36	2.3
Northern red oak	0.82	0.43	1.8
Silver birch	0.72	0.28	2.6

Source: compiled by the authors

Scots pine in the forests of the Poltava Oblast showed an average Fv/Fm value of 0.78, which indicates minor photochemical disturbances, but an increased NPQ value (2.1) indicates activation of protective mechanisms in response to stressful conditions, in particular drought. Northern red oak showed the highest values of Fv/Fm (0.81) and Y(II) (0.4), which indicates a more efficient photosynthetic apparatus, but a lower level of NPQ (1.9), which may mean less stress resistance compared to pine. Silver birch showed the highest level of NPQ (2.4), indicating an increased stress response to exposure to high temperatures and low humidity, which are characteristic of climate change.

In the Sumy Oblast, Scots pine showed an average Fv/Fm value of 0.76, which indicates minor photochemical disturbances, but an increased NPQ value (2.2) indicates activation

of protective mechanisms under stress, in particular, drought. Northern red oak in the Sumy Oblast showed higher indicators of Y(II) (0.42), suggesting more efficient operation of the photosynthetic apparatus, but with NPQ (2), which indicates moderate stress resistance compared to pine. Silver birch shows the highest level of NPQ (2.5), which indicates an increased stress response to exposure to high temperatures and low humidity.

In the Chernihiv Oblast, Scots pine also showed satisfactory Fv/Fm values (0.77), with NPQ (2.3) indicating its ability to adapt to stressful conditions. Northern red oak in the Chernihiv Oblast showed the highest values of Fv/Fm (0.82) and Y(II) (0.43), which indicates a high efficiency of photosynthesis, but with a lower NPQ (1.8), which may indicate lower stress resistance. Silver birch in the Chernihiv

Oblast also has a high level of NPQ (2.6), indicating strong stress reactions.

The quantum yield FSII under normal conditions should be approximately 0.83, but due to climate change, slightly reduced values for all species were observed, which indicates the influence of stressors (Murchie & Lawson, 2013). Based on these trends, photochemical efficiency indicators are expected to decrease further in all the studied species in the period 2029-2034, if climatic conditions (rising temperatures and decreasing precipitation) remain at the same level. This can lead to a gradual decrease in the overall productivity

of these forests and, consequently, their ability to recover sustainably.

Monitoring climate conditions such as temperature and humidity was an important part of the study to assess stressors affecting the condition of trees and their biological properties (Lindsey & Dahlman, 2020). Based on the data obtained, significant fluctuations in temperature and humidity were recorded during this time, which allowed assessing stressful conditions for forest ecosystems. The average values of temperature and humidity at different stages of the growing season were as follows (Figs. 1 and 2).

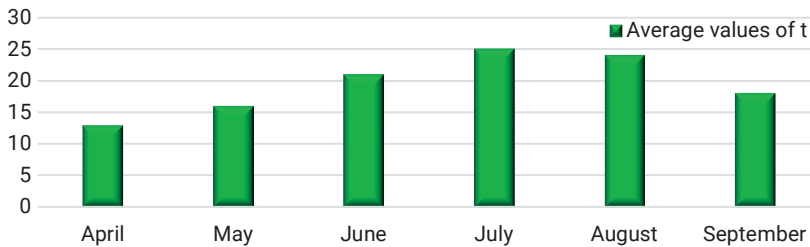


Figure 1. Average temperature values for the study months in three regions

Source: compiled by the authors

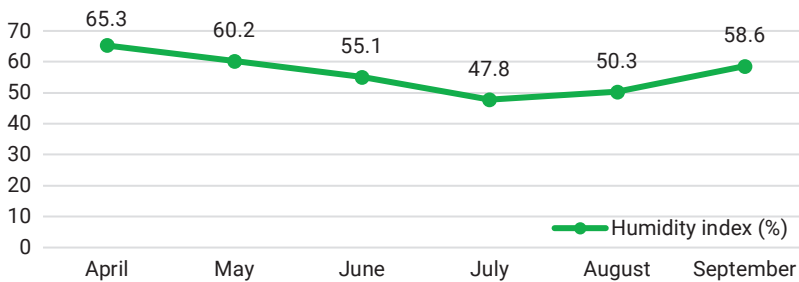


Figure 2. Average air humidity values by study month in the three regions

Source: compiled by the authors

These data are summarised based on the results of studies conducted in the Poltava, Sumy, and Chernihiv regions, which reflects general trends in the impact of climate changes on the physiological processes

of tree species in the forest-steppe zone of Ukraine. The MAI score helped assess stress levels for plants at different stages of the growing season. For example, in June in the Poltava Oblast:

$$\text{MAI June} = \frac{55.1}{20.8} = 2.65,$$

$$\text{MAI July} = \frac{47.8}{25.3} = 1.89.$$

Sumy Oblast:

$$\text{MAI June} = \frac{53.2}{19.5} = 2.73,$$

$$\text{MAI July} = \frac{45}{24.5} = 1.84.$$

Chernihiv Oblast:

$$\text{MAI June} = \frac{54}{21} = 2.57,$$

$$\text{MAI July} = \frac{46.5}{23.8} = 1.95.$$

The low index in July indicated a critical level of water stress for pine and birch trees. The forecast for 2029-2034 shows a possible increase in temperature by another 1-2°C, which will lead to a further decrease in humidity, especially in July-August. This can cause severe water stress in tree species and a decrease in their viability. An increase in the frequency of droughts

is a possible scenario, which is especially dangerous for silver birch and northern red oak.

It was important to analyse the growth rate of plants and their biomass indicators during the study. Scots pine has reduced its leaf area by 10% in drought conditions. Northern red oak lost up to 8% of the leaf area, but adapted faster to the changes. In silver birch, the leaf area decreased by 15%, which was also accompanied by a decrease in the amount of chlorophyll. Scots pine showed a 5-7% decrease in annual growth under stressful climatic conditions. Northern red oak reduced its growth rate by 4-6%, but due to its deep root system, it retained its productivity. Silver birch experienced the greatest decline – by 10-12%, especially in drought conditions.

Evaluation of the morphological characteristics of trees showed that pine trees have a thickening of the bark tissue by 10-15%, which increases resistance to drought. Northern red oak increased wood density by 5-7% in response to stress (Table 7). Silver birch exhibited less adaptive plasticity, showing a change only in the number of shoots formed (a decrease of 20%).

Table 7. Morphological characteristics of the main tree species in comparison with the climatic norm of 1961-1990, average values for three areas of research

Tree type	Parameter	Norm (1961-1990)	Current state	Deviation, %
Scots pine	Height of young trees (m/year)	0.6	0.55	-8.33
	Height of adult trees (m/year)	0.4	0.35	-12.5
	Diameter of young trees (cm/year)	1	0.9	-10
	Diameter of adult trees (cm/year)	0.6	0.55	-8.33
	Biomass of young trees (t/ha)	2.7	2.7	0
	Biomass of adult trees (t/ha)	4	4	0
	Needle length (cm)	7.5	6.9	-8
	Number of small roots (%)	10	12	+20
Northern red oak	Height of young trees (m/year)	0.5	0.45	-10
	Height of adult trees (m/year)	0.3	0.25	-16.67
	Diameter of young trees (cm/year)	0.8	0.7	-12.5
	Diameter of adult trees (cm/year)	0.5	0.4	-20
	Biomass of young trees (t/ha)	3.2	3.2	0
	Biomass of adult trees (t/ha)	5	5	0
	Leaf area (cm ²)	100	115	+15
	Root system depth (m)	2	2.36	+18

Table 7, Continued

Tree type	Parameter	Norm (1961-1990)	Current state	Deviation, %
Silver birch	Height of young trees (m/year)	0.7	0.65	-7.14
	Height of adult trees (m/year)	0.45	0.4	-11.11
	Diameter of young trees (cm/year)	1.2	1.1	-8.33
	Diameter of adult trees (cm/year)	0.8	0.7	-12.5
	Biomass of young trees (t/ha)	3.8	3.8	0
	Biomass of adult trees (t/ha)	4.5	4.5	0
	Leaf thickness (mm)	1.5	1.35	-10
	Main root length (m)	1.5	1.32	-12

Source: developed by the authors based on O. Shevchenko & S. Snizhko (2019), and V.O. Balabukh (2013)

Tree biomass calculation indicators show the amount of organic mass accumulated in the wood, root system, leaves, and other parts of the plant. They are important for assessing the ecological role of forests, the ability of trees to accumulate carbon, and regulate the carbon cycle. For example, if for Scots pine the value of the constants $a = 0.05$ and $b = 2.5$, and the

diameter of the tree at chest height is 25 cm, the equation will look like this:

$$M = 0.05 \times 25^{2.5} \approx 49.67 \text{ kg.}$$

These calculations are important for estimating carbon stocks in forest ecosystems and studying environmental changes under the influence of climate (Fig. 3).

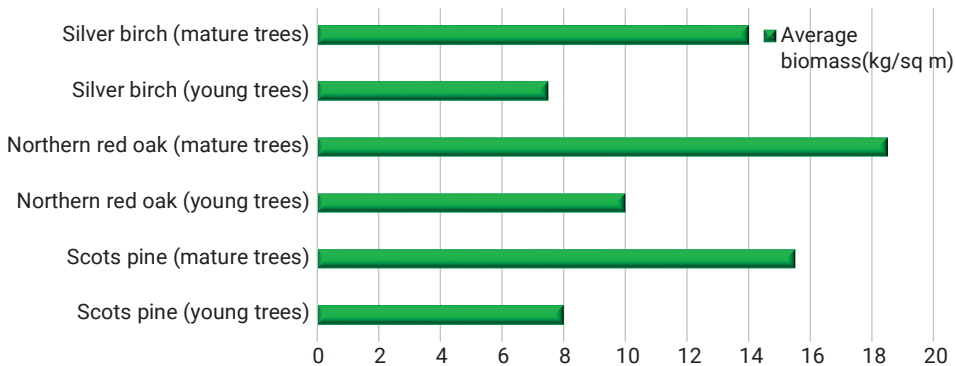


Figure 3. Indicators of biomass of tree species, average values for three study areas

Source: compiled by the authors

The data obtained in the study allow analysing and determining the main adaptive mechanisms of tree species of the forest ecosystem under study, which are important for their survival and function in the context of climate change. Scots pine adapts to dry conditions by reducing the leaf surface area (needles), which helps to reduce water evaporation. Needles often become thinner and have a smaller

surface area. Pine has a deep root system that allows it to extract water from the lower layers of the soil during droughts. During the cold season, pine has the ability to synthesise anti-freeze substances (for example, sugars), which protects cells from damage from low temperatures. Pine can recover from forest fires due to cones that open only at high temperatures, and sowing seeds in places cleared of burning

materials. Northern red oak has the ability to adapt to changes in moisture due to its powerful and widely branched root system, which allows it to get water from different layers of the soil. Oak leaves can change their shape and size depending on environmental conditions. Under stressful conditions, the leaves may become smaller, which reduces water evaporation. Oaks have a long life cycle and can recover slowly, which helps them withstand prolonged climate change and environmental stresses. Oaks have a high ability to accumulate energy reserves in their roots and trunks, which allows them to withstand periods of stress. Silver birch has a high growth rate and the ability to quickly recover from damage, which allows it to successfully compete for resources in the face of rapid changes. Birch can grow in a variety of soil types, including poor and acidic soils, due to its symbiotic relationship with root fungi, which help it absorb the necessary elements. Trees of this species have phytochemicals that repel many pests and pathogens, which helps it to maintain its health even in conditions of environmental stress. Birch leaves can adapt to changes in light and moisture conditions, for example, by changing their shape and size to optimise photosynthetic activity.

All of these species have common adaptive mechanisms, such as changing the shape, size, and thickness of leaves, needles, or roots, storing energy as spare substances for use under stressful conditions, and being able to recover quickly from environmental stresses such as droughts or floods (Resolution of the..., 1995; Miniaylo *et al.*, 2014).

These adaptation methods allow tree species to maintain their viability and functionality in changing climates, ensuring their resilience and longevity in forest ecosystems. The results of field work and experimental studies clearly demonstrate significant changes in the biological characteristics of tree species in the

context of global climate change. Observations of growth rates, productivity, and morphological changes in Scots pine, northern red oak, and silver birch indicate clear deviations from the climatic norm of 1961-1990. Studies have clearly shown that existing climate changes have a significant impact on the biological characteristics of tree species in forest ecosystems. Observations of growth rates, productivity, and morphological changes confirm the need for urgent search and development of new forest management strategies. Given the identified trends, the task of creating adaptive management approaches that will ensure the effective conservation and sustainable use of forest resources in the context of global climate change is extremely urgent.

The state forest management strategy until 2035 in Ukraine can play a key role in ensuring the adaptation of forest ecosystems to global climate change (Order of the..., 2021). The strategy includes risk assessment for different forest zones, which will identify the most vulnerable regions, development of recommendations for changing reforestation and forestry practices that consider new climatic conditions, in particular, changes in the species composition of forests, development of programmes for the conservation of biodiversity, including for the support of rare and threatened species. The introduction of monitoring systems to track changes in biodiversity and conservation effectiveness is part of the strategy (Convention on International..., 1973; Solomakha *et al.*, 2020).

Forests play a key role in combating climate change and promoting sustainable development because of their ability to absorb carbon, maintain biodiversity, and ensure the sustainable use of natural resources. Their conservation and restoration are important for regulating global climate processes, as forests act as huge reservoirs for carbon, absorbing up to 30% of greenhouse gas emissions caused

by human activities (Hartmane *et al.*, 2024). Through photosynthesis, trees absorb carbon dioxide (CO₂) from the atmosphere, fixing it in its biomass, including trunks, roots and leaves. Conservation of existing forests and restoration of felled areas contribute to reducing CO₂ concentrations in the atmosphere, which is crucial for mitigating the effects of global warming. Young trees absorb carbon faster during active growth, and older forests store significant amounts of carbon in the soil and wood (Tykhonova *et al.*, 2024). Thus, the restoration of forest stands and sustainable management of existing forests allow both the capture of new carbon and the storage of previously accumulated carbon in soil systems. According to research, plantation forests have the potential to absorb carbon quickly, but it is older woodlands that contribute most to long-term carbon storage. This means that a strategy to combat climate change should combine both planting new trees and preserving old ecosystems that are carbon “warehouses”. In the long run, forest conservation can help to stabilise the climate by balancing the carbon cycle and reducing greenhouse effects (Didukh *et al.*, 2024).

The use of forest resources in a circular economy makes them a key element of sustainable development. The circular economy involves the rational use of resources, waste reduction and maximising the efficiency of renewable natural resources such as wood. Forests are becoming important suppliers of biomass that can be used for the production of bioenergy, building materials, and even for the production of biodegradable materials that replace plastics. Forest-based bioeconomics promotes economic growth while reducing dependence on fossil energy sources (Mishenin & Oliynyk, 2010; Shtuk, 2022). Wood and other forest products are renewable resources that can be reused and recycled. For example, wood waste can be recycled to create biofuels or

compost, which reduces carbon emissions and promotes cyclical use of resources. Forests also play an important role in supporting ecosystem services such as water conservation, preventing soil erosion, and providing habitat for many plant and animal species. The integration of forest resources into the circular economy allows not only to ensure the sustainable use of natural resources, but also to preserve ecosystem functions that are vital for ecological balance (Kirchherr *et al.*, 2017). However, the use of forests in bioeconomics requires a balanced approach, since excessive or uncontrolled use of wood can lead to ecosystem degradation. Modern technologies, such as remote sensing and geoinformation systems, contribute to more accurate monitoring of the state of forests, helping to identify negative trends in forest stands and implement timely measures for restoration and protection.

Discussion

The study of the impact of global climate change on the biological characteristics of tree species in forest ecosystems is of great importance not only for science, but also for practical aspects of forest management. The findings highlight important trends that may have long-term implications for biodiversity, ecosystem functioning, and climate change adaptation strategies. The study of the biological characteristics of trees has shown that an increase in temperature and changes in humidity regimes have a noticeable effect on the growth and productivity of tree species. For example, species that have adaptive mechanisms, such as increased root systems or reduced foliage, have been found to have a better chance of surviving in a changing climate.

The study, in particular, demonstrated that these adaptations not only contribute to the survival of individual species, but can also affect the overall structure of forest communities.

The data obtained can also serve as a basis for formulating evidence-based recommendations for managing forest resources in the face of climate change. This is consistent with the study by I. Buksha *et al.* (2023), who noted that some tree species show particular sensitivity to climate change, while others can adapt to new conditions. Such observations highlight the importance of monitoring tree species and their adaptation strategies. Experiments have shown that changes in temperature significantly affect photosynthetic processes in tree species, which, in turn, leads to changes in the structure of forests. Our results support this trend, as it was found that an increase in the average annual temperature leads to an increase in the intensity of photosynthesis in some species, such as Scots pine.

The Fourth National Climate Assessment (2018), as part of the US Climate Change study, highlighted the importance of adaptive strategies for maintaining ecosystem sustainability. The assessment focuses on the urgency of taking measures to minimise the effects of global warming. The analysis is consistent with the provisions of this report, as it also examines the impact of climate change on forest ecosystems and biodiversity, in particular, on the adaptation strategies of tree species in response to rising temperatures and changing humidity regimes. This study is part of an overall trend aimed at predicting and minimising the negative effects of climate change.

United Nations Framework Convention on Climate Change (1992) is an important international agreement aimed at reducing greenhouse gas emissions and stabilising the climate. It emphasises the need for adaptive measures to prevent the negative effects of climate change, including the conservation of natural ecosystems. The analysis of environmental processes carried out within the framework of this project is consistent with the goals of the convention,

focusing on the study of the impact of climate change on forest ecosystems and the development of strategies for adapting tree species to changing environmental conditions. However, the results of this study also show that not all species respond equally to climate change. For example, in conditions of reduced humidity, a decrease in productivity was observed in silver birch, which may be conditioned by its high sensitivity to water deficiency. This is an important aspect, as it indicates potential risks for specific species that may be displaced by more resilient competitors in a changing climate.

The adaptive mechanisms of tree species in response to climate change are also worth analysing. As indicated by O. Shevchenko (2017) and Z.M. Budnik *et al.* (2023), some species are capable of changing morphological characteristics to ensure their survival. This includes changes in leaf size, shape, and depth of the root system. For example, in the present study, Scots pine showed a marked increase in the root system, which may indicate its ability to adapt to conditions of limited water supply.

V.S. Oliynyk & R.M. Viter (2021) focused on studying the impact of climate change on ecological processes in forest ecosystems. The researchers considered how rising temperatures and changing humidity patterns can affect the growth, productivity, and resilience of tree species. They also focused on the adaptive mechanisms that different species use to survive under stress, in particular, the study of morphological changes in root systems and leaf mass. The current study provides new data on specific morphological changes in Scots pine under elevated temperature conditions, such as a marked increase in the root system, indicating the adaptive mechanisms of this plant. Thus, the results of this study complement the conclusions of the above researchers, expanding the understanding of the adaptive responses of tree species at the local level.

Yu. Shtuk (2022) analysed climate change in Ukrainian cities, considering their impact on urban infrastructure and ecosystems, with a focus on forecasts for the end of the 21st century based on representative concentration pathways (RCP) scenarios. The researcher noted that changes in temperature and reduced water resources can seriously affect urban living conditions. The current study also includes forecasts of the impact of climate change on the biological characteristics of tree species in forest ecosystems. Although the above study focused on an urban context, this project offers predictions about how global climate change might affect specific plant species, highlighting the importance of analysing not only urban but also natural ecosystems in the face of climate change. This analogy demonstrates the need for an integrated approach to studying the impact of climate change on various aspects of the environment.

The results are important for understanding the impact of global climate change on tree species. Adaptive mechanisms such as root system changes and photosynthetic activity have been found to contribute to the survival of certain species under stress. This can affect the biodiversity and functioning of forest ecosystems. Knowledge of these adaptations is important for developing forest management strategies that will help to maintain ecological balance and maintain ecosystem resilience in the face of climate change. The conducted research opens up a number of areas for further study. Firstly, it is important to conduct long-term monitoring of tree species to better understand how climate change affects their growth and adaptation mechanisms. In particular, it will be of interest to study how different types of soils and landscapes affect the adaptation of species to changing conditions. Secondly, it is promising to study the impact of climate change on interactions between different species in forest

ecosystems. This will help to understand how changes in one species can affect other species and the ecosystem as a whole.

The adaptive mechanisms of tree species in the context of climate change should continue to be studied to develop effective forest management strategies. This includes integrating research results into natural resource management policies, which are critical to ensuring the sustainable development of forest ecosystems. The results indicate the need to develop new forest management models that consider the specific adaptive mechanisms of tree species. Understanding how climate change affects morphological and functional characteristics can serve as a basis for shaping environmental policy. This knowledge is important not only for the scientific community, but also for practical management decisions. In particular, it is worth focusing on preserving biodiversity and maintaining ecosystem stability. In light of the findings, further research should focus on the long-term effects of climate change that may affect the future of forest ecosystems.

Conclusions

The study, conducted to analyse physiological and morphological changes in Scots pine, northern red oak, and silver birch under the influence of climate change, revealed significant adaptive mechanisms that these species use to overcome stressful conditions. In particular, it was found that an increase in average temperature and changes in precipitation regimes negatively affect the growth and development of these trees. Findings show that when the temperature increased by +1°C, the intensity of photosynthesis in Scots pine decreased by 12-15% in the Poltava Oblast, while in the Sumy and Chernihiv Oblasts the drop reached 11-19% and 9-17%, respectively. The greatest losses of photosynthetic activity were recorded in the summer, when the temperature increased by

2-3°C, especially vulnerable was the silver birch, which showed a decrease in the intensity of photosynthesis up to 28% in the Chernihiv Oblast.

Analysis of the level of protective reactions of tree species confirmed the presence of various adaptive mechanisms. For example, the average NPQ values for Scots pine in the Poltava Oblast reached 2.1, which indicates the activation of photoprotective mechanisms under stress. In Sumy and Chernihiv oblasts, NPQs for pine trees were higher (2.2 and 2.3, respectively), which indicates an increased response to stressful conditions. Northern red oak showed more stable FV/Fm and Y(II) scores, indicating better adaptation to climate change in all regions.

According to MAI calculations, in June in the Poltava Oblast, this figure was 2.65, and in July it decreased to 1.89, which indicates a critical level of water stress for pine and birch. Sumy Oblast showed similar trends: MAI in June was 2.73, and in July – 1.84. Chernihiv Oblast had the highest MAI in June (2.57) and the lowest level in July (1.95), which indicates the influence of high temperatures on the water supply of plants.

The data obtained indicate possible changes in the species composition of Ukrainian forests, which may lead to a decrease in their productivity and overall ecological sustainability.

The identified adaptations include changes in the morphology of leaves and root systems, which allows plants to optimise water and nutrient supply under stress. Important recommendations for further research are the development of methods for monitoring the impact of climate change on forest ecosystems, which may include analysis of phytodiversity and environmental regimes. This will better assess the vulnerability of forests to climate change and provide more effective conservation strategies.

The conditions of this study are that it was conducted for a limited period, which may not reflect long-term trends in changes in vegetation and their adaptation to climate. The results may be specific to the regions under study and cannot be directly generalised to other climatic or geographical areas. Consideration of these aspects in subsequent research will help to better understand the processes of adaptation of forest species to climate change and identify more effective approaches for their conservation in the face of global warming.

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Conflict of Interest

None.

References

- [1] Balabukh, V.O. (2013). *Current and expected climate change, its impacts and consequences on the territory of Ukraine, Transcarpathia and Rakhiv district*. Retrieved from https://ucn.org.ua/wp-content/uploads/2013/07/resume_climatechange_ukr.pdf.
- [2] Budnik, Z.M., Hrytsiuk, V.V., Kondratiuk, N.V., Pysarenko, V.O., & Tsipan, Yu.R. (2023). Influence of climate factors on the forest ecosystems of the Rivne region. *Bulletin National University of Water and Environmental Engineering*, 2(102), 45-60. doi: 10.31713/vs220232.
- [3] Buksha, I., Pyvovar, T., Bondaruk, M., Pasternak, V., & Krakovska, S. (2023). Vulnerability assessment of Ukrainian forests as the basis of nature-based solutions for mitigation and adaptation to climate change. *Proceedings of the Forestry Academy of Sciences of Ukraine*, 25, 138-145. doi: 10.15421/412311.
- [4] Climate Change 2021: The Physical Science Basis. (2021). Retrieved from <https://www.ipcc.ch/report/ar6/wg1>.

- [5] Convention on Biological Diversity. (1992). Retrieved from <https://www.cbd.int/doc/legal/cbd-en.pdf>.
- [6] Convention on International Trade in Endangered Species of Wild Fauna and Flora. (1973). Retrieved from <https://cites.org/eng/disc/text.php>.
- [7] Didukh, Y.P., Sokolenko, U.M., Rasevych, V.V., & Gavrilov, S.O. (2024). *Methodology for calculating environmental damage to natural ecosystems and their components*. Lviv, Kyiv: M.G. Kholodny Institute of Botany of the National Academy of Sciences of Ukraine.
- [8] Floqi, T., Shumka, S., Malollari, I., Vezi, D., & Shabani, L. (2009). *Environment and sustainable development of the Prespa park*. *Journal of Environmental Protection and Ecology*, 10(1), 163-175.
- [9] Forest Code of Ukraine. (1994). Retrieved from <https://zakon.rada.gov.ua/laws/show/3852-12>.
- [10] Fourth National Climate Assessment. (2018). Retrieved from <https://nca2018.globalchange.gov>.
- [11] Furdychko, O., Tymochko, I., & Solomakha, I. (2021). Ecological and functional features of forest plantations of the Forest-steppe of Ukraine. *Balanced Nature Using*, 4, 30-39. doi: 10.33730/2310-4678.4.2021.253081.
- [12] Hartmane, I., Biyashev, B., Getman, A.P., Yaroshenko, O.M., & Anisimova, H.V. (2024). Impacts of war on Ukrainian nature. *International Journal of Environmental Studies*, 81(1), 455-462. doi: 10.1080/00207233.2024.2314856.
- [13] Ivanova, I., Serdiuk, M., Malkina, V., Bandura, I., Kovalenko, I., Tymoshchuk, T., Tonkha, O., Tsyz, O., Mushtruk, M., & Omelian, A. (2021). The study of soluble solids content accumulation dynamics under the influence of weather factors in the fruits of cherries. *Potravinarstvo Slovak Journal of Food Sciences*, 15, 350-359. doi: 10.5219/1554.
- [14] Kirchherr, J., Reike, D., & Hekkert, M. (2017). Conceptualizing the circular economy: An analysis of 114 definitions. *Resources, Conservation and Recycling*, 127, 221-232. doi: 10.1016/j.resconrec.2017.09.005.
- [15] Law of Ukraine No. 1264-XII "On Environmental Protection". (1991, June). Retrieved from <https://zakon.rada.gov.ua/laws/show/1264-12>.
- [16] Lindsey, R., & Dahlman, L. (2020) *Climate change: Global temperature*. Retrieved from <https://www.climate.gov/news-features/understanding-climate/climate-change-global-temperature>.
- [17] Miniaylo, A.A., Miniaylo, N.V., & Chayka, V.M. (2014). Main environmental factors identification of disappearance of biota species in Ukraine. *Scientific Reports of the National University of Life and Environmental Sciences of Ukraine*, 85(3). doi: 10.31548/dopovidi2020.03.004.
- [18] Mishenin, Y.Y., & Oliynyk, N.V. (2010). *Development of the market of ecosystem services as a direction of post-crisis growth of the Ukrainian economy*. *Mechanism of Economic Regulation*, 3(3), 104-116.
- [19] Moroz, V. (2024). Bioproductivity of pine forests in Polissia. *Scientific Reports of the National University of Life and Environmental Sciences of Ukraine*, 20(5), 120-134. doi: 10.31548/dopovidi/5.2024.120.
- [20] Murchie, E.H., & Lawson, T. (2013). Chlorophyll fluorescence analysis: A guide to good practice and understanding some new applications. *Journal of Experimental Botany*, 64(13), 3983-3998. doi: 10.1093/jxb/ert208.

- [21] Oliynyk, V.S., & Viter, R.M. (2021). *Forestry science*. Ivano-Frankivsk: Symphony forte.
- [22] Order of the Cabinet of Ministers of Ukraine No. 1777-r “On Approval of the State Forest Management Strategy of Ukraine until 2035”. (2021, December). Retrieved from <https://zakon.rada.gov.ua/laws/show/1777-2021-%D1%80>.
- [23] Radomska, M.M., Huz, V.V., & Yarokhmedova, I.V. (2022). Vulnerability and adaptation of protected areas to climate changes: Case study of National Natural Parks in Ukraine. *Scientific Bulletin of UNFU*, 32(6), 38-44. doi: 10.36930/40320606.
- [24] Resolution of the Cabinet of Ministers of Ukraine No. 555 “On Approval of Sanitary Rules in the Forests of Ukraine”. (1995, July). Retrieved from <https://zakon.rada.gov.ua/laws/show/555-95-%D0%BF#Text>.
- [25] Shevchenko, O. (2017). Causes of global climate change. *Modern Historical and Political Issues*, (35-36), 269-282. doi: 10.31861/mhpi2017.35-36.269-282.
- [26] Shevchenko, O., & Snizhko, S. (2019). Climate change and Ukrainian cities: Manifestations and projections on 21st century based on RCP-scenarios. *Bulletin of Taras Shevchenko National University of Kyiv, Geography*, 75(2), 11-18. doi: 10.17721/1728-2721.2019.75.2.
- [27] Shevchenko, O., Vlasiuk, O., Stavchuk, I., Vakoliuk, M., Ilyash, O., & Rozhkova, A. (2014). *Climate change vulnerability assessment: Ukraine*. Kyiv: Myflaer.
- [28] Shtuk, Yu. (2022). Formation and development of the ecosystem services market in Ukraine. *Economic Space*, 180, 159-162. doi: 10.32782/2224-6282/180-26.
- [29] Shvydenko, A., Lakida, P., Shchepachenko, D., Vasylyshyn, R., & Marchuk, Y. (2014). *Carbon, climate and land management in Ukraine: The forest sector*. Korsun-Shevchenkivskiy: V.M. Gavrilenko.
- [30] Solomakha, I.V., Solomakha, V.A., Tymochko, I., & Chornobrov, O. (2020). *Ecological and economic functions of protective forest plantations in the provision of ecosystem services*. Kyiv: Institute of Agroecology and Nature Management.
- [31] Stojko, S. (2011). [Global climate changes impact on the forest ecosystems in the Carpathians](#). *Proceedings of the Forestry Academy of Sciences of Ukraine*, 9, 21-29.
- [32] Tykhonova, O., Marukha, T., Rybalko, P., Butenko, S., & Horbas, S. (2024). Ecological typology of woody vegetation of the Starohut forest massif as a component of the restoration of disturbed ecotopes. *Scientific Horizons*, 27(10), 124-135. doi: 10.48077/scihor10.2024.124.
- [33] United Nations Framework Convention on Climate Change. (1992). Retrieved from https://unfccc.int/files/essential_background/background_publications_htmlpdf/application/pdf/conveng.pdf.
- [34] Yanitskyi, V. (2024). Impact of climate change on forest ecosystems in Western Polissia. *Ecological Safety and Balanced Use of Resources*, 15(1), 100-110. doi: 10.69628/esbur/1.2024.100.

Вплив глобальних змін клімату на біологічні характеристики деревних видів у лісових екосистемах

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Анотація. Мета даного дослідження – аналіз фізіологічних і морфологічних змін у найпоширеніших деревних видів лісової екосистеми під впливом кліматичних змін, а також дослідження адаптаційних механізмів, які ці види використовують для подолання стресових погодних умов. У дослідженні розглядається вплив глобальних змін клімату на біологічні характеристики сосни звичайної, дуба червоного і берези повислої. Зокрема, аналізуються адаптаційні механізми дерев, які дозволяють їм виживати та пристосовуватись до умов, що змінюються. Вивчено вплив підвищення середньої температури, зміни режимів опадів та екстремальних погодних явищ на ріст, розвиток і розмноження деревних рослин. Використані методи польового моніторингу та лабораторні експерименти для збору даних про фізіологічні та морфологічні зміни, що відбуваються з видовими групами дерев під впливом кліматичного тиску. Результати дослідження показують, що глобальні зміни клімату можуть призвести до значних трансформацій у видовому складі лісів, їхньої продуктивності та загальної екологічної стійкості. Отримані дані підкреслюють необхідність адаптаційних стратегій для управління лісовими ресурсами та збереження біорізноманіття в умовах глобальних кліматичних змін. Дослідження також розглядає

інструкції для практичних дій, спрямованих на пом'якшення негативних наслідків зміни клімату на лісові екосистеми. Оцінено вразливості лісів України у зв'язку зі зміною клімату у XXI столітті порівняно із кліматичною нормою (1961-1990 рр.). Надані рекомендації щодо оцінювання впливу кліматичних змін на ліси, аналізу фіторізноманіття та екологічних режимів за даними моніторингу лісів у контексті нормативно-правових актів України, зокрема, Державної стратегії управління лісами до 2035 року та рекомендацій Державного лісового кадастру України. Результати дослідження можуть бути використані для розробки стратегій управління лісовими ресурсами, впровадження адаптаційних заходів у лісовому господарстві, а також для моніторингу стану лісових екосистем і прогнозування їхньої стійкості до кліматичних змін у рамках національних екологічних програм

Ключові слова: кліматичний тиск; біорізноманіття; фізіологічні зміни; продуктивність лісів; моніторинг екосистем; адаптаційні механізми