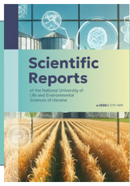
Received 29.10.2024 Revised 22.01.2025 Accepted 27.02.2025

Vol. 21, No. 1
2025



Scientific Reports of the National University of Life and Environmental Sciences of Ukraine

Journal homepage: https://scireports.com.ua/en

UDC 582.47

DOI: 10.31548/dopovidi/1.2025.76

The impact of climate change on the sanitary condition of pine forests in Polissia

Vira Moroz*
PhD in Agriculture, Associate Professor
West Ukrainian National University
46009, 11 Lvivska Str., Ternopil, Ukraine
https://orcid.org/0000-0002-1457-4641

Abstract. The study was aimed at identifying the key factors that affect the sanitary condition of pine forests in Polissia under climate change, as well as developing recommendations for their adaptation to new environmental challenges. For the analysis, 30 trial plots of 0.1 hectare each were laid out, where pine stands of different age classes were studied. The work recorded key climate trends: the average annual temperature increased by 1.2°C over the period 1968-2024, precipitation decreased by 25 millimetres, and the hydrothermal moisture coefficient decreased from 1.3 to 0.9, indicating drought. In regions with a moisture deficit, the proportion of dry-topped trees increased from 8% to 20%, and root sponge damage from 5% to 12%. Decreased soil moisture levels disrupted transpiration, limited photosynthesis and reduced wood growth by 18% compared to healthy trees. It was found that the number of pine sawfly and bark beetles increased by 67% and 150%, respectively, in dry conditions. The analysis showed that mechanical damage caused by strong winds creates conditions for the active spread of pests and diseases. The results obtained indicate that climate change has caused degradation of forest stands due to increased physiological stress of trees. To adapt, the authors propose the selection of resistant pine varieties, the introduction of irrigation systems, monitoring of forest conditions using geographic information technologies, and an increase in the area of forestry in favourable areas. These measures will help preserve forest ecosystems in the region in the face of climate change

Keywords: drought; hydrothermal coefficient; dryland; environmental factors; root sponge

Suggested Citation:
Moroz, V. (2025). The impact of climate change on the sanitary condition of pine forests in Polissia. *Scientific Reports of the National University of Life and Environmental Sciences of Ukraine*, 21(1), 76-89. doi: 10.31548/dopovidi/1.2025.76.

**Corresponding author*

Introduction

Climate change is one of the most pressing challenges of the modern world, affecting ecosystems on a global scale. Forests, in particular pine forests in Polissia, are under significant anthropogenic and climatic pressure, which manifests itself in the form of rising temperatures, decreasing precipitation, frequent extreme weather events and moisture deficit. These factors disrupt the sanitary condition of forests, causing trees to dry out and spread pests and diseases. Polissia's forests play an important ecological role, including maintaining biodiversity, regulating water regimes, and providing valuable resources such as timber. However, increasing physiological stress due to environmental degradation threatens their sustainability. Scientific approaches to assessing the impacts of climate change on forest ecosystems are critical to developing adaptation measures that can sustain these ecosystems in the long term.

The decrease in soil moisture is one of the most important factors that disrupts the water balance of trees and their physiological activity. V. Turko & V. Moroz (2023) noted that insufficient soil moisture leads to reduced transpiration of pine trees, which in turn affects photosynthetic activity and metabolic processes in wood. Their results also show that insufficient transpiration significantly affects the ability of trees to maintain water balance in dry conditions, but the study did not consider the long-term effects of these changes in the context of the Polissia climate.

Pests, such as pine beetle and bark beetles, are another significant factor contributing to the degradation of forest stands in drought conditions. V. Moroz & Y. Nykytiuk (2021) noted that under conditions of moisture deficit, the number of pine beetles can double, and the activity of bark beetles can increase by more than 150%. Their study showed that weakened trees become an easy target for these pests, which accelerates the drying out of trees. The authors also noted that the pests develop resistance to standard control measures under high temperatures, but their findings did not take into account the specific interaction between the pests and the mechanical damage to trees often caused by storms.

Mechanical damage caused by strong winds is an important additional factor in the degradation of forest stands. S.K. Ghosh *et al.* (2022) investigated the impact of storms on the structural integrity of pine trees and found that damaged trees become more vulnerable to bark beetles and root diseases such as sponge. According to them, strong winds contribute to the spread of pathogens through mechanical cracks in tree trunks. At the same time, the authors' study did not include a comprehensive analysis of the synergy between mechanical damage and drought, which is relevant for Polissia.

Root sponge is one of the most common diseases of pine trees, which significantly affects their viability. A. Buras *et al.* (2023) studied the impact of the disease on the physiological state of stands and found that affected trees reduce wood growth by 15-20%. In addition, they found that root sponge infection increases under conditions of prolonged periods of moisture deficit. However, their study focused mainly on the conditions in Central Europe, leaving aside the specific climate conditions of Polissya.

The physiological stress caused by water deficit is exacerbated by climatic factors such as rising temperatures. H. Dang *et al.* (2021) showed that with decreased soil moisture, transpiration decreases by 30%, which is accompanied by impaired photosynthesis and reduced biomass production. Their study confirmed the critical importance of water regime for maintaining the stability of forest stands, but did not take into account the long-term impact of climate change on the dynamics of these processes.

Among the physiological consequences of climate change, an increase in the level of oxidative stress is of particular importance. E.X. Ellis *et al.* (2024) proved that under conditions of chronic drought, oxidative stress becomes the main cause of tree cell damage. They found a 25-30% decrease in antioxidant protective activity, which makes trees more vulnerable to external stressors. However, their study did not consider the specifics of the impact of oxidative stress on pine forests in Polissia.

Geographic information systems (GIS) and other modern monitoring technologies are important tools for analysing changes in the sanitary condition of forests. M. Hartmann *et al.* (2023), A.K. Bose *et al.* (2022) emphasised the effectiveness of GIS in the early diagnosis of degradation processes, in particular tree drying. They also pointed out that these technologies allow for real-time assessment of pest risks, but their study was limited to lowland forests, making it difficult to adapt the results to the worse environmental conditions of Polissia.

The study aimed to assess key climate trends and their impact on the health status of pine forests in Polissia, as well as to develop practical measures to ensure the adaptation of these ecosystems to climate change.

The study identified the following objectives: to study the impact of climate change, such as increased temperature, decreased precipitation and reduced hydrothermal coefficient, on the health of pine forests; to analyse the dynamics of pests and tree diseases in arid conditions; to study physiological changes in trees, including transpiration activity, photosynthesis, and wood growth; and to develop practical recommendations for adapting Polissia forests to climate change.

Materials and Methods

The study was conducted in 2020-2024 in the Polissia region of Ukraine, in particular in the Zhytomyr and Kyiv regions. The objects of the study were pine forests (*Pinus sylvestris* L.) belonging to different age classes and growing in natural conditions of fresh subsoil. It was established 30 trial plots (15 plots in each oblast) of 0.1 ha each, covering areas with different levels of climate change impact, including altitude, soil types and microclimatic features. The geographical coordinates of the test plots were determined using a Garmin GPSMAP 64st (USA) and are located within 50°15′53″N 28°40′36″E (Zhytomyr region) and 50°27′00″N 30°31′00″E (Kyiv region).

To assess the sanitary condition of the stand, it was used the methodology of categorising trees by sanitary characteristics in accordance with Forest Stewardship Council (FSC) standards. The assessment was carried out by recording such signs as dryness, pest or disease damage, mechanical damage and other pathologies. A Nikon Forestry Pro II laser height meter (Japan) was used to determine the height of the trees, and the diameter at breast height was measured with a Haglöf Mantax Precision diameter tape (Sweden).

Climatic parameters, including mean annual air temperature, precipitation, and hydrothermal coefficient of humidification (HCH), were obtained from the Ukrainian Hydrometeorological Centre for the period 1968-2024. Temperature was measured in degrees Celsius (°C), and precipitation in millimetres (mm). The HCH was calculated using the Selyaninov formula (1), which takes into account the ratio of precipitation to the sum of active temperatures above 10°C during the growing season:

$$HCH = \frac{\sum P}{0{,}1 \times \sum t_{act>10}}, \quad (1)$$

where: ∑P – total precipitation per month, in mm; ∑t – the sum of the average daily temperature above 10°C. The dynamics of pests was studied using pheromone traps Csalomon (Hungary), which were placed in the test plots at a height of 1.5-2 m from the ground. The traps were collected every two weeks during the growing season. The detected pests were identified by morphological features using an Olympus SZ61 binocular microscope (Japan). For the study of phytodiseases, molecular diagnostics was carried out by polymerase chain reaction (PCR). DNA was extracted from the tissues of root sponge (*Heterobasidion annosum*) using a Qiagen DNeasy Plant Mini Kit (Germany), and amplification was performed on an Applied Biosystems 2720 thermocycler (USA). The data obtained were analysed using the CLC Genomics Workbench software.

Correlation analysis was performed to analyse the relationship between climate change and the sanitary condition of forest stands. The number of damaged trees affected by pests or diseases was compared with the average annual temperature, precipitation and HCH. Statistical calculations were performed using SPSS Statistics software (version 27, IBM, USA). Correlation analysis to assess the strength and direction of the relationship between variables included the method of determining the Pearson correlation coefficient (r). The significance of the correlation was tested at the level of $p < 0.05$.

To assess the impact of solar activity, it was used data on the Wolf number obtained from the international solar activity centre Solar Influences Data Centre (SIDC). These data were compared with the number of major pests by year. Histological studies of tree tissues were performed using a Leica RM2125 RTS microtome (Germany). Samples were fixed in 10% neutral formalin, dehydrated, embedded in paraffin and sections were made 5-7 μm thick. Haematoxylin and eosin staining allowed assessing pathological changes in the tissues.

Results

An analysis of the Polissia region's climate data for the period 1968-2024 shows significant changes in key climate indicators that are of great importance to the ecosystem, including the state of pine forests, which are the main forest-forming species in the region (Table 1). Over these 56 years, air temperature increased by an average of 1.2°C, reaching 8.6°C in 2018-2024. The largest changes were recorded in the summer, when temperatures not only exceeded long-term averages but also reached extreme values more often, which creates increased stress on forest ecosystems.

Table 1. *Climate indicators of the Polissia region (average values for decades)*

Indicator	1968-1977	1978-1987	1988-1997	1998-2007	2008-2017	2018-2024
Average annual temperature, °C	7.4	7.6	7.8	8.1	8.5	8.6
Average annual precipitation, mm	620	615	610	605	600	595
HCH	1.3	1.2	1.1	1.0	0.9	0.9

Source: processed by the author

The rise in temperature was accompanied by an uneven distribution of precipitation, which was another key change in climate conditions. Total annual precipitation decreased by only 25 mm, but this figure does not reflect a significant change in its seasonal distribution. The growing season, which is critical for the growth and development of trees, was characterised by a significant moisture deficit due to long periods without rain. This led to a decrease in soil moisture levels, which became particularly noticeable during periods of active pine growth. In winter, rising temperatures resulted in more frequent thaw episodes, which were accompanied by the formation of an ice crust that impedes normal gas exchange in the soil and can cause damage to root systems. In the spring, earlier snowmelt combined with a lack of uniform precipitation led to a deterioration in conditions for the initial phase of forest growth.

The HCH, which is a complex indicator that considers the relationship between precipitation and temperature, has shown a significant deterioration in recent decades. In the period 1968-1977, the average value of the HCH was 1.3, which characterises the conditions of excessive moisture favourable for the growth and development of pine forests. However, by 2018-2024, this figure dropped to 0.9, indicating that the region is transitioning to moderate drought conditions. This is an important signal of the deterioration of the hydrothermal balance in the Polissia region.

The decline in the HCH has serious environmental consequences, as moisture levels play a key role in the formation and maintenance of natural ecosystems. A decrease in moisture levels leads to a deficit of soil moisture, which negatively affects physiological processes in trees, including photosynthesis, transpiration, and biomass accumulation. In pine forests, this is manifested through reduced wood growth rates, decreased crown density, and increased vulnerability to stressors such as pests, diseases, and droughts.

The decline in HCH is a crucial factor affecting the stability of pine stands, especially in natural fresh-successional conditions. Under moisture deficit, there is a decrease in wood growth, which is confirmed by long-term field studies. In particular, the deterioration of the sanitary condition of forest stands in Zhytomyr region coincided with periods of abnormally high temperatures in 2010-2020. An additional negative factor that significantly affects the sanitary condition of pine forests is the increasing frequency of extreme weather events. Strong winds cause mechanical damage to trees, including dryness, branch breakage, and even partial uprooting of weakened trees. Such damage significantly reduces the trees' resistance to pests and pathogens. For example, mechanically damaged trees become a favourable environment for the spread of the root sponge (*Heterobasidion annosum*), which can infect neighbouring trees through the root system, creating foci of infection in forest stands.

This phenomenon is particularly noticeable in regions with low HCH, where climatic conditions make it difficult to regenerate damaged trees. In such areas, the share of trees with mechanical damage increased from 15% in 1980 to 35% in 2020 (Moroz & Nykytiuk, 2021). Reduced moisture availability, rising temperatures, and frequent weather anomalies create additional stress for trees, which reduces their defence potential, including their ability to secrete resin, which is a natural barrier to pests.

Affected areas of the forest become centres of active reproduction of the pine sawfly (*Neodiprion sertifer*) and other pests. The increase in the number of these insects in damaged forest stands reached 50-70% compared to healthy areas. A similar situation is observed with bark beetles, whose populations increase significantly in drought conditions and after mechanical damage. This leads to a chain reaction: mechanical damage increases the vulnerability of trees to pests, and the spread of pests contributes to further deterioration of the sanitary condition of forests. Such climate change has a significant impact on the forest ecosystems of Polissia, in particular on the ability of pine trees to adapt to new conditions. For example, prolonged periods of drought affect the depth of penetration of root systems, which reduces their ability to receive moisture and nutrients. At the same time, changes in the temperature regime led to a reduction in the period of active photosynthesis, which negatively affects the overall condition of the stand.

The sanitary condition of pine forests in Polissia clearly depends on climatic conditions, especially the level of moisture, which is determined by the HCH. In regions with sufficient moisture, where the HCH exceeds 1.0, the stands demonstrate a stable ecological condition with minimal signs of pathology. Such areas are characterised by a low incidence of dry tops and diseases such as root sponge (*Heterobasidion annosum*), indicating optimal conditions for tree growth and regeneration (Table 2).

Table 2. *Categorisation of the sanitary condition of pine trees depending on the HCH*

Indicator	HCH > 1.0	HCH = 1.0	HCH < 1.0
Share of dry-topped trees, %	8.0	14.5	20. 0
Root sponge infestation, %	5.0	8.0	12. 0
Total level of damage, %	13. 0	22.5	32. 0

Source: processed by the author

However, in arid zones, where the HCH drops below 1.0, there is a sharp deterioration in the sanitary condition of the stands. Reducing the level of available moisture creates conditions for physiological stress in trees, reducing their ability to withstand pathogens and pests. Out of 30 test plots, it was observed that the proportion of dry-top trees increases from 8% in regions with sufficient moisture to 20% in areas with moisture deficit. In addition, the prevalence of root sponge is increasing in arid areas: while it affects 5% of trees in humid conditions, this figure reaches 12% in arid areas.

These changes are largely due to a decrease in soil and atmospheric moisture, which disrupts the water balance of trees. The lack of moisture limits transpiration, weakens plant immunity and promotes the development of pathogens that actively use the weakened state of trees to reproduce. In particular, the root sponge becomes more aggressive in conditions of reduced soil moisture, which further complicates the situation.

The increase in the frequency of dry tree canopy in arid regions is a consequence of reduced moisture availability, which negatively affects the vital activity of trees, in particular photosynthesis. Moisture deficit causes a disturbance in the water balance, which causes needles to lose turgor and gradually die, leading to a decrease in the photosynthetic surface of the tree, which is critical for maintaining its physiological processes. Trees with significant damage to the upper tiers of the crowns, where photosynthetic activity is most intense, lose up to 18% of their growth compared to healthy trees. The reduction in growth is directly related to the restriction of the production of organic substances necessary for growth and tissue regeneration. This also reduces the ability of trees to adapt, as energy resources are spent on compensating for damage rather than strengthening the structure. In addition, damage to the upper tiers of crowns increases the impact of environmental stresses such as drought, as it reduces the ability of trees to transpire, which is important for maintaining temperature balance and protecting against overheating. Affected trees become more vulnerable to pathogens, which further reduces their viability and threatens the sustainability of the entire forest.

In addition, in regions with a moisture deficit, there is an increase in the number of trees affected by pests (Table 3). In particular, populations of pests such as the pine sawfly (*Diprion pini*) have been found to increase rapidly in dry years when air humidity drops to critical levels, in particular below 30%. This phenomenon is explained by the weakening of trees under the influence of stress caused by a lack of moisture. Trees experiencing a moisture deficit reduce the production of protective resinous substances, which makes them more vulnerable to pests. This dynamic is an additional factor that threatens the stability of forest ecosystems in arid regions.

Table 3. *The number of main pests and the frequency of disease attacks in pine forests*

Indicator	HCH > 1.0	HCH = 1.0	HCH < 1.0
Pine sawfly, individuals/100 trees	45	60	75
Bark beetles, individuals/100 trees	20	35	50
Root sponge damage, %	5	8	12
General level of damage, %	10	18	28

Source: processed by the author

The incidence of root sponge disease (*Heterobasidion annosum*) is also increasing significantly in regions with low HCH. This disease not only weakens the physiological state of trees, but also significantly reduces their mechanical stability, increasing the risk of falling during strong wind loads or storms. Affected trees demonstrate weakened connections between the tissues of the root system, which negatively affects their ability to withstand external influences.

An analysis of histological sections of wood showed that trees affected by root sponge have up to 30% more necrotic changes in the structure of the root system compared to healthy trees. This includes degeneration of the vascular system, reduced water and nutrient conductivity, and loss of structural integrity of the wood. These changes significantly limit the trees' ability to regenerate and contribute to their further degradation.

Physiological changes in pine stands caused by moisture deficit include a significant decrease in chlorophyll content in needles, which reaches 12% compared to trees with sufficient moisture. A decrease in chlorophyll content indicates a weakening of photosynthetic activity, as this pigment is responsible for absorbing light and generating energy for tree growth. In addition, moisture deficit leads to metabolic disorders, including the transport of nutrients and water in the vascular system of wood.

Weakening of photosynthetic activity is a key factor that causes a decrease in wood growth, stunted growth of young shoots and loss of trees' ability to adapt to external stressors. Studies also show that weakened trees are more likely to be targeted by pests such as bark beetles and pathogens, such as fungi of the genus *Heterobasidion*. This is due to a decrease in the production of protective resinous substances that normally inhibit the growth of pathogens and repel pests.

Pest and disease damage to pine forests is an important factor that significantly affects their sanitary condition, especially in the context of climate change. Increasing average annual temperatures and decreasing precipitation create ideal conditions for an increase in the number of pests such as pine sawfly (*Neodiprion sertifer*), bark beetles and other insects that can actively damage trees weakened by environmental stressors. The weakening of trees is caused by a lack of moisture, which significantly reduces their natural defences, including the ability to secrete resin, which is a barrier to pests.

Field studies confirm a significant dependence of pest activity on HCH. In regions with a HCH of less than 1.0, which are characterised by dry conditions, the number of pine beetle infestations reached 75 individuals per 100 trees. This is 67% more than in regions with a HCH of more than 1.0, where the number of pests was only 45. This trend can be explained not only by the weakness of trees due to lack of moisture, but also by the fact that dry conditions are favourable for pest reproduction, as they reduce the effectiveness of natural predators and entomophages that control pest populations. Bark beetles also show a clear correlation with soil and air moisture levels. In areas with low HCH, their numbers reached 50 individuals per 100 trees, which was 2.5 times higher than in regions with sufficient moisture, where the number of bark beetles was only 20. Such a significant increase in bark beetle populations in arid conditions indicates their ability to quickly adapt to climate change and attack trees whose defence mechanisms are significantly weakened.

The study of the impact of climate change and solar activity on pine forests confirmed the significant role of environmental factors in shaping their sanitary condition. A long-term increase in the average annual air temperature, accompanied by a decrease in precipitation, creates favourable conditions for the spread of pests and diseases. In particular, rising temperatures promote the development of pathogens such as the root sponge (*Heterobasidion annosum*), which is particularly active in trees in conditions of low soil moisture.

In addition to climate change, solar activity, as measured by the Wolfe number, has a significant impact on the spread of pests. The data show that an increase in the intensity of solar activity correlates with an increase in the number of pine sawfly (*Neodiprion sertifer*). In the years with the highest solar activity (2019-2021), the number of this pest increased by 15%. This phenomenon can be explained by the cumulative impact of solar radiation on environmental conditions, in particular on the microclimate in forests, which favours the development of pests.

Climate change has significantly affected the structure and condition of pine forests. In arid regions, there has been a marked decrease in tree density, which is associated with an increase in mortality due to moisture deficit. In areas with high intensity of solar activity, stem damage caused by increased stress from ultraviolet radiation was recorded more often. These changes indicate that traditional approaches to forest management may not be sufficient to maintain ecological balance in the face of new climate challenges (Levchenko & Gumeniuk, 2024). Adaptation of forest ecosystems requires the implementation of integrated forest management systems (Table 4). This includes the selection of resistant pine varieties that can better tolerate higher temperatures, moisture deficits and intense solar radiation. The use of biological methods of pest control, such as the introduction of entomophages, can significantly reduce the negative impact of pests on forest stands.

Table 4. *Recommendations for adapting pine forests to climate change*

Climatic conditions	Recommendations	Expected effect
Arid regions (HCH < 1.0)	Introduction of drip irrigation	Reducing stress from moisture deficit
Areas with high solar activity	Use of biological products against pests	Reducing the number of harmful insects
Regions with frequent diseases	Selection of varieties resistant to fungal diseases	Improved resistance to pathogens
Areas with variable precipitation	Mulching the soil to preserve moisture	Increased tree vitality

Source: developed by the author

Remote sensing and regular monitoring of forest conditions will allow for a prompt response to changes in the sanitary condition of plantations. The introduction of geographic information systems and the use of satellite data will help to identify damage at an early stage, which will prevent the spread of pests and diseases. It is also advisable to update the regulatory framework for forest management to take into account climate change, which will allow for more effective conservation of pine forests as a valuable natural resource.

In addition, it is recommended to increase the area under forestry in regions with medium humidity, such as the central part of Polissia. These areas are optimal for growing new forest stands due to favourable hydrothermal conditions that ensure stable tree growth. Expansion of forest areas in these regions will help compensate for the losses caused by degradation of plantations in arid zones and contribute to the preservation of ecosystem functions of forests.

These measures should be implemented in close cooperation with local communities, whose involvement will ensure better adaptation to the socio-economic conditions of the region. Educational campaigns aimed at raising environmental awareness and citizen participation in the planning and maintenance of new plantations will lay the groundwork for the long-term sustainability of these measures. It is also important to integrate these initiatives into local development programmes, which will optimise the use of resources and gain additional support at the national level.

Discussion

An analysis of climate change in the Polissia region over the past 56 years has shown a significant increase in the average annual air temperature by 1.2 °C, accompanied by significant changes in the seasonal distribution of precipitation. This research has confirmed that such changes affect the region's ecosystems, especially the state of pine forests. J. Li *et al.* (2023) noted that an increase in temperature in summer creates conditions for increased tree stress, which is consistent with the results obtained. According to L. Matallana-Ramirez *et al.* (2021), the impact of heat stress is exacerbated by long periods without rain. This is confirmed by the above analysis of changes in the hydrothermal coefficient.

Calculations of the hydrothermal coefficient showed a decrease from 1.3 to 0.9, indicating a transition to moderate drought conditions. This is a determining factor in the deterioration of the sanitary condition of pine stands. B. Sensuła & S. Wilczyński (2022) emphasised the critical role of soil moisture in maintaining tree viability, which correlates with the results of field studies. A. Acarer (2024) also confirmed that moisture deficit reduces transpiration and biomass accumulation, which is consistent with observations in areas with a low hydrothermal coefficient.

Extreme weather events, such as strong winds and droughts, have a significant impact on pine forests, contributing to mechanical damage to trees. The proportion of trees with mechanical damage has increased to 35% in arid regions. K. Mechergui *et al.* (2021) pointed to an increase in the vulnerability of damaged trees to pests and diseases, which is consistent with the results above, which showed an increase in the number of pine beetle in such conditions. Á. Enríquez-de-Salamanca (2024) emphasised the importance of sanitary measures to limit the spread of pests, which confirms the need for an integrated approach to forest management.

Climate change has also led to an increase in the number of bark beetles and the spread of root sponges, which significantly weaken trees. It was found that in arid regions, the proportion of trees affected by root sponge reached 12%, which correlates with the research of X. Ouyang *et al.* (2022), which indicate an increase in the aggressiveness of pathogens under conditions of moisture deficit. M. Mikalajūnas *et al.* (2021) also noted that root diseases increase the risk of tree fall during storms, which correlates with the observation in the Polissia region.

Physiological changes caused by climatic factors clearly demonstrate a significant impact on the state of pine forests in the Polissia region. This research has confirmed that a decrease in the chlorophyll content of needles is accompanied by impaired transpiration, which makes it difficult to maintain the water balance of trees. The decrease in photosynthetic activity has led to a reduction in wood growth to critical levels. The analysis of wood sections revealed up to 30% of necrotic changes in the structures of the root system, which reflects the accumulation of physiological stress in trees. These results coincide with the studies of N. Markos *et al.* (2023), which also indicated the impact of moisture deficit on root tissue damage. T. Dimitrijević *et al.* (2023) emphasised that in arid regions, reduced wood growth is a common consequence of climate change, which is consistent with the reductions in photosynthetic activity and reduced adaptive capacity of trees that it was found in current research.

Increasing pest populations, such as pine beetle and bark beetle, pose a serious threat to the sustainability of pine forests in the region. This current research has confirmed that the reduced production of protective resinous substances, which is typical for trees in drought conditions, greatly facilitates the spread of pests. This correlates with the findings of V. Loewe-Muñoz *et al.* (2024), who pointed out the crucial role of these substances in counteracting the invasion of insect pests. Additionally, the observations of the current study show that in regions with low SOC, natural predators that usually control pest populations lose their effectiveness due to moisture deficits. This is confirmed by the research of R.M. Navarro-Cerrillo *et al.* (2022), who focused on the impact of drought conditions on the ecological balance in forest ecosystems. Thus, it was found that the combination of weakening of the natural resistance of trees and a decrease in the activity of natural predators contributes to an uncontrolled increase in the number of pests, which negatively affects the sanitary condition of pine forests.

The sanitary condition of pine forests deteriorates significantly under the influence of extreme temperatures and reduced precipitation. The results of the study showed that in arid zones, the proportion of dry-topped trees increased to 20%. J. Stolz *et al.* (2021) highlighted that such changes reduce the photosynthetic activity and adaptive potential of trees, which correlates with the above data. J. Brichta *et al.* (2024) also pointed out the critical role of water balance in maintaining the sustainability of forest stands, which is confirmed by the results of the above studies.

The impact of solar activity on the sanitary condition of pine forests was significant and requires more detailed study. It was found that the number of pine sawfly increased by 15% during increased solar activity, which correlates with microclimate changes that promote the development of pests. These results confirm the findings of K. Bowman & X. Chen (2022), who emphasised the correlation between solar radiation intensity and the spread of insect pests. D. Karnosky *et al.* (2003) added that an increase in ultraviolet radiation affects the formation of a drier microclimate in forest stands, creating conditions for the activation of pests. The findings are consistent with the identified trends showing how changes in solar activity affect the biological balance of pine ecosystems.

Recommendations for adaptation of pine forests to climate change include the introduction of drip irrigation, the use of biological products for pest control and the selection of resistant pine varieties. R.S. Pacaldo *et al.* (2024) noted the effectiveness of biological control of pests, which is supported by research proposals for the integration of these methods into forest management systems. D. Nadal-Sala *et al.* (2017) also pointed out the importance of remote sensing for monitoring forest health, which is consistent with recommendations on the use of geographic information systems.

Involvement of local communities in forest management is a key factor for the conservation of Polissia ecosystems. The participation of local residents in forest restoration activities not only increases the effectiveness of such initiatives, but also increases the level of community responsibility for the state of forests. The study showed that communities that are actively involved in environmental programmes are reducing uncontrolled deforestation and improving the quality of restoration work. A.L. Giambelluca *et al.* (2024) emphasised the importance of integrating educational campaigns that teach local residents effective reforestation methods, which is consistent with the above recommendations for the development of environmental education. According to a study by X. Tang *et al.* (2021), community involvement in local development programmes increases the resilience of forests to climate change, creating conditions for the long-term conservation of forest resources. The results of the current study also highlight that cooperation with communities will ensure better consideration of local environmental conditions and facilitate forest adaptation to climate challenges, which is in line with the findings of other authors.

An integrated approach to forest management, including the introduction of modern monitoring methods, selection of resistant varieties and community engagement, is essential for the adaptation of forest ecosystems to climate challenges. M. Tsaktsira *et al.* (2023) emphasised the importance of updating the regulatory framework for forest management, which coincides with the recommendations of the study of the sanitary condition of pine forests in Polissia. D. Nadal-Sala *et al.* (2021) also highlighted the need to expand the area of afforestation in favourable regions, which is consistent with the findings on optimising forest management in the face of climate change.

Overall, the conducted research highlights the complex and multidimensional impact of climate change, moisture deficit, and solar activity on the sanitary condition and stability of pine forests in the Polissia region. The observed deterioration in hydrothermal balance, increased frequency of extreme weather events, and rising pest and disease pressures significantly reduce the resilience of pine ecosystems. Long-term changes in key climatic indicators, coupled with physiological stress in trees, have led to a decline in growth rates, crown density, and adaptive capacity, especially in arid zones.

Conclusions

The study of climate change in the Polissia region over the period 1968-2024 revealed a significant increase in the average annual temperature (+1.2°C) and a decrease in the HCH level from 1.3 to 0.9, indicating a deterioration in moisture conditions. Changing climatic conditions have had a negative impact on pine forests, causing moisture deficits, frequent droughts and extreme weather events that increase stress on trees. Soil moisture deficit and frequent winter thaws have contributed to the deterioration of forest health, including an increased risk of root sponge disease (*Heterobasidion annosum*) and an increase in pest populations such as pine sawfly and bark beetle. In regions with a HCH below 1.0, the number of pests increased to 75 individuals per 100 trees, which is twice as high as in areas with sufficient moisture.

The analysis of pine physiological processes showed a decrease in photosynthetic activity and chlorophyll accumulation in the needles, which reduced wood growth and the adaptive potential of trees. Changes in the temperature regime affected the duration of active pine growth, and mechanical damage to trees due to strong winds increased vulnerability to pathogens and pests. Field data confirmed that the proportion of dry-top trees in arid regions with a HCH<1.0 reached 20%, and the level of root sponge damage increased to 12%.

For the adaptation of pine forests, it is recommended to introduce drip irrigation, select resistant tree varieties, mulch the soil and use biological products against pests. Regular monitoring using geographic information systems and the involvement of local communities in forest management will help preserve forests in the new climate conditions. Prospects for further research include modelling adaptation strategies and studying the long-term impact of climate change on forest ecosystems.

The study has certain limitations, including insufficient detail on local environmental conditions and the impact of anthropogenic factors, such as logging and pollution, which can exacerbate the negative effects of climate change. In addition, the analysis was based on long-term averages, which may not consider short-term fluctuations in climate parameters and their impact on pine forests. Prospects for further research include expanding the number of test plots, integrating remote sensing to monitor forest conditions, and modelling possible scenarios for forest ecosystems to adapt to climate change. It is also important to study the genetic characteristics of pine trees' resistance to drought, diseases, and pests to develop breeding programmes aimed at creating sustainable forest plantations.

Acknowledgements

None.

Conflict of Interest

None.

References

[1] Acarer, A. (2024). Response of black pine (*Pinus nigra*) in southwestern Anatolia to climate change. *BioResources,* 19(4), 8594-8607. doi: 10.15376/biores.19.4.8594-8607.

[2] Bose, A.K., *et al.* (2022). Lessons learned from a long-term irrigation experiment in a dry Scots pine forest: Impacts on traits and functioning. *Ecological Monographs,* 92(2), article number e1507. doi: 10.1002/ecm.1507.

[3] Bowman, K., & Chen, X. (2022). Current standing of longleaf pine trees under climate change. *Journal of Botanical Research,* 4(1), 28-39. doi: 10.30564/jbr.v4i1.4350.

[4] Brichta, J., *et al.* (2024). Effects of climate change on scots pine (*Pinus sylvestris* L.) growth across Europe: Decrease of tree-ring fluctuation and amplification of climate stress. *Forests,* 15(1), article number 91. doi: 10.3390/f15010091.

[5] Buras, A., Rehschuh, R., Fonti, M., Lange, J., Fonti, P., Menzel, A., Gessler, A., Rigling, A., Treydte, K., & von Arx, G. (2023). Quantitative wood anatomy and stable carbon isotopes indicate pronounced drought exposure of Scots pine when growing at the forest edge. *Frontiers in Forests and Global Change,* 6, article number 1233052. doi: 10.3389/ffgc.2023.1233052.

[6] Dang, H., Han, H., Chen, S., & Li, M. (2021). A fragile soil moisture environment exacerbates the climate change-related impacts on the water use by Mongolian Scots pine (*Pinus sylvestris* var. *mongolica*) in northern China: Long-term observations. *Agricultural Water Management*, 251, article number 106857. doi: 10.1016/j.agwat.2021.106857.

[7] Dimitrijević, T., Ratknic, M., & Hadrović, S. (2023). Climate characteristics and diameter increment of Eastern white pine: Potential use in afforestation in the Belgrade area (Republic of Serbia). *Sustainable Forestry: Collection,* 87-88, 99-113. doi: 10.5937/sustfor2388099d.

[8] Ellis, E.X., Guy, R.D., & Wei, X.A. (2024). Seasonal shifts in depth-to-water uptake by young thinned and overstocked lodgepole pine (*Pinus contorta*) forests under drought conditions in the Okanagan Valley, British Columbia, Canada. *Hydrology and Earth System Sciences,* 28, 4667-4684. doi: 10.5194/hess-28-4667-2024.

[9] Enríquez-de-Salamanca, Á. (2024). Influence of climate change on carbon sequestration in pine forests of central Spain. *Atmosphere,* 15(10), article number 1178. doi: 10.3390/atmos15101178.

[10] Ghosh, S.K., Slot, J.C., Visser, E.A., Naidoo, S., Sovic, M.G., Conrad, A.O., Kyre, B., Vijayakumar, V., & Bonello, P. (2022). Mechanisms of pine disease susceptibility under experimental climate change. *Frontiers in Forests and Global Change,* 5, article number 872584. doi: 10.3389/ffgc.2022.872584.

[11] Giambelluca, A.L., Hermosilla, T., Álvarez-Mozos, J., & González-Audícana, M. (2024). Identifying forest harvesting practices: Clear-cutting and thinning in diverse tree species using dense Landsat time series. *Forest Ecology and Management*, 578, article number 122442. doi: 10.1016/j.foreco.2024.122442.

[12] Hartmann, M., Herzog, C., Brunner, I., Stierli, B., Meyer, F., Buchmann, N., & Frey, B. (2023). Long-term mitigation of drought changes the functional potential and life-strategies of the forest soil microbiome involved in organic matter decomposition. *Frontiers in Microbiology*, 14, article number 1267270. doi: 10.3389/fmicb.2023.1267270.

[13] Karnosky, D., Percy, K., Chappelka, A., & Krupa, S. (2003). Air pollution and global change impacts on forest ecosystems: Monitoring and research needs. In D.F. Karnosky, K.E. Percy, A.H. Chappelka, C. Simpson & J. Pikkarainen (Eds.), *Air pollution, global change and forests in the new millennium* (pp. 447-459). Oxford: Elsevier. doi: 10.1016/s1474-8177(03)03025-0.

[14] Levchenko, V., & Gumeniuk, V. (2024). Regarding the issue of growing Scots Pine forests in Polissya. *Ukrainian Journal of Forest and Wood Science*, 15(4), 25-39. doi: 10.31548/forest/4.2024.25.

[15] Li, J., Xie, Y., Wulan, T., Liu, H., Wang, X., Zheng, Y., Qi, Q., Gao, Z., Gao, S., & Shen, Z. (2023). Drought resilience of Mongolian Scotch pine (*Pinus sylvestris* var. *mongolica*) at the southernmost edge of its natural distribution: A comparison of natural forests and plantations. *Forest Ecology and Management*, 542, article number 121104. doi: 10.1016/j.foreco.2023.121104.

[16] Loewe-Muñoz, V., Cachinero-Vivar, A.M., Camarero, J.J., del Río, R., Delard, C., & Navarro-Cerrillo, R.M. (2024). Dendrochronological analysis of Pinus Pinea in Central Chile and South Spain for sustainable forest management. *Biology*, 13(8), article number 628. doi: 10.3390/biology13080628.

[17] Markos, N., Preisler, Y., Radoglou, K., Rotenberg, E., & Yakir, D. (2023). Physiological and phenological adjustments in water and carbon fluxes of Aleppo pine forests under contrasting climates in the Eastern Mediterranean. *Tree Physiology,* 44(1), article number tpad125. doi: 10.1093/treephys/tpad125.

[18] Matallana-Ramirez, L., Whetten, R., Sanchez, G., & Payn, K. (2021). Breeding for climate change resilience: A case study of loblolly Pine (*Pinus taeda* L.) in North America. *Frontiers in Plant Science*, 12, article number 606908. doi: 10.3389/fpls.2021.606908.

[19] Mechergui, K., Altamimi, A., Jaouadi, W., & Naghmouchi, S. (2021). Climate change impacts on spatial distribution, tree-ring growth, and water use of stone pine (*Pinus pinea* L.) forests in the Mediterranean region and silvicultural practices to limit those impacts. *Iforest – Biogeosciences and Forestry*, 14(2), 104-112. doi: 10.3832/IFOR3385-013.

[20] Mikalajūnas, M., Pretzsch, H., Mozgeris, G., Linkevičius, E., Augustaitienė, I., & Augustaitis, A. (2021). Scots pine's capacity to adapt to climate change in hemi-boreal forests in relation to dominating tree increment and site condition. *Iforest – Biogeosciences and Forestry,* 14(5), 473-482. doi: 10.3832/ifor3703-014.

[21] Moroz, V., & Nykytiuk, Y. (2021). Current state of pineries in Zhytomyr Polissia under the influence of environmental factors. *Scientific Horizons*, 24(8), 37-46. doi: 10.48077/scihor.24(8).2021.37-46.

[22] Nadal-Sala, D., Grote, R., Birami, B., Lintunen, A., Mammarella, I., Preisler, Y., Rotenberg, E., Salmon, Y., Tatarinov, F., Yakir, D., & Ruehr, N.K. (2021). Assessing model performance via the most limiting environmental driver in two differently stressed pine stands. *Ecological applications: A Publication of the Ecological Society of America*, 31(4), article number e2312. doi: 10.1002/eap.2312.

[23] Nadal-Sala, D., Keenan, T.F., Sabaté, S., & Gracia, C. (2017). Forest eco-physiological models: Water use and carbon sequestration. In F. Bravo, V. LeMay & R. Jandl (Eds.), *Managing forest ecosystems: The challenge of climate change* (pp. 81-102). Cham: Springer. doi: 10.1007/978-3-319-28250-3_5.

[24] Navarro-Cerrillo, R.M., Ruiz-Gómez, F.J., Camarero, J.J., Castillo, V., Barberá, G.G., Palacios-Rodríguez, G., Navarro, F.B., Blanco, J.A., Imbert, J.B., Cachinero-Vivar, A.M., Molina, A.J., & del Campo, A.D. (2022). Long-term carbon sequestration in pine forests under different silvicultural and climatic regimes in Spain. *Forests,* 13(3), article number 450. doi: 10.3390/f13030450.

[25] Ouyang, X., Chen, A., Li, Y., Han, X., & Lin, H. (2022). Predicting the potential distribution of pine wilt disease in China under climate change. *Insects*, 13(12), article number 1147. doi: 10.3390/insects13121147.

[26] Pacaldo, R.S., Aydın, M., & Amarille, R.K. (2024). Soil respiration and controls in warmer winter: A snow manipulation study in postfire and undisturbed black pine forests. *Ecology and Evolution*, 14(3), article number e11075. doi: 10.1002/ece3.11075.

[27] Sensuła, B., & Wilczyński, S. (2022). Dynamics changes in basal area increment, carbon isotopes composition and water use efficiency in Pine as response to water and heat stress in Silesia, Poland. *Plants*, 11(24), article number 3569. doi: 10.3390/plants11243569.

[28] Stolz, J., van der Maaten, E., Kalanke, H., Martin, J., Wilmking, M., & van der Maaten-Theunissen, M. (2021). Increasing climate sensitivity of beech and pine is not mediated by adaptation and soil characteristics along a precipitation gradient in northeastern Germany. *Dendrochronologia*, 67, article number 125834. doi: 10.1016/j.dendro.2021.125834.

[29] Tang, X., Yuan, Y., Li, X., & Zhang, J. (2021). Maximum entropy modeling to predict the impact of climate change on pine wilt disease in China. *Frontiers in Plant Science*, 12, article number 652500. doi: 10.3389/fpls.2021.652500.

[30] Tsaktsira, M., Tsoulpha, P., Economou, A., & Scaltsoyiannes, A. (2023). Mitigation of global climate change through genetic improvement of resin production from resinous pines: The case of *Pinus halepensis* in Greece. *Sustainability,* 15(10), article number 8052. doi: 10.3390/su15108052.

[31] Turko, V., & Moroz, V. (2023). The impact of weather conditions on natural regeneration of *Pinus sylvestris* in the central Polissya region. *German International Journal of Modern Science*, 58, article number 5.

Вплив кліматичних змін на санітарний стан соснових лісостанів Полісся

Віра Мороз
Кандидат сільськогосподарських наук, доцент
Західноукраїнський національний університет
46009, вул. Львівська, 11, м. Тернопіль, Україна
https://orcid.org/0000-0002-1457-4641

Анотація. Дослідження було спрямоване на визначення ключових чинників, які впливають на санітарний стан соснових лісостанів у Поліссі в умовах кліматичних змін, а також розробити рекомендації для їх адаптації до нових екологічних викликів. Для аналізу закладено 30 пробних ділянок по 0,1 гектара, на яких досліджували соснові деревостани різних вікових класів. У ході роботи зафіксовано ключові кліматичні тенденції: середньорічна температура за період 1968-2024 років зросла на 1,2°C, кількість опадів зменшилася на 25 міліметрів, а гідротермічний коефіцієнт зволоження знизився з 1,3 до 0,9, що свідчить про посуху. У регіонах із дефіцитом вологи частка суховерхих дерев зросла з 8 % до 20 %, а ураження кореневою губкою – з 5 % до 12 %. Зниження рівня ґрунтової вологи порушило транспірацію, обмежило фотосинтез і знизило приріст деревини на 18 % порівняно зі здоровими деревами. Виявлено, що чисельність соснового пильщика і короїдів збільшилася на 67 % і 150 % відповідно у посушливих умовах. Аналіз показав, що механічні пошкодження, спричинені сильними вітрами, створюють умови для активного поширення шкідників і хвороб. Отримані результати свідчать, що кліматичні зміни спричинили деградацію лісостанів через посилення фізіологічного стресу дерев. Для адаптації запропоновано селекцію стійких сортів сосни, впровадження зрошувальних систем, моніторинг стану лісів із використанням геоінформаційних технологій та збільшення площі лісорозведення у сприятливих зонах. Застосування цих заходів сприятиме збереженню лісових екосистем у регіоні в умовах змін клімату

Ключові слова: посуха; гідротермічний коефіцієнт; суховерхість; екологічні чинники; коренева губка