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Ecological aspects of climate change impact on tree species in forest ecosystems

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Abstract. The study aimed to assess how rising temperatures, changing precipitation patterns and increasing frequency of extreme weather events such as droughts, floods, and frosts affect forest ecosystems, and to identify possible consequences for their biodiversity and stability. This study encompassed a review of scientific literature, a comparative analysis of several climate

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change scenarios, and an evaluation of data about tree physiological processes, including photosynthesis, root development, and tree growth. The primary conclusions of the study indicated that climate change could exacerbate stressors for certain tree species, perhaps resulting in the substitution of these species with those that are more resilient or less dependent on specific climatic conditions. The results are important for predicting further changes in forest ecosystems and developing recommendations for their conservation. One of the key conclusions was the need to adapt forestry to new climate conditions, including the selection of climate-resistant tree species and the use of strategies to restore degraded forests. It is also relevant to improve the effectiveness of monitoring the state of forest ecosystems to respond to changes promptly and prevent the degradation of forest resources. Predicting possible climate change and analysing local conditions allowed for more effective planning of measures to conserve biodiversity and forest ecosystem services. Taking into account the data obtained, it is possible to create recommendations for sustainable forest management, which will help preserve their ecological and economic value in the face of climate change

Keywords: flora; biodiversity; environment; species vulnerability; vegetation

Introduction

Climate change represents a significant challenge of our era, impacting all ecosystems globally, including forests. Forests are essential for delivering ecosystem services, including carbon sequestration, water balance regulation, biodiversity conservation, and soil erosion prevention. Forests harbour almost 80% of terrestrial species and furnish resources for billions of individuals who rely on them to satisfy their needs (Huang *et al.*, 2024). Nevertheless, increasing temperatures, alterations in precipitation patterns, and the prevalence of extreme weather events provide a significant danger to the integrity of forest ecosystems. An elevation in average air temperature results in alterations in the photosynthetic activity of flora, potentially leading to a decline in arboreal growth and output. Under high temperatures, plants can show signs of stress, such as stomatal closure, which reduces carbon dioxide consumption and, consequently, reduces photosynthetic activity. Simultaneously, alterations in precipitation patterns result in droughts or, alternatively, heightened precipitation, so impacting the hydrological regime in forests. This adversely affect the growth of tree root systems, as insufficient moisture may result in the mortality of young plants or diminish their capacity to respond to severe situations.

The occurrence of extreme weather events, including hurricanes, floods, wildfires, and frosts, can inflict physical harm on trees and lead to the devastation of forest stands. For example, climate change can facilitate the spread of new pests that are detrimental to forest health and can weaken forests' resilience to stress. A concerning element of climate change is its effect on the species makeup of forests. Changes in climate conditions may lead to the gradual displacement of certain tree species that are unable to adapt to new temperature and humidity conditions in favour of more resilient or invasive species (Skliar *et al.*, 2020).

Given these issues, it is essential to examine the adaptation mechanisms of forest ecosystems to climate change. Research focused on elucidating the physiological mechanisms of trees, their resilience and adaptive capacity, and the formulation of appropriate forest management strategies in response to climate change is crucial for the preservation of these vital ecosystems in the future. Achieving sustainable development and forest conservation for future generations necessitates a thorough examination of the effects of climate change on forest ecosystems and associated ecosystem services.

J. Huang *et al.* (2024) investigated how photosynthetically active radiation affects the dynamics of sap flow at different stages of forest succession in subtropical forests. The authors noted that light intensity is a critical factor for tree growth, but questions remain about adaptation to climate change in different regions. The impact of altitude and slope exposure on carbon storage in Himalayan Forest soils was analysed by S. Kumar *et al.* (2024), focusing on the ecosystem processes that contributed to carbon storage in different landscape conditions and considering these aspects as a means of supporting natural climate change mechanisms. D. Srivastava (2024) focused on the biological aspects of climate-induced changes in ecosystems and offered practical recommendations for the adaptation of forest systems. A separate section was devoted to the ecosystem services of forests, their conservation, and their role in global environmental stability.

A. Sojitra *et al*. (2024) underscored the necessity of an interdisciplinary approach to forest research in relation to climate change, highlighting the importance of future research planning, while also indicating the ongoing requirement for practical recommendations for the conservation of certain forest types. The possibility of using controlled species migration to reduce the impact of climate change was considered by W. Xu & S. Prescott (2024). They noted the promise of this approach, but that it requires additional experimental evidence. J. Konic *et al*. (2024) evaluated the contribution of imported trees to ecosystem services in Austrian woods. Despite the potential of introduced species, there are gaps in the study of their long-term impact on biodiversity.

Long-term changes in radial tree growth in mixed forests in China were investigated by X. Gong *et al*. (2024). The scientists analysed how climate change affected tree growth, in particular, whether these changes contributed to the spread of deciduous species. The study showed that changing climatic conditions could create more favourable conditions for deciduous species compared to conifers, which was important for predicting the future dynamics of these forests. S. Tampekis *et al*. (2024) presented the concept of planning and managing forestry operations using the principles of functional complex systems' science. The authors developed a systematic management method that considered the influence of multiple elements on the resilience of forest ecosystems and enabled forest adaptation to climate change. V. Kutskyi & I. Lakyda (2024) examined the influence of climatic variables on the distribution of this species, used modelling techniques to forecast future alterations in pine distribution. The work is aimed at improving conservation and management strategies for this species in changing ecological conditions. Finally, V. Kyyak *et al*. (2022) analysed the impact of climate change on habitats and proposed science-based methods for their conservation. In particular, they considered adaptive management strategies aimed at minimizing biodiversity loss and maintaining ecosystem resilience.

Despite significant focus on the effects of climate change on forests, numerous inquiries persist. The long-term effects on species composition and ecosystem services offered by forests remain little comprehended. There is a deficiency of generalized data regarding the adaptive potential of various tree species within a regional framework. This study aims to evaluate the effects of climate change on arboreal growth and development, examine alterations in the species composition of forest ecosystems, and ascertain the implications of these changes for forest ecosystem services. The primary emphasis was on elucidating the methods by which trees adapt to fluctuating climatic circumstances, alongside formulating recommendations for the conservation and sustainable use of forest resources amid climate challenges.

Materials and Methods

Several theoretical methods were used to assess the impact of climate change on forest ecosystems, allowing for a comprehensive analysis and formulation of recommendations for the conservation of these ecosystems in the future. First, the analytical method was applied, which consisted of a thorough study of scientific literature and existing studies describing the impact of climate change on various aspects of forest ecosystems. This included the physiological processes of trees, alterations in forest species composition, and modifications in forest ecosystem functions, such as carbon sequestration, water circulation, and soil stabilization. The analytical strategy enabled to consolidate data from several research undertaken globally and locally, enhancing our comprehension of the possible effects of climate change on forest ecosystems.

As the study was of a theoretical nature, a significant part of the work was focused on systematizing and analysing the available data. This encompassed an examination of many papers detailing climate change and its effects on forests across diverse geographical areas. A review of studies examining alterations in temperature, precipitation, and extreme weather events and their effects on forest ecosystems was undertaken (Forzieri *et al.*, 2022; Seidl & Turner, 2022). This enabled the evaluation of the resistance levels of various tree species to climate change and alterations in forest structure resulting from these causes. The findings from experimental studies by other researchers regarding the impact of climate change on the physiological processes of trees, encompassing photosynthesis, growth, and root system development, were also analysed, contributing to a more comprehensive understanding of the interaction between trees and climatic conditions, as well as their adaptive capacity to change (De Frenne *et al.*, 2021; Varol *et al.*, 2021).

The comparative analysis method enabled the comparison of several approaches to evaluating the effects of climate change on forest ecosystems, namely by contrasting different climate change scenarios, including alterations in temperature and humidity, and analysing their influence on diverse forest kinds. The comparison study facilitated the identification of forest ecosystems most susceptible to climate change and determined which tree species might adapt or extend their ranges.

The study was conducted in accordance with the ethical standards set out in the Convention on Biological Diversity (1992) and the Convention on International Trade in Endangered Species of Wild Fauna and Flora (1973). This guaranteed that the research adhered to international norms for the conservation of natural resources and biodiversity, assuring that the outcomes would not adversely affect ecosystems and endangered species.

Results and Discussion

The impact of climate change on tree growth and development

Climate change affects woody plants' key physiological processes, altering their growth, development, and resilience through interrelated factors like rising temperatures, shifting precipitation patterns, and more frequent extreme weather events that can amplify each other's impacts.

An elevation in mean annual temperatures alters the dynamics of photosynthesis, transpiration, and respiration in trees. For many tree species, optimal photosynthetic conditions depend on a certain temperature range. Increasing the temperature up to this range can increase the activity of photosynthetic enzymes, in particular rubisco, which leads to an increase in productivity. However, at temperatures above the optimum, enzyme activity decreases, and photosynthesis becomes less efficient, increasing the risk of heat stress. Heat stress also affects plant structures. In conifers, chloroplast damage is observed, which reduces carbon assimilation. In deciduous trees, tissue development processes are disrupted, and leaf expansion slows down. At the same time, the duration of the dormant period is reduced in many species, causing trees to enter the active growth phase prematurely, making them vulnerable to spring frosts. In regions with short winters, this cycle disruption can lead to yield losses and tree exhaustion (Allen *et al.*, 2010; Forzieri *et al.*, 2022).

Reduced precipitation in arid regions causes a chronic moisture deficit, which leads to a reduced water supply in the root system. This directly reduces transpiration and reduces the amount of nutrients reaching the leaves, disrupting photosynthesis. This is especially critical for young trees, whose root system is not yet sufficiently developed to access deep aquifer. In regions with excessive precipitation, the risk of soil flooding increases, which causes a lack of oxygen for the roots. Under anaerobic conditions, root decay is activated, which significantly weakens trees. In addition, constant humidity creates favourable conditions for the development of fungal infections that can spread rapidly through the wood (Körner, 2021; Seidl & Turner, 2022).

Droughts significantly reduce transpiration, which leads to the drying of leaves and shoots. In the case of prolonged droughts, a tree can lose its secondary roots, which are responsible for water absorption, making it more vulnerable to other stress factors. Frosts are particularly dangerous for young shoots and flowers, which often develop after the shortened winter period. Even short-term exposure to low temperatures can cause damage to cell membranes, leading to tissue necrosis (Natalchuk & Rudnyk-Ivashchenko, 2024). In colder regions, this can reduce tree survival, reduce productivity and even cause death. Floods, in turn, damage the root system, cause soil erosion and create unfavourable conditions for rooting. The result is a decrease in the resilience of forests to windstorms and damage to the mechanical structure of trees.

Warming creates favourable conditions for many insects, such as bark beetles or sawflies, which reproduce and spread faster (Shahini *et al.*, 2024). New warm regions become available for invasive species that were previously restricted to cold temperatures. Increased humidity favours the development of fungal diseases, such as fusarium or rust, which attack leaves, branches, and wood (Table 1). Affected trees often have reduced vigour and become more vulnerable to other stress factors. At the same time, some diseases that were previously considered insignificant can become epidemic due to changes in environmental conditions.

Table 1. Impact of climatic factors on physiological processes of trees and their consequences

The climate factor	Physiological effects	Consequences for trees
Increase in temperature	Disruption of photosynthesis, reduction of dormancy	Exhaustion, heat stress, risk of frost
Precipitation deficit	Water stress, reduced transpiration	Reduced growth, root death

Table 1, Continued

The climate factor	Physiological effects	Consequences for trees
Excessive rainfall	Flooding of the root system	Root rot, fungal infections
Frequent droughts	Disruption of the water balance	Leaves drying out, trees dying
Frosts	Tissue necrosis	Reduced productivity, damage to young shoots
Spread of pests	Invasions of new species	Damage to wood, reduction of biodiversity
Fungal diseases	Damage to leaves, branches, wood	Reduced viability, slower growth

Source: C.D. Allen *et al*. (2010), C. Körner (2021)

To formulate successful methods for adapting forest ecosystems to climate change, it is essential to consider the ecological traits of various tree species, their resilience to water scarcity, excessive moisture, thermal stress, and biotic influences. Trees with high resistance to flooding, such as white willow (*Salix alba*), black poplar (*Populus nigra*) and aspen (*Populus tremula*), are well suited to high humidity. For example, in regions with frequent flooding, these species demonstrate stable viability due to their ability to form adventitious roots and anaerobic respiration. However, even these species require adaptation measures such as soil reclamation to reduce the duration of water stagnation.

Pine (*Pinus sylvestris*), oak (*Quercus robur*) and juniper (*Juniperus communis*) are well suited to regions with low rainfall. These species demonstrate the ability to conserve water due to their smaller leaf blade, waxy coating on needles or leaves, and strong root systems that reach deep aquifers. In countries with Mediterranean climates, the olive tree (*Olea europaea*) has successfully adapted to extreme droughts through stomatal transpiration regulation mechanisms (Shahini *et al.*, 2009; Niinemets, 2010).

The duration of adaptation to climate change varies for different species. For example, Scots pine shows the first signs of adaptation to rising temperatures in 10-15 years, which is reflected in changes in the chemical composition of wood and the structure of the root system. Common oak takes about 20-30 years to fully adapt to lower precipitation due to the formation of deeper roots. Moisture-loving species such as poplar or willow adapt more slowly, as their adaptation mechanisms are limited to physiological processes without significant changes in tissue structure (Intergovernmental Panel on Climate Change, 2021).

Enhancing the resilience of forest ecosystems necessitates the integration of biological, engineering, and management strategies. Selecting species that combine high levels of productivity with adaptive resilience is a key step. For example, in drought conditions, the use of lodgepole pine hybrids with resistance to water deficit can be an effective solution. In humid regions, it is advisable to implement drainage and mulching systems to maintain a stable level of soil moisture. Adapting forests to climate change is a protracted endeavour necessitating continuous ecosystem monitoring and the implementation of innovative management strategies aimed at conserving natural resources and biodiversity.

Changes in the species composition of forest ecosystems

Climate change is altering forest ecosystems' species composition by transforming the growing conditions for various tree species. Through rising temperatures, altered precipitation patterns, and more frequent extreme weather events like droughts, frosts, and floods, it's reshaping competitive dynamics between species while affecting their geographic distribution and survival rates. Cold-loving tree species, such as spruce, white fir and larch, are the most vulnerable to warming. They traditionally grow in cold climates and have a limited ability to adapt to higher temperatures. As temperatures rise, their ranges shift northwards or upwards to higher mountainous areas. This leads to a decline in their numbers in their usual territories, where the climate is no longer optimal for their growth. At the same time, warmer climatic conditions are contributing to the expansion of the ranges of warmth-loving species, such as fluffy oak, Scots pine and other species that can withstand higher temperatures and less humid conditions. These species are actively developing new ecological niches in regions that are becoming warmer, which can change the balance between different types of forests. Climate change also has a significant impact on moisture-loving trees. Rising temperatures combined with insufficient moisture are leading to a decline in species such as common oak, linden, or alder. These species require stable moisture for normal growth, and water shortages are becoming a serious problem for their survival. Alterations in the quantity and distribution of precipitation result in modifications to forest structure, as moisture-dependent plants are progressively supplanted by more drought-tolerant species like oak or pine (De Frenne *et al.*, 2021; Varol *et al.*, 2021).

At the same time, climate change creates favourable conditions for invasive tree species. For example, Gleditsia or Amorpha bush, which are highly adaptable to environmental changes, can expand their ranges to new regions, occupying vacant ecological niches. They are able to quickly develop new territories and often displace native species, which leads to a decrease in biodiversity and disruption of natural ecological links in forests. Climate change affects the structure of forest communities, changing not only the composition of species but also the physiological characteristics of forest ecosystems. For example, in regions where temperatures are rising, coniferous forests may gradually change to mixed or deciduous forests, reducing the overall density of forest cover and changing the nature of the undergrowth and reducing soil fertility. These changes not only affect the aesthetic appearance of forests but also impair crucial ecosystem functions like water purification, moisture retention, and soil conservation, while climate change further threatens vulnerable species such as conifers, reducing their ability to perform vital ecological services including carbon sequestration and erosion protection. At the same time, replacing these species with more heat- and drought-tolerant species may help maintain some ecosystem functions, but reduce overall forest biodiversity (Peñuelas & Boada, 2003).

In general, climate change affects the species composition of forest ecosystems through complex interactions between temperature, precipitation, moisture, and competition between species. These changes can lead to significant structural changes in forests, as well as the loss of some ecological functions, such as biodiversity stability and water regulation. Table 2 illustrates the responses of various tree species to climate change.

Table 2. Effects of climate change on the species composition of forest ecosystems and its repercussions

Type of changes	Examples of species that respond	Consequences
Warming	Spruce, fir, larch	Range reduction, migration to mountainous areas or north
Moisture deficiency	Common oak, linden, alder	Loss of productivity, degradation of ecosystems

Table 2, Continued

Type of changes	Examples of species that respond	Consequences
Expanding our habitats	Fluffy oak, Scots pine	Replacement of cold-loving species, expansion to warmer regions
Infestation	Gleditsia, Amorpha	Displacement of native species, reduction of natural diversity
Structural changes	Deciduous forests instead of conifers	Reduction of density, change in functional characteristics of ecosystems

Source: J. Peñuelas & M. Boada (2003), D.M. Richardson & M. Rejmánek (2011)

Changing forest species composition affects the economy by reducing resource availability, changing forest productivity and increasing management costs. For example, the shrinking ranges of cold-loving species such as spruce and fir reduce the amount of valuable timber used in construction and furniture production. At the same time, the expansion of warmth-loving species, such as fluffy oak, is changing the structure of raw materials, which requires the woodworking industry to adapt. The moisture deficit, which leads to a loss of productivity in species such as linden and alder, affects forestry, which depends on a stable supply of resources.

Invasive species, such as Gleditsia, create additional costs for their control, which increase as they spread. The lack of adaptation to local climatic conditions and the poor quality of their wood limits their economic value, while threatening to lose natural forest resources.

Invasive species management strategies include several approaches aimed at reducing their negative impact on forest ecosystems. Early detection and monitoring are key measures that allow localizing new areas of invasive species using modern technologies such as remote sensing and GIS systems. Physical removal of young trees of invasive species, combined with planting of native resistant species, helps to preserve natural biodiversity. Simultaneously, the implementation of biological control strategies, including the utilization of natural predators of invasive species, aids in diminishing their populations without adversely affecting ecosystems. Encouraging the planting of native tree species adapted to climate change ensures their superiority over invasive species. This measure is important for creating sustainable forest plantations. Raising environmental awareness and informing local communities about the negative effects of invasive species is paramount. The integrated application of these strategies contributes to the adaptation of forest ecosystems to climate change, while maintaining their ecological stability and economic value.

Ecosystem services of forests in the context of climate change

Forests are one of the key components of the global ecosystem, performing numerous functions that maintain ecological balance. Some of the most important functions of forests include carbon sequestration, water cycle regulation, soil erosion protection, biodiversity maintenance, water filtration and ensuring the stability of local climatic conditions. All these processes are being seriously disrupted, which affects not only the condition of the forests themselves, but also human well-being. The ability of forests to absorb carbon dioxide, which is the main greenhouse gas, is critical to slowing global warming. This process depends on the level of photosynthetic activity of trees, their growth, and biomass accumulation. Climate change, such as rising average annual temperatures and frequent droughts, significantly reduces the efficiency of photosynthesis, especially in moisture-loving species such as fir, beech, or oak. As a result, trees grow more slowly, which reduces the amount of carbon that is sequestered and retained in forests. Moreover, catastrophic weather phenomena, including wildfires and hurricanes, facilitate the swift release of carbon sequestered in wood, transforming forests from natural carbon sinks into sources of carbon dioxide.

The root systems of trees play a key role in retaining moisture in the soil, preventing it from evaporating and running off quickly during storms. In arid conditions, trees, especially those with shallow root systems such as alder or aspen, are unable to maintain the required level of soil moisture. This leads to the depletion of aquifers and increased droughts, which negatively affects both local ecosystems and agriculture. Erosion protection and soil stabilization are important functions of forests, especially in mountainous and sloping areas. Climate change, which is leading to more extreme precipitation events and increased intensity of storms, is exacerbating erosion processes. In areas where forest cover is degraded due to drought or felling, soil becomes more vulnerable to leaching. This not only reduces soil fertility, but also leads to flooding in low-lying areas due to the accumulation of sediment in water bodies (Abbass *et al.*, 2022).

The water filtration capacity of forests relies on the diversity of tree species and their efficacy in purifying water from detrimental contaminants. Under climate change, the risk of losing this mechanism increases as species diversity decreases, and invasive plants spread. Monocultures, which are often created for reforestation, have a limited ability to filter water because their root system does not provide sufficient interaction with soil microorganisms that are involved in natural water purification. Maintaining the biodiversity of forests is the basis of their ecological sustainability, but this process is also under threat. Climate change is disrupting the ecological balance, contributing to the displacement of some species by others that are less vulnerable to changing conditions (Ismayilzada *et al.*, 2023). For example, the spread of invasive species such as Gleditsia or Amorpha often leads to the displacement of native species such as linden or maple (Table 3). This disrupts the complex ecological relationships that maintain the stability of forest ecosystems, including interactions between trees, pollinating insects, birds and other organisms.

Table 3. Ecosystem services of forests and their disruption under climate change

Ecosystem service	Disruption due to climate change	Environmental impacts
Carbon sequestration	Reduced photosynthesis, emissions from fires	Increasing CO_2 levels in the atmosphere, increasing the greenhouse effect
Regulation of the water cycle	Moisture deficit, reduced water retention	Deteriorating access to water, increasing frequency of droughts
Erosion protection	Loss of forest cover, increased surface run-off	Soil destruction, increased flood risk
Water filtration	Decrease in tree diversity, spread of monocultures	Accumulation of harmful substances in aquifers
Supporting biodiversity	Displacement of native species, loss of interconnections between organisms	Reduced ecological sustainability of forests, disruption of ecosystem functionality

Source: K. Abbas *et al*. (2022), A. Łubek *et al*. (2021)

To preserve the ecosystem services of forests in the context of climate change, it is necessary to implement adaptation measures, such as enriching forests with resilient tree species, creating conservation corridors and managing water resources. At the same time, it is important to reduce anthropogenic pressure on forests, in particular by reducing illegal logging and promoting natural forest regeneration.

Climate change poses unprecedented challenges for forest conservation, demanding both proactive management and flexible adaptation strategies. A critical focus lies in preparing forest plantations for shifting climate patterns through careful tree species selection. Foresters must identify varieties capable of thriving under higher temperatures and water scarcity. This often means leveraging native species already adapted to changing conditions while thoughtfully introducing hardy newcomers that can weather future climate shifts. Biodiversity plays a vital role in maintaining healthy forests – the more diverse an ecosystem, the better it can withstand environmental pressures. Building climate resilience requires transitioning away from monocultures toward mixed-species and natural forest systems that better mirror nature's complexity. Mixing tree species and incorporating natural plant communities reduces the risks of diseases and pests, which are a serious threat to monotonous forests.

The creation of nature conservation corridors is also an important element of adaptation. Thanks to such corridors, plant and animal populations can be maintained and preserved, which contributes to the conservation of biodiversity. Water management is another critical aspect. The introduction of technologies that promote water conservation, such as irrigation and protection against surface run-off, can increase the efficiency of water use in forest ecosystems. Additionally, establishing a rainwater harvesting system can help maintain soil moisture levels during dry periods. Conservation and restoration of degraded forests is an important area of adaptation. This can include measures to restore natural ecosystems, such as reforesting areas that have lost cover and supporting natural regeneration processes. The education and engagement of local communities in forest management activities are crucial components of adaptation. Enhancing public knowledge on the significance of forests and their ecological role fosters the development of local conservation projects. Community participation in forest restoration programmes can ensure their sustainability and long-term results.

Protecting and restoring the ecosystem functions of forests is also an important aspect. Forests perform numerous ecological functions, such as carbon sequestration, water balance regulation and protection against soil erosion. Monitoring climate change and the state of forest ecosystems is equally important. Regular monitoring facilitates the timely identification of alterations, including increasing temperatures, variations in precipitation, and the advent of novel pests or illnesses, so enabling a swift reaction to these developments. This will make it possible to make the necessary management decisions based on scientific data and predict possible changes in the future.

Reducing greenhouse gas emissions is another important area. Proactive measures to mitigate emissions will aid in decelerating climate change and alleviating its adverse effects on forest ecosystems. Forests are crucial for sustaining the carbon balance as carbon reservoirs; thus, their protection and regeneration are vital for addressing climate change (Huseynli *et al*., 2024). Education and public engagement significantly contribute to forest conservation. Enhancing knowledge of the significance of forests and their contribution to combating climate change fosters community initiatives for forest conservation and participation in replanting efforts. The engagement of local communities in the preservation of forest ecosystems guarantees their sustainability and enduring outcomes. The development of adaptation strategies for forestry and agriculture will help avoid conflicts between the use of forest resources and ecosystem conservation. This entails a sustainable methodology for utilizing forest resources that preserves the ecological functions of forests and sustains their resilience to climate change. Taking these factors into account will allow forest ecosystems to maintain their functions even in the future, contributing to the stability of ecological processes on the planet.

A reduction in trees' capacity to sequester carbon results in heightened greenhouse gas concentrations in the atmosphere, hence exacerbating global warming. This therefore influences climatic conditions, augmenting the frequency and severity of extreme meteorological phenomena, including hurricanes, floods, and droughts. This results in increased costs for infrastructure restoration, as well as increased costs for adaptation to new climate conditions. Secondly, the decline in water quality due to the loss of forests has a negative impact on public health. Forests perform an important function of water filtration, and their degradation leads to water pollution. This can cause an increase in the incidence of diseases among the population, which, in turn, creates additional financial burdens on the healthcare system.

Social impacts also include reduced resources for local communities that depend on forests for their livelihoods. Many people, especially in rural areas, rely on forests for timber, medicinal plants, food, and even income from ecotourism. The loss of these resources can lead to lower living standards, increased poverty and social tensions in these communities. The disappearance of species that play an important role in agroecosystems can lead to lower crop yields and, as a result, food shortages. This may trigger social conflicts due to competition for limited resources. Thus, the economic and social consequences of the loss of forest ecosystem services are complex and multifaceted, requiring urgent response and implementation of measures to conserve and restore them.

A. Łubek *et al*. (2021) analysed the impact of climate change on the functional diversity of ecosystems, in particular on the distribution of lichens, which are indicators of ecological condition. The results of the study showed that invasive tree species, such as Gleditsia, are displacing native species, which has a negative impact on biodiversity. The authors also noted that such changes contribute to the imbalance of ecosystems, creating new challenges for forest management.

The importance of modelling future forest change scenarios was highlighted by J. Huang *et al*. (2021), who used virtual reality data to predict climate impacts on forests. This is consistent with the study's findings on the need to develop adaptation strategies for forestry. L. Suz *et al*. (2021) emphasized the critical role of mycorrhiza in the adaptation of trees to stressful conditions, in particular under conditions of moisture deficit. The study confirmed that changes in the precipitation regime negatively affect the ability of trees to maintain water balance, which reduces the efficiency of forests in performing key ecosystem functions. Similar results were reported by L. Nunes *et al*. (2021), who analysed the impact of climate change on forests in the Mediterranean region and highlighted the need for adaptation measures to stabilize these functions.

The research indicated that increasing temperatures induce alterations in the photosynthetic mechanisms of trees, particularly conifers, which possess a restricted capacity to acclimate to thermal stress. N. Naudiyal *et al*. (2021) noted that species such as *Abies* and

Picea are particularly vulnerable to warming, which changes their potential distribution range. Y.-S. Wang & J.-D. Gu (2021) investigated the adaptation mechanisms of mangrove ecosystems to heat and moisture stress. This indicates the universality of mechanisms that may be common to different types of ecosystems.

S. Bandh *et al*. (2021) analysed the spread of invasive species in the context of climate change and noted that this can reduce the functionality of local ecosystems. The results showing changes in the photosynthetic activity of trees and their adaptive mechanisms to water stress are in line with the findings of Y. Liu *et al*. (2020), who emphasized the importance of mycorrhiza in ensuring nutrient metabolism under climate change. P. Baldrian *et al.* (2023) emphasized that the forest microbiome is essential for the resilience of tree species to climate change, corroborating findings on the interaction between root systems and soil bacteria.

The findings on the replacement of less resilient tree species with more adapted ones are confirmed by X. Morin *et al*. (2021), which highlights changes in the species structure of tree communities through succession models. They pointed out that a decline in the number of certain species can have negative consequences for forest stability. The result indicates a necessity for additional investigation into the relationship between tree species and microbial populations to enhance the adaptive potential of forests. The study's findings, which reveal a decline in forests' capacity to control the water cycle, align with the analysis conducted by F. Orsi *et al.* (2020), who noted the loss of essential ecosystem services resulting from forest degradation in Europe.

A. Ali (2023) emphasized the importance of an integrative approach to preserve forest ecosystem services in the face of global change. The results obtained on the degradation of certain tree species under the influence of changes in temperature and precipitation are confirmed by the findings of J. Blanco & Y. Lo (2023). The identified changes in species composition and adaptive capacity of tree species correlate with their recommendations on the need to apply integrated methods to predict the consequences. The study also found a decrease in the carbon sequestration capacity of forests due to loss of productivity and tree degradation. This is in line with the findings of the scientists, who emphasized that new modelling approaches can improve the accuracy of assessing changes in forest ecosystem functions under climate change.

The results on the reduction of cold-loving species' ranges and the expansion of warm-loving and invasive species are in line with the findings of S. Chivulescu *et al*. (2023). Their study noted that maintaining forest resilience is key to ensuring ecological balance, particularly in the face of climate change, as observed in the peri-urban forests of Romania. The data obtained confirm the importance of implementing adaptation measures, in particular through maintaining biodiversity and preserving the resilience of forests. The researchers noted that the transition to mixed forests and the integration of protected areas into the management structure can significantly increase climate change resilience. Studies on the increased spread of tree pests and diseases under the influence of climate change are consistent with the findings of J. Guegan *et al*. (2023). They highlighted that climate change facilitates the proliferation of novel pests and pathogens that endanger the stability of forest ecosystems.

The findings validated the intricate and multifaceted influence of climate change on forest ecosystems. Consistency with international research highlights the global importance of adaptation strategies for maintaining forest stability and functionality. This work enhances the comprehension of forest processes and can provide a foundation for formulating successful forest ecosystem management strategies.

Conclusions

The research established that climate change, characterized by elevated temperatures, altered precipitation patterns, and a rise in extreme weather occurrences, significantly affects forest ecosystems, including tree physiological processes, species composition, and ecosystem functioning. Variations in temperature and humidity directly influence the growth and development of trees, modifying their capacity for photosynthesis, growth, and root system formation. As a result, some tree species may be vulnerable to changes, leading to their replacement by more resilient species or to a reduction in the number of trees of certain species.

Modifications in forest species composition, particularly the displacement of tree species, are increasingly influencing the capacity of forests to fulfill their ecological roles, such as carbon sequestration, water regulation, erosion mitigation, and soil stabilization. Disruption of these functions can have serious consequences for climate, agriculture and water resources, in particular by reducing the ability of forests to absorb carbon dioxide and maintain water flow in ecosystems. A comparative investigation of various climate change scenarios indicates that forest ecosystems exhibiting high biodiversity are more tolerant to the adverse impacts of climate change. Consequently, conserving and restoring biodiversity is essential for the response of forests to climate change. Specifically, altering forest structures and substituting non-adapted species with more climate-resilient varieties can be a crucial measure in safeguarding forest ecosystems for the future.

It has been proven that adapting forestry to new conditions is a crucial undertaking in the context of climate change. It is essential to formulate and execute forest management methods that would aid in preserving their ecological functions and stability. This encompasses the selection of climate-resilient tree species capable of enduring elevated temperatures, altered precipitation patterns, and other harsh weather phenomena. To preserve the ecosystem services of forests, methods should be used to restore degraded forests and prevent the degradation of forest land. Given the identified trends and changes, there is a growing need for regular monitoring of forest ecosystems.

Despite the importance of the results, the study has several limitations. One of the main ones is the lack of accurate experimental data on changes in forest ecosystems as a result of climate change. The theoretical nature of the study limits the ability to accurately predict the impact of changes on specific forest areas, as different regions may respond differently to climate change. It should also be borne in mind that factors not directly related to climate, such as anthropogenic pressure, can have a significant impact on the state of forest ecosystems. Further study should focus on creating more precise models to forecast the effects of climate change on forest ecosystems, including local variables. This involves examining the adaptive strategies of tree species in response to climate change and formulating techniques for the conservation and restoration of forest ecosystems threatened by global climate change.

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Conflict of Interest

None.

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Екологічні аспекти впливу кліматичних змін на деревні види в лісових екосистемах

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Анотація. Метою дослідження було оцінити, як підвищення температури, зміна режиму опадів та збільшення частоти екстремальних погодних явищ, таких як посухи, повені та заморозки, впливають на стан лісових екосистем, а також визначити можливі наслідки для їх біорізноманіття та стабільності. Дослідження включало аналіз наукової літератури, компаративний аналіз різних сценаріїв кліматичних змін, а також оцінку наявних даних про фізіологічні процеси дерев, таких як фотосинтез, розвиток кореневої системи та зростання дерев. Основними результатами дослідження стали висновки про те, що зміни клімату можуть сприяти посиленню стресових факторів для деяких видів дерев, що в свою чергу може призвести до заміни деревних видів більш стійкими або менш вимогливими до кліматичних умов. Отримані результати мають важливе значення для прогнозування подальших змін у лісових екосистемах та розробки рекомендацій для їх збереження. Одним з ключових висновків була необхідність адаптації лісового господарства до нових кліматичних умов, що включає вибір стійких до змін клімату видів дерев, а також використання стратегій для відновлення деградованих лісів. Також важливо підвищити ефективність моніторингу стану лісових екосистем для своєчасного реагування на зміни та запобігання деградації лісових ресурсів. Прогнозування можливих змін у кліматі й аналіз локальних умов дозволило ефективніше планувати заходи щодо збереження біорізноманіття та екосистемних послуг лісів. Враховуючи отримані дані, можна створити рекомендації для стійкого управління лісами, що сприятиме збереженню їх екологічної та економічної цінності в умовах змін клімату

Ключові слова: флора; біорізноманіття; навколишнє середовище; вразливість видів; рослинність