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Use of environmental indicators to assess the state of forest ecosystems

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Abstract. The purpose of the study was to comprehensively analyse the effectiveness of environmental indicators in determining the state of forest ecosystems and their ability to reflect changes in the ecological balance. During the study, the influence of anthropogenic factors on biomass, soil acidity, and species diversity of forest ecosystems in the Sumy Oblast of Ukraine

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was evaluated. Field studies were conducted to determine the soil acidity, the biomass of plants and animals in anthropogenic and natural forest areas, followed by statistical analysis of the data. The degree of degradation of forest areas as a result of human activity was determined and the environmental consequences of these changes for natural systems were evaluated. The results showed that anthropogenically modified areas have reduced biomass (100 t/ha) and species diversity (20 plant species), increased soil acidity (pH 6.5-7) and high concentrations of nitrates and phosphates, compared to mixed forests, where biomass reaches 200 t/ha, species diversity – 50 species of flora, and soil acidity varies from moderately acidic to neutral (pH 5.5-6). These data confirmed the negative impact of human activity on ecosystems, in particular on biomass and soil acidity. It was established that environmental indicators allow forming a comprehensive picture of the state of ecosystems, which is necessary for making informed management decisions aimed at preserving and restoring ecosystems, and at effective management of natural resources. The results obtained demonstrated serious environmental problems as a result of anthropogenic impact on forest ecosystems. A decrease in biomass and species diversity, and an increase in soil acidity in anthropogenic zones indicate the need for urgent implementation of measures for the conservation and restoration of natural forests. The study will be useful in the context of long-term monitoring of ecosystems, which would allow a more detailed investigation of the dynamics of their changes

Keywords: bioindicators; biodiversity; sustainable development; environmental monitoring; natural environment

Introduction

Forest ecosystems perform critical ecological functions that are fundamental to maintaining the health of the planet. These functions include maintaining biodiversity, which ensures the existence of various plant and animal species, regulating the water cycle that affects climatic conditions, and preserving soil resources that are important for agriculture and food security. However, anthropogenic impacts, including deforestation, pollution and climate change, pose significant threats to the health and functioning of these ecosystems. Determining the state of forest systems is a complex task that requires an integrated approach, because it is associated with a variety of factors that affect them, such as changes in the species composition of flora, soil degradation, and socio-economic factors that can affect the management of forest resources. It is important to conduct regular monitoring and assessment of the state of forest ecosystems to timely detect negative changes and take appropriate measures for their conservation and restoration.

Modern research actively highlights the use of various environmental indicators for monitoring the state of the environment. F. Pendrill *et al.* (2019) investigated the role of various environmental indicators in monitoring forest ecosystems in the context of climate change. They focus on integrating vegetation biomass and soil quality data for a comprehensive ecosystem assessment, so their study highlights the importance of a multi-factor approach to more accurately assess the impact of climate change on forest ecosystems. R. Pilli & A. Pase (2018), A.M.I. Kallio (2024) focus on methods for measuring biodiversity as indicators of environmental change in forests. They compare different

approaches to assessing species diversity, noting the advantages and disadvantages of each method, which helps to determine the most effective tools for monitoring forest ecosystems.

A. Koshel *et al.* (2024) and S. Hirahara (2020) offered new methods for assessing the state of forest ecosystems, in particular, by analysing soil and water pollution levels. The studies by these researchers demonstrate how these indicators can be used to identify problem areas and predict environmental changes. R. Haines-Young & M. Potschin (2017) examined the role of environmental indicators in territory planning and forest management. Their study emphasised the importance of integrating environmental data into management strategies to preserve ecosystems and improve their sustainability. N. Tsehelnyk (2021) analysed environmental indicators in the context of regional ecosystems, this study highlighted the importance of local factors in monitoring and managing forest ecosystems, and the role of national and international standards. S. Liu *et al.* (2023) and S. Huang *et al.* (2011) focused on the use of remote sensing to assess the state of forest ecosystems. Their results show how the latest technologies can be used to collect data on environmental indicators, which allows for more efficient resource management. I. Hartmane *et al.* (2024) examined the application of environmental indicators to assess the health of forest ecosystems under variable environmental conditions. Their study examined various approaches to collecting and integrating them to assess the overall state of ecosystems.

The conclusions of these studies indicate significant progress in the development and application of environmental indicators for monitoring forest ecosystems. Despite this, many of these studies do not comprehensively cover the relationship between different environmental indicators and their ability to reflect dynamic changes in ecosystems. Existing research mainly focuses on individual aspects, such as air or water pollution levels and species diversity, without properly integrating these data into an overall assessment of the state of ecosystems. This leads to a lack of understanding of how these indicators interact with each other and how their changes can affect overall environmental stability. It is important to pay attention to the need to develop integrated models that consider not only individual indicators, but also their interaction, to provide a more accurate and comprehensive assessment of the environmental state. Such approaches can contribute to better management of natural resources and conservation of biodiversity, because only through systematic analysis can key factors affecting the health of ecosystems be identified. In this context, there is an urgent need for a comprehensive study that will help to better understand the effectiveness and accuracy of environmental indicators for a comprehensive assessment of forest ecosystems. This research is important because forest ecosystems perform critical functions such as maintaining biodiversity, regulating climate, and providing ecosystem services that directly affect human well-being. The problematic issue of this study is to determine which environmental indicators most adequately reflect changes in the state of forest ecosystems in the context of various anthropogenic impacts, such as deforestation, pollution, and climate change.

The purpose of the study is a detailed analysis of the effectiveness of various environmental indicators in determining the state of forest ecosystems, and an assessment of their ability to provide reliable data for making informed management decisions.

Materials and Methods

The study was conducted from July 2023 to June 2024 in the forest ecosystems of the Sumy Oblast, Ukraine. The study covered three sites in

different types of forest ecosystems within the Sumy geobotanic district, in particular: mixed forests, coniferous forests, and areas affected by anthropogenic impact. Throughout the year, research was conducted to assess seasonal fluctuations in environmental indicators and their changes due to various factors. Various types of forest plots were selected to ensure representativeness, including natural and anthropogenic areas. The sample included vegetation, soil, and water samples.

Vegetation species diversity was determined by detailed identification of plants in samples that were collected at each individual site. This process included not only a description of the flora found at these sites, but also a systematic count of the number of species, which allows for a more in-depth analysis of the ecosystem. The study also considered various factors, such as environmental conditions, soil types, and climatic conditions that can affect plant distribution and growth, so the results contribute to a better understanding of the region's biodiversity and its ecological relationships.

Standard instruments for field measurements and laboratory materials for analysis were used. To collect data on vegetation biomass and species diversity, calipers were used to measure tree diameter, squares to assess vegetation cover, and trimmers to take plant samples. Chemical analyses of soil and water were performed using spectrophotometers (model UV-1800, Shimadzu, Japan) to determine the level of pollutants, pH meters (model pH 3110, Wissenschaftlich-Technische Werkstätten, Germany) to assess acidity, and scales (ExplorerEX2202, Ohaus, USA) to accurately measure samples. Aerial photography was used to assess changes in the landscape and biomass (drone – DJI Phantom 4 RTK, DJI, China).

For contextual comparison, archival data on forest ecosystems of Sumy Oblast and regulatory documents on the management of forest resources in Ukraine were used, namely: Forest Code of Ukraine (1994) – the main regulation of relations in the field of forest protection, use, and reproduction. The Law of Ukraine No. 1264-XII "On Environmental Protection" (1991) – defines the general principles of environmental protection, including forest resources. The Law of Ukraine No. 2456-XII "On the Nature Reserve Fund of Ukraine" (1992) – regulates the creation, organisation and protection of territories and objects of the nature reserve fund, which include forest ecosystems. The Law of Ukraine No. 1862-IV "On Ecological Audit" (2004) – establishes the legal basis for ecological audit, which includes an assessment of the ecological state of forest resources. Resolution of the Cabinet of Ministers of Ukraine No. 521-2014-p "On Approval of the Regulation on State Control in the Field of Forestry" (2014) – regulates state control over the use and protection of forest resources.

The pilot study followed institutional, national and international guidelines. The authors of the study followed the standards of Convention on Biological Diversity (1992) and Convention on International Trade in Endangered Species of Wild Fauna and Flora (1979).

Results

Analysis of environmental indicators in different types of forests is a key to understanding their resilience and adaptive capabilities in response to changing environmental conditions. For mixed forests that include both coniferous and deciduous species, it is important to assess their biodiversity and ecological functions that determine their ability to regenerate and maintain resilience. Coniferous forests, due to their specific flora and fauna, have unique needs that require a separate approach to monitoring the impact of anthropogenic changes (The Law of Ukraine No. 1862-IV, 2004). On the other hand, anthropogenic sites often lose some of their

natural function, which requires special measures to restore ecological balance. After conducting an experiment, the following results were obtained. The average vegetation biomass in mixed forests was 200 t/ha, which indicates significant ecosystem productivity. This result is closely related to the large species diversity, which includes numerous species of trees, shrubs, and herbaceous plants. It is important to note that mixed forests are characterised not only by a variety of species, but also by a high density of vegetation, which creates optimal conditions for the development of various organisms. Such ecosystems play a critical role in maintaining ecological balance, as they provide habitat for many animal species, including birds, mammals, and invertebrates. The conservation and protection of such forests is extremely important for the conservation of biodiversity, as they serve as a food source and shelter for many living things. Mixed forests contribute to climate regulation by preserving carbon and reducing the negative impact of climate change.

The average biomass in coniferous forests was 160 t/ha, i.e., a decrease in biomass, which can be explained by the relatively low diversity of vegetation species, and a limited amount of undergrowth. This phenomenon is conditioned by the specifics of the ecological conditions that form coniferous forests. Usually, such forests are characterised by a more uniform vegetation structure, which leads to the fact that the undergrowth, which includes young trees, shrubs, and herbaceous plants, often does not develop properly. The lack of developed undergrowth negatively affects the total amount of biomass in these ecosystems, as the undergrowth performs important ecological functions, such as providing an environment for many animal and plant species, and maintaining soil structure. Thus, to maintain the health and sustainability of coniferous forests, it is important to consider the conservation of species diversity and undergrowth development. Preserving species diversity not only contributes to environmental sustainability, but also provides a balance in the ecosystem that allows it to adapt to climate change and other environmental challenges. Undergrowth development can be achieved through active conservation measures, such as planting new plants, controlling pests and diseases, and managing forest resources, which will create more favourable conditions for the growth and development of various types of vegetation.

The average biomass in anthropogenically modified areas was 100 t/ha. In these areas, a significant decrease in biomass was observed, which was a consequence of the active use of land resources and changes in natural conditions that significantly affected ecosystems. This decline in biomass can be caused by a number of factors, including intensive agriculture, which involves excessive use of chemical fertilisers and pesticides, urbanisation, which leads to the destruction of natural habitats, and climate change, which causes extreme weather events and disrupts the usual ecological balance. Such processes lead to the degradation of natural habitats, a decrease in the diversity of flora and fauna, and to a decrease in soil productivity, which has serious consequences for agriculture and food security. It is important to take urgent measures to restore these areas, in particular through the introduction of sustainable farming practices, the conservation of natural resources, and the creation of protected areas that will not only contribute to the conservation of biodiversity, but also ensure environmental sustainability for future generations, allowing them to enjoy the richness of nature that is available today. To summarise, it is worth adding that mixed forests have the highest biomass, as shown in Figure 1, due to their large species diversity and dense vegetation, which contributes to high ecosystem

productivity. Coniferous forests have less biomass due to the uniformity of vegetation and poor undergrowth. Anthropogenically modified areas have the lowest biomass due to active land use and ecosystem degradation. It is important to take measures to restore such areas and preserve the natural balance.

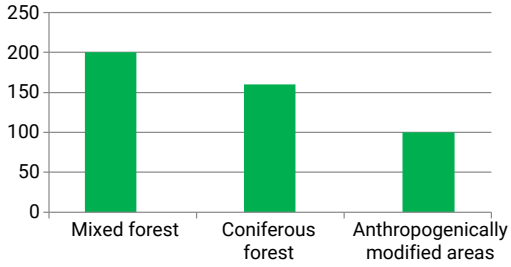

Figure 1. Distribution of vegetation biomass in different types of forests, t/ha

Source: developed by the authors based on Forest Code of Ukraine (1994)

Based on the results of the analysis of the species diversity of vegetation, the following data were obtained: mixed forest – 50 plant species were identified, which indicates a high species diversity and richness of the flora of this region. This is evidence of ecological stability and ecosystem health, as species diversity is an important indicator of biological activity and adaptive capacity of nature. The mixed forest in which these species have been recorded is characterised by a variety of both woody and herbaceous plants, which creates unique conditions for the development of many animal and plant species, and provides important ecological functions such as air purification, water conservation and soil fertility support. During the study of coniferous forest, 35 plant species were identified, which indicates an average level of flora diversity in this region. Coniferous forests, which occupy a significant part of the territory, are characterised by a smaller number of plant species compared to other types of forests. This is conditioned by the fact that coniferous forests mainly consist of coniferous trees, such as pines, firs and firs, which create special conditions for the growth of other plants. As a result, the undergrowth in such forests is less developed, which limits the opportunities for the development of broad-leaved plants and herbaceous species, so the ecosystem of coniferous forests is more homogeneous, which affects the overall biodiversity of these territories. As a result of the conducted studies, 20 different plant species were identified in anthropogenically modified areas, which indicates a low level of biodiversity in these ecosystems. However, a significant decrease in species diversity in these areas is caused by many factors related to human activity, including urbanisation, agricultural expansion, and environmental pollution, which lead to reduction in flora. As a result, not only the number of species decreases, but also the sustainability of ecosystems, which can have negative consequences for the ecological balance and environmental health. Figure 2 shows the number of plant species in each type of forest.

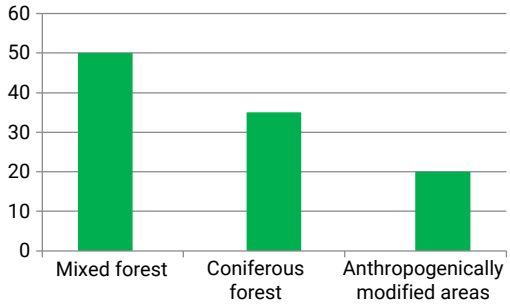

Figure 2. Distribution of species diversity in different types of forests, number of plants species

Source: developed by the authors based on Forest Code of Ukraine (1994)

Soil acidity was assessed using pH meters, which made it possible to obtain accurate data

on the level of acidity in different areas. The results showed that in mixed forest, the pH of the soil ranges from 5.5 to 6, which indicates a moderately acidic reaction. This level of acidity is optimal for the growth and development of many plant species, as it promotes better absorption of nutrients. Moderately acidic soil provides a balance between the availability of trace elements, such as iron and manganese, and prevents excessive activity of toxic elements, so this pH level creates favourable conditions for various plant species, which allows them to develop effectively and ensure high yields. In coniferous forests, the pH of the soil, which ranges from 4.5 to 5, indicates an acidic environment that can have a significant impact on the ecosystem. In such conditions, specific conditions for plant growth are created, since many plant species prefer acidic soils. Coniferous forests, which are usually characterised by a high level of soil acidity, create special ecological niches that affect the species diversity of the undergrowth. This environment promotes the development of certain plant species that can adapt to such conditions, and also limits the distribution of other species that require less acidic soils, so soil acidity is an important factor determining the ecological structure and biodiversity of coniferous forests. The anthropogenically modified areas had a soil pH ranging from 6.5 to 7, which is considered neutral to alkaline, which is optimal for most crops. Neutral acidity in these areas can be a consequence of the use of fertilisers that contain a variety of macro- and microelements necessary for plant growth. In addition, anthropogenic factors, such as changes in land cultivation methods, the use of agrochemicals, and the impact of agricultural activities, can significantly affect the chemical composition of the soil, highlighting the importance of monitoring soil pH to ensure sustainable farming and preserve soil fertility. Figure 3 shows the maximum soil pH values for each forest type.

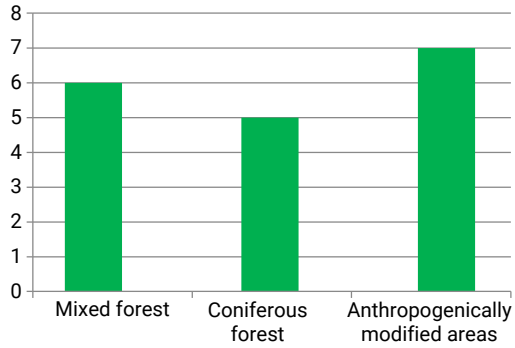

Figure 3. Maximum level of soil acidity in different types of forests, soil pH

Source: developed by the authors based on Forest Code of Ukraine (1994)

Indicators of nitrate and phosphate concentrations are important components in determining the level of water pollution, since their excessive presence can indicate a negative impact of anthropogenic activities on ecosystems. Measuring nitrate and phosphate concentrations allows not only to assess the current state of water, but also to identify potential sources of pollution, which is crucial for developing effective environmental protection measures (Matkivskyi & Taras, 2024). The study found that the level of water pollution in the mixed forest was assessed as moderate, which indicates that there are no serious environmental threats to the environment and public health. The concentrations of nitrates and phosphates shown in Table 1 remained within acceptable limits, which indicates the effectiveness of water quality control measures. It also highlights the importance of maintaining ecological balance, as the stable state of water resources is crucial for maintaining biodiversity and ecosystem health. Such results may indicate the proper state of water protection zones, which serve as natural barriers that prevent water pollution. Compliance with the standards established for the protection of water resources is an important

indicator of the effectiveness of environmental policy in the region, which indicates the need to continue monitoring and implement additional measures to maintain high water quality and ensure sustainable development of the territory (The Law of Ukraine No. 1264-XII, 1991; The Law of Ukraine No. 2456-XII, 1992). The concentrations of nitrates and phosphates in the coniferous forest samples under study were recorded at a level slightly higher than the recommended norms, as can be seen from Table 1, however, these indicators did not reach critical levels that could significantly affect the environmental situation or public health. This indicates the relative stability of the ecological state in the region, but it is important to continue systematic monitoring of these parameters. Regular monitoring will ensure their stability within safe values, and timely detection of any deviations that may lead to potential negative consequences for the environment and human health. Therefore, systematic monitoring is an important tool for maintaining environmental balance and preventing possible threats. Increased levels of environmental pollutants were found in anthropogenic sites, indicating a significant impact of anthropogenic factors such as industrial activity, agriculture, and urbanisation. Nitrate and phosphate concentrations exceed the permissible limits, which is described in detail in Table 1. This is a wake-up call and indicates serious water pollution, which can have negative consequences not only for ecosystems, but also for human and animal health. Increased levels of these pollutants can lead to degradation of water resources, which will affect the quality of water used for drinking and irrigation of crops. In the face of global climate change and growing pressures on natural resources, urgent measures must be taken to monitor and reduce pollution. This should include developing and implementing effective waste management strategies, improving wastewater treatment technologies, and enhancing environmental education among the population. Only thro ugh joint efforts can we ensure environmental safety and preserve natural resources for future generations.

Table 1. Concentrations of pollutants in water of different types of forest areas

Type of forest	Nitrates (mg/l)	Phosphates (mg/l)
Mixed forest	5	0.5
Coniferous forest	6.5	0.7
Anthropogenically modified areas	12	1.2

Source: developed by the authors

The data obtained confirmed that the negative impact of anthropogenic factors on the state of forest ecosystems is significant and has numerous negative consequences. In particular, several key aspects were identified that indicate this. Reduction of vegetation biomass in anthropogenically modified areas compared to natural forests. This suggests that human activities such as deforestation, urbanisation, and agricultural development lead to a significant reduction in vegetation, which affects the ecosystem services that forests provide, such as air purification and biodiversity conservation (Resolution of the Cabinet of Ministers of Ukraine No. 521-2014-p, 2014). Reduction of species diversity in anthropogenically modified areas due to changes in natural conditions and human intervention. This means that as a result of anthropogenic impacts, such as the introduction of invasive species, pollution,

and habitat changes, many plant and animal species are lost, which can lead to a violation of the ecological balance and reduce the sustainability of ecosystems Increased levels of water pollution and changes in soil acidity in anthropogenically modified areas. In particular, water pollution from industrial waste and agricultural pesticides negatively affects aquatic ecosystems, while changes in soil acidity can lead to degradation of soil resources and reduced forest productivity, which can also have serious consequences for the health of plants and animals that depend on these ecosystems.

Thus, the results highlight the need to take urgent measures to preserve and restore forest ecosystems, and to reduce the negative impact of anthropogenic factors on the environment.

The study also analysed the effectiveness of various environmental indicators to determine the state of forest ecosystems and assess their ability to provide reliable data for management decisions. A key indicator of ecosystem productivity is vegetation biomass. The results showed that mixed forests have the highest biomass of 200 t/ha compared to coniferous forests (160 t/ha) and anthropogenically modified areas (100 t/ha). High levels of biomass in mixed forests confirm their significant ecological productivity, while reduced biomass in anthropogenic areas indicates a negative impact of human activity. Vegetation biomass is an important indicator for assessing ecological productivity and ecosystem health for several reasons. It reflects the total amount of organic mass produced by plants, and thus serves as an indicator of ecosystem productivity, noting its ability to effectively use resources for plant growth and development. Higher biomass is often associated with greater species diversity and the ecosystem's ability to maintain diverse ecological niches, which contributes to the overall health of the ecosystem. In addition, vegetation performs numerous ecological functions such as water retention, soil structure maintenance, and climate regulation, providing important functions for biodiversity. Therefore, the analysis of vegetation biomass is key to assessing the ability of ecosystems to maintain ecological balance and effectively perform their functions.

Species diversity is critical to ecological stability. The results of the study show that mixed forests have the most plant species (50), while coniferous forests – 35, and anthropogenically modified areas – 20. The high species diversity in mixed forests indicates their ecological stability and ability to support diverse ecological functions. Species diversity is an important indicator of ecological sustainability, as it reflects the ability of an ecosystem to support diverse species and functions that ensure its stability and adaptability. A wide variety of species contributes to an increase in ecological poverty, which helps the ecosystem adapt to changes such as climate change or environmental disturbances. This diversity also supports complex interactions between species, which contributes to the sustainability of the ecosystem and its ability to recover from stressful conditions or disturbances. That is, high species diversity is important for maintaining functional integrity and ecological balance in natural systems. Soil acidity affects the availability of nutrients for plants. The results of the experiment showed that mixed forests have moderately acidic soil (pH 5.5-6), coniferous forests have acidic soil (pH 4.5-5), and anthropogenic altered areas have neutral or alkaline soil (pH 6.5-7). This indicates the specific environmental conditions of each type of forest. Soil acidity is an important environmental indicator, as it directly affects the availability of nutrients for plants. The optimal pH level ensures efficient absorption of elements such as iron and calcium, which is critical for plant growth and development. Deviations from normal pH values can limit the

availability of these elements, which leads to a decrease in plant productivity and a violation of the ecological balance. This indicator affects microbiological activity, since some beneficial microorganisms that maintain soil fertility have specific pH requirements. Accordingly, monitoring of soil acidity is key to maintaining the ecological sustainability and productivity of ecosystems, as it helps to identify and correct problems that may arise as a result of its degradation or pollution.

Nitrate and phosphate concentrations are crucial for assessing water pollution. In mixed forests, the level of pollution was moderate, in coniferous forests – slightly increased, and in anthropogenically modified areas – high. This indicates a different level of anthropogenic impact on water resources. Monitoring nitrate and phosphate concentrations is important because these elements are key indicators of water pollution. High concentrations of nitrates and phosphates can indicate a negative impact of anthropogenic factors, such as agriculture or industrial activity, leading to problems such as eutrophication of water bodies. Eutrophication causes excessive algae growth, which can disrupt the ecological balance, reducing oxygen levels in the water and harming aquatic organisms. Therefore, monitoring these concentrations is crucial for assessing water quality, ensuring sustainable water management, and preventing serious environmental problems. Combined analysis of biomass, species diversity, soil acidity, and water pollution levels provides a comprehensive picture of the state of forest ecosystems. These indicators provide important information for making informed management decisions aimed at preserving and restoring ecosystems. Systematic monitoring and analysis of environmental indicators are critical to developing effective management strategies and ensuring the sustainability of natural resources in the long term.

Discussion

The study carefully analysed a number of environmental indicators, in particular biomass, species diversity and soil acidity in forest ecosystems of the Sumy region. This integrated approach helped to better understand environmental trends and identify changes that occur in these systems under the influence of natural and anthropogenic factors. The findings revealed clear differences between different types of forests, such as coniferous, deciduous, and mixed forests, and between anthropogenically modified areas, which confirms and complements existing scientific data in this area.

The results of the conducted studies indicate that anthropogenically modified areas are characterised by significantly lower biomass and higher soil acidity. These facts confirm the negative impact of human activities on ecosystems, which is a serious problem for the conservation of biodiversity and ecological balance. Studies conducted by R. Bun *et al.* (2024) and J. Reiff *et al.* (2024) are consistent with these findings because it details the increase in greenhouse gas emissions resulting from military operations in Ukraine. This increase in emissions not only worsens the state of the environment, but also contributes to a further increase in the level of acidity in anthropogenically modified areas. The increase in soil acidity is a consequence of increased pollution caused by various factors, in particular, the loss of organic components in the soil, which, in turn, negatively affects land fertility and the ability of ecosystems to recover (Gonfa, 2024).

In the course of the study, it was found that species diversity in forests decreases due to intensive land use, which partially echoes the findings of V. Myroniuk *et al.* (2022) and D. Pilling *et al.* (2020). They analysed in detail the impact of wildfires on various landscapes in Eastern Ukraine, focusing on how such natural disasters can change ecosystems and their

biological diversity. The researchers stressed the importance of systematic monitoring and effective management of forests after fires, as this is crucial for restoring ecosystems and maintaining their health. They noted that these strategies should also be applied to anthropogenically modified areas where human activity has significantly affected natural processes. This highlighted the need to integrate environmental principles into land management practices to ensure the sustainable development of forest ecosystems and preserve their biological diversity in the future.

The results of the study confirm the importance of using environmental indicators for a comprehensive assessment of the health of forest ecosystems. This is consistent with the findings presented in the papers by L. Qiao *et al.* (2022), V. Carignan & M. Villard (2002), L. Su *et al.* (2024). Environmental indicators play a key role in understanding changes occurring in ecosystems, as they help to identify trends and patterns that may indicate the state of the environment. In addition, these indicators provide a reliable basis for developing strategies for the conservation and management of natural resources. The use of indicators for monitoring ecosystems has become an important tool that allows not only to assess the sustainability of ecosystems, but also to analyse their performance in various conditions, which contributes to making informed decisions in the field of environmental management and biodiversity conservation (Fedoniuk *et al.*, 2024).

The study found that a high level of species diversity has a positive impact on ecosystem services, which is confirmed by E. Babur *et al.* (2022). This study highlights the critical importance of biodiversity for monitoring the sustainability of forest ecosystems, as species diversity ensures the stability and adaptability of ecosystems to environmental changes. The high level of biodiversity in the forests studied not only contributes to better functioning of ecosystems, but also increases their ability to recover from environmental stresses such as climate change or anthropogenic impacts. This suggests that the conservation and maintenance of biodiversity is key to ensuring the sustainability and productivity of forest ecosystems in the long term (Bragina *et al.*, 2018).

The research results highlighted the urgent need for further research, particularly in the context of climate change and its impact on forest ecosystems, which are important for biodiversity and environmental stability. The study by H. Beygi Heidarlou *et al.* (2023) highlighted the importance of using environmental indicators for a comprehensive assessment of forest health in the long term. These indicators may include species diversity, soil and water conditions, and other factors affecting ecosystems. This highlights the need for continuous monitoring and detailed analysis of changes caused by global climate change; as such changes can have serious consequences for the ecological balance and sustainable development of forest resources.

Research conducted by N. Kovalchuk & N. Tolstushko (2022) identified a significant impact of the war in Ukraine on forest phytocenoses, which is an important aspect of environmental changes in the region. The present study confirms these findings by demonstrating in detail the negative changes in ecosystems resulting from human activity and military conflicts. These changes include, but are not limited to, reduced species diversity, degradation of natural habitats, and disruption of ecological balances. L. Bezlatnia *et al.* (2024) also stressed the critical importance of biodiversity conservation for providing ecosystem services such as air purification, climate regulation, and food security support. Their findings support the results that highlight the importance of biodiversity for ecosystem health and their ability to adapt to environmental

changes, highlighting the need for action to protect and restore natural ecosystems, especially in the face of current challenges related to conflict and climate change.

Results of studies conducted by M. Jenssen *et al.* (2021) and P. Eslaminejad *et al.* (2020), concerned the methodology for assessing the integration of forest ecosystems in Germany, which is based on quantitative indicators. These results not only confirm the validity of the research methodology, but also highlight the importance of using clear, evidence-based indicators for a comprehensive assessment of the state of ecosystems, which is critical to ensuring effective management of natural resources and biodiversity conservation. The use of such indicators allows not only to monitor changes in ecosystems, but also to develop strategies for their conservation and restoration, which is an integral part of sustainable development.

M. Ali Mustofa (2022) emphasised the extreme importance of ecotourism as a tool for socio-economic development, and for the conservation of natural ecosystems. Ecotourism not only contributes to economic growth, but can also become an important factor in developing effective forest conservation strategies in Ukraine (Trusova *et al.*, 2020). This approach involves the active participation of local communities in the conservation of natural resources, which, in turn, can encourage the development of eco-tourism in regions rich in natural resources. Implementation of such strategies can significantly support the health of forest ecosystems, preserve their biodiversity, and promote the economic development of local communities that depend on the sustainable use of natural resources. Thus, ecotourism becomes not only a means of generating profit, but also an important element in preserving the environment and developing regions.

E.B. Salas (2024) and R. Zuccarini *et al.* (2020) provided detailed data on changes in forest area in Ukraine, which is an important aspect for a deeper understanding of general trends in the country's forest cover. These data can serve as a basis for comparison with these results, which allows identifying specific regional features and changes in ecosystems. The decline in forest cover in Ukraine may be partly due to anthropogenic impacts such as deforestation, environmental pollution, and climate change (Belmega *et al.*, 2024). These factors require serious attention from the state and society to ensure sustainable forest management, which will contribute to the conservation of biodiversity and environmental stability in the region.

Summarising, the results of the study not only confirm the conclusions of previous studies, but also complement them, providing new data on the impact of anthropogenic factors, such as changes in land use, air and water pollution, and climate change on the state of forest ecosystems in Ukraine. These new findings are extremely important for understanding the complex relationships between human activity and natural processes occurring in forests. They can serve as a basis for developing effective forest conservation and restoration strategies, which is critical in the context of global changes, such as climate warming, and local environmental challenges faced by various regions of Ukraine. The development of such strategies will not only preserve biodiversity, but also provide environmental, economic, and social benefits for future generations.

Conclusions

The study found that anthropogenically modified territories in the Sumy Oblast have significantly reduced biomass and increased soil acidity compared to natural forests. It is revealed that species diversity in forest ecosystems is directly related to the level of anthropogenic impact, where intensively exploited territories

show less diversity of flora and fauna. The obtained qualitative indicators confirm the negative impact of anthropogenic factors on ecosystems, which is consistent with the results of international studies on biodiversity loss and forest degradation.

Assessment of environmental indicators such as vegetation biomass, species diversity, soil acidity, and nitrate and phosphate concentrations is a key to providing reliable data for making informed management decisions. It was found that mixed forests with high biomass (200 t/ha) and the greatest plant species diversity (50 species) show the highest ecological productivity and stability, which indicates their ability to support various ecological functions. Compared to them, coniferous forests (biomass 160 t/ha, 35 species of flora) and anthropogenically modified areas (biomass 100 t/ha, 20 species of plants) show lower productivity and stability. Soil acidity, which varies from moderately acidic to neutral depending on the type of forest, affects the availability of nutrients for plants, and high concentrations of nitrates and phosphates in anthropogenic areas indicate problems with water pollution. These indicators allow to develop a comprehensive picture of the state of ecosystems, which is necessary for making informed management decisions aimed at preserving and restoring ecosystems, and at effective management of natural resources.

The results highlight the critical importance of preserving natural forest ecosystems and the need to implement effective measures to reduce anthropogenic impact. The data confirm trends in environmental degradation as a result of human activities, which have significant implications for biodiversity and ecosystem services. It is recommended to focus on developing and implementing strategies to reduce anthropogenic impact, such as preserving natural forests, restoring degraded areas, and controlling resource use. It is also necessary to strengthen monitoring of the ecological state of forests and regularly update data on the state of ecosystems.

Further research may focus on the impact of climate change and human activity on environmental performance, and on long-term monitoring of changes in forest ecosystems. It is also useful to investigate the effectiveness of various methods of forest restoration and natural resource management.

The main limitations include the limited scale of the study, which may affect the generality of the results, and the possible unreliability of some measurements due to environmental changes. In addition, the impact of other potential factors, such as climate change or the impact of biological invasions, has not been considered in detail and may affect the accuracy of the data obtained.

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Conflict of Interest

None.

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Використання екологічних показників для оцінки стану лісових екосистем

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Анотація. Метою дослідження був всебічний аналіз ефективності екологічних показників у визначенні стану лісових екосистем, а також їх здатності відображати зміни в екологічному балансі. Під час дослідження було оцінено вплив антропогенних факторів на біомасу, кислотність ґрунту та видове різноманіття лісових екосистем в Сумській області України. Проведено польові дослідження, де визначалися кислотностність ґрунту, біомаса рослин і тварин на антропогенно змінених і природних ділянках лісів з подальшим статистичним аналізом даних. Визначено ступінь деградації лісових територій внаслідок людської діяльності та оцінено екологічні наслідки цих змін для природних систем. Результати показали, що антропогенно змінені ділянки мають знижену біомасу (100 т/га) і видове різноманіття (20 видів рослин), підвищену кислотність ґрунту (pH 6,5-7) та високі концентрації нітратів і фосфатів, в порівнянні з мішаними лісами, де біомаса досягає 200 т/га, видове різноманіття – 50 видів флори, а кислотність ґрунту варіює від помірно кислого до нейтрального (pH 5,5-6). Ці дані підтвердили негативний вплив людської діяльності на екосистеми, зокрема на біомасу та кислотність ґрунту. Встановлено, що екологічні показники дозволяють формувати комплексну картину стану екосистем,

що є необхідною для прийняття обґрунтованих управлінських рішень, спрямованих на збереження та відновлення екосистем, а також на ефективне управління природними ресурсами. Отримані результати продемонстрували серйозні екологічні проблеми в наслідок антропогенного впливу на лісові екосистеми. Зменшення біомаси та видового різноманіття, а також підвищення кислотності ґрунту в антропогенно змінених зонах вказують на потребу в терміновому впровадженні заходів для збереження і відновлення природних лісів. Дослідження буде корисним у контексті довгострокового моніторингу екосистем, що дозволить більш детально вивчити динаміку їх зміни

Ключові слова: біоіндикатори; біорізномаїття; сталий розвиток; моніторинг довкілля; природне середовище