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CLIMATIC RISKS AND FOREST ECOSYSTEMS: THE INTERACTION BETWEEN DEFORESTATION AND CLIMATE CHANGE

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The article provides a comprehensive analysis of the interaction between deforestation and climate change, with particular emphasis on the impact of military actions on the reduction of forest ecosystems. The research utilized general scientific methods (data analysis and synthesis), retrospective and comparative analysis, analytical-synthetic methods (study of scientific and statistical data, archival materials, etc.), and remote sensing techniques. The aim of the study was to identify the main causes of the reduction in forested areas in Ukraine and their role in the context of global climate change, as well as their significance for the socio-economic development of the country during wartime and the post-war period. The role of forest ecosystems as a source of a wide range of ecosystem services and as a significant component of the socio-economic status of the Ukrainian Polissya region is analyzed. Special attention is given to the interaction between the reduction of forest-covered areas and the intensification of climate change. The main factors contributing to the reduction of Ukraine's forest ecosystems are presented, with a particular focus on forest fires, including those caused by military actions. It was established that from April 2023 to April 2024, the highest number of forest fires occurred in the eastern and southern parts of the country, where active military actions are ongoing. An automated methodology for decoding satellite images to detect areas of Scots pine dieback due to infestation by the pine shoot beetle was developed, resulting in a map of the study area showing the boundaries of forestry districts, the grid of forest compartments, the contours of damaged forest areas, and new dieback hotspots. The study demonstrates that forest ecosystems are essential for mitigating climate change and ensuring sustainable regional development. This is particularly true for the Ukrainian Polissya region, especially Zhytomyr Oblast, which has the highest forest cover in the country but also leads in the loss of forest-covered areas.

Keywords: *climate change, forest ecosystems, forest fires, ipid bark beetle, satellite monitoring.*

INTRODUCTION

Among terrestrial ecosystems, forests play the most significant ecological role due to their complexity, biological productivity, and regulatory capacity. This results in maximum levels of carbon sequestration, water utilization, water storage accumulation, and enrichment of the atmosphere with moisture and oxygen. The role of forest plantations and shelterbelts in agriculture is particularly notable, as they contribute to soil cover preservation and increased crop yields while minimizing the need for intensive technologies. The preservation of forests, expansion of forested areas, improvement of forest structure, and enhancement of productivity are also economically important, not only in terms of increasing raw material potential but also in the valuation of carbon emission quotas and their absorption from the atmosphere. This latter factor depends on various conditions, including forest growing conditions, species composition, structural features of ecosystems, and the age and condition of stands.

The volumes of carbon dioxide sequestration, which are crucial for establishing emission quotas, are determined according to the area of forest vegetation and the average current productivity of forests. Considering the comprehensive role of forest ecosystems, their impact on the socio-economic well-being of adjacent areas must be noted. Thus, the area and quality of forest plantations are significant factors influencing the state's fulfillment of international climate commitments and the achievement of sustainable development goals. This is especially relevant for traditionally forested areas such as Ukrainian Polissya, where forest ecosystems, predominantly composed of coniferous species, cover relatively large areas and play a substantial role in the economic balance of the region.

The overall forest cover of our country is low — 15.9% [1]. Before the onset of full-scale Russian military aggression, Ukraine ranked 7 th (as of 2022, now 9 th) in Europe in terms of forest area and 6th in timber reserves [2]. Due to the direct and indirect impacts of climate change, such as the spread of pests and diseases, as well as anthropogenic influences, the forested areas of Ukraine are diminishing. For the pine plantations of Ukrainian Polissya, bark beetles (family *Scolytidae*) pose a particular threat, as their activity leads to the mass dieback of pine stands. From 2001 to 2021, the regions of Ukrainian Polissya — Zhytomyr, Rivne, Kyiv, Volyn, and Chernihiv oblasts (in descending order) — were leaders in the loss of forest-covered areas. The first four of these accounted for 52% of the country's loss of forest-covered areas [3].

Forest fires, both natural and anthropogenic, pose an additional threat to Ukraine's forest ecosystems and risk accelerating climate change. Overall, there is a trend in Ukraine of increasing loss of forest-covered areas due to fires. According to Global Forest Watch, over the past decade, the greatest loss of forest plantations due to fires has been characteristic of Polissya [3]. Active military actions have caused additional significant losses and extensive damage to Ukraine's forest ecosystems.

Given the apparent critical role of forest ecosystems in various spheres of human activity, the preservation and expansion of forested areas deserve special attention, particularly now, when the loss of forest-covered areas is critical. Therefore, **the aim of our study** was to outline the main causes of the reduction in forested areas in Ukraine, their role in the context of global climate change, and their importance as a key component of the country's socio-economic development during wartime and the post-war period.

ANALYSIS OF RECENT RESEARCH AND PUBLICATIONS

Contemporary climate changes are leading to the deterioration of growth conditions, reduced biological stability, and the weakening of trees, resulting in increased susceptibility to insect pests and diseases. Of particular concern is the damage to forest plantations caused by harmful insects, which have found climate change to be especially favorable.

The mass infestation of coniferous plantations by bark beetles has become a global issue, affecting many countries, including North America, Central Europe, and Asia [4–10]. The ipid pine bark beetle has always been a regular inhabitant of pine forests, primarily infesting isolated weakened and fallen pine trees. Currently, dry and warm weather conditions are favorable for its mass reproduction, posing a significant threat to the integrity of pine ecosystems. This pest can now produce several generations per year, significantly increasing its destructive impact [11–13].

One of the factors contributing to the reduction of forest cover in our country is anthropogenic activity, both legal and illegal. According to Global Forest Watch [3], this has been the predominant cause of the reduction in forest-covered areas in Ukraine since at least 2012. Since 2022, the problem of forest loss due to pyrogenic effects caused by military actions has reached catastrophic proportions in Ukraine. Currently, approximately 40 state forestry enterprises, managing 600,000 hectares of forests out of a total of approximately 10.5 million hectares, are under occupation. Preliminary estimates indicate that as of the end of 2022, direct damages from military actions amounted to 13.2 million UAH [14]. However, there are also so-called indirect damages, which are challenging to assess, partly because the issues of de-occupation and demining of territories remain unresolved, and the figures for losses continue to rise.

While the scale of legal and illegal logging can be somewhat regulated institutionally, climate change and military actions are threats beyond our control. However, we can monitor the situation and develop compensatory measures and alternative strategies for forest management. Remote sensing methods (RS) can be effectively applied to identify damaged forest areas and their reduction due to various factors, including the detection of pine tree dieback hotspots [13; 15–16].

MATERIALS AND METHODS OF RESEARCH

In line with the research objectives, the theoretical foundation was built upon the studies

of domestic and international scholars in the fields of environmental protection, climate change, and remote sensing. Economic-statistical methods (processing of statistical data) and abstract-logical methods (theoretical generalizations and formulation of conclusions) were also employed. The theoretical and informational basis for studying the causes, scales, and trends of the reduction in forested areas in Ukraine included reports from the State Forest Resources Agency of Ukraine, legislative and regulatory acts of Ukraine and the European Union, and data from the Global Forest Watch platform [3].

The study of pine stand dieback due to infestation by bark beetles focused on the pine bark beetle *Ips acuminatus* (Gyllenhal, 1827: *Curculionidae*, *Scolytinae*) in the forest plantations of Polissya, Ukraine. This included state forestry enterprises in the Ovruch and Narodychi districts of Zhytomyr Oblast during 2017–2019.

For remote monitoring of forest conditions, satellite imagery data with medium and high spatial resolution from the European Space Agency's Sentinel-2 satellites were used. The spectral quality coefficient for healthy and pest-infested forest areas was compared across different spectral bands. Automated classification of satellite images, based on a database of reference samples obtained from UAV (unmanned aerial vehicle) route surveys, was conducted using the maximum likelihood method with channel synthesis.

To create the cartographic basis, topographic maps of the study area and electronic maps with the boundaries of forestry districts and forest compartment grids at a scale of no worse than 1 : 100,000 were used. For classification purposes, the Semi-Automatic Classification Plugin for QGIS (Semi-Automatic Classification Plugin for QGIS) was utilized.

RESEARCH RESULTS AND DISCUSSION

Based on the analysis of satellite data, a methodology for automated interpretation of satellite images was developed to identify areas of pine forest dieback due to infestation by the ipid bark beetle. The application of this methodology enables the monitoring of pine stand conditions, early detection of ipid bark beetle outbreaks, determination of affected areas, and prompt planning of forest sanitation measures. This, in turn, helps reduce the loss of pine stands and timber.

The final result of the satellite monitoring and analysis is a map of the study area at a scale of 1 : 50,000, delineating the boundaries of the forest districts (*Fig. 1*), with a forest compartment grid, outlines of damaged forest areas, and new dieback hotspots.

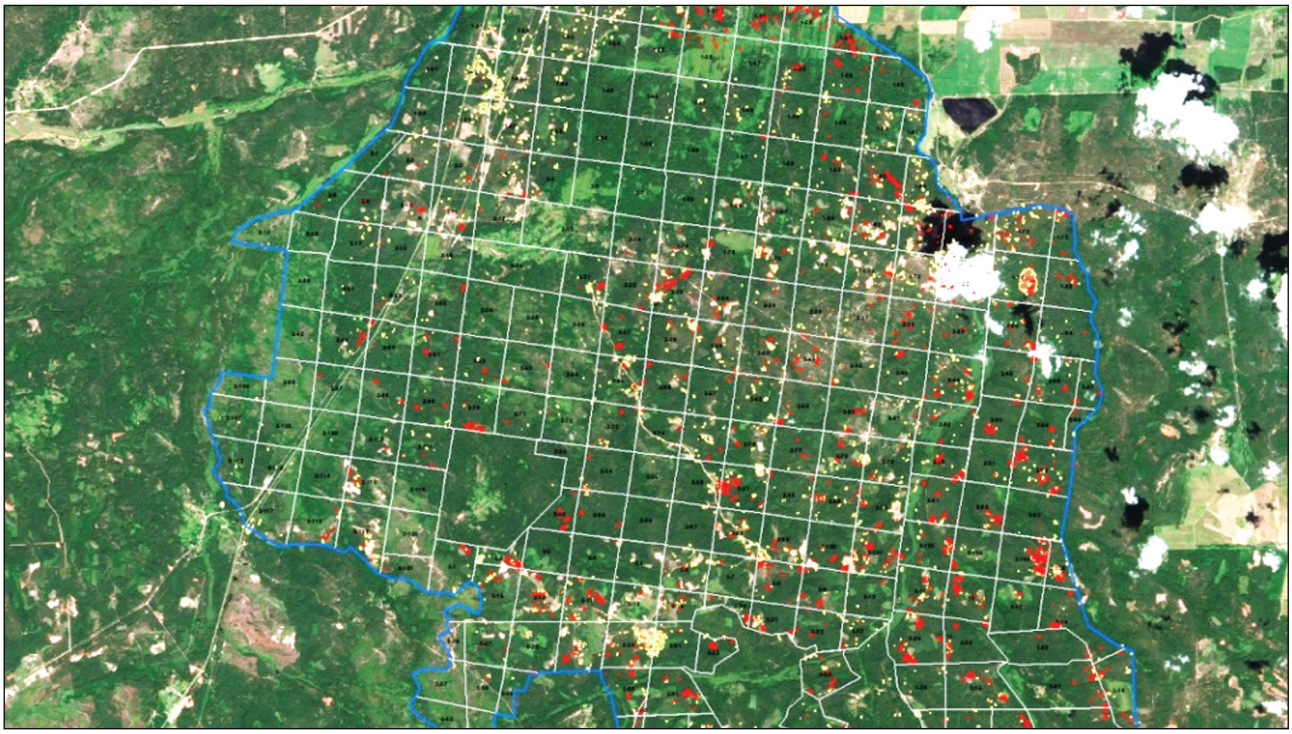

Figure 1. Fragment of the final map showing dieback hotspots (red polygons) in the forest management area

Source: created by the authors.

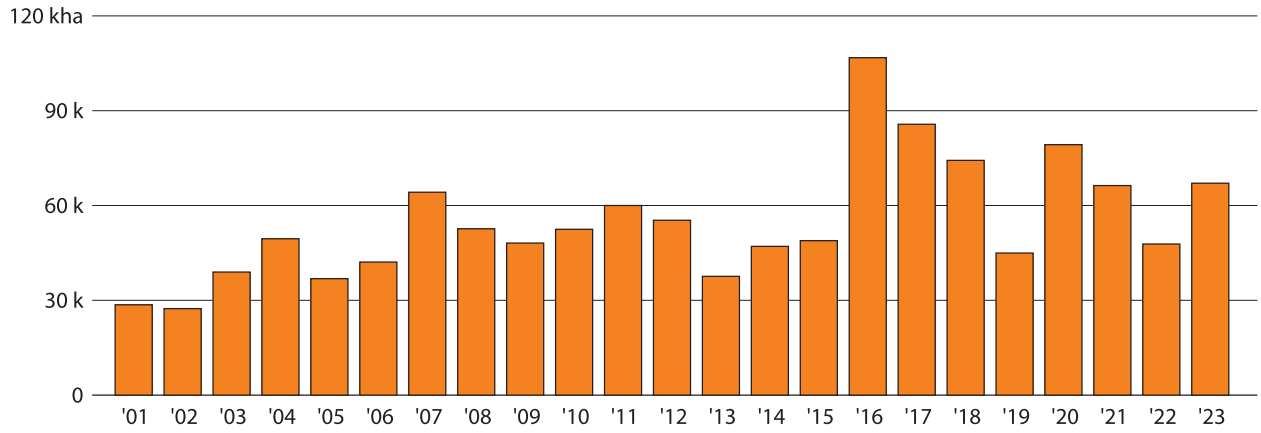

Figure 2. Annual forest cover loss in Ukraine due to forest fires, 2001–2023
Source: compiled by the authors based on data from the Global Forest Watch platform.

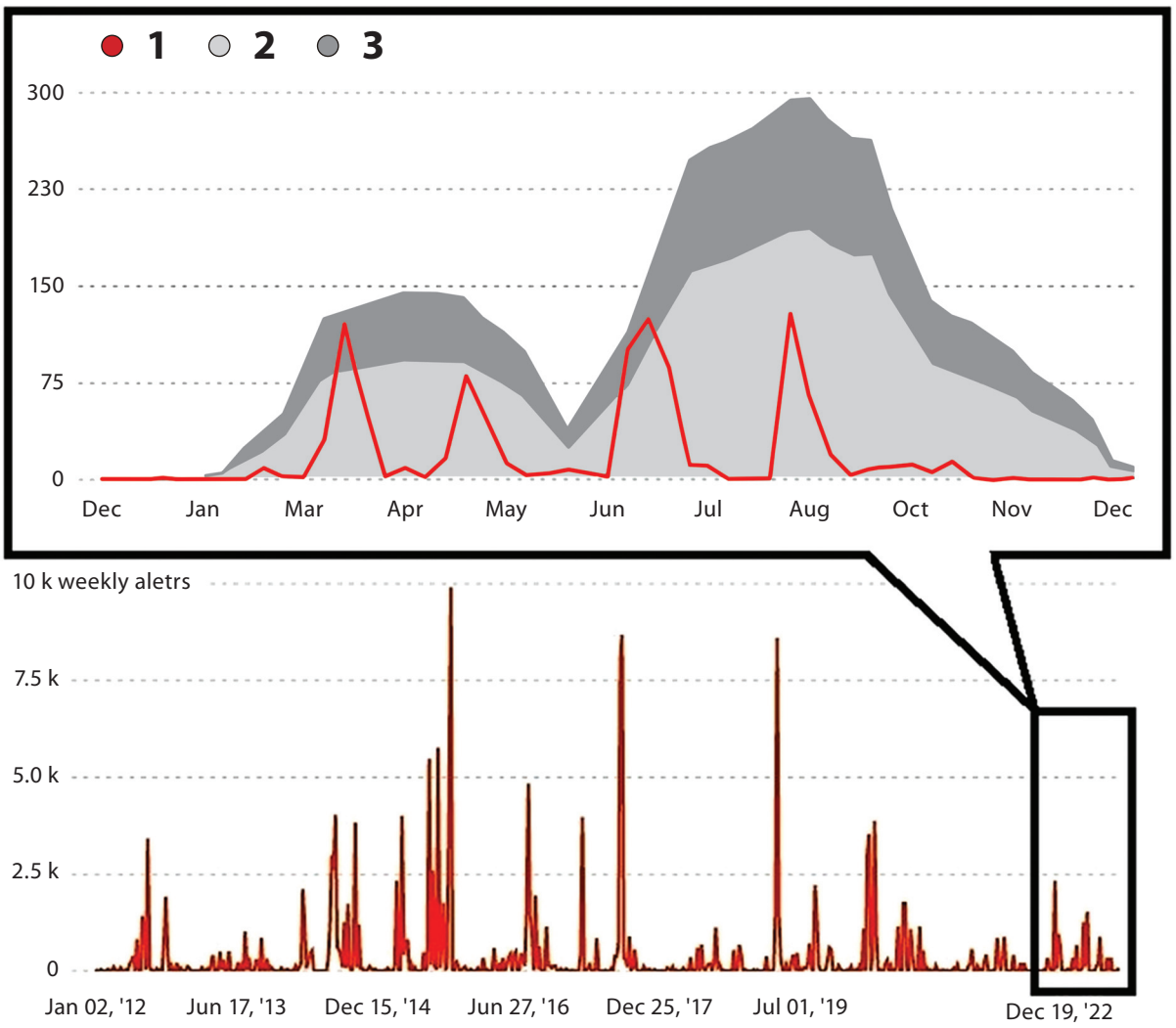

Figure 3. Fires in Ukraine, 2012–2022:
1 — number of fires in 2022; *2* — average value; *3* — above average
Source: compiled by the authors based on data from the Global Forest Watch platform.

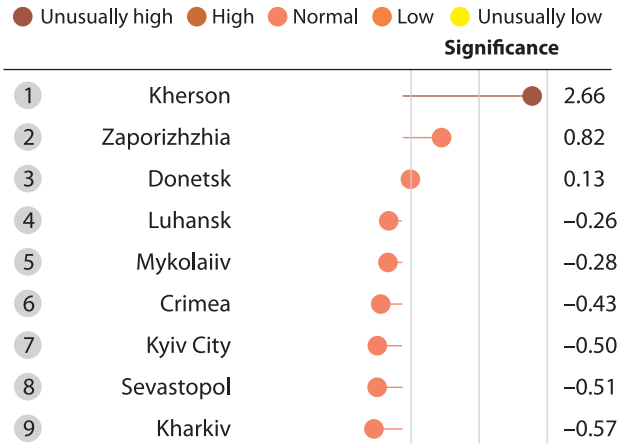

Figure 4. Regions of Ukraine with the highest number of registered forest fires, April 2023 – April 2024

Source: compiled by the authors based on data from the Global Forest Watch platform.

For each forest district, it is also possible to calculate zonal statistics, including the total area and the number of tree dieback hotspots within each forest compartment.

The full-scale Russian military aggression against Ukraine has also led to the loss of some forested areas. This loss is due to the direct destruction of stands by combat actions and the limited ability to extinguish fires and mitigate their consequences due to a shortage of equipment, personnel, fuel, and lubricants, as well as restricted or absent access to fire hotspots. According to the Global Forest Watch platform, from 2001 to 2023, Ukraine lost 11% of its forests compared to the year 2000 (*Fig. 2*).

However, overall, the forest fires in 2022 were not higher than the annual average (*Fig. 3*). Nevertheless, data from the Global Forest Watch platform clearly show that the majority of forest fires during this period occurred in combat zones — occupied territories and the front line.

The weather conditions in 2022 did not favor the extensive spread of forest fires, and forested areas were still relatively accessible to firefighting services. This explains the significant proportion of forest fires caused by combat actions, despite the relatively low loss of forested areas compared to previous years. However, in subsequent periods, the situation regarding the accessibility of fire-affected forest areas, the availability of sufficient firefighting resources, and the necessary personnel has rapidly deteriorated. An additional risk factor is the abnormally high temperatures, which contribute to the occurrence and spread of forest fires. From April 2023 to April 2024, Kherson region was the area with the highest number of forest fires in Ukraine, with 602 registered incidents (*Fig. 4*). This accounts for 29% of all detected fires in Ukraine during this period and is considered an extremely high level since 2012.

The reduction in forest ecosystem area has not only ecological but also significant economic consequences. Substantial losses of forested areas due to military actions — affecting nearly 30% of Ukraine's forests, according to the Ministry of Environmental Protection and Natural Resources — predictably lead to a shortage in the supply of timber products on the global market. This may result in unauthorized logging. Additionally, the decrease in forest area undermines Ukraine's efforts to achieve sustainable development goals and mitigate climate change impacts.

Restoration of disturbed ecosystems and the resumption of at least pre-war development rates across all sectors of the region's economy requires innovative approaches and solutions. Given that the forestry sector is one of the main industries in Ukrainian Polissya, rehabilitating forest ecosystems is a key element for the region's sustainable development.

Thus, forest ecosystems are essential for slowing climate change and ensuring balanced territorial development. As the most complex terrestrial ecosystems, forests provide numerous ecosystem services crucial for economic well-being. Therefore, minimizing risks to forest ecosystems is integral to the resilience and adaptability of any natural production system. From this perspective, cooperation among forestry, remote sensing, climatology, and economic specialists appears particularly promising.

CONCLUSIONS

The close interrelationship between the loss of forested areas and climate change is evident. The increase in climate risks exacerbates the reduction of forest ecosystems, particularly in regions like Ukrainian Polissya. The war presents an additional threat, significantly increasing both the number and severity of forest fires. Consequently, the loss of forest areas considerably slows the accumulation of carbon dioxide, while forest fires increase its emission. The analysis of fire dynamics and forest area loss, conducted using the Global Forest Watch platform, confirms the impacts of climate change and the effects of military actions on forested areas.

According to the analysis, the most significant factors contributing to the reduction of forested areas in Ukraine include logging, urbanization, and fires. While the first two can be controlled through institutional methods, the number of fires continues to rise due to climate

change, weakened tree stands, increased pest and disease infestations, and frequent natural and war-induced fires. Additionally, the loss of forest ecosystems is exacerbated by reduced maintenance, the inability to promptly extinguish fires due to a lack of equipment, fuel, personnel, and access to fire sites.

Satellite monitoring is an effective tool for detecting, monitoring, and predicting crisis phenomena such as pest infestations or the development of forest fires. This can enhance the efficiency of preventive and mitigation measures, especially during wartime. Specifically, a methodology for automated decryption of satellite images has been developed to detect areas of Scots pine forest decline caused by the ipid bark beetle.

Forest ecosystems play a vital role in the socio-economic development of the Ukrainian Polissya region, and their preservation is essential for ensuring sustainable development and biodiversity conservation. This requires a comprehensive approach to forest management that considers both ecological and socio-economic aspects. Emphasis should be placed on forest management strategies, the introduction of new forest protection methods, and integrated fire management in the context of climate change and military actions to reduce climate risks. Incorporating modern technologies, such as satellite monitoring, into forest management practices can help conserve and restore forest resources.

It is necessary to strengthen legislative control over forest resources and combat illegal logging, which threatens the stability of forest ecosystems. Legislative changes and an effective monitoring system can help reduce forest cover loss.

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КЛІМАТИЧНІ РИЗИКИ ТА ЛІСОВІ ЕКОСИСТЕМИ: ВЗАЄМОВПЛИВ СКОРОЧЕННЯ ЛІСИСТОСТІ ТА ЗМІН КЛІМАТУ

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У статті наведено комплексний аналіз взаємовпливу скорочення лісистості площ і кліматичних змін, а також наголошено на впливі бойових дій на зменшення лісових екосистем. У межах досліджень використовували загальнонаукові методи (аналіз та синтез даних), ретроспективний і порівняльний аналіз, аналітико-синтетичний метод (вивчення наукових та статистичних даних, фондових матеріалів тощо), метод дистанційного зондування землі з космосу. Метою дослідження було окреслити основні причини скорочення площ лісових екосистем України, а також їхню роль у контексті глобальних кліматичних змін та як важливої складової соціально-економічного розвитку держави у воєнний і повоєнний періоди. Проаналізовано роль лісових екосистем як джерела великої кількості різноманітних екосистемних послуг, а також вагомого елементу соціально-економічного статусу регіону Українського Полісся. Окрему увагу було приділено взаємовпливу зменшення лісовкритих площ та інтенсифікації кліматичних змін. Наведено основні чинники скорочення лісових екосистем України, зокрема виділено лісові пожежі, включно з тими, що були спричинені бойовими діями. Встановлено, що за період із квітня 2023 р. до квітня 2024 р. найбільша кількість лісових пожеж простежувалася на сході та півдні держави, де відбуваються активні бойові дії. Було розроблено методику автоматизованого дешифрування супутникових знімків для виявлення осередків усихання лісових насаджень сосни звичайної внаслідок ураження верхівковим короїдом, на основі якої було створено карту території дослідження з межами лісництв, квартальною сіткою, контурами пошкоджених лісових ділянок і нових осередків усихання. Доведено, що лісові екосистеми є необхідним елементом сповільнення кліматичних змін і забезпечення збалансованого розвитку території. Особливо це стосується Українського Полісся, зокрема Житомирської обл., лісистість якої є найвищою в державі, але яка водночас є лідером за втратою лісовкритих площ.

Ключові слова: *кліматичні зміни, лісові насадження, лісові пожежі, верхівковий короїд, супутниковий моніторинг.*

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