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Integrated aerial and ground unmanned systems for assessing war-induced forest ecosystem damage

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Abstract. Armed conflicts pose severe and multidimensional threats to forest ecosystems, including large-scale fires, mechanical destruction of vegetation, soil degradation, chemical contamination, and biodiversity loss. The aim of this study was to theoretically substantiate the use of integrated aerial and ground unmanned systems for monitoring war-induced forest ecosystem damage under limited-access conditions. The study used a theoretical-analytical approach combining systematic literature review, comparative analysis, and conceptual synthesis of remote forest monitoring methods based on aerial and ground unmanned systems. It was established that traditional methods for monitoring forest damage, despite the high accuracy and comprehensiveness, were ineffective under armed conflict conditions due to physical danger, labour intensity, and limited access to affected areas. This determined the need to transition to innovative remote technologies to ensure continuous and accurate observation of forest ecosystem conditions. According to data from specialised studies and open environmental sources, unmanned aerial vehicles

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and ground platforms demonstrated high efficiency in conducting rapid monitoring of forest ecosystems in combat zones, particularly under conditions of restricted access. The methods considered make it possible to promptly detect manifestations of natural area degradation and assess the scale of tree stand damage both in Ukraine and beyond its borders. The practical significance of the study lay in the use of unmanned systems for environmental monitoring, damage assessment, and support of forest restoration in combat zones

Keywords: remote sensing; multispectral camera; drone; aerial photography; satellite image; multicopter

Introduction

One of the main environmental challenges for Ukraine was the problem of mass forest destruction due to fires, particularly those caused by hostilities. Forest ecosystems suffered significant damage – loss of tree cover, soil degradation, and reduction of biodiversity – which complicated natural regeneration processes and posed a threat to the existence of many species. The relevance of the study was driven by the fact that forest ecosystems suffered extensive damage due to the armed conflict, while traditional monitoring methods proved ineffective under conditions of limited access, increased danger, and the need for rapid and reliable environmental information. Therefore, the need for the use of advanced technologies increased. The research problem lay in the absence of methods adapted to wartime conditions for comprehensive monitoring capable of promptly and accurately detecting environmental damage. An analysis of modern publications revealed insufficient application of an integrated approach using ground and aerial unmanned systems to assess the condition of forests in hazardous areas.

The destruction of tree vegetation, changes in soil structure, and the reduction of biodiversity in forests in armed conflict zones were studied by S.G. Chornyy (2023). According to the study, due to the decrease in the normalised difference vegetation index (NDVI) during the period of maximum photosynthetic activity – from June to July 2023 – partial destruction of both primary and secondary vegetation occurred, which negatively affected the soil-protection and windbreak functions of shelterbelts. Under conditions of limited access to combat zones, traditional methods for monitoring forest damage proved ineffective. The issue was studied by Y.B. Kyryliv *et al.* (2024). According to the study, the greatest advantage of unmanned aerial vehicles (UAVs) use during the war was the high response speed and reduced resource and personnel costs required for the operation.

The issue of shelterbelt degradation in Donetsk Region, where a significant portion of shelterbelt plantations was damaged by fires between 2021 and 2025, was studied by S. Popov & O. Orechov (2024). The research involved the development of intelligent forest fire monitoring systems using swarms of UAVs. The researchers identified the need for comprehensive monitoring of the state of protective forest plantations and the development of effective measures for the conservation and restoration using geodetic methods and UAVs. Research in this field was conducted by S.G. Mohylnyi *et al.* (2023). The authors' findings indicated that the condition of protective forest plantations required constant monitoring, as these plantations were subject to degradation from both anthropogenic and natural factors. Notably, the greatest losses of field shelterbelts were recorded in Kherson (3,271.2 ha) and Zaporizhzhia regions (2,266.4 ha), due to extensive illegal logging.

In parallel, the study of changes in urban forests due to military actions emerged as an important issue for modern ecologists. The matter attracted the attention of M. Seneta *et al.* (2024). In the work, the authors proposed using quadcopters for environmental monitoring, particularly in urban forests, which enabled effective tracking of vegetation degradation in occupied territories and active combat zones. The research highlighted the importance of improving monitoring methods for urban forests, especially through the use of high-precision UAVs. Special attention was given to the use of advanced UAV technologies in forest fire protection. This issue was studied by B. Kozka & V.-P.O. Parkhomenko (2023). The authors explored the possibilities of using UAVs for reconnaissance and monitoring of forest fires, including the detection of fire outbreaks and assessment of extinguishing effectiveness. The issue of UAV use due to the ongoing war since February 2022 was studied by V.H. Shpyrna (2023). According to the author's research, effective use of UAVs in land management and environmental monitoring during the war enabled the prompt collection of spatial data, assessment of land condition, and detection of anthropogenic impacts on the environment. The significant environmental damage inflicted on Ukraine's forests by hostilities highlighted the need for forest ecosystem restoration and the implementation of effective rehabilitation measures, particularly using modern monitoring technologies such as UAVs.

The issue of the deterioration of coniferous forests in the Tukhlianske Forestry of the Prykarpattia Region due to fires was studied using UAV imagery, with proposed solutions offered by Kh. Burshchynska & Y. Dekalyuk (2021). The researchers proposed a method for assessing the condition of coniferous forests based on high-resolution imagery and UAV data. The method could be applied across various forestry structures and adapted to combat conditions. The problem of forest damage assessment in Kharkiv Region under occupation or active combat conditions was studied by N.V. Maksymenko *et al.* (2023). Based on UAV data, the researchers identified 2.9 million hectares of damaged forests and noted that large-scale tree stand destruction and forest fragmentation required the implementation of systematic and technologically advanced monitoring. According to O.V. Rybalova *et al.* (2019), the importance of implementing environmental measures to reduce the impact of chemical pollutants on soil and public health after forest fires should be emphasised. The study showed that the integral indicator of soil chemical content (IPCS) corresponded to Class 2 (good condition) before the fire, and Class 4 (poor condition) afterwards.

These studies did not give sufficient attention to a comprehensive approach to examining the impact of warfare on the ecological state of forest ecosystems – particularly regarding forest degradation monitoring, biodiversity loss, and destruction of protective plantings in combat zones. The purpose of this study was to validate and assess the function of integrated aerial and ground unmanned systems as a conceptual framework for tracking damage to forest ecosystems caused by war in situations with restricted access and increased environmental risk. The study objectives were: to conceptualise an integrated unmanned monitoring framework, analyse key indicators of war-induced forest ecosystem damage, and assess the complementary roles of aerial and ground platforms under limited-access conditions.

Materials and Methods

This work is based on a theoretical-analytical research methodology that aims to conceptualise and systematise modern methods for monitoring forest ecosystems in the context of armed conflict. In line with the theoretical focus and the findings, the methodological framework integrates conceptual modelling, comparative analysis, and qualitative synthesis. Peer-reviewed scientific publications discussing forest damage, fire effects, vegetation stress, and the use of remote sensing in conflict and post-conflict settings made up the analytical corpus. Additionally, reports from national and international organisations devoted to environmental monitoring in war-affected areas were included. The use of unmanned aircraft and ground-based systems for forest evaluation in dangerous or inaccessible places was also investigated through case studies that were reported. All of the materials were chosen based on their applicability to forest ecosystems that have been impacted by military operations and their contribution to the methodological advancement of remote monitoring techniques. Materials that did not address remote or unmanned monitoring techniques, did not clearly focus on forest ecosystems impacted by military or high-risk conditions, or did not have methodological or analytical relevance to the study's aims were excluded from the analytical corpus.

To guarantee a logical interpretation of forest damage monitoring during armed conflict, the study used a variety of complimentary analytical techniques. To categorise and organise the various forms of forest damage linked to military operations, such as thermal, mechanical, chemical, and biological impacts, thematic analysis was used. The functional capabilities, data resolution, spatial coverage, operational dangers, and suitability for employment in combat scenarios of several kinds of unmanned systems, both aerial and ground-based, were assessed using comparative analysis. The integration of various data sources, sensor setups, and operating platforms allowed for the examination of forest monitoring through system analysis. Additionally, an integrated model of remote forest assessment during armed conflict was developed by using conceptual synthesis to identify dominant monitoring paradigms. Together, these techniques made sure that the monitoring technologies examined and the damage typologies mentioned were in line, which supported the comparative analyses shown in the Results section.

Unmanned monitoring systems were analysed within the analytical framework using a common set of evaluation criteria, which included platform type (differentiating between aerial and ground-based systems) and onboard sensor configuration (such as RGB, multispectral, thermal, and LiDAR instruments). Along with operational constraints related to weather, terrain complexity, and security threats in combat situations, consideration was also given to the degree of spatial and thematic information each system offered. Additionally, the suitability of various technologies for site-specific assessment versus large-scale monitoring was taken into account. The comparative features and performance metrics, such as resolution, coverage area, autonomy, and damage detection accuracy, discussed further were based on this analytical approach. Kharkiv Region is considered in this study as a representative case frequently documented in publications on war-induced forest ecosystem damage.

Results

Types of tree damage in forests due to military actions

Types of tree damage in forests as a result of military actions are classified as thermal, mechanical, chemical, and biological. The war has negatively affected forest ecosystems, as forests were used as natural shelters for military equipment and personnel, and were also subjected to armed attacks, which led to the damage. As a result of shelling with various types of weapons, trees were destroyed, soils degraded, chemical contamination occurred, and biodiversity was lost. In addition, explosions and fires disrupted the ecological balance, leading to changes in forest stand composition and causing long-term environmental consequences. In particular, there was mass tree death, which in turn led to the replacement of native species with less resilient ones. Craters formed due to explosions, and mechanical destruction of soil occurred due to military equipment digging trenches and foxholes.

Soils and groundwater were polluted with remnants of ammunition, fuels, and lubricants (petrol, liquefied natural gas, engine oils), heavy metals, and toxic chemicals. Explosions, fires, and mechanical damage resulted in the death of animals and plants, leading to forced migration of fauna. When trees were damaged or completely died, and dry biomass accumulated, forest fires spread. Explosions caused crater-like depressions in the ground and disrupted the plant cover, which altered the water balance of forests, contributing to either waterlogging or, conversely, drying out of forest areas. This reduced forest water availability due to the loss of natural vegetation layers that help retain moisture in the soil. Such changes led to quicker soil drying and increased erosion risk. The accumulation of dry biomass after fires contributed to greater fire spread, which also affected the water balance. After such fires, the soil surface lost its moisture retention ability, as organic matter layers were burned and high temperatures dried the soil. If these processes led to crater formation or significant damage to vegetation, water would accumulate in lower areas, raising the groundwater level.

The crash of aircraft, helicopters, missiles, and UAVs containing ammunition, explosives, and fuel caused significant damage to forest ecosystems. Shockwaves, shrapnel, and debris broke tree trunks, branches, and roots, resulting in mechanical plant damage and forest fires. Powerful explosions created craters, leading to tree falls, root damage, and soil layer disruption. Typical damage symptoms detectable remotely by UAVs or satellites include a decrease in NDVI, indicating reduced photosynthetic activity; canopy cover disruption, indicating mechanical or thermal damage; and reduced forest stand density, which may result from fires, logging, or vehicle movement.

Overview of modern remote forest monitoring methods during armed conflict in Ukraine

The following provides an overview of existing monitoring practices and technologies essential for understanding the context and comparing with obtained results. The collection and processing of environmental data using UAVs is a modern and effective method for monitoring forest ecosystem conditions, especially under limited access or high-risk conditions, such as mine-contaminated areas. During full-scale armed aggression, systemic deterioration of forest ecosystems was recorded in areas directly impacted by combat. Theoretical analysis identified several key environmental consequences: firstly, a significant increase in damaged forest cover area, particularly in riparian forests along the Dnipro Delta in the administrative district unit "Kherson", indicating natural barrier destruction and biodiversity loss; secondly, increased fire risk due to degraded firefighting infrastructure and inability to control fires in temporarily occupied areas. These processes pose risks of long-term environmental changes, especially prominent in Kyiv, Kharkiv, Donetsk, and Luhansk regions, where anthropogenic and military impacts intersect with environmental vulnerability (Matsala *et al.*, 2024). In response to fire threats and limited access to parts of forest areas, a national remote forest resource monitoring system was developed and implemented. The theoretical foundation of this system was based on integrating data from various sources (satellite imagery, GIS, risk assessment models), enabling comprehensive forest condition assessment even in hard-to-reach zones. Thus, the theoretical concept of monitoring during armed conflict transformed into a practical environmental security tool at the state level (Myroniuk *et al.*, 2024).

Satellite monitoring was another important source of forest condition information. The use of medium and high-resolution satellite imagery (e.g., Sentinel-2, Landsat 8) allowed large areas to be assessed in a short time. Spectral analysis enabled detection of burned areas, decreased leaf surface, reduced biomass, etc. However, satellite methods are limited by weather conditions (e.g., cloud cover), insufficient detail for small damage areas, and data update delays, which can hinder timely ecosystem response. Using ground photogrammetry and laser scanning (LiDAR), 3D models of forests can be created, and vegetation structure, tree and understorey damage levels can be accurately determined. Ground laser scanners are particularly effective for detailed site analysis, but the use is limited by high time costs, the need for physical personnel presence, and difficulty operating in dangerous or mine-contaminated zones.

The integration of aerial imaging, laser scanning (LiDAR), and satellite data has formed a modern paradigm of remote environmental monitoring, enabling not only rapid detection of structural changes in forest ecosystems but also dynamic modelling of the spatial-temporal development (Borghi *et al.*, 2025; Dahan *et al.*, 2025). A special role in this approach is played by the Pure Forest Index (PFI), which synthesises spectral characteristics from satellite and LiDAR data, allowing for continuous assessment of forest disturbance levels (Cai *et al.*, 2023). Such approaches enabled an expanded range of ecological indicators for analysis and adapted monitoring systems to limited-access conditions, particularly in combat zones. Conceptually, this transforms remote sensing from a supplementary tool into a key component of environmental security strategy.

In armed conflict contexts, traditional monitoring methods proved ineffective due to high danger, difficult access to observation sites, and the need for timely information. Ukrainian forests have been affected by combat operations, including explosions, fires, contamination with heavy metals and ammunition remnants, leading to forest ecosystem degradation. To assess damage and plan restoration efforts, precise, timely, and safe monitoring methods should be prioritised. Hence, there was a need for innovative solutions, among which remote technologies using unmanned systems played a central role – combining mobility, safety, and high data resolution.

In current conditions, where traditional field monitoring methods were insufficient or even dangerous – especially in conflict zones – remote technologies were used as the main tool for forest ecosystem condition assessment. Scientific focus shifted to implementing autonomous UAV-based systems, which, due to the manoeuvrability and adaptability to complex landscapes, can perform high-precision mapping and dynamic monitoring. Robotic drones equipped with trajectory planners (e.g., EGO-Planner-v2) were particularly promising, capable of autonomously navigating complex environments – opening new possibilities for constructing spatial-temporal forest cover change models (Karjalainen *et al.*, 2024). The proposed remote monitoring concept included not only prompt detection of vegetation changes, but also integration of high-resolution image time series to assess anthropogenic impact. This transforms the approach to studying protected areas: from static condition capture to real-time ecosystem dynamic analysis. Thus, UAV use became not only a technical advancement but also defined a new methodology for environmental monitoring under high ecological risk (Ancin-Murguzur *et al*., 2020).

Sensor systems played an important role in improving monitoring efficiency using aerial and ground unmanned platforms. These included: multispectral cameras to analyse vegetation via vegetation indices (e.g., NDVI) and detect tree stress; hyperspectral sensors providing highly detailed physiological plant condition and damage type data; laser scanners (LiDAR) enabling accurate 3D forest structure models, including tree height, canopy density, and biomass volume; thermal cameras for detecting fires, decay zones, or other thermal anomalies; and high-resolution visual cameras for identifying mechanical trunk damage, logging, and technogenic impact traces.

With the active implementation of aerial UAV platforms (quadcopters, planes, or hybrid systems) equipped with high-quality optical and multispectral cameras, it became possible to generate detailed orthophotomaps, analyse canopy condition, and detect signs of fires, diseases, or mechanical damage. Aerial UAV use in forest monitoring opened new possibilities for prompt ecosystem condition assessment across large areas (Wójcik *et al*., 2022). The ability to produce accurate orthophotomaps and 3D terrain models enabled not only identification of forest damage zones but also laid the foundation for spatial-temporal change analysis. In this context, particular attention was paid to implementing hyperspectral remote sensing systems capable of detecting subtle physiological and biochemical deviations in vegetation. Mounting a Hyspex VS-620 hyperspectral thermal imager on a DJI Agras T30 platform demonstrated the potential for developing specialised aerial systems for monitoring forest biogeocenoses. Despite technical limitations – such as vibrations at 9.6 Hz, limited flight time, and safety requirements for operating drones over 25 kg – this solution showed the feasibility of creating adaptive monitoring systems capable of autonomous operation in complex conditions (Arroyo-Mora *et al*., 2023). Conceptually, this marked a transition from general sensing to highly specific, targeted diagnostics of forest ecosystems, particularly relevant under ecological risk and natural disaster conditions.

In the structure of modern environmental monitoring, the application of ground-based unmanned platforms (Unmanned Ground Vehicles (UGVs)) gained particular importance. Unlike aerial systems, such vehicles provided high-precision point control of environmental parameters at soil and understorey levels (Bruno *et al*., 2019). The ability to measure physical, chemical, and biological characteristics enabled detailed spatial ecosystem structure analysis, including assessing litter condition, structural tree damage, and microclimatic changes (Segaran *et al*., 2023). At the same time, the application in hard-to-access or potentially dangerous (e.g., mined) areas required new adaptation and integration strategies. The "air-ground" collaborative robotic systems concept formed a new level of situational awareness, where the combination of UAV and ground platform advantages allowed improved environmental data collection accuracy, timely environmental response, and comprehensive monitoring of areas with varying accessibility (Shults & Annenkov, 2023; Zhang *et al*., 2024). This approach is reported to improve the accuracy of degradation, fire, or other threat detection and localisation in dynamic environments. Theoretically, integrating multi-level unmanned platforms could become the foundation for building a new generation of autonomous monitoring systems capable of functioning under high-risk conditions without compromising data quality.

A comprehensive assessment of forest ecosystems required integration of diverse information sources. Combining aerial photography, satellite monitoring, ground visual observation, GPS tracking, and LiDAR scanning enabled the construction of 3D models of territories and provided multi-level diagnosis of forest structure and dynamics. This approach realised the principle of multi-sensor data fusion, which could theoretically form the basis of a new forest monitoring paradigm – adaptive, spatially differentiated, and highly detailed. Applying artificial intelligence algorithms in image processing enabled automatic classification of damaged areas, identification of vegetation changes, and formulation of scenario forecasts for environmental consequences. Integrating LiDAR data with satellite, hyperspectral, and radar materials allowed for more accurate assessment of attributes such as tree stand height, species composition, biomass, and canopy density. Theoretically, such interdisciplinary technological synergy created the prerequisites for developing the concept of remote, risk-resilient environmental monitoring. It was especially relevant in regions with increased military risk, where direct access to territories was restricted. In this context, multi-sensor data fusion not only reduced anthropogenic burden and personnel life risks but also improved forest monitoring accuracy (Balestra *et al*., 2024).

The combination of aerial and ground-based unmanned platforms as part of integrated environmental monitoring systems proved particularly effective under current combat conditions. Aerial UAVs equipped with high-quality optical, multispectral, and hyperspectral sensors enabled rapid sensing of large areas with high resolution, as well as the creation of detailed orthophoto maps and 3D terrain models. The UAVs could detect signs of fires, diseases, and mechanical tree damage, and conduct spatial-temporal analysis of forest ecosystem changes. Meanwhile, the key advantage of ground-based unmanned platforms was the ability to perform point measurements of physical, chemical, and biological parameters, allowing for more detailed analysis of litter layer condition, tree damage structure, and soil changes. The use of "air-ground" collaborative robotic systems created a synergistic effect, improving data collection accuracy, response speed, and monitoring safety in high-risk zones such as combat areas. Theoretically, this model of UAV platform integration formed the basis for developing the next generation of autonomous adaptive monitoring systems capable of effective operation under restricted access and heightened threat conditions, ensuring continuous control and assessment of forest ecosystem condition.

Comparative analysis of unmanned system types in the context of forest monitoring

Modern forest ecosystem remote monitoring technologies involve the use of both aerial (aerospace) and ground-based unmanned platforms. In combat zones, where territorial access is difficult or dangerous, innovative UAVs (drones) are widely reported as crucial tools for detecting forest damage caused by fires, explosions, logging, and other anthropogenic impacts. In eastern Ukraine, including the de-occupied territories of Kharkiv Region, forest monitoring activities are significantly constrained by mine contamination, damaged infrastructure, and ongoing security risks, which makes remote sensing and unmanned monitoring approaches the primary sources of spatial information on forest ecosystem condition (Maksymenko *et al*., 2023; Myroniuk *et al*., 2024; State Agency of Forest Resources of Ukraine, 2024). Table 1 presents a comparative description of the main UAV types used for forest monitoring, synthesised from published studies.

Figure 1 shows a conceptual comparison of the level of data detail reported for different types of UAV platforms, synthesised from published studies and interpreted for forest monitoring in war-affected regions, including case evidence from the de-occupied territories of Kharkiv Region.

Table 1. Comparative characteristics of ground and air-based UAVs

Criterion	Ground-based UAVs (robot rovers)	Aerial UAVs (multicopters/aircraft)
Sensor type	RGB camera, thermal imagers, LiDAR, gas analysers	RGB camera, multispectral, LiDAR, thermal imagers
Level of detail	High (soil and undergrowth details)	Medium-high (covering crowns, large areas)
Coverage area	Limited (up to 1 ha per session)	Wide (up to 100 ha per flight)
Survey speed	Low (0.5-1 km/h)	High (10-40 km/h)
Weather restrictions	Limited (poorly performs on wet ground)	Dependent on wind, rain
Obstacle avoidance (trees, terrain)	High mobility in complex terrain	Low mobility, possible collisions
Sample collection/interaction with the environment	Possible	Not possible
Risk of loss/failure in the combat zone	Medium	High (due to air defence, radio interference)
Equipment cost	High (due to complex navigation systems)	Relatively available

Source: created by the authors

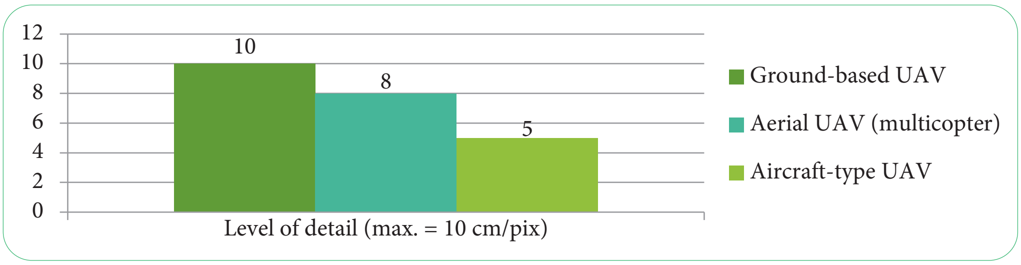

Figure 1. Comparison of the level of data detail reported for different types of UAVs within the deoccupied territories of Kharkiv Region

Source: compiled by the authors based on N.V. Maksymenko *et al.* (2023), V. Myroniuk *et al.* (2024), M. Matsala *et al.* (2024), State Agency of Forest Resources of Ukraine (2024)

The synthesis presented in Table 1 and Figure 1 indicates that, according to the reviewed literature, ground-based UAVs generally provide the highest level of data detail among the considered platform types. As for aerial multicopters, it should be noted that although the level of detail is somewhat lower, these multicopters remained effective for rapid mapping of large damaged areas, particularly burn zones, logging, or shelling, mainly through tree crown analysis and detection of localised damage. The lowest level of spatial detail is typically associated with fixed-wing aerial UAVs, which, although capable of covering vast areas, are reported as less suitable for fine-scale damage assessment. The comparative synthesis of data detail levels reported for different UAV types supports the feasibility of a combined approach, in which aerial systems are used for general surveys, while ground-based are applied for detailed analysis of key areas. Figure 2 presents a comparison of reported ranges of resolution (cm/pixel), flight altitude (m), autonomous operation time (min), and task-dependent damage detection accuracy for different types of UAV platforms.

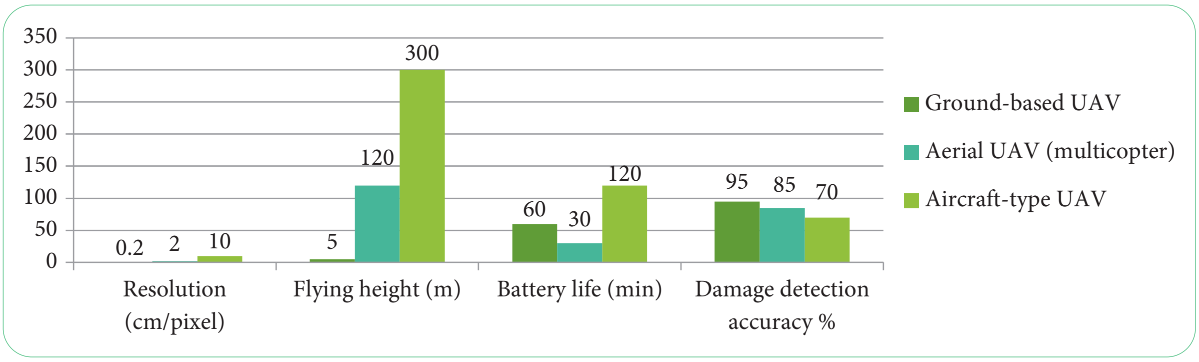

Figure 2. Comparison of reported ranges of spatial resolution, flight altitude, autonomous operation time, and task-dependent damage detection accuracy for different types of UAVs in war-affected forest regions, including the de-occupied territories of Kharkiv Region

Source: compiled by the authors based on S. Ecke *et al.* (2022), H. Zhang *et al.* (2023), N.V. Maksymenko *et al.* (2023), V. Myroniuk *et al.* (2024), State Agency of Forest Resources of Ukraine (2024)

According to the reviewed studies, ground-based UAVs are reported to achieve the highest spatial resolution and damage detection accuracy, making them particularly suitable for detailed analysis of individual trees or small forest plots with severe damage. However, this type of unmanned platform is characterised by limited operational range and low movement speed, which restricts its applicability for large-area surveys. Aerial UAVs of the multicopter type are widely described in the literature as offering balanced performance characteristics, combining relatively high spatial resolution with sufficient detection accuracy for medium-scale monitoring tasks, albeit with limited autonomous operation time and sensitivity to weather conditions (Seidaliyeva & Smailov, 2025). Multicopters are therefore considered effective tools for rapid monitoring of medium-sized areas, especially in challenging terrain or under limited-access conditions.

Fixed-wing UAVs are consistently reported as capable of operating at higher flight altitudes and maintaining longer autonomous flight durations, making them suitable for large-scale forest surveys and strategic planning. However, due to comparatively lower spatial resolution and task-dependent damage detection accuracy, these platforms are less effective for detecting minor damage or assessing the condition of individual trees and understorey layers. For detailed analysis of individual trees, understorey vegetation, soil structure, detection of explosive objects, and other small-scale damage, the use of ground-based UAVs (robotic rovers) is therefore considered advisable based on the reviewed literature. These platforms provide the highest level of data detail and enable interaction with the environment (e.g., sampling or identification of hazardous objects). However, the limited coverage area, low travel speed, and relatively high equipment cost due to complex navigation systems should be taken into account. For rapid assessment of medium-sized areas, including burn zones, logging, shelling, or local forest stand damage, the use of aerial multicopter UAVs is reported as an appropriate solution, offering a balance between spatial detail, mobility, and operational flexibility, despite constraints related to flight duration and weather dependence (DJI Enterprise, n.d.).

For large-scale monitoring of vast forest areas, strategic planning, and detection of large-scale changes in forest ecosystems, the use of fixed-wing aerial UAVs is widely described as appropriate. Their advantages include the ability to cover large territories within a single flight, operate at higher altitudes, and maintain longer autonomous flight times. At the same time, their lower spatial resolution and limited suitability for fine-scale damage assessment restrict their application for detailed forest diagnostics. Considering the above, the reviewed literature supports a combined application of different UAV types. Fixed-wing aerial systems can be used for general reconnaissance and preliminary detection of affected areas, multicopters can clarify the extent and spatial pattern of damage, and ground-based platforms can provide high-precision analysis and documentation of environmental threats in restricted or hazardous zones. Such an integrated approach is consistently associated with improved operational efficiency and monitoring reliability under conditions of increased risk and limited access (State Agency of Forest Resources of Ukraine, 2024). Overall, the synthesis of reported values for resolution, flight altitude, autonomous operation time, and damage detection accuracy indicates that UAV platform selection should align with specific monitoring objectives and spatial scales.

Innovative approach to monitoring under armed conflict conditions

In Ukraine, UAV use for environmental monitoring of forests in combat zones has been actively implemented since 2022. According to the State Agency of Forest Resources of Ukraine (2024), unmanned systems were used to inspect forest areas with dried-out stands. Due to the use of multispectral aerial imaging, forestry workers were able to promptly identify 194,000 hectares of forest lands damaged due to the drying out of forest trees and shrubs (due to military operations and temporary occupation of territories, the information is presented without data from Luhansk Region and parts of Donetsk, Zaporizhzhia, Kharkiv, Kherson regions and the Autonomous Republic of Crimea).

At the international level, examples of successful UAV use for forest damage assessment under limited access conditions were observed, notably in Syria and Iraq, where the humanitarian organisation UNOSAT (Fiol *et al*., 2021) used small-scale (mini) drones (e.g., DJI Phantom, DJI Matrice), multispectral drones (e.g., SenseFly eBee, Parrot Anafi USA), hexacopters and octocopters (e.g., DJI Matrice 300 RTK, Quantum Systems Trinity F90+), large drones (transport UAVs, e.g. Lockheed Martin Indago, AeroVironment Raven), and thermal drones (e.g., DJI Matrice 210 RTK, FLIR SkyRanger R70) for monitoring the degradation of natural areas in conflict zones, including UNESCO World Heritage Sites. Small (mini) drones were used to collect high-quality photos and videos in limited-access conditions. Multispectral drones equipped with sensors were used to monitor vegetation health, analyse landscape and ecosystem changes. Hexacopters and octocopters enabled lifting of heavy sensors, including LiDAR, multispectral cameras, and high-quality photo cameras. Large drones (transport UAVs) were capable of transporting heavy sensors and cameras, particularly for extended missions in low-visibility and adverse weather. Thermal drones with thermal imaging cameras were used to detect fires or heat anomalies in the area.

A case study of the Global Forest Watch (2025) project demonstrated the effectiveness of using satellite data combined with UAV-collected data for monitoring changes in forest cover in tropical regions affected by military action or illegal logging. Using multisource data allowed rapid detection and localisation of forest loss areas, assessing the scale and pace of ecosystem degradation, as well as tracking vegetation recovery. This approach improved the accuracy and speed of threat response, enhanced natural resource use control, and supported informed decision-making in complex ecological and social conditions. The main technical advantages of UAVs and ground-based unmanned platforms included mobility, enabling rapid deployment in any conditions, including rugged terrain and damaged infrastructure; autonomy of modern platforms that could perform flight missions on pre-set routes without direct operator involvement, reducing human risk; data collection speed, as UAVs could survey hundreds of hectares within hours – crucial for rapid response; and high resolution, allowing for detailed images and 3D models to accurately assess damage even at the level of individual trees.

The application of artificial intelligence (AI) methods is reported to improve the efficiency of processing data obtained from unmanned systems. Modern deep learning algorithms can automatically classify types of tree cover damage (e.g., fires, mechanical damage, diseases); detect changes in vegetation cover by analysing image series; create risk maps for further forest recovery planning; and generate forecasts of ecosystem degradation development based on trend models. AI-based solutions were actively implemented in Ukraine, for example, projects based on UAV-LiDAR technologies with automatic data processing through neural networks for detecting changes in forest stand structures.

Since 2022, UAVs and ground-based unmanned platforms have been actively used in Ukraine for environmental monitoring of forests in combat zones. According to the Forest Agency, multispectral aerial imaging enabled prompt detection of large areas of damaged forest lands despite restricted access to some regions. Domestic developments, such as the "Skif" UAV and the automated network system "Menatir", enabled highly accurate real-time data collection and processing, significantly improving monitoring responsiveness. Internationally, similar technologies were used in conflict zones in Syria and Iraq, employing various types of drones – from miniature to large transport ones – with multispectral, thermal, and LiDAR sensors. These multifunctional systems enabled assessment of vegetation conditions, forest damage detection, and environmental monitoring even in hard-to-access conditions. The main advantages of UAVs and ground-based unmanned platforms are mobility, autonomy, data collection speed, and high resolution, ensuring detailed damage assessment. The use of artificial intelligence, especially deep learning algorithms, improved the quality of analysis and automated damage type classification, risk map creation, and ecological forecasting, which was actively introduced in domestic projects.

Practical significance for forestry and management

The use of UAVs in forestry plays an important role in restoring natural resources after the end of military actions. The UAVs are an effective tool for identifying priority forest plots requiring urgent restoration. Multispectral analysis, NDVI index, LiDAR imaging, and RGB photogrammetry allow identification of the most degraded zones: completely burned areas, clear-cut zones, plots with disease spread or mechanical damage. Multispectral photography helps collect data on soil condition and crop health using UAV-mounted multispectral sensors. With the collected data, it became possible to determine vegetation dynamics, chlorophyll content, fungal outbreaks, frost damage, and seedling unevenness (Multispectral mapping with MENATIR…, 2022).

The data obtained through multispectral imaging form the basis for creating NDVI maps, which allow for comparisons of seedling conditions at different growth stages and across study areas. Since NDVI map data is processed quickly, it helps forestry workers save time and money by implementing efficient fertiliser and plant protection application technologies. Indicators obtained through multispectral mapping with MENATIR allow farmers to identify problem areas at early stages from the air without damaging crops, detect pests, diseases, and weeds, as well as nutrient deficiencies, and optimise the use of plant protection products (Multispectral mapping with MENATIR…, 2022).

Data from UAVs are used to plan reforestation activities. Digital terrain models, tree height inventory, canopy density and vegetation type allow identification of the most suitable forest recovery areas, selection of tree species, and calculation of the required scope of silvicultural measures. Important is the assessment of losses in ecosystem services, such as reduction in carbon reserves, loss of soil protection or climate regulation functions of forests. The use of hyperspectral and LiDAR data allows quantitative assessment of biomass reduction, stand volume, and soil degradation degree. Moreover, the integration of UAV data into forest management practices holds significant potential for shaping the post-war bioeconomy, offering the opportunity to transition to fully digitised, precise, and resource-efficient forest management that includes not only recovery from losses but also the creation of sustainable development conditions for the sector. Thus, the use of innovative UAVs can facilitate the adaptation of forest policy to post-war conditions, enabling rapid response to environmental threats and the integration of natural recovery principles.

Discussion

Analysing the obtained research results, it can be concluded that effective monitoring of forest ecosystem damage in combat zones is possible through the combination of different types of UAVs – aerial ones for rapid coverage of large areas and identification of general damage, and ground ones for highly detailed recording of critical zones and data collection in hard-to-reach or potentially hazardous areas. In contrast to R. Ashari *et al.* (2021), who found that management and urban stressors led to slow losses in tree condition and diversity in urban green areas, the current study shows a qualitatively different pattern of armed conflict-induced forest degradation. The results here show sudden, extensive damage leading to quick canopy loss and dramatic NDVI reduction, observable only by integrated remote sensing methodologies, while physical condition assessments in Ternate support long-term urban greening initiatives. This contrast shows how forest monitoring goals change from routine diversity assessment to high-resolution, risk-resilient systems that may capture abrupt ecosystem shocks under acute disturbance.

The study of chlorosis of trees interested K. Mladenovic *et al.* (2020). Following the research, the authors presented results showing that certain tree species, such as maples (*Acer negundo, A. pseudoplatanus*), horse chestnut (*Aesculus hippocastanum*), linden, poplar, and plane tree were susceptible to pathogenic fungi and fungus-like organisms. The results of the conducted study did not correspond to the findings of K. Mladenovic *et al.*, since this work examined a non-infectious plant disease manifested as a disruption in chlorophyll formation in leaves, while the work of the aforementioned authors concerned an infectious disease caused by wood-decaying fungi.

Soil pollution negatively affected the root system of pines and reduced the efficiency of photosynthesis (Grinfelde *et al.*, 2017). This topic was studied by N. Tatuśko-Krygier *et al.* (2023). According to the research, bioactive concentrations of magnesium (Mg) and iron (Fe) can protect Scots pine needles from the toxic effects of heavy metals such as zinc (Zn), lead (Pb), copper (Cu), and cadmium (Cd). One can agree with the opinion of N. Tatuśko-Krygier *et al.*, as elevated concentrations of these elements indeed promote better needle survival, given that magnesium and iron are actively involved in photosynthesis and can provide effective resistance to the adverse effects of pollution. The deterioration and drying of pine trees in mixed forest stands is a consequence of soil pollution due to fires caused by military actions. A similar issue was studied by M. Peris-Llopis *et al.* (2024). According to this scientific research, higher mortality after fire was observed in mixed stands compared to pure stands. Agreeing with this statement, it should be noted that the opinion of M. Peris-Llopis *et al.* is accurate, since in mixed stands different tree species may have varying fire resistance.

It was established that the increasing intensity of forest fires and logging in temporarily occupied territories and combat zones during 2022-2024 had serious negative consequences for the ecosystem, particularly for landscapes, due to soil cover degradation, loss of biodiversity, changes in the hydrological regime, increased erosion processes, and accumulation of toxic substances. A similar issue was raised by M.M. Bennett *et al.* (2022). The authors found that open satellite data, despite lower spatial resolution compared to commercial sources, were extremely valuable for the prompt identification, documentation, and analysis of environmental changes caused by war, including population displacement, infrastructure destruction, and land cover transformation. Similar conclusions were obtained in the presented study, as the results showed that fires significantly degraded landscapes, reduced biodiversity, increased greenhouse gas emissions, and caused soil degradation, complicating the recovery in conditions of armed conflict.

Combining data from sources such as aerial and ground imagery, satellite images, GPS coordinates, and LiDAR scanning makes it possible to create 3D models of territories and conduct multi-level forest condition assessments. This topic was studied by C.J. Iheaturu *et al.* (2024). According to the researchers' work, the combination of LiDAR and multispectral UAV data allowed accurate mapping of forest damage levels, which could be useful for monitoring damage in combat zones. Similar conclusions were made in the completed study, as the application of a comprehensive approach using various spatial data sources, including aerial imagery, satellite images, GPS coordinates, and LiDAR scanning, also enabled detailed visualisation and spatial analysis of changes in the forest ecosystem.

According to the conclusions of the current work, it is known that the use of both ground and aerial UAVs in a comprehensive approach to forest ecosystem damage monitoring makes it possible to achieve high efficiency in spatial data collection, especially in conditions of limited access to territories in combat zones. A similar issue was studied by F. Afghah *et al*. (2019). The authors found that the use of autonomous UAVs significantly improved the efficiency of forest fire monitoring due to the drones' ability to adaptively change routes based on changing fire conditions and terrain topography. The approach proposed by F. Afghah *et al*. ensured rapid response, optimal coverage of the affected zone, and reduced energy consumption, making it promising for practical implementation in conditions of limited human access and high risks. Thus, a comparison of the results of this work with the research of F. Afghah *et al*. confirmed that the use of autonomous unmanned systems based on a distributed "leader-follower" model, which grouped a set of drones into several coalitions, proved to be an effective strategy for forest fire monitoring in remote regions.

It was noted that during 2022-2025 in Ukraine, there was active implementation of an innovative approach based on artificial intelligence, in particular, a project based on UAV-LiDAR technologies with automatic data processing via neural networks for detecting changes in forest stand structures. A similar issue was studied by J. Xiang *et al*. (2024). The researchers found that the use of a combination of UAV data, POS positioning systems, and artificial intelligence algorithms significantly improved the efficiency and accuracy of forest change monitoring, ensuring reliable detection of forest area reductions even in complex urbanised conditions. This statement is agreeable, as the integration of remote sensing technologies, artificial intelligence, and precise geospatial information indeed significantly enhances the efficiency of forest ecosystem change detection, minimises the human factor, shortens data processing time, and ensures high reliability of the obtained results.

Traditional fixed-wing UAVs proved ineffective for detecting minor damage or assessing the condition of individual trees due to low resolution and limited damage detection accuracy. A similar issue was raised by H. Sun *et al*. (2023). The authors obtained results showing that the use of UAVs had significant advantages compared to traditional approaches such as manned surveys, watchtower observations, and piloted operation. In particular, it improved the efficiency of forestry tasks due to high data collection accuracy, the possibility of frequent repeated flights, and adaptability to different environmental conditions. Thus, UAVs proved to be a promising tool for monitoring, managing, and conserving forest ecosystems. The statement by H. Sun *et al*. is agreeable, as the research confirmed that the use of UAVs in forestry contributes to obtaining more detailed, up-to-date, and large-scale information about forest ecosystem conditions, enables prompt detection of disease outbreaks, pests, or fires, and also ensures effective forest resource mapping and inventory with minimal environmental interference.

In 2024, it was established that aerial multicopters proved effective for prompt mapping of large damaged areas, particularly zones of burning, logging, or shelling. A similar issue was raised by L.K.B. Melhim *et al*. (2024). The researchers obtained results showing that the use of drones in combination with a developed set of advanced algorithms significantly improved forest monitoring efficiency, allowing timely threat detection and prompt response to forest fires and other incidents. The statement by L.K.B. Melhim *et al*. is agreeable, as the research truly confirmed that the implementation of intelligent drone-based systems significantly improves early detection of forest fires, reduces response time, and contributes to more effective resource use during emergencies.

It was found that fixed-wing aerial UAVs demonstrated a low level of detail. A similar issue was studied by F.C. Eugenio *et al*. (2020). In the course of the research, the authors found that remotely piloted aircraft systems (RPAS) can improve the process of obtaining aerial images and the quality of derived products in terms of spatial and temporal resolution, which, in turn, enhanced the accuracy of forest inventories, prompt detection of pests and diseases, and effective monitoring of dynamic changes in forest ecosystems. Thus, a comparison of the results of this work with those of F.C. Eugenio *et al*. did not confirm that fixed-wing aerial UAVs were optimal for tasks requiring a high level of detail. On the contrary, multirotor RPAS platforms demonstrated higher effectiveness in tasks related to accurate mapping and monitoring of short-term changes.

It is demonstrated that fixed-wing UAVs are capable of covering large damaged forest areas; however, the obtained images were characterised by a low level of detail. A similar study was conducted by K. Kokamägi *et al*. (2023). According to the researchers' work, the orthophotomap created from UAV images was not an effective tool for assessing large areas of forest damage caused by storms, as this method required significant time and technical resources. Instead, for such research, it is more effective to use a fixed-wing drone or, in the absence of suitable take-off and landing sites, a multirotor drone. This statement is agreeable, as the use of orthophotomaps may prove too labour-intensive: on average, data collection took 96 person-hours, and result processing could take four full working weeks, which is not always appropriate in the context of rapid response to natural disasters.

It was found that aerial multicopter UAVs were able to provide a medium level of resolution (up to 2 cm/pixel) and accuracy (up to 85%) under conditions of complex terrain or limited access. A similar issue was studied by M. Evita *et al*. (2021). According to the authors' research, the use of aerial UAV technology was an effective alternative for forest fire monitoring and early warning in Indonesia, as it allowed high-accuracy data collection on vegetation condition and potential ignition points, creation of detailed 2D and 3D maps with minimal error, and detection of moving objects. The conclusion of M. Evita *et al*. is agreeable, as the research results confirm the high effectiveness of aerial UAV use for forest observation and prompt fire source detection. This is especially relevant given the increasing number of fires in Indonesia, where timely detection and response can significantly reduce damage to ecosystems, public health, and the economy. The analysis of the considered research results showed that effective monitoring of forest ecosystem damage in combat zones was achieved through the combination of aerial and ground UAVs. Aerial UAVs were able to cover large territories, while ground UAVs provided detailed recording and data collection in hard-to-reach areas.

Conclusions

In the course of the analysis of published studies, it was found that ground-based UAVs are reported to provide the highest spatial resolution and damage detection accuracy, while being characterised by limited coverage area and reduced mobility in wet or obstructed environments. Aerial multicopters are consistently described in the literature as a balanced option for rapid monitoring of medium-sized areas, whereas fixed-wing UAVs are widely reported as effective platforms for large-scale forest surveys due to their long flight duration, although they are inferior in spatial detail and task-dependent detection accuracy. In general, aerial UAVs offer wide area coverage and high data collection speed, but are more vulnerable under combat conditions and have limited ability to interact with the physical environment. In contrast, ground-based platforms enable detailed on-site inspections, including interaction with environmental objects, but are constrained by smaller operational range and lower overall efficiency for large-area monitoring.

Therefore, the reviewed literature supports a combined monitoring strategy based on the complementary use of different UAV types: fixed-wing systems for general reconnaissance and large-scale overview, multicopters for rapid assessment of medium-sized areas, and ground-based platforms for in-depth analysis of critical zones. This integrated approach is particularly relevant for de-occupied territories, where territorial access is limited and the balance between monitoring accuracy and data acquisition speed is crucial for timely environmental assessment of the consequences of hostilities.

Several limitations frequently reported in studies of war-affected forest areas include uncertainty regarding the exact boundaries of fire-affected zones, limited availability of timely high-resolution satellite imagery during critical periods, and restricted access to forest territories due to mine contamination and the absence of safe routes for field observations. These constraints highlight the need for further methodological and technological development. Prospects for further research identified in the literature include the development of UAV platforms resistant to electronic warfare interference, improvement of autonomous control algorithms for operation in GPS-denied environments, implementation of artificial intelligence modules for automated forest damage detection based on multispectral and LiDAR data, enhanced assessment of explosion- and fire-induced structural changes in forest ecosystems, and adaptation of early warning systems for environmental change monitoring to conditions of armed conflict.

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Conflict of Interest

None.

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Інтегровані повітряні та наземні безпілотні системи для оцінки шкоди, заподіяної лісовим екосистемам внаслідок військових дій

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Анотація. Збройні конфлікти становлять серйозну та багатовимірну загрозу для лісових екосистем, включаючи великомасштабні пожежі, механічне руйнування рослинності, деградацію ґрунтів, хімічне забруднення та втрату біорізноманіття. Метою цього дослідження було теоретичне обґрунтування використання інтегрованих повітряних та наземних безпілотних систем для моніторингу пошкоджень лісових екосистем, спричинених війною, в умовах обмеженого доступу. У дослідженні використовувався теоретико-аналітичний підхід, що поєднував систематичний огляд літератури, порівняльний аналіз та концептуальний синтез методів дистанційного моніторингу лісів на основі повітряних та наземних безпілотних систем. Було встановлено, що традиційні методи моніторингу пошкоджень лісів, незважаючи на високу точність та повноту, були неефективними в умовах збройного конфлікту через фізичну небезпеку, трудомісткість та обмежений доступ до уражених територій. Це зумовило необхідність переходу до інноваційних дистанційних технологій для забезпечення безперервного та точного спостереження за станом лісових екосистем. За даними спеціалізованих досліджень та відкритих екологічних джерел, безпілотні літальні апарати та наземні платформи продемонстрували високу ефективність у проведенні швидкого моніторингу лісових екосистем у зонах бойових дій, особливо в умовах обмеженого доступу. Розглянуті методи дозволяють оперативно виявляти прояви природної деградації територій та оцінювати масштаби пошкодження деревостану як в Україні, так і за її межами. Практичне значення дослідження полягало у використанні безпілотних систем для моніторингу навколишнього середовища, оцінки збитків та підтримки відновлення лісів у зонах бойових дій

Ключові слова: дистанційне зондування; мультиспектральна камера; дрон; аерофотозйомка; супутникове зображення; мультикоптер