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MONITORING STUDY OF THE SPATIAL DYNAMICS OF BELLIGERENT-RECREATIONAL SYSTEMS (CASE STUDY OF IRPIN, HORENKA AND BUCHA)

Background. ***The 2022 hostilities in Kyiv's suburbs (Irpin, Horenka, Bucha) triggered substantial anthropogenic environmental change and the emergence of so-called belligerent-recreational systems (BRS), where pockets of war-related destruction coexist with recreational resources. Vegetation degradation and other alterations of land cover in these areas require detailed investigation and assessment to inform subsequent revitalization. The aim of this study was to detect spatial changes in the structure of land (vegetation) cover and to assess the degree of degradation within belligerent-recreational systems using Earth observation (remote sensing) methods by calculating spectral indices and their differenced forms.***

Methods. ***To monitor the spatial dynamics of BRS, Sentinel-2 and Landsat-8 imagery was used to construct pre- and post-hostilities snapshots within the study sites. We computed the NBR (Normalized Burn Ratio) and NDVI (Normalized Difference Vegetation Index) and, chiefly, their differenced forms – dNBR (Differenced Normalized Burn Ratio) and dNDVI (Differenced Normalized Difference Vegetation Index) – which reflect degrees of land-cover damage due to burning and other biomass losses. The resulting dNBR and dNDVI values were classified by damage severity (from critical to minimal). Validation of the proposed classification scales was carried out by calculating pairwise (Pearson) correlation coefficients. The results revealed a strong correlation between dNBR and dNDVI (r ≈ 0.87).***

Results. ***Monitoring of spatial changes in BRS land-cover structure showed that the most intense fighting resulted in large-scale fires – in the northern quarters of Irpin and Bucha, and the central and eastern parts of Horenka – captured by the computed dNBR. According to dNBR, 12 % of the study area fell into the critical damage class, 20.5 % into the severe class; roughly one-third of the territory exhibited moderate damage, about one-quarter minor damage, and 9 % was almost unaffected. Analysis of dNDVI indicates that more than 80 % of biomass was lost over 13 % of the area, 50–80 % over 32 %, while 39 % experienced moderate losses and 16 % minimal losses. Additionally, NDVI analysis helped identify sites with mechanically induced vegetation damage resulting from warfare.***

Conclusions. ***Calculating the dNBR and dNDVI spectral indices enabled a quantitative assessment and delineation of degradation levels in the land (vegetation) cover of BRS, as well as visualization of the spatial differentiation of damage by severity classes. Among these, areas with weak or moderate damage were observed to show rapid vegetation recovery, whereas zones of critical and severe damage require the implementation of robust reclamation and remediation measures. The high correlation between dNBR and dNDVI confirms the dominant role of fires in degradation; however, a combined analysis of these indices provides a more complete assessment that also captures mechanical damage. The quantitative and qualitative results of the monitoring of land-cover conditions across the study sites, together with their map-based modeling, can be used to design strategic measures for the ecological rehabilitation of areas affected by military actions.***

Keywords: **belligerent-recreational systems; warfare; remote sensing; dNBR; dNDVI; degradation of land (vegetation) cover.**

Background

Armed hostilities are a powerful driver of anthropogenic transformation of landscape systems and, as a consequence, of the formation of specific beligeratively transformed types of these systems. Such systems are characterised by a significant degree of destruction of natural elements and anthropogenic objects, changes in the soil cover's structure, degradation of vegetation, and disruption of ecological balance.

The military operations that took place in 2022 on the territory of Ukraine, particularly in the suburban zone of Kyiv, led to substantial changes in landscape systems in the settlements of Irpin, Horenka and Bucha and in adjacent areas. These settlements were strongly affected by intense combat operations, artillery shelling, bombardments and war-induced fires, which resulted in the formation of beligerative systems that require comprehensive study, assessment and subsequent modelling of their states. Given that these systems continue to serve as places of residence for the population and, paradoxical as it may seem, as spaces for the restoration of human vitality (recreation), the study of beligerative-recreational systems (hereinafter also BRS) becomes particularly relevant.

Assessing the degree of transformation of beligerative-recreational systems, as well as monitoring the processes of their change and subsequent recovery, requires a comprehensive approach and the application of Earth remote sensing methods, which are especially useful when direct (physical) access to the study sites is impossible. Spectral indices NBR and NDVI are particularly informative for detecting changes caused by military actions in land and vegetation cover. They make it possible to assess the degree of vegetation damage due to fires and the overall state of vegetation biomass, respectively.

The relevance of this research is further determined by the fact that the need, importance and timeliness of assessing the condition of the land cover of the study areas form an unquestionable basis for the subsequent planning of measures for their restoration, reclamation and remediation. Therefore, the results of such research can be used to develop comprehensive programmes for the ecological rehabilitation of territories affected by military actions.

The aim of this study is to determine the spatial changes in vegetation cover in territories transformed as a result of hostilities (using the settlements of Irpin, Horenka and Bucha as case studies) and to assess the degree of beligerant-induced degradation of vegetation cover using Earth remote sensing methods.

To achieve this aim, it was considered necessary to: 1) analyse the theoretical and methodological foundations for studying beligerative-recreational systems and the possibilities of applying spectral indices to assess their states; 2) identify the specifics of the dynamics of beligerative-induced changes in vegetation cover within the territory of Irpin, Horenka and Bucha before and after the active phase of hostilities by calculating the dNBR index; 3) assess vegetation biomass losses in the study area using the dNDVI index; 4) identify trends in the spatial differentiation of vegetation damage and their dependence on the intensity of hostilities; 5) develop recommendations for the restoration of beligerative-recreational systems and for monitoring their states in the future.

Literature review. The theoretical foundations for the study of beligerative systems have been developed in the works of Western scholars, in particular Woodward (2014), who considers military geography as a distinct branch of geographical science and analyses the impact of armed conflict on landscape transformation. The application of Earth remote sensing methods to assess the environmental consequences of military actions is presented in the works of Witmer (2015), Witmer and O'Loughlin (2009), where the authors demonstrate the effectiveness of satellite imagery for determining the extent of destruction and environmental change in conflict-affected territories.

The use of spectral indices to assess the condition of vegetation cover is a widespread practice in Earth remote sensing. The NBR (Normalized Burn Ratio) index was developed to assess the degree of fire damage. Researchers (Key, & Benson, 2021) developed a methodology for using the NBR index to evaluate the consequences of fires and to monitor vegetation recovery in affected territories.

The NDVI (Normalized Difference Vegetation Index) is one of the most widely used metrics, actively applied to assess the condition of land (vegetation) cover and, at the same time, regarded as an effective tool for monitoring vegetation condition and evaluating its seasonal dynamics (Pettorelli, 2013).

Studies on the consequences of hostilities on the territory of Ukraine using Earth remote sensing methods include the works of Ukrainian researchers (Denysyk, Kiziun, & Kanskyi, 2023), (Bondar, Finin, & Shevchenko, 2022), (Lisova, 2017), among others. However, comprehensive studies of beligerative systems in general and beligerative-recreational systems in particular, including within the territory of Kyiv Region and especially those formed as a result of the impact of military actions in 2022, using the spectral indices dNBR and dNDVI, are still lacking and remain to be carried out.

Methods

The methodology for investigating spatial changes in beligerative-recreational systems is based on the integrated use of Earth remote sensing methods and geoinformation (GIS-based) modelling, through: calculation of spectral indices and their difference forms, construction of distribution scales for the calculated indices and their validation, as well as spatial modelling and mapping.

The study was conducted in several stages. One of the first stages involved selecting satellite images with appropriate temporal and spatial resolution for the study area, both before and after the active phase of hostilities. For this purpose, Sentinel-2 (spatial resolution 10 m) and Landsat-8 (spatial resolution 30 m) satellite imagery were used for the following periods: the active phase of hostilities (April-May 2022) and the period after the active phase (the beginning of the recovery period) (July-August 2022).

At the next stage, spectral indices and their difference forms were calculated. The NBR (Normalized Burn Ratio) index was calculated according to equation (1):

$$\mathrm{NBR} = (\mathrm{NIR} - \mathrm{SWIR})/(\mathrm{NIR} + \mathrm{SWIR}) \quad (1)$$

where NIR is Near Infrared radiation, with a wavelength range of 0.75–1.3 μm, and SWIR is Shortwave Infrared radiation, with a wavelength range of 1.5–2.3 μm.

To assess territorial changes that occurred as a result of fires, the dNBR (Differenced Normalized Burn Ratio) was calculated according to equation (2):

$$\mathrm{dNBR} = \mathrm{NBR\ pre} - \mathrm{NBR\ post} \quad (2)$$

where NBR pre is the pre-fire NBR ("before" the fire), and NBR post is the post-fire NBR ("after" the fire).

For the interpretation of the obtained dNBR values, the classification proposed by the USGS (Key, & Benson, 2021) was used. According to this classification, the resulting dNBR values are evaluated as follows:

less than 0.1 – unburned area or very low change;
0.1–0.27 – low burn severity;
0.27–0.44 – moderate burn severity;
0.44–0.66 – high burn severity;
greater than 0.66 – very high burn severity.

The NDVI (Normalized Difference Vegetation Index) was calculated according to equation (3):

$$\mathrm{NDVI} = (\mathrm{NIR} - \mathrm{RED})/(\mathrm{NIR} + \mathrm{RED}) \quad (3)$$

where NIR is Near Infrared radiation, reflected light in the near-infrared range with a wavelength of 0.75–1.3 μm, and RED is the Red band (red spectral channel), visible red light with a wavelength range of 0.63–0.69 μm.

To assess the dynamics of changes in vegetation cover, the dNDVI (Differenced Normalized Difference Vegetation Index) was calculated according to equation (4):

$$\mathrm{dNDVI} = \mathrm{NDVI\ pre} - \mathrm{NDVI\ post} \quad (4)$$

where NDVI_pre is the pre-event NDVI ("before" the event) and NDVI_post is the post-event NDVI ("after" the event).

By analysing the obtained dNBR values, five zones with different degrees of BRS damage caused by fires were identified (Key, & Benson, 2021):

1. Zone of critical damage (dNBR > 0.66) covers areas where intense hostilities occurred and led to large-scale fires. Field surveys confirmed that at dNBR > 0.66 there is a complete loss of vegetation and significant disturbance of the upper soil horizons, which necessitates the implementation of active reclamation measures.
2. Zone of severe damage (dNBR = 0.44–0.66) includes areas with substantial damage to vegetation cover as a result of fires. This range corresponds to areas with intense, but not total, burning, where individual ecosystem elements capable of self-recovery are still preserved.
3. Zone of moderate damage (dNBR = 0.27–0.44) covers areas with partial damage to vegetation cover. Field surveys carried out to validate the identified damage classes show that at such dNBR values, the ecosystem retains sufficient recovery potential, although time is required for regeneration.
4. Zone of low damage (dNBR = 0.1–0.27) includes areas with minor damage to vegetation cover. This range characterises sites with limited fire impact, where surface-level damage prevails, and the overall ecosystem structure remains unaffected.
5. Zone of minimal impact (dNBR < 0.1) covers areas that were practically unaffected by fires, and index values < 0.1 correspond to its natural variability in undisturbed geosystems (which is also confirmed by validation results obtained from control plots located outside the combat zone).

By analysing the calculated dNDVI values, four zones were distinguished, each characterised by a different degree of biomass loss in beligerative-recreational systems (Pettorelli, 2013):

1. Zone of critical losses (dNDVI > 0.5), which covers areas with almost complete destruction of vegetation cover. Analysis of control points established within the model plots of the study showed that at dNDVI > 0.5 there is a critical decline in the photosynthetic activity of plants, indicating an almost complete loss of ecosystem functionality.

2. Zone of substantial losses (dNDVI = 0.3–0.5), which includes areas with a pronounced reduction in vegetation biomass. This range corresponds to territories with significant, though not catastrophic, biomass decline, where gradual self-recovery is possible over the course of several subsequent growing seasons.

3. Zone of moderate losses (dNDVI = 0.1–0.3) covers areas with a moderate reduction in vegetation biomass: at such dNDVI values, the ecosystem is capable of self-recovery within 1–2 growing seasons without the implementation of special reclamation measures.

4. Zone of minimal losses (dNDVI < 0.1), which includes areas with minor changes in vegetation biomass. In this case, the threshold value dNDVI < 0.1 corresponds to the state of natural seasonal variability in geosystems. For the study area, this index value (according to previous monitoring observations) is typical of the dNDVI time series for the period 2019–2021 (in other words, prior to the onset of the active phase of hostilities).

Validation of the identified categories was carried out by comparing them with the results of field observations, during which damage to vegetation, soil cover, and changes in the structure of plant communities were recorded. For the purpose of substantiating the delineation of classification categories describing the transformation of beligerative-recreational systems, the methodological toolkit of correlation analysis was used as the primary analytical basis (Janse et al., 2021). It was found that the correlation coefficient between the classification scheme based on dNBR and the field-based assessment of burn severity is 0.89, and between the classification scheme based on dNDVI and the corresponding field-based assessment of damage severity it is 0.85, which confirms the validity of the chosen scale for monitoring-based assessment of beligerative-recreational systems within the study area.

Results

In the context of studying the impacts on geosystems caused by military actions, and taking into account the operating conditions of contemporary nature-use systems (Udovychenko, 2017) characteristic of the model sites under investigation, beligerative-recreational systems are understood here as complex entities that have experienced direct or indirect effects of warfare and within which, in a single spatial "framework", elements of beligerative nature use (military-defence infrastructure, loci of destruction, zones of restrictions and safety risks, places of memory, etc.) and recreational activity (natural and urban green spaces, water and climate-related recreational resources, cultural-tourist objects and service infrastructure, etc.) co-exist and interact (Udovychenko, & Petrovskyi, 2024).

The monitoring study of their spatial dynamics was considered feasible to carry out in a logical sequence of reasoning and applied methods and methodological techniques, starting from the identification of the specific features of the formation of beligerative-recreational systems and the analysis of changes in such systems using the dNBR and dNDVI indices, through a comparative analysis of the dNBR and dNDVI calculation results, and finally to the substantiation of a score-based assessment of the respective areals and the classification criteria for beligerative-recreational systems according to the computed dNBR and dNDVI indices.

Thus, it is a proven fact that the spatial differentiation of beligerant-recreational systems depends on the intensity and nature of hostilities occurring within them. It is also evident that geosystems become most highly transformed in zones affected by intense, massive artillery shelling and air strikes, where, as a consequence, large-scale fires and destruction of infrastructure facilities occur, followed by changes in the functional trajectories of such geosystems.

The degrees of transformation of these systems, on the one hand, depend on the level and depth of damage to plant communities, while, on the other hand, they determine the rate and feasibility of post-war (or post-active-phase) recovery. In particular, coniferous forests experience deeper and more extensive fire-induced damage compared to broadleaved forests, as they are more vulnerable to the effects of fire. Urban green spaces likewise suffer substantial damage. At the same time, recovery proceeds more rapidly in those areas where measures for sustainable urban greening and maintenance are implemented. However, the rate of recovery of different types of BRS varies significantly: systems with moderate and low degrees of damage exhibit relatively rapid restoration of vegetation cover over the following growing seasons, whereas territories with critical and substantial degrees of damage require a prolonged period for recovery, provided that active reclamation measures are implemented.

The identified degrees of damage/transformation of BRS were determined in accordance with the assessment scales based on the calculated dNBR and dNDVI indices.

Thus, the existing classification of territories by degree of fire damage, based on dNBR (Differenced Normalized Burn Ratio) values and grounded in the methodology introduced by the United States Geological Survey (USGS) (Key, & Benson, 2021), was adapted to the specifics of the object–subject domain of this research (the nature of beligerative-recreational systems in the study area in the context of the concept of current nature-use systems). The threshold dNBR values for each classification category of BRS damage were substantiated as follows:

1. Zone of critical damage, where dNBR > 0.66, generally comprises sites/BRS in which total destruction of vegetation cover is observed, the complete burning of the forest floor down to the mineral layer and the destruction of soil organic matter, resulting in the exposure of the mineral soil; the presence of burn scars, ruins of buildings and debris of various origin, etc. Due to such deep-seated damage, these geosystems exhibit no potential for self-recovery over the next several years. Within the study area delineated in the north-western outskirts of Kyiv, the total area identified and calculated as experiencing a critical degree of BRS damage from military-induced fires in early 2022 (late February–March) is 4.8 km², or 12 % of the total study area (Fig. 1 – graphical, and Fig. 2 – spatially visualised representation of the obtained results).

2. Zone of substantial damage, with dNBR values in the range 0.44–0.66, is characterised by severe damage to tree stands, mortality of more than 75 % of trees, burning of the herb and shrub layers, and damage to the upper organic soil layer, while at the same time individual viable plant specimens are preserved and there remains a limited potential for self-recovery. Within the study polygon, the total area of BRS with this degree of damage is 8.2 km², or 20.5 % of the total study area (see Fig. 1).

3. Zone of moderate damage (dNBR = 0.27–0.44) comprises areas where 40–75 % of tree stands are damaged. It is characterised by partial burning of the understorey and herb layer, minimal damage to the soil cover, and the preservation of a substantial share of the "seed bank", and therefore demonstrates the potential for self-recovery within 1–3 years. The identified and calculated area within the north-western outskirts of Kyiv with a moderate degree of BRS damage totals 13.5 km², or 33.8 % of the total study area.

4. Zone of low damage (dNBR = 0.1–0.27). In such BRS, damage affects up to 40 % of tree stands; surface burning of the herb layer is recorded; the structure and stratification of vegetation are preserved; no significant damage to the soil profile is observed; and there is a high potential for rapid self-recovery. In total, the area of BRS with this degree of damage is 9.8 km², or 24.5 % of the total study area.

5. Zone of minimal impact, where dNBR < 0.1, is characterised by the absence of visible signs of fire influence/manifestation or other types of thermal damage; it shows a high degree of "preservation" of all geosystem components, within which only shallow mechanical disturbances with limited transformative effect may occur. Within the study polygon in the north-western outskirts of Kyiv, the area of BRS with this degree of impact is 3.7 km², or 9.2 % of the total study area (see Figs 1 and 2).

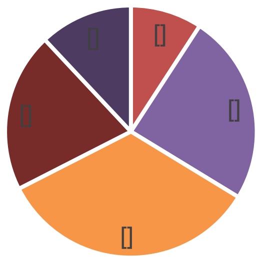

Fig. 1. Percentage distribution of land-cover damage zones of BRS within the study sites based on the calculated dNBR

The above-mentioned degrees of damage/transformation of BRS, identified on the basis of the threshold dNBR values for each classification category and according to the described assessment scale for the calculated dNBR index, exhibit the following spatial characteristics within the model sites of the study polygon. The highest degree of damage is found in extensive forest tracts in the western–south-western and eastern–south-eastern parts of the territory of Irpin, almost throughout the territory of Bucha, and sporadically – with a predominance in the northern part of the town – within Horenka. At the same time, a high level (substantial damage) caused by military-induced fires is observed in Irpin in the forested areas located to the south-west of the town, and in Bucha in residential neighbourhoods, especially in the central and north-western parts of the town. Within the territory of Horenka, a relatively low degree of fire damage (moderate and low) predominates; however, high (substantial damage) and very high (critical damage) levels are recorded across the entire western half of the town.

Thus, as can be seen from the results of the dNBR calculations and spatial modelling within the study polygon, BRS with low, moderate and substantial degrees of fire damage are represented in approximately equal proportions (≈34 %, 33 % and 32 %, respectively), while their development patterns are spatially heterogeneous across the three model sites.

Another equally important component in assessing the degree of BRS transformation caused by military actions was the identification and substantiation of the levels of damage to land (vegetation) cover and the degrees of biomass loss based on the dNDVI (Differenced Normalized Difference Vegetation Index).

The classification of BRS by degree of vegetation biomass loss based on the obtained dNDVI values was developed taking into account the structure of land cover and the prevailing types of plant communities in the study area, as well as the type of loss caused by warfare. The threshold dNDVI values for each classification category of BRS damage were substantiated as follows:

1. Zone of critical losses (dNDVI > 0.5) includes sites where the vegetation index decreases by more than 50% compared to the pre-war period, where more than 80 % of vegetation biomass is lost, the vertical structure of plant communities is completely destroyed, and there are no signs of photosynthetic activity in the vast majority of biocenoses. Within the study polygon delineated in the north-western outskirts of Kyiv, the total area identified and calculated as belonging to the zone of critical losses of BRS plant communities due to military impacts is 5.2 km², or 13 % of the total area of the study polygon.

2. Zone of substantial losses (dNDVI = 0.3–0.5) is characterised by a decrease in the vegetation index by 30–50 %, a loss of 50–80 % of vegetation biomass, a pronounced disruption of the vertical structure of plant communities, and the preservation of photosynthetic activity over 20–50 % of the area. The identified and calculated area within the north-western outskirts of Kyiv that falls into the zone of substantial BRS losses totals 12.8 km², or 32 % of the total area of the study polygon.

3. Zone of moderate losses (with dNDVI values of 0.1–0.3). This category includes areas where the vegetation index decreases by 10–30 %, vegetation biomass losses amount to 20–50 %, the vertical structure of plant communities is partially disturbed, and photosynthetic activity is preserved over most of the area. Within the study polygon, the total area of BRS with this level of loss is 15.6 km², or 39 % of the total study area.

4. Zone of minimal losses (with dNDVI < 0.1) is characterised by a decrease in the vegetation index of less than 10 %, losses of up to 20 % of vegetation biomass, and the preservation of plant community structure together with ongoing photosynthetic activity. Within the study polygon in the north-western outskirts of Kyiv, the area of BRS with this level of loss is 6.4 km², or 16 % of the total study area (Fig. 3).

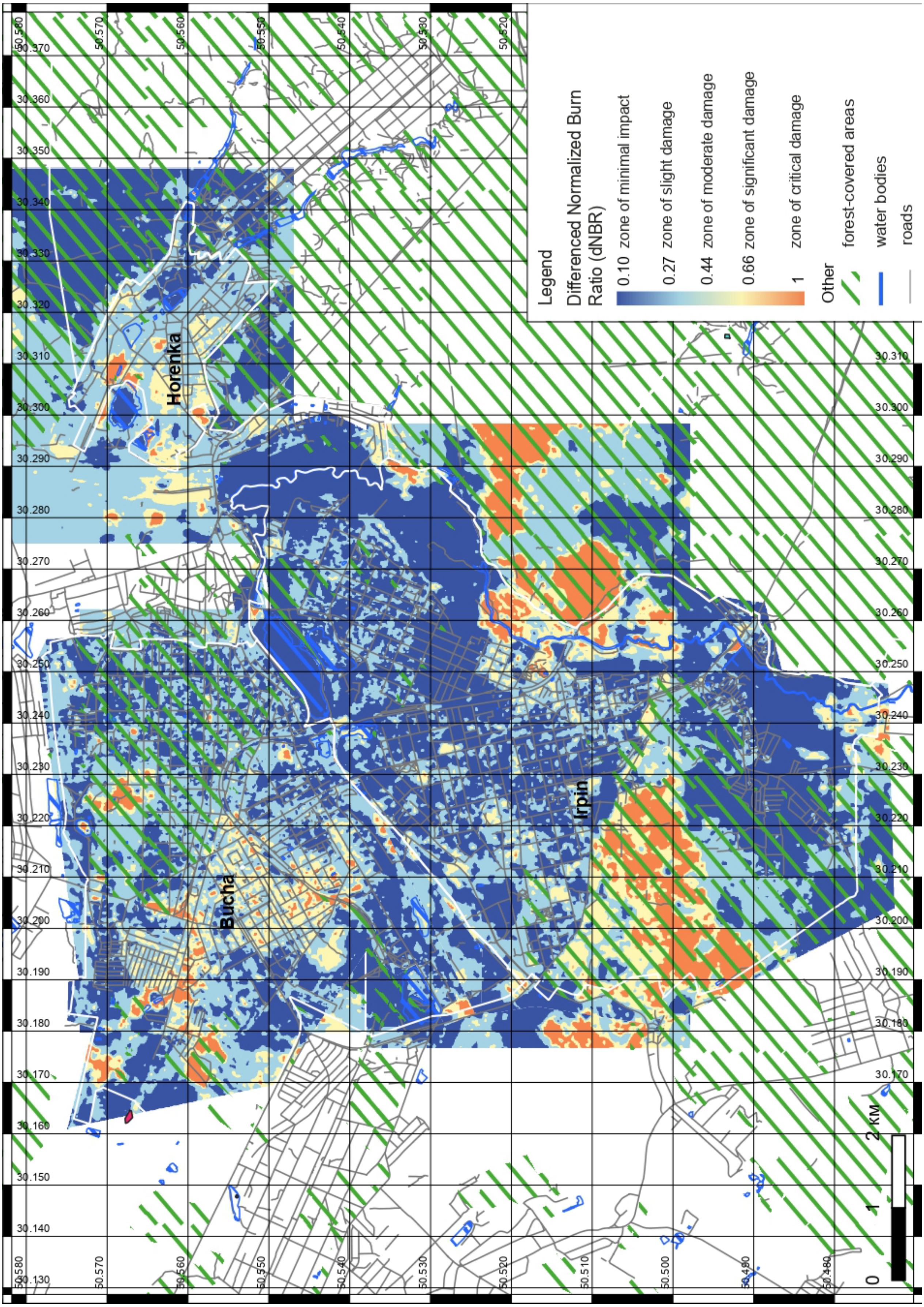

Fig. 2. Land-cover damage zones of the study sites based on the calculated dNBR

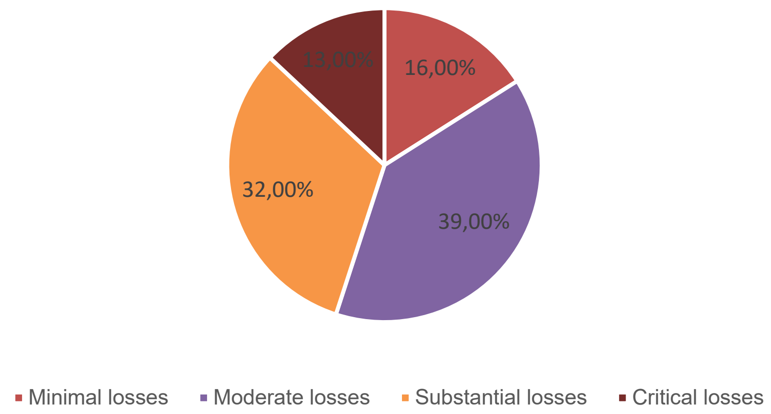

Fig. 3. Proportions of damage zones (land-cover loss) within the study sites derived from dNDVI

The above-described levels of vegetation biomass loss and degrees of damage to the land (vegetation) cover of BRS, identified according to the threshold dNDVI values for each classification category and the corresponding assessment scale for the calculated dNDVI index, exhibit the following spatial characteristics within the model sites of the study polygon (Fig. 4). The highest degree of damage to the land (vegetation) cover is observed almost throughout the BRS of Irpin and Bucha, with the exception of their peripheral areas, which are predominantly characterised by substantial losses and, to a lesser extent, moderate losses. The situation is more favourable within the model site of Horenka, where loss levels are predominantly minimal (minor) and moderate, with only small patches of the zone of critical losses, mainly in the northern and extreme western parts of the town.

Thus, based on the results of the dNDVI calculations and spatial modelling within the study polygon, it can be concluded that BRS of different degrees and zones of vegetation biomass loss are represented unevenly: zones of critical and substantial losses dominate overall (together accounting for 45 %), while areas with moderate losses are somewhat less represented (39 %), and patches with minimal losses are very weakly represented (16 %) (see Figs 3 and 4). The same heterogeneity is exhibited by these classification categories in terms of the spatial patterns of their development within the three model sites.

Validation of the above-developed and substantiated classification schemes based on the calculated dNBR and dNDVI was carried out using data from field observations conducted within the model sites, as well as remote monitoring data and high-resolution imagery. By applying correlation analysis techniques, it was established that the proposed scales have high accuracy (87 %) in determining and differentiating levels of vegetation biomass loss: the greatest biomass losses are observed in the same zones where high dNBR values occur, which once again demonstrates the strong impact of fires on vegetation cover degradation. However, in contrast to dNBR, the calculation and spatial modelling of dNDVI also makes it possible to identify BRS within which mechanical damage to vegetation has occurred. It was found that a high correlation between these indices (r = 0.87) is observed in areas where fires were the dominant impact factor. In contrast, in areas where mechanical disturbance (craters from explosions, trenches, dugouts, etc.) predominates, the correlation is significantly lower (r = 0.42), which confirms the need for a comprehensive approach to the classification of territories affected by beligerative impacts.

The validation carried out in this way confirms the reliability of the obtained results and strengthens the rationale for further determining the degrees of transformation of beligerative-recreational systems, which will make it possible to comprehensively assess the scale and intensity of changes within the study areas caused by fires and associated anthropogenic (military) factors.

For a comprehensive assessment of the degrees of transformation of beligerative-recreational systems, and taking into account existing experience (Key, & Benson, 2021), it was considered necessary to develop an integrated classification of the relevant categories. By adapting existing classification approaches to the needs of assessing beligerative and recreational systems per se, considering the different mechanisms by which warfare affects geosystems and BRS, and based on overlaying the dNBR and dNDVI indicators, it was deemed possible to distinguish the following classification categories:

1. Catastrophic transformation (dNBR > 0.44 and dNDVI > 0.5), characterised by complete degradation of vegetation cover as a result of intense fires and mechanical damage, destruction of the natural landscape structure and, consequently, the need to implement comprehensive reclamation measures for BRS.
2. Severe transformation (dNBR = 0.27–0.44 and dNDVI = 0.3–0.5), marked by substantial disruption of landscape structure caused by various impacts of military actions. Restoration of such BRS is only possible if a series of targeted reclamation and remediation measures is carried out.
3. Moderate transformation (dNBR = 0.1–0.27 and dNDVI = 0.1–0.3), manifested as partial disturbance of landscape structure while maintaining the main functional linkages between its components and neighbouring areas. Such territories are capable of self-recovery within 1–3 years.
4. Low transformation (dNBR < 0.1 and dNDVI < 0.1), characterised by minor disturbances to individual landscape components and the preservation of their structure and functions. Such territories recover rapidly, usually within a single growing season.

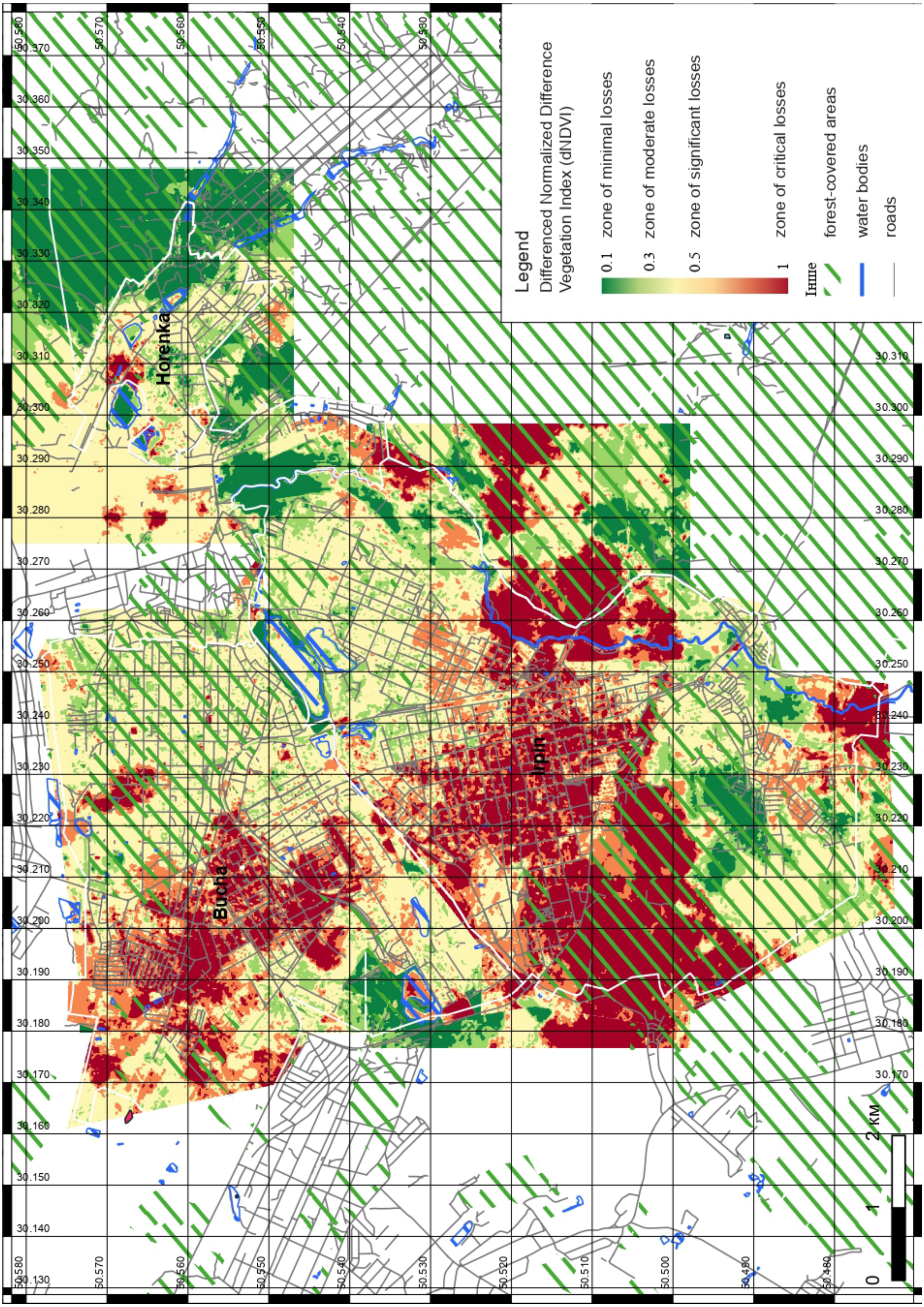

Fig. 4. Vegetation loss zones of the study sites based on the calculated dNDVI

Thus, the overlay of the dNBR and dNDVI indices applied in the course of classification makes it possible not only to determine the intensity of biomass losses but also to identify mechanical disturbances of the vegetation cover, which renders the proposed approach a universal tool for analysing the complex changes experienced by BRS. The proposed system provides a scientifically grounded basis for further planning of restoration, reclamation, remediation and monitoring measures, since it allows clear identification of zones of military intervention, indicates the potential for territorial self-recovery, and reflects the degree of diversification in the implementation of the necessary management actions. This approach makes it possible to move from a mere recording of disturbances to the development of effective strategies for the rehabilitation of affected geosystems.

At the same time, the classification of degrees of transformation of beligerative-recreational systems developed in this way makes it possible to generalise the nature and scale of the impact of military actions on landscape complexes, while further cartographic modelling of the delineated taxa (in the course of future research) will provide a structured understanding of the spatial differentiation of the degradation processes that have taken place.

Discussion and conclusions

The above-outlined findings of the study have made it possible to provide a multifaceted characterisation of the scale and specific features of the transformations undergone by beligerative-recreational systems in the north-western part of the suburban belt of Kyiv under the impact of military actions in the first half of 2022. The integrated combination of remote sensing data, index-based analysis, field observations, validation and overlay analysis has ensured a holistic understanding of the spatial structure of changes, their intensity and the mechanisms by which they manifest. The results obtained provide a scientifically substantiated basis for developing further recommendations on the restoration, monitoring and management of the affected territories.

Comparative analysis of the results of assessing changes in beligerative-recreational systems caused by military actions, carried out by calculating the dNBR and dNDVI indices and verifying the obtained values, made it possible to identify general patterns and differences in the spatial distribution of affected areas and to distinguish classification categories corresponding to different levels of military damage.

At the same time, the results of analysing these two indices demonstrate certain differences. The NBR index is more sensitive for detecting areas affected by fires, whereas NDVI better reflects the overall state of vegetation biomass; the dNDVI index reveals areas with mechanical damage to vegetation in the absence of fire, which are not detected using dNBR. Furthermore, a high level of correlation is observed between dNBR and dNDVI values (correlation coefficient $r = 0.87$), which indicates the validity of the applied methodology for assessing the military impact and fires on vegetation cover degradation within the study area. Monitoring both indices demonstrates gradual recovery of vegetation cover, particularly during the first growing season following the disturbances in 2022, especially in areas with low and moderate degrees of military and pyrogenic transformation.

The proposed integrated classification of BRS by degree of damage caused by military impacts is based on the results of overlaying dNBR and dNDVI values for different types of warfare-related impacts on geosystems. It was found that high correlation between these indices is observed in areas where fires were the dominant impact factor, whereas in areas with a predominance of mechanical military damage (craters from explosions, trenches, dugouts, etc.) the correlation level is significantly lower, which confirms the need for a comprehensive approach to classifying territories affected by beligerative impacts.

Areal analysis of beligerative-recreational systems investigated using monitoring tools and of the levels of their damage by military impacts suggests that the most heavily transformed systems are those located in the peripheral districts of Irpin and throughout Bucha, and, sporadically but predominantly in the northern part of the town, within Horenka, where the most intense hostilities occurred. Calculation of the dNBR index made it possible to identify territories affected by fires resulting from military actions and to establish that about 12 % of the area experienced a critical level of damage and another 20.5 % a severe level of damage. Analysis of NDVI changes revealed substantial losses of vegetation biomass: critical losses were recorded on 13 % of the territory and substantial losses on 32 %. Verification of the calculated dNBR and dNDVI values revealed a high level of correlation, which confirms the dominant influence of fires on vegetation cover degradation. At the same time, the calculation of dNDVI made it possible to identify areas with mechanical damage to vegetation that are not detected using dNBR.

The dynamics of the spatial distribution of both indices during the first subsequent growing season showed gradual vegetation recovery in areas with moderate and low degrees of military impact. However, in areas that experienced critical and severe impacts, the recovery process is extremely slow, indicating the need to introduce active measures for reclamation, remediation and comprehensive restoration of degraded landscapes and beligerative-recreational systems. These aspects determine the prospects for further research aimed at generalising the nature of the impact of military actions on landscape complexes, scaling the applied methodology to other model sites in Kyiv Region with mandatory cartographic modelling of the substantiated and proposed taxa to be distinguished, which will ensure a structured understanding of the spatial differentiation of degradation processes that occurred as a result of military events.

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МОНІТОРИНГОВІ ДОСЛІДЖЕННЯ ПРОСТОРОВОЇ ДИНАМІКИ БЕЛІГЕРАТИВНО-РЕКРЕАЦІЙНИХ СИСТЕМ (НА ПРИКЛАДІ ІРПЕНЯ, ГОРЕНКИ, БУЧІ)

В с т у п . ***Воєнні дії 2022 року у передмісті Києва (Ірпінь, Горенка, Буча) зумовили значні антропогенні зміни довкілля й формування так званих белігеративно-рекреаційних систем (БРС), де поєднуються осередки мілітарних руйнувань та рекреаційні ресурси. Деградація рослинності й інші зміни стану наземного покриву на цих територіях потребують детального дослідження й оцінювання для цілей подальшої їх ревіталізації. Метою дослідження було виявити просторові зміни у структурі наземного (рослинного) покриву та оцінити ступінь деградації белігеративно-рекреаційних систем з використанням дистанційних методів зондування Землі й шляхом обрахунку спектральних індексів та їх різницевих форм.***

М е т о д и . ***Для потреб здійснення моніторингового дослідження просторової динаміки БРС використовувалися космічні знімки Sentinel-2 та Landsat-8 для побудови часових зрізів БРС "до" та "після" активних бойових дій, що мали місце в межах дослідних ділянок. Було обраховано індекси NBR (Normalized Burn Ratio) та NDVI (Normalized Difference Vegetation Index), а головно – їх різницеві форми dNBR (Differenced Normalized Burn Ratio) та dNDVI (Differenced Normalized Difference Vegetation Index), що відображають ступені ураження наземного покриву внаслідок вигоряння та інших втрат біомаси. Отримані значення dNBR та dNDVI було класифіковано за ступенями ураження (від критичних до мінімальних). Валідацію запропонованих шкал розподілу обрахованих індексів було здійснено шляхом обрахунку коефіцієнтів парної кореляції. За результатами обрахунку останньої було виявлено сильний кореляційний зв'язок (r≈0,87) між dNBR і dNDVI.***

Р е з у л ь т а т и . ***Моніторингові дослідження просторових змін у структурі наземного покриву БРС довели, що наслідком найінтенсивніших бойових дій стали масштабні пожежі (північні квартали Ірпеня й Бучі та центральні й східні – Горенки), відображенням чого став обрахований dNBR. За dNBR критичним рівнем ураження охоплені 12 % площі дослідження, сильним – 20,5 %; третина території має помірні пошкодження, близько чверті – слабкі, а 9 % майже не постраждали. Аналіз обрахованого dNDVI свідчить, що на 13 % площі втрачено понад 80 % біомаси, на 32 % – 50–80 %, тоді як 39 % мають помірні втрати й 16 % – мінімальні. Крім того, обрахунок NDVI дозволив ідентифікувати ділянки із механічними пошкодженнями рослинності, спричиненими воєнними впливами.***

В и с н о в к и . ***Обрахунок спектральних індексів dNBR і dNDVI дозволив кількісно оцінити та виокремити ступені деградації наземного (рослинного) покриву БРС, візуалізувати просторову диференціацію пошкоджень за виділеними ступенями ураження. Серед них фіксуються ділянки із слабким або помірним ураженням, які, разом з тим, демонструють швидке відновлення рослинності, тоді як "зони" критичного й сильного ступеня ураження потребують запровадження стійких рекультиваційно-ремедіаційних відновних заходів. Високий коефіцієнт кореляції між dNBR і dNDVI підтверджує домінуючу роль пожеж у деградації, проте комбінований аналіз цих індексів забезпечує повнішу оцінку, яка враховує також механічні пошкодження. Отримані результати кількісного та якісного оцінювання даних моніторингових спостережень за станом наземного покриву дослідних ділянок, їх картографічного моделювання можуть бути використані для цілей розробки стратегічних заходів з екологічної реабілітації постраждалих внаслідок воєнний дій територій.***

К л ю ч о в і с л о в а : **белігеративно-рекреаційні системи, воєнні дії, дистанційне зондування Землі, dNBR, dNDVI, деградація наземного (рослинного) покриву.**

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