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Land Cover Mapping of War-Affected Areas

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A b s t r a c t

Remote sensing is a promising technology for large-scale applications and long-term trends to monitor land use/land cover changes quickly, dynamically, efficiently, and cost-effectively. Remote sensing based research holds significance, especially in areas that may be too dangerous for scientists to conduct fieldwork on-site. To better understand how armed conflicts affect land use/land cover, we conducted analyses of PlanetScope data in selected regions in Ukraine. We analysed and classified the manifestations of damaged areas (burnt residential buildings, destroyed industrial buildings, destroyed roads, damaged green areas, etc.). The aim of this paper is to propose the nomenclature applicable in large-scale land use/land cover mapping and explain in detail the content of the proposed land use/land cover classes in the context of the future development of a war-affected territory. The size of the minimum mapping unit was established at 0.1 ha. The detailed nomenclature can serve as a basis for detailed mapping of land use/land cover and its changes in war-affected regions worldwide.

Key words: *land cover, war-affected areas, satellite images, nomenclature*

1 INTRODUCTION

Understanding what drivers influence land cover changes and land use management is important to know how land systems may be transformed. This knowledge is essential for land use planning, resource management, and disaster mitigation. The systematic analysis of land use/land cover changes is decisive in precisely understanding the extent of changes and taking essential measures to curb the rate of changes and protect the land cover resources sustainably. Alterations in ecosystem services caused by land use and land cover change may provide feedback to the underlying drivers of these transformations. These drivers are a combination of the following fundamental high-level causes: resource scarcity leading to an increase in the pressure of production on resources, changing opportunities created by markets, outside policy intervention, loss of adaptive capacity and increased vulnerability, and changes in social organisation, resource access, and attitudes (Lambin et al., 2003). Among outside policy interventions, warfare and armed conflicts play important roles. Land use decisions can change abruptly in response to wars, causing the most drastic and globally frequent shocks (Baumann & Kuemmerle, 2016).

Currently, there are 56 conflicts, the highest number since World War II (Global Peace Index, 2024). These conflicts have increasingly taken on an international dimension, with 92 countries involved in disputes beyond their borders, marking the most extensive involvement since the Global Peace Index (GPI) began. The rise in minor conflicts raises the chances of more significant conflicts arising in the future. For instance, Ethiopia, Ukraine, and Gaza were categorised as minor conflicts in 2019. In 2023, there were 162,000 deaths related to conflict, the second-highest toll in the last 30 years. Conflicts in Ukraine and Gaza accounted for nearly three-quarters of these fatalities, with Ukraine alone representing over half of the total, with 83,000 recorded conflict-related deaths (Global Peace Index, 2024).

A specially detailed dataset on armed conflicts and a literature review were completed to explore how land use patterns are impacted and how far-reaching and persistent these changes are (Baumann & Kuemmerle, 2016). In terms of methodological approaches of 38 selected studies, 76% were based on remote sensing to quantify land use changes, whereas 16% of all studies relied on statistical information such as forest inventories or agricultural production statistics. The analysis highlighted that specific land systems, such as urban and densely populated systems, are strongly affected by armed conflict. The findings also highlight that conflicts occur predominantly in areas most valuable for humans, possibly prompted by conflicts over access to these lands or their resources. Several studies also highlighted widespread agricultural abandonment.

The use of satellite technology has a long history as a tool of warfare, but much less research has used satellite technologies to study the effects of war (Witmer, 2008). Multi-spectral Landsat Thematic Mapper (TM) data were applied to study the land use/land cover changes in northeast Bosnia after the war between 1992 and 1995. Four change detection methods were used to evaluate effectiveness in detecting abandoned agricultural land with an overall accuracy of 82.5%. The use of remote sensing to monitor war-affected areas has increased over the past two decades. Remote sensing based research holds significance, especially in areas that may be too dangerous for scientists to conduct fieldwork on-site. War-affected urban areas in Syria were examined using a composite band sensitive to urban destruction with an accuracy of 74% created from a pre-conflict baseline over a six-year period (Marx, 2016). Analysis of change in surface reflectance caused by building destruction was performed using data derived from the Landsat Enhanced Thematic Mapper Plus (ETM+) and Operational Land Imager (OLI) on Landsat 7 and Landsat 8. A novel methodology that combines remote sensing products, machine learning techniques, and quasi-experimental statistical analysis to understand better land use/land cover changes in Syria between 2004 and 2022 was also developed (Mhanna et al., 2023).

Warfare activities are military operations between enemies – an activity undertaken by a political unit (such as a nation) to weaken or destroy another. They can include terrorist activities, bombardment, invasion, civil war, insurrection, rebellion, revolution, coup, or actions of armed forces while engaged in a war, whether declared or not. The most serious consequences can be caused by nuclear incidences, nuclear explosions or contamination by radioactive material. War activities can significantly impact land cover in various ways, often resulting in changes to ecosystems, landscapes, and land use. Tab. 1 presents some key warfare-related activities that can impact land cover.

Modern remote sensing technologies, such as hyperspectral imaging, can detect many types of damage, pollution, and landscape degradation (e.g. Warren et al., 2015). However, despite its advantages, there are cases where remote sensing cannot directly detect landscape damage. The use of chemicals to incapacitate or harm the enemy or pollution from weapons causes contamination of soil and water or long-term ecological damage, however it does not have a direct impact on land cover change. The severity and type of impact depend on the intensity, duration, and location of the conflict, as well as post-war recovery efforts. For example, some damage has no visible surface expression: chemical contamination of soil or groundwater may not result in noticeable changes in vegetation or surface colour; biochemical changes in soil may significantly affect fertility without changing spectral properties; deep subsurface disturbances or the early stages of degradation may go undetected. In addition, damage smaller than the sensor's spatial resolution can be 'smoothed out' by the average pixel value. Weather conditions, atmospheric effects, and seasonal factors (cloud cover, smoke, fog, snow, etc.) may obscure or distort remote sensing images. Dense vegetation can hide surface or subsurface damage, although technologies such as LiDAR or multi-seasonal monitoring can help in such cases. Also, in some regions, data availability with the required spatial or spectral resolution may be limited, or satellite data may not cover the required time period to track changes.

The current war conflict in Ukraine and its effects on the country have been the object of interest of several researchers. The consequences of the Russian invasion in the sustainability context in selected Ukrainian cities were analysed through the damage caused to the population, housing stock, transport and other infrastructure, green spaces, and water bodies (Maruniak et al., 2023). A classification of

Tab. 1. Overview of warfare activities related to land cover

Warfare activity	**Purpose**	**Impact on land cover**
Urban warfare	Conflict in cities and towns	Destruction of buildings, conversion of urban green spaces into rubble, and creation of wastelands.
Bombing and explosions	Destruction of enemy targets or infrastructure	Creation of craters, bombturbations (Hupy & Schaetzl, 2006), destruction of forests, grasslands, and agricultural fields, and exposure of soil leading to erosion.
Use of land mines and explosives	Defensive or offensive tactics to control land	Abandonment as a result of restricted land use due to danger, soil destruction and pollution.
Deforestation	Clearing forests for military bases, roads, and other infrastructure or to deny enemies cover.	Loss of vegetation, fragmentation of forest habitats.
Deliberate waterlogging of the soil (Harper, 2008), flooding of river floodplains	Creation of difficulties for the enemy‘s movement	Threats to biodiversity and the sustainability and natural value of landscapes in flooded areas.
Fires	Intentional or incidental burning of landscapes during combat	Loss of forest cover, release of carbon into the atmosphere, and changes in soil fertility.
Trench warfare and fortifications	Construction of trenches, bunkers, and other defensive structures	Changing soil structure, soil contamination with fuels and lubricants, removing vegetation, degrading agricultural land and long-term damage to the landscape.
Military vehicle movement and its maintenance	Deployment of tanks, trucks, and other military vehicles	Soil compaction, destruction of vegetation, and creation of informal tracks or roads, clogging of the soil surface, chemical pollution, deformation of the soil cover.
Military training exercises	Simulation of combat scenarios	Regular disruption of land cover due to explosions, movement, and other activities.
Forced migration and refugee camps	Displacement of populations due to conflict	Conversion of natural landscapes into temporary settlements, deforestation for fuel and construction, and increased pressure on local ecosystems.
Nuclear and large-scale explosions	Use of highly destructive weapons	Landscape abandonment due to long-term radiation contamination, destruction of ecosystems.

the consequences of the war for ecosystems was proposed, considering the duration of impacts, their nature, scale, and the vulnerability of ecosystems (Didukh et al., 2024). A comprehensive analysis of the consequences of military-caused environmental changes based on Sentinel-1 synthetic aperture radar data was performed by (Udovychenko, 2024). The analysis was oriented mainly on the destruction of life support and economic systems, housing, and the degradation of the natural environment. Armed conflict also caused damage to valuable arable land and agricultural infrastructure, reducing food production and significantly affecting the world food supply. Grain production loss of the six eastern oblasts in 2022 was up to 31% compared to the average yield level between 2016 and 2020 (He et al., 2023). Therefore, the impact of armed conflict on changes in cropland use has received widespread attention.

There are several approaches when mapping the land use/land cover of war-affected territories. In the studies mentioned above, there is often an unequivocal definition of the nature of the mapped classes and the degree of damage to the mapped territories.

The aim of this study is to point out specific land cover features in the physiognomy of war-affected territories and to propose the nomenclature framework for large-scale land cover mapping of post-conflict landscapes. The nomenclature aims to improve the accuracy of environmental damage assessments, provide scientific support for post-conflict reconstruction, and inform ecological restoration policies in the context of the following principles and requirements (Oťaheľ et al., 2017):

- respect the CORINE land cover (CLC) nomenclature to the third hierarchical level;
- delimiting more detailed classes is based on aerial orthophotos or VHR satellite images;
- distinguish the autonomy of classes according to the size of the minimum mapping area and spatial neighbourhood;
- respect the association feature, i.e. spatial relationship in the context of hierarchically higher classes (e.g. accompanying vegetation of transport routes, riparian vegetation of watercourses);
- include repeatable objects in the appropriate class if they characterise the overall appearance and consistency of the class (terraced vineyards, terraced small-block plowed fields, etc.);
- compile the legend hierarchy in a way that allows for effective integrated data aggregation and application for various types, especially environmental assessments. This study investigates how war-induced changes to landscape features can be effectively captured through an extended CLC-based nomenclature. We analysed and classified the manifestations of damaged places (burnt residential buildings, destroyed industrial buildings, destroyed roads, damaged green areas, etc.) based on PlanetScope data with a spatial resolution of 3 m as a basis for subsequent proposals for restoration or land use change.

2 MATERIAL AND METHODS

Remote sensing is a promising technology for monitoring land use/land cover changes quickly and cost-effectively for large-scale applications. It is of great importance in the evaluation of currently imminent dangers, as well as long-term trends.

When choosing the classification method, we took into account the fact that in many cases, despite the extensive damage, the war-affected areas do not have to be significant in the area (e.g. a collapse of a bridge or destruction of individual buildings) to be assessed with sufficient accuracy by automatic classification. For this reason, we have favoured computer-assisted photo interpretation for the pilot land cover mapping of the Hostomel settlement using the proposed nomenclature. The total interpreted area was 66.5 square kilometres. This methodology is a visual interpretation method used to recognize, identify, and assess land cover objects in satellite or aerial images. It analyses the relationship between landscape objects and their texture and pattern representation in images, requiring knowledge of the physical properties of these objects and their influence on electromagnetic radiation. Although computer-assisted photo interpretation is a human-driven interpretation method, specific algorithms and predefined land use/land cover classes assist in this process to make it more efficient and accurate. These classification algorithms support the analyst in interpreting the imagery based on spectral characteristics like colour, texture or spatial arrangement in the image. According to (Feranec & Oťaheľ, 2001), texture is the spatial variability of tones arranged on the image representing objects or groups of objects on the surface of the Earth that are too small to discern as individual entities. The identical objects are represented on the images of the same type and scape by identical textures (stripes, circles, etc.). The pattern is alternation, the repeating of textures, which represents arrangements of landscape objects. Each land use/land cover class in the proposed nomenclature is described by a list of dominant objects, their typical arrangement in the landscape, and the textures that help identify them through visual interpretation. These interpretation signs allow experts to distinguish land cover types such as forests, urban areas or agricultural fields in satellite imagery. The analysis of textures and patterns helps refine the proposed nomenclature and improve the accuracy of land use/land cover mapping. This methodology provides a detailed understanding of war-affected landscapes and their spatial features through careful interpretation of satellite images.

For the purposes of this study, RGB composite PlanetScope satellite images were used for visual interpretation, as they provide a clear and intuitive means of data analysis. Historical Google Earth images were used as an additional source. The images of the study area were selected to cover three periods: before Russia's full-scale invasion (September 2021), the phase of active hostilities, and the period of restoration and intensification of agricultural activities after de-occupation (June 2024).

PlanetScope, operated by Planet, is a constellation of approximately 130 CubeSat satellites (10 by 10 by 30 centimetres), able to image the entire land surface of the Earth every day (a daily collection capacity of 200 million km^2/day). PlanetScope images are approximately 3 meters per pixel resolution in 8 spectral bands: blue, green, red, near-infrared (NIR), green I, red edge, yellow, and coastal blue. PlanetScope Scene imagery products are available for download in the form of imagery assets. Multiple asset types are made available for Scene products, each with differences in radiometric processing and/or rectification. For the purpose of this study, orthorectified, colour-corrected, RGB imagery products (visual assets) were used, that are optimized for the human eye, providing images as they would look if viewed from the perspective of the satellite. These products are designed for simple and direct visual inspection, and can be used and ingested directly into a Geographic Information System (Planet Team, 2022).

To ensure a systematic and repeatable approach to visual interpretation, this study explicitly incorporated key visual elements – tone, shape, size, pattern, texture, shadow, and association. These interpretation signs guided the identification of land use/land cover objects in conflict-affected areas where automated classification methods often fail. For instance, tone and shape were crucial for distinguishing damaged infrastructure from intact urban fabric, while texture helped identify damaged agricultural areas. To enhance repeatability and reduce subjectivity, interpretation signs described by Kosztra et al. (2019) were employed and cross-checked to ensure coherence across the dataset.

In war-affected areas, a different texture and pattern emerges in the originally defined classes. For the purpose of our research, we proposed an extended and modified CLC classification on the fourth hierarchical level (Fig. 1) based on the nomenclature presented by (Oťaheľ et al., 2017). Basic definitions of CLC classes (Kosztra et al., 2019) at the third level are valid for European countries at a scale of 1:100,000. The modification of the CLC nomenclature for the identification of land cover at the local scale of 1:10,000 is based on the concepts and procedures applied to hierarchically higher CLC classes. The size of the minimum identified area was established at 0.1 ha. It approximately corresponds to a square with a side of 31.6 m, a circle with a diameter of 35.7 m or a 20 x 50 m rectangle, as the resolution capacities of aerial images allow. The minimum recorded width of linear elements such as roads, railways, and streams was 2 m.

The thematic classification was conducted utilizing QGIS software tools, with the initial stage of the study employing the method of visual interpretation of satellite images. This visual interpretation encompassed the geometric, optical, and structural characteristics of objects (direct interpretation features: object shape, size, colour, image phototone, texture, structure, object shadows, brightness contrast), in addition to various relationships and interdependencies between them (indirect interpretation features). For instance, the identification of arable land was facilitated by direct interpretation features, such as rectangular or near-rectangular shapes, light or saturated image tones relative to other land cover types, which are associated with higher spectral reflectivity. Indirect interpretation features, such as linear image texture, indicative of soil cultivation, were also employed. Bombturbations sites were distinguished by their round and oval shapes and dark coloration.

The proposed attributes (criteria) of the particularized nomenclature are based on studies of (Feranec & Oťaheľ, 1999; Bossard et al., 2000), which respect the following principal groups of attributes: (i) size of identified and recorded land cover objects by minimum area and spatial relationships; (ii) morphostructural and physiognomic attributes of land cover object differentiating heterogeneity of classes on the 4th level; (iii) attributes of the way of use (function) of land cover objects according to their spatial relationship and association interpretation attribute.

The modification of the CLC method for identifying and recording land use/land cover at a scale of 1:10,000 was based on the concepts and procedures for creating hierarchically higher classes (Feranec & Oťaheľ, 1999; Bossard et al., 2000; Feranec & Oťaheľ, 2001; Oťaheľ et al., 2017). The primary consideration was the morphostructural and physiognomic features distinguishing individual landscape objects (natural, modified, and man-made), which, together with their spatial relationships, allow the application of the associative interpretation aspect and the differentiation of objects also according to the features of landscape use (function).

For the principles of modification and delimitation of CLC classes at the fourth hierarchical level to

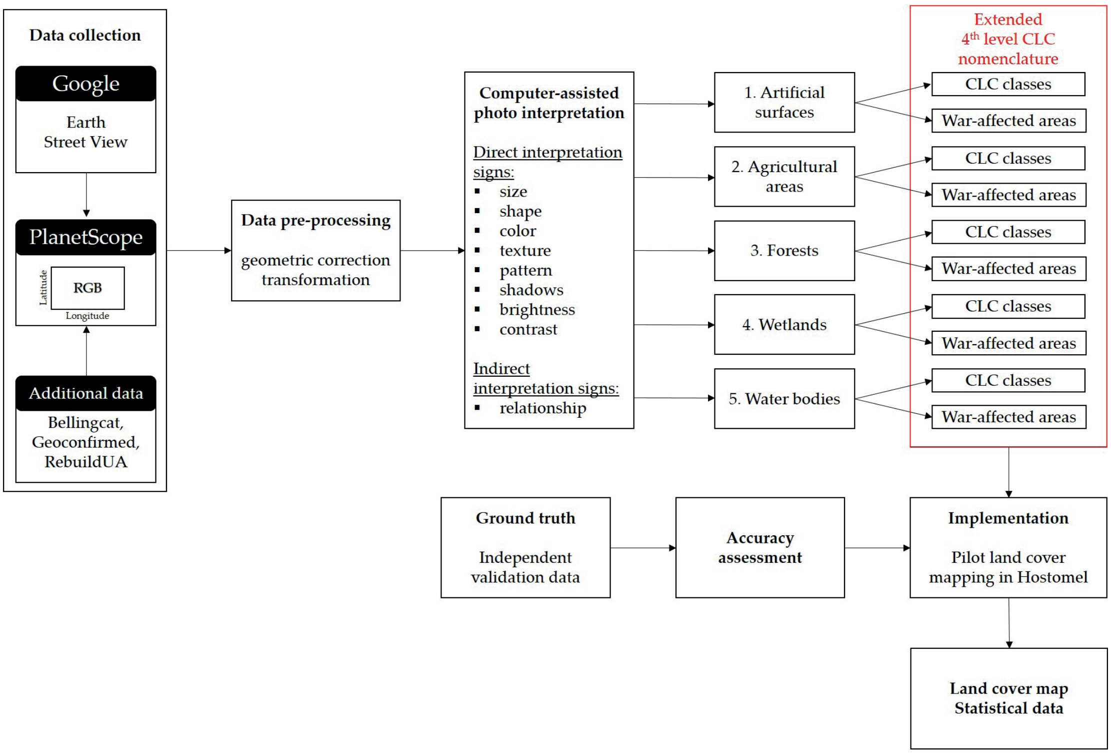

Fig. 1. Classification algorithm of the extended CLC nomenclature

be clearer in terms of their general applicability, it is necessary to define their differentiating features (criteria). Their selection is influenced by the previous research (Bossard et al., 2000; Feranec & Oťaheľ, 1999; Oťaheľ et al., 2017), which respect the following main groups of features:
- the size of the identified landscape objects according to the minimum mapping unit and spatial relationships;
- morphostructural and physiognomic features of landscape cover objects, differentiating the internal heterogeneity of the third and fourth level classes;
- features of the method (function) of use of landscape cover objects also according to their spatial relationships and associative interpretative feature.

The selected features are specified within the characteristics of the identified classes with reference to the data source used. In war-affected urban landscapes, previously used criteria for density of sealed surfaces were retained, in the description of the abandoned classes 1125 and 1213 the criterion presence of destroyed residential and commercial buildings has been added. Similarly, the classes ports (1233 and 1234) and airports (1243) were classified in more detail. In the case of transport infrastructure, the criterion for the allocation of a separate class (class 1222) was the significant sign of damage to transport infrastructure (destroyed bridges, roads, etc.).

In the agricultural landscape, the main criterion for the separation of war-affected classes were visible traces of bombing and land destruction. The existing CLC class 334 Burnt forest can include areas burned not only as a result of war activities but also natural fires.

It should be emphasised that without additional data, several characteristics cannot be obtained by interpreting aerial images, e.g. functions of urbanised and agricultural areas, therefore thematic maps, large-scale topographic maps, city plans, geobotanical maps, and other background materials are needed.

The accuracy assessment of the pilot land use/land cover mapping in Hostomel settlement in Ukraine was carried out in ArcGIS Desktop 10.5 and consists of the following steps: (i) random sampling of polygons, (ii) visual inspection of selected samples using VHR satellite data as a referential basemap, (iii) evaluation of results. A minimum of 10 samples were assessed for each fourth-level class. Five additional samples (a total of 15) were tested for each war-affected class. As some classes contained less than 10 polygons, a total of 303 polygons were evaluated for the whole Hostomel settlement. For the selected polygons, the correct class identification was individually verified using the assigned code, considering the minimum mapped unit. Next, the correctness of the geometry of the sample polygon was evaluated with the following options: (i) correctly delineated, (ii) unnecessary parts included, (iii) missing parts, (iv) both missing parts and unnecessary parts included. In terms of the detail of the polygon boundary, it was assessed whether it was correct, too coarse or too detailed. In terms of positional accuracy, it was evaluated whether the polygon was positioned correctly or shifted.

Fig. 2. (a) residential area in the settlement of Moshchun in Bucha Raion (© PlanetScope, Imagery Date: Sep 10, 2021) and (b) the same area after it was almost completely destroyed (© CNES / Airbus, Imagery Date: Apr 15, 2022)

3 RESULTS

War-affected urban landscape

In urban areas, most of the land is covered by structures of buildings, roads, and other artificial surfaces. This class contains settlements of various sizes and soil sealing. It consists of different types of buildings, such as family houses, apartments, administrative and multifunctional buildings, schools, hospitals, shopping centres, etc. Artificial surfaces also include roads and railways. In the land cover pattern of war-affected areas, degraded, damaged areas of buildings with original residential functions, demolished buildings with damaged roofs (Fig. 2), damaged or destroyed industrial or commercial units, non-functional bodies of roads, motorways, bridges (Fig. 3), and railways as well as destroyed or damaged port areas including facilities associated to port activities and airports including terminals, hangars, and technical installations (e.g. radars, towers) can be found. As a result of the abandonment of the area, it is also possible to observe an increase in localities with predominantly synanthropic settlement greenery situated mainly in unused areas. War-affected areas in an urbanized landscape are represented in the modified CLC nomenclature on the 4th level by the following classes: 1125 – Abandoned residential areas, 1213 – Abandoned industrial or commercial units, 1222 – Damaged roads and railways, 1233/1234 – Damaged port areas, 1243 – Damaged airports, 1413 – Uncultivated settlement greenery (Tab. 2). From a financial point of view, the category of residential areas, with a share of 37.5%, saw the largest proportion of property damage due to the Russian invasion of Ukraine (Andrienko et al., 2024).

War-affected rural landscape

The land cover of the rural landscape is represented mainly by agricultural and forest land and water areas. The war-affected agricultural landscape is represented by land use/land cover classes with signs of large-scale damage (traces of bombing, unexploded bombs, trenches) or arable land after a wildfire. Depending on the crops grown, these may

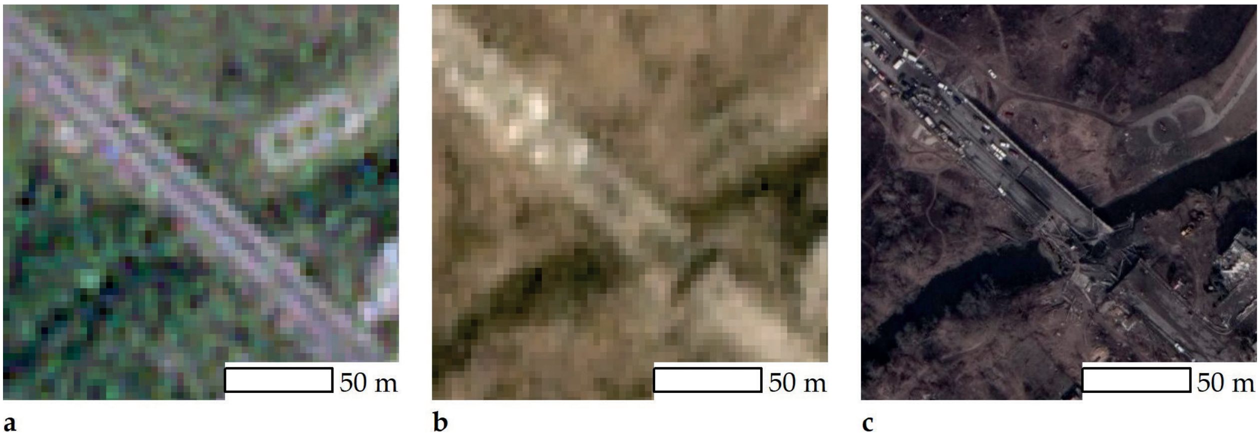

Fig. 3. (a) a bridge across the Irpin River near Kyiv (© PlanetScope, Imagery Date: Sep 10, 2021), (b, c) the same bridge after it was destroyed in February 2022 (© PlanetScope, Imagery Date: Mar 12, 2022), and (© Maxar Technologies, Imagery Date: Mar 31, 2022) respectively

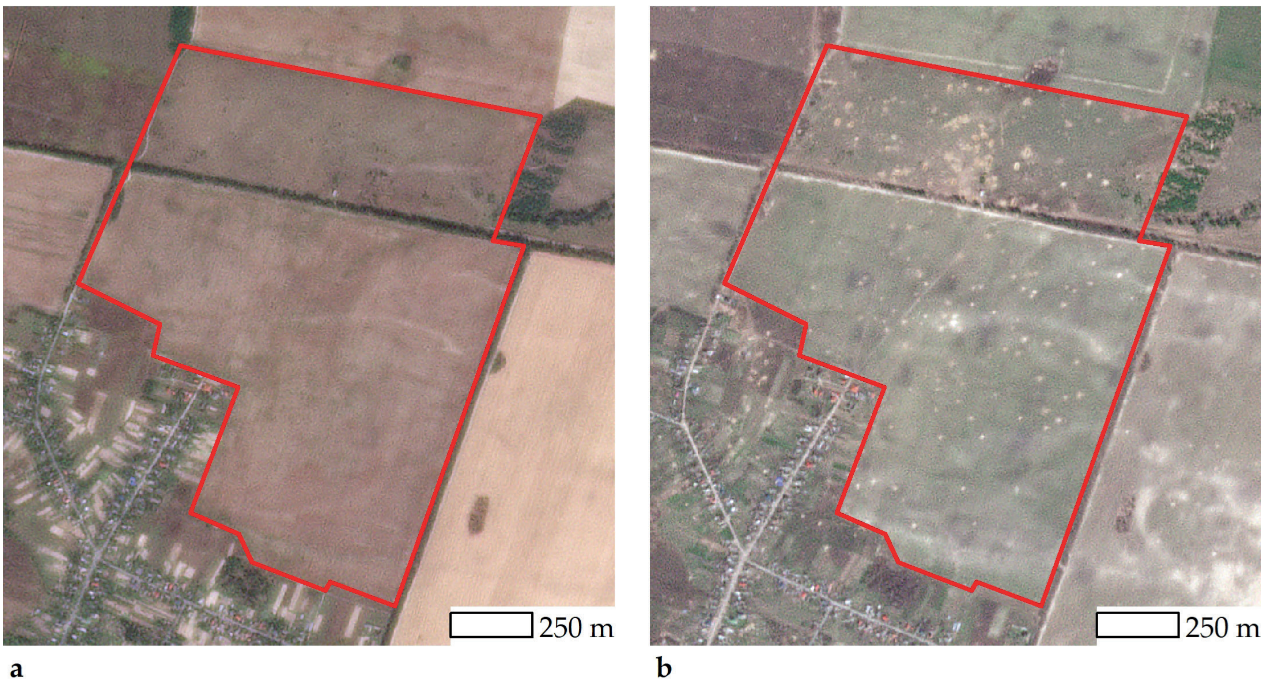

Fig. 4. (a) large-block arable land (class 2112) near the settlement of Ozera in Bucha Raion on Sep 10, 2021 (before the Russian invasion of Ukraine) and (b) the same area on Mar 25, 2022 classified as damaged large-block arable land (class 2114) – the fields to the north of the main road are littered with trenches, while on the southern side there are clearly visible traces of bombing (PlanetScope imagery)

be the following classes: 2113/2114 – Damaged arable land (Fig. 4), 2122 – Damaged permanently irrigated land, 2132 – Damaged rice fields, 2213 – Damaged vineyards, 2223 – Damaged orchards and berry plantations, 2232 – Damaged olive groves, 2313/2314 – Damaged grasslands (Tab. 3). The war-affected landscape in the forest and semi-natural areas is represented by classes of damaged and burnt forests (3243 and 3341, respectively); in water areas mainly by formerly flooded bare areas after the destruction of dams (5123 – Fig. 5).

Proposal for an extended CLC nomenclature for war-affected areas

Based on the accuracy assessment, the highest accuracy was recorded for the war-affected classes representing rural landscapes, especially Damaged arable land (2113 and 2114) and Damaged forests (3243), as well as Damaged airports (1243) where large homogeneous areas allow accurate identification of the war affects. The User Accuracy (UA) of these classes is 100%. On the contrary, the lowest accuracy (UA 86.7%) was recorded for the class Abandoned residential areas (1125). The most frequent errors were the confusion between the Abandoned residential areas (1125) and Abandoned areas of production, warehouses, and services (1213) or Discontinuous built-up areas (1121-1123). The identification of these classes can be challenging due to image quality (e.g. shadow or degraded resolution due to high angle outside the building). Also, visual signs may include the presence of debris, rubble or sand around the building. For example, a building that appears to be intact on a satellite image may show a huge hole on one side only, where a shell hit. The overall accuracy of the assessed data was 94.9%.

Tab. 4 and Fig. 6 illustrate the advantages of the proposed nomenclature compared to the standard CLC data. For this comparison, we selected the neighbourhood of Ozera village in the Hostomel settlement – an area with the highest number of identified land use/land cover classes. Since standard CLC data is not available for Ukraine, third-level land use/land cover data was derived using updated CLC nomenclature guidelines (Kosztra et al., 2019). The fourth-level data represents results from pilot mapping, based on the nomenclature outlined in Tab. 2 and 3. The proposed classification system includes twice as many land use/land cover classes as the CLC database – 89 classes with a minimum mapping unit (MMU) of 0.1 hectare, compared to 44 classes in the original CLC database with an MMU of 25 hectares – allowing for significantly more detailed mapping. In the selected area, we identified 24 distinct land use/land cover classes and delineated 206 polygons (objects), with an average area of 7.1 hectares.

Fig. 5. (a) The Nova Khakovka hydro-electric dam across the Dnipro River in Ukraine on June 4, 2023 (class 5122) and (b) the same area on June 22, 2023 (class 5123) (PlanetScope imagery)

Tab. 2. Extended CLC nomenclature for the war-affected urban landscape

		1 - Artifical surfaces
Level 3	**Level 4**	**Definition**
111	1111 – Areas of continuous low-rise to mid-rise buildings	Urban/settlement built-up areas with prevailing residential buildings. Continuous built-up areas of prevailingly residential or multi-functional often historical cores of settlements with buildings counting not more than 14 storeys.
	1112 – Areas of continuous high-rise buildingsww	Areas of continuous prevailingly residential buildings with more than 14 storeys.
112	1121 – Discontinuous built-up areas with prevailing multi-flat houses	Typical housing estates with 3 to 14 storied buildings with shops and services at the ground floors. Part of these areas may be the greenery with an area below the size of the minimum area, squares, sidewalks, less administrative and service buildings and single-family houses. Built-up areas account for less than 80% of the overall area.
	1122 – Discontinuous built-up area with single-family houses and gardens	Built-up areas where the substantial part consists of single-family houses, yards and sheds of various nature. Part of this class may be gardens, squares and sidewalks. To be found mainly in rural settlements and parts of towns.
	1123 – Discontinuous built-up area of residential buildings in settlement greenery	Areas of dispersed prevailingly residential buildings in forest environment or tree (settlement) greenery with an area exceeding 50% of surface.
	1124 – Homesteads and hamlets	Individual buildings with residential function on an area between 0.1 ha and 5 ha, sometimes smaller than the area of the minimum mapped area situated more than 100 m away from built-up area.
	1125 – Abandoned residential areas	**Degraded, damaged areas of buildings with original residential functions, destroyed houses.**
121	1211 – Areas of services	Department stores, hotels, restaurants, shopping centres, administrative buildings of the local government, companies, banks, hospitals, spas, areas of schools, dormitories, research institutions, cultural facilities, archaeological localities, cemeteries without vegetation, churches, etc.
	1212 – Areas of production and warehouses	Areas of industrial productive firms, power stations, farms, warehouses, open spaces within these areas with a paved surface, greenhouses, areas of technical infrastructure such as transformers, wind turbines, photovoltaic facilities, military facilities, etc.
	1213 – Abandoned industrial or commercial units	**Non-functional, degraded and devastated areas, destroyed buildings with damaged roofs, brownfields, etc**.
122	1221 – Road and rail network and associated land	Bodies of motorways, roads with width exceeding 2 m, railways including associated areas (bridges, overpasses, parking lots, etc.), areas of buildings of bus stations and platforms, accompanying vegetation.
	1222 – Damaged roads and railways	**Non-functional and damaged bodies of motorways, roads with width exceeding 2 m, including associated areas (e.g. bridges).**
123	1231 – River and lake ports	Areas of ports situated on river or lake banks, with associated infrastructure of buildings and communications.
	1232 – Sea ports	Areas of naval ports with piers and associated infrastructure.
	1233 – Damaged river and lake ports	**Non-functional, damaged or destroyed river and lake ports.**
	1234 – Damaged sea ports	Non-functional, damaged or destroyed sea ports.
124	1241 – Airports with artificial surface of runways	Areas of airports with artificial surface, take-off and landing runways, infrastructure of airport buildings and parking lots and grass areas neighbouring on airport infrastructure.
	1242 – Airports with grass surface of runways	Areas of airports with grass surface of take-off and landing runways and infrastructure of airport buildings
	1243 – Damaged airports	**Non-functional and damaged airports.**
131	1311 – Open extraction spaces	Areas of extraction of surface coal, crude, gravel, sand, loam, kaolin, etc.
	1312 – Quarries	Areas of quarries.
132	1321 – Areas of solid waste landfills	Areas of public and industrial landfills.
	1322 – Areas of liquid waste landfills	Areas of landfills with liquid waste, which is mostly product of chemical production.
133	1331 – Construction of residential areas	Areas of residential buildings under construction and the associated earthworks.
	1332 – Construction of industrial or commercial units	Areas of production and service areas under construction and the associated earthworks.
	1333 – Construction of transport communications	Areas of transport communications under construction and the associated earthworks.

141	1411 – Parks, urban gardens and other cultivated public settlement greenery	Areas of parks, urban gardens and other cultivated public settlement greenery.
	1412 – Cemeteries in inner settlement territories	Areas of cemeteries with grass and woody vegetation.
	1413 – Uncultivated settlement greenery	**Prevailingly synanthropic settlement greenery situated first of all in unused and abandoned areas.**
142	1421 – Areas of sports	Areas of stadiums, playgrounds within or outside settlements, horseracing or golf areas, sport airports, ski resorts, halls, motor-racing circuits, etc.
	1422 – Areas of leisure and recreation	Areas of leisure and recreation, most often spaces with cottages and cottage colonies with yards, mountain hotels with infrastructure of servicing buildings, zoological gardens, open-air museums, amphitheatres, cemeteries outside the inner territory of settlement with grass and woody vegetation.

Tab. 3. Extended CLC nomenclature for the war-affected rural landscape

		2 – Agricultural areas
Level 3	**Level 4**	**Definition**
211	2111 – Small-block arable land	Areas of small-block arable land (narrow strip parcels up to 5 ha), where are grown oil plants, legumes, technical crops, fodder, vegetables, flowers, etc. Arable land may be seasonally irrigated.
	2112 – Large-block arable land	Areas of large-block arable land (parcels over 5 ha), where are grown oil plants, legumes, technical crops, fodder, vegetables, flowers, etc. Arable land may be seasonally irrigated.
	2113 – Damaged small-block arable land	**Areas of former small-block arable land with visible signs of large-scale damage (traces of bombing, unexploded bombs, trenches) or arable land after a wildfire.**
	2114 – Damaged large-block arable land	**Areas of former large-block arable land with visible signs of large-scale damage (traces of bombing, unexploded bombs, trenches) or arable land after a wildfire.**
212	2121 – Permanently irrigated land	Cultivated land parcels under agricultural use for arable crops that are permanently or periodically irrigated, using a permanent infrastructure.
	2122 – Damaged permanently irrigated land	**Areas of former permanently irrigated land with visible signs of large-scale damage.**
213	2131 – Rice fields	Cultivated land parcels for rice production, consisting of periodically flooded flat surfaces with irrigation channels.
	2132 – Damaged rice fields	**Areas of former rice fields with visible signs of large-scale damage.**
221	2211 – Cultivated vineyards without dispersed buildings	Areas of vineyards without areas overgrown with shrubs (below 5%).
	2212 – Overgrown vineyards	Abandoned areas of vineyards with dispersed areas overgrown by shrubs (5-40%).
	2213 – Damaged vineyards	**Areas of former vineyards with visible signs of large-scale damage (traces of bombing, destroyed stands) or after a wildfire.**
222	2221 – Cultivated orchards and berry plantations	Areas of orchards (apple, pear, plum, cherry, sour cherry, peach, apricot, welsh nut, sweet nut trees, etc.) without plots overgrown by shrubs, hop plantations.
	2222 – Overgrown orchards and berry plantations	Areas of orchards with dispersed plots overgrown by shrubs (15-40%).
	2223 – Damaged orchards and berry plantations	**Areas of former orchards with visible signs of large-scale damage (traces of bombing, destroyed stands) or after a wildfire.**
223	2231 – Cultivated olive groves	Cultivated areas planted with olive trees.
	2232 – Damaged olive groves	**Areas of former olive groves with visible signs of large-scale damage (traces of bombing, destroyed stands) or after a wildfire.**
231	2311 – Grassland prevailingly without trees and shrubs	Areas of grass stands resulting from agricultural activity, prevailingly without trees and shrubs (less than 15%).
	2312 – Grassland with dispersed trees and shrubs	Areas of grass stands resulting from agricultural activity with trees and shrubs (15-40% while the woody vegetation is not independently recordable).
	2313 – Damaged grassland without trees and shrubs	**Areas of former grass stands prevailingly without trees and shrubs (less than 15%) with visible signs of large-scale damage (traces of bombing, destroyed stands) or grasslands after wildfire.**
	2314 – Damaged grassland with dispersed trees and shrubs	**Areas of former grass stands with trees and shrubs (15-40%) with visible signs of large-scale damage (traces of bombing, destroyed stands) or grasslands after wildfire.**
241	2410 – Annual crops associated with permanent crops	Cultivated land parcels with non-permanent crops (mostly arable land) associated with permanent crops (fruit trees or olive trees or vines) on the same parcel.

242	2420 – Mosaic of fields, meadows and permanent cultures	Areas of alternating parcels with annual and perennial crops, meadows and permanent cultures with a proportion of woody vegetation below 20%.
243	2430 – Land principally occupied by agriculture, with significant areas of natural vegetation	Areas principally occupied by agriculture, interspersed with significant natural or semi-natural areas (including forests, shrubs, wetlands, water bodies, mineral outcrops) in a mosaic pattern.
244	2440 – Agro-forestry areas	Annual crops or grazing land under the wooded cover of forestry species.
		3 – Forests and semi-natural areas
311	3111 – Broad-leaved forests with continuous canopy	Areas of broad-leaved forests with continuous canopy (over 80%).
	3112 – Broad-leaved forests with discontinuous canopy	Areas of broad-leaved forests with discontinuous canopy (60-80%).
312	3121 – Coniferous forests with continuous canopy	Areas of coniferous forests with continuous canopy (over 80%).
	3122 – Coniferous forests with discontinuous canopy	Areas of coniferous forests with discontinuous canopy (60-80%).
313	3131 – Mixed forests with continuous canopy	Areas of forests with alternating broad-leaved and coniferous tress or their small groups with continuous canopy (over 80%).
	3132 – Mixed forests with discontinuous canopy	Areas of forests with alternating broad-leaved and coniferous trees or their small groups with discontinuous canopy (60-80%).
321	3211 – Natural grassland without trees and shrubs	Areas of natural grass stands without trees and shrubs (below 15%). These stands are not agriculturally exploited.
	3212 – Natural grassland with trees and shrubs	Areas of natural grass stands with trees and shrubs (15-40%). These stands are not agriculturally exploited.
322	3220 – Moors and heatland	Areas of heath stands represented mainly by shrub and herbaceous communities (Calluna vulgaris, Erica sp., Vaccinium sp., Genista sp., Rubus sp., Juniperus sp. etc.), shrubby willow stands, black thorn (Prunus spinosa), hazel (Corylus avellana) and juniper (Juniperus communis, dwarf Russian almond (Amygdalus nana), snowstorm (Spiraea media) and burnet rose (Rosa pimpinellifolia), of high-mountain dwarf pine (Pinus mugo).
323	3230 – Sclerophyllous vegetation	Bushy sclerophylious vegetation, including maquis and guarrigue.
324	3241 – Clear-cut sites	Areas of clear-cut sites before planting; bare or overgrown by grass occasionally with local occurrence of natural young forest with an area smaller than the smallest identified area.
	3242 – Young forest	Areas of forest succession (including clear-cut sites after planting or overgrowing) with more than 40% canopy of wood species, areas of forest nurseries growing seedlings of forest wood species.
	3243 – Damaged forests	**Areas of evidently damaged forest (e.g. dry) due to biological pests (typically bark beetle), natural disaster (e.g. wind calamity, slope movement, etc.) or anthropogenic interventions (e.g. bombing, emissions).**
331	3310 – Beaches, dunes, sands	Areas of dunes and sands almost without vegetation or with sporadic occurrence of mainly thin grasses (below 15%), areas of belts of river banks or bars consisting of accumulated gravel almost without vegetation, areas of bare soil result of natural processes (landslides, mudflows, erosion, etc.) or uncovered clayey and loamy bottoms of streams and lakes without vegetation.
332	3320 – Areas of rocks	Areas of unbroken bedrock, typically cliffs, reefs, broken rocks, block fields, debris cones, screes, etc.
333	3330 – Rare discontinuous grass-herbaceous vegetation	Areas with discontinuous vegetation cover accounting for 15-50% of overall area on dunes and blown sand, bare clay, gravel, rare alpine herbaceous formations on rocks, saline areas covered by rare halophytic vegetation.
334	**3340 – Burnt forest**	**Areas of forest after wildfire.**
335	3350 – Glaciers and perpetual snow	Land covered by glaciers or permanent snowfields.
		4 – Wetlands
411	4111 – Marshes with the mosaic of water bodies and vegetation	Areas of marshes with reed stands (coverage over 80%) and stands of sedges alternating with water bodies.
	4112 – Wetlands with continuous herbaceous growth	Areas of wetlands with continuous herbaceous growth (e.g. reed stands, sedges) over 80%, seasonally flooded.
	4113 – Wetlands with continuous herbaceous growth and dispersed wood species	Areas of wetlands with sedges growths and dispersed wood species seasonally flooded.
412	4121 – Moors	Areas of moors.
	4122 – Peat bogs and raised bogs	Areas of peat bogs and raised bogs, including areas under exploitation and bare peat.

421	4210 – Salt marshes	Vegetated low-lying areas in the coastal zone, above the high-tide line, susceptible to flooding by seawater. Often in the process of being filled in by coastal mud and sand sediments, gradually being colonized by halophilic plants.
422	4220 – Salines	Salt-pans for extraction of salt from salt water by evaporation, active or in process of abandonment. Sections of salt marsh exploited for the production of salt, clearly distinguishable from the rest of the marsh by their parcellation and embankment systems.
423	4230 – Intertidal flats	Coastal zone under tidal influence between open sea and land, which is flooded by sea water regularly twice a day in a ca. 12 hours cycle. Area between the average lowest und highest sea water level at low tide and high tide. Generally non-vegetated expanses of mud, sand or rock lying between high and low water marks.
		5 – Water bodies
511	5111 – Rivers and brooks	Natural streams 2 m wide.
	5112 – Channels	Artificial channels or regulated streams at least 2 m wide.
512	5121 – Natural water bodies	Areas of water bodies of natural origins.
	5122 – Artificial water bodies	Areas of water bodies created by humans.
	5123 – Damaged artificial water bodies	**Areas formerly under water, now bare areas after the destruction of dams.**
521	5210 – Coastal lagoons	Stretches of salt or brackish water in coastal areas which are separated from the sea by a tongue of land or other similar topography. These water bodies can be connected to the sea at limited points, either permanently or for parts of the year only.
522	5220 – Estuaries	The mouth of a river under tidal influence within which the tide ebbs and flows.
523	5230 – Sea and ocean	Zone seaward of the lowest tide limit.

Tab. 4. Comparison of land use/land cover mapping results using the standard CLC nomenclature and the proposed extended nomenclature

Land use/land cover identification according to:	**standard CLC nomenclature**	**proposed extended nomenclature**
Land use/land cover classes in the nomenclature	44	89
Minimal mapping unit	25 hectares / 100 m	0.1 hectare / 2 m
Different land use/land cover classes in the selected territory	8	24
Number of polygons in the selected territory	11	206
Mean area of the polygons in the selected territory	203.3	7.1

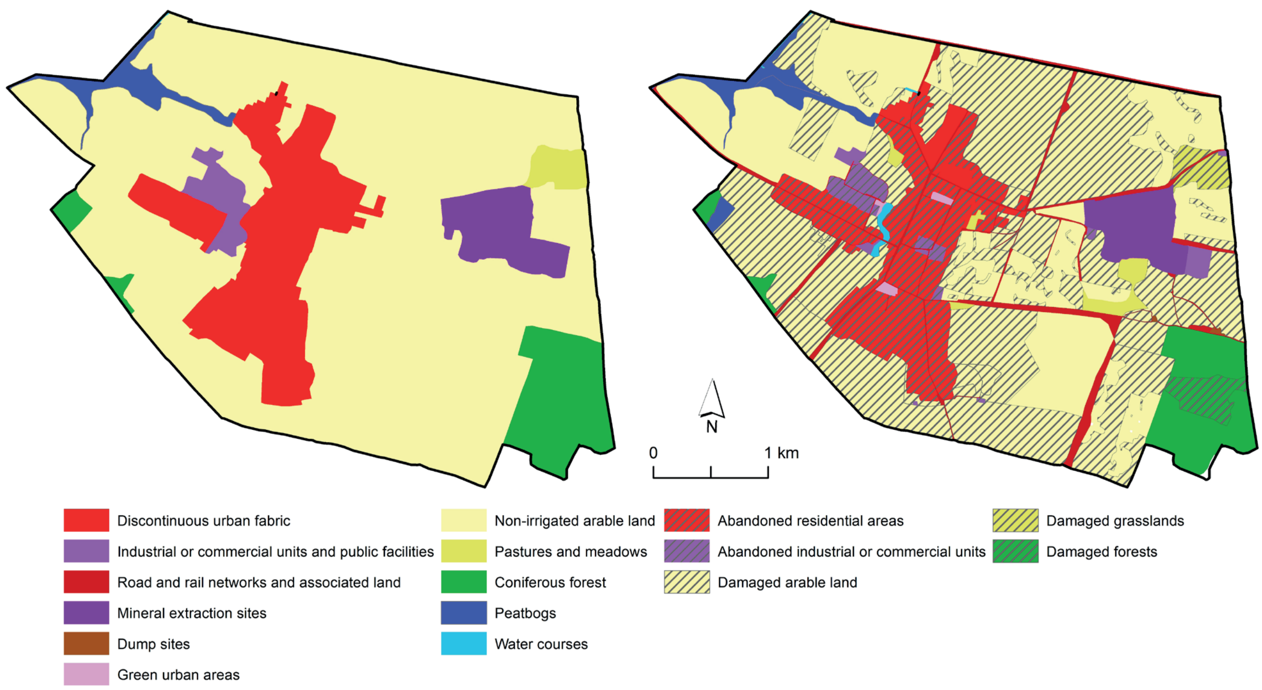

Fig. 6. Comparison of land use/land cover mapping results using the standard CLC nomenclature (left) and the proposed extended nomenclature (right) in Ozera village (classes unaffected by the war are aggregated)

4 DISCUSSION

Increasing the spatial resolution of Earth observation (EO) data used in detailed land use/land cover monitoring allows researchers and landscape planners to monitor large areas that are threatened or currently involved in conflict, where the restoration of the urban environment and rural landscape would be necessary due to the destruction caused by the war.

When applying EO data (e.g. PlanetScope) for landscape mapping (or monitoring), it is essential to consider the spatial and temporal resolution of the specific satellite imagery in relation to the features of interest. The basic prerequisite for the detection of landscape object changes by application of EO data is the existence of change in the spectral response of objects that is recordable by the imaging facility (Feranec & Oťaheľ, 2008). The PlanetScope imagery with a 3-meter spatial resolution allows monitoring of widespread damage in urban regions. It is sufficient to detect collapsed buildings, especially industrial units, shopping centres, hangars, warehouses, etc. However, the identification of fine details, such as the collapse of small buildings, roof destruction, or minor infrastructure changes like partial destruction of roads, as well as distinguishing between (partially) collapsed structures and intact structures in densely built-up areas, remain challenging. On the other hand, the great advantage of this imagery is the frequent revisit time, which is helpful for change detection, i.e., observing ongoing changes over time. Very high resolution (VHR) satellite images (e.g. Pléiades) are necessary in the cases where the ability of PlanetScope to distinguish smaller damage is limited, i.e., for the detection of subtle damage, such as roof destruction, distinguishing between completely destroyed buildings and partially damaged structures, what makes them irreplaceable for damage assessment in the context of urban warfare or monitoring of specific damages and recovery over time. Higher costs and the need for large storage capacities must be considered.

In the case of the rural landscape, the PlanetScope satellite imagery is sufficient for most objects, such as destructed agricultural lands, deforestation or landscape changes resulting from military activities (e.g. craters from bombing raids). The temporal resolution, in combination with a wide field of view, makes it more cost-effective for damage monitoring across extensive areas or periodic surveys of large forests or farmlands affected by the broader environmental consequences of war (e.g. forest fires caused by airstrikes), makes them an effective tool for environmental monitoring. VHR images are needed only for precise identification of damages where the spatial resolution of the PlanetScope images is a limiting factor (tree loss, changes in soil texture and field geometry, damage to irrigation systems, etc.). Still, they may not be cost-effective, which makes them less suitable for continuous monitoring of extensive rural conflict zones.

For comprehensive post-conflict damage assessment, a combination of PlanetScope for wide-area monitoring and VHR imagery for detailed damage analysis of focal points should be recommended.

While Google Earth orthophotos typically offer higher spatial resolution and are often preferred for visual interpretation, the use of PlanetScope imagery in this study is justified by several key advantages. Most notably, PlanetScope provides global coverage, including areas where Google Earth imagery may be outdated, unavailable, or of insufficient resolution for consistent analysis. Additionally, PlanetScope offers high temporal resolution, with near-daily image acquisition, critical for applications requiring time-sensitive or dynamic monitoring. In contrast, Google Earth imagery is updated infrequently and varies greatly in recency across geographic regions. PlanetScope data are also delivered in standardised formats with accompanying metadata. These factors collectively support the choice of PlanetScope as a suitable data source for the objectives of this study despite its lower spatial resolution relative to Google orthophotos.

Remote sensing technologies work well as detection, monitoring, and mapping tools. However, additional information is often required to accurately confirm, interpret, and determine the nature of the damage. In cases where remote sensing capabilities are limited or insufficient to fully assess the situation, alternative or complementary research methods are used: field surveys, mobile laboratories, drone data, in-situ monitoring tools, eyewitness testimonies, local volunteers, and secondary effects assessment.

The Ukrainian Researchers Society, with FAO's technical support, conducted a study on conflict-affected soils in Kharkiv oblast. Emphasising methodological rigour, the researchers highlight the need to complement EO data with ground-based investigations for reliable environmental assessments (Bonchkovskyi et al., 2025). We can also mention a study by the NGO Ecodia Centre for Environmental Initiatives on the impact of military operations on soils, assessing their ecological and geochemical condition in areas of active hostilities. In addition to remote sensing, the study includes laboratory analyses of the soils' physical and chemical properties (Ecoaction, 2023). In the NECU project "Assessment of the Environmental Consequences of War for Communities", particular attention is paid to on-site research in cooperation with local communities, the collection of testimonies from local residents, field visits, and the involvement of experts to interpret the results (https://necu.org.ua/proyekty/wedua/). The RebuildUA project complements satellite data with drone imagery, ground-level photos, and videos, providing a richer visual basis for damage classification and analysis (https://eng.rebuildua.net/). The EcoZagroza platform is an official web resource of the Ministry of Environmental Protection and Natural Resources of Ukraine which integrates data from automated monitoring systems (including air quality and radiation background) with reports from citizens who can send photos and videos of environmental violations (https://ecozagroza.gov.ua/en). The collected information is processed by the State Environmental Inspectorate. Similar to the EcoZagroza platform, SaveEcoBot combines data from monitoring stations with eyewitness reports and citizen-submitted evidence, including photos and observations from local volunteers (https://www.saveecobot.com/en).

In addition to the studies mentioned above, the UN report also includes an inventory of other assessments and projects related to environmental damage in Ukraine, providing a broader overview of ongoing efforts (UNECE, 2023).

Overall, the adoption of a more detailed land cover nomenclature provides significant benefits in terms of data quality, environmental protection, policy formulation, and scientific research. It promotes a deeper understanding of the complex interactions within ecosystems and facilitates effective management of natural resources in a way that acknowledges the diverse nature of land cover.

The presented approach is particularly useful in the following areas:

(i) Environmental Monitoring – tracking changes in war-affected ecosystems and important habitats;

(ii) Urban Planning – assisting in urban land use planning, identification and restoration of destroyed areas;

(iii) Agriculture – monitoring of damaged cropland, assessment of subsequent agricultural abandonment.

The advantage of the proposed extended nomenclature over the standardised CLC is a higher number of land cover classes together with a lower MMU, resulting in higher thematic accuracy of the resulting land cover maps.

5 CONCLUSIONS

The core contribution of the study is to propose a classification system to address the complexity and variability of war-affected landscapes. In this study, RGB composite PlanetScope images were used as the primary tool for visual interpretation. These composites supported the identification and delineation of objects of interest, following well-established principles of aerial photo interpretation. While PlanetScope imagery includes eight spectral bands, various combinations of RGB composites and the application of histogram enhancement techniques may further support the effective identification of proposed war-affected land use/land cover classes under varying geographical conditions. Future studies may benefit from more detailed documentation of these techniques to improve reproducibility and methodological transparency, thereby supporting the generalisation of results across different datasets. The proposed methodology is a flexible approach which can be applied to various land use/land cover investigations related to war-affected regions worldwide. Comparison of similarities and differences between different war-affected areas can help to understand the impacts of armed conflicts on land cover. The latest release of the CLC database for the year 2018 covers 39 countries and consists of 44 land cover classes in the third hierarchical level. The extended CLC nomenclature presented in this article consists of 89 land cover classes in the fourth hierarchical level. The proposed nomenclature has been tested in a pilot land cover mapping of Hostomel settlement where the original CLC database is not available. The proposed nomenclature provides a valuable framework for understanding and monitoring the environmental impact of conflict. Adopting a more detailed land use/land cover classification specific to conflict zones allows the identification of both immediate and long-term environmental changes, such as the destruction of infrastructure, vegetation changes, and shifts in land use patterns. More detailed nomenclature allows for precise categorisation of land cover types, reducing ambiguity and misclassification. Using specific war-affected classes leads to more accurate and high-resolution maps that reflect the actual land use and cover.

The proposed nomenclature advances land change science by enhancing traditional classification systems to capture conflict-induced transformations, enabling more precise monitoring and analysis of war-affected landscapes. This extended nomenclature facilitates more accurate environmental damage assessments, aids in disaster response, and guides post-conflict reconstruction efforts. Furthermore, it enables the monitoring of recovery trajectories, the identification of regions in need of urgent intervention, the formulation of policies to restore ecological balance, and improve the resilience of affected communities. Ultimately, the nomenclature serves as a tool for decision-makers and humanitarian organisations to coordinate efforts for land restoration in both an effective and sustainable way.

A detailed analysis of the unique impacts of war on the environment requires the application of the presented nomenclature to several study areas, which are the subject of ongoing detailed land use/land cover monitoring in Ukraine. This research aims to document the environmental impact in specific locations and prepare proposals for post-war restoration.

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