THE RESULTS OF SOCIO-ECOLOGICAL MONITORING DURING MILITARY OPERATIONS IN UKRAINE USING SATELLITE INFORMATION

LESIA YELISTRATOVA [*], ALEXANDR APOSTOLOV [**], VADIM LYALKO [***], OLHA TOMCHENKO [****], ANNA KHYZHNIAK [*****], ARTUR HODOROVSKY [******]

Key-words: military actions, remote sensing, socio-economic monitoring, impact on the environment, night illumination, fires, air pollution, destruction of dams.

Abstract. The article is the review of the impact on the Ukrainian environment (rather a review of the results of the social and ecological monitoring of the environment) in 2022 caused by military operations, using the analysis of remotely sensed data. The purpose of the study is to substantiate the theoretical and methodological foundations using multispectral images for operational monitoring of socio-ecological processes and their consequences during the period of military operations on the territory of Ukraine in 2022. To achieve this goal, the work used remote sensing data from the Sentinel-2, Sentinel-5P, Suomi NPP satellites. The visible results of the ecological damage after the Russian invasion of Ukraine, such as atmospheric air pollution, the destruction of dams (the drainage of the Oskil reservoir and the flooding of the Irpin river floodplain) and forests, grass fires, as well as the destruction of agricultural land are shown using images from Sentinel satellites for the March-June 2022 period. The article also presents the results of the analysis of the night illumination of Ukrainian cities from the Suomi NPP/VIIRS satellite for March and April 2021, 2022. In particular, it was established that the cities of Mykolaiv, Kramatorsk, Sumy and Mariupol were the most affected, where the values of night illumination decreased 13–20 times and range between 0.3–0.7 nanoWatts/cm^2/sr. A comprehensive analysis of the consequences of ecocide (the degradation of the natural environment, the destruction of economic, life support systems, housing, migration and the death of the population) is provided, and points towards a man-made humanitarian disaster and a high probability of an ecological disaster. The complex consequences of ecocide (the degradation of the natural environment, the destruction of economic complexes, life support systems, housing, migration, and the death of the population) indicate a man-made humanitarian disaster and a high probability of for an ecological disaster. In order not to waste time, it is necessary today, even in the conditions of war, to make balanced decisions regarding the environmental situation in order to at least mitigate the current and future environmental consequences of said military operations.

[*] PhD, Head of the EMOGS department of the State institution "Scientific Centre for Aerospace Research of the Earth of the Institute of Geological Science of the National Academy of Sciences of Ukraine" 55–B, O. Gonchar Str., Kyiv, 01054, Ukraine; tkach_lesya@ukr.net.

[**] PhD, Researcher of the EMOGS department of the State institution "Scientific Centre for Aerospace Research of the Earth of the Institute of Geological Science of the National Academy of Sciences of Ukraine" 55–B, O. Gonchar Str., Kyiv, 01054, Ukraine; alex_aaa_2000@ukr.net.

[***] PhD. in Geol. and Mineral., Professor, NASU academician, Chief Researcher of the EMOGS department of the State institution "Scientific Centre for Aerospace Research of the Earth of the Institute of Geological Science of the National Academy of Sciences of Ukraine" 55–B, O. Gonchar Str., Kyiv, 01054, Ukraine; vilyalko31@ukr.net.

[****] PhD, Researcher of the Geospatial modelling in the aerospace research department of the State institution "Scientific Centre for Aerospace Research of the Earth of the Institute of Geological Science of the National Academy of Sciences of Ukraine" 55–B, O. Gonchar Str., Kyiv, 01054, Ukraine; tomch@i.ua.

[*****] PhD, Scientific secretary of the Geospatial modelling in aerospace research department of the State institution "Scientific Centre for Aerospace Research of the Earth of the Institute of Geological Science of the National Academy of Sciences of Ukraine" 55–B, O. Gonchar Str., Kyiv, 01054, Ukraine; avsokolovska@gmail.com.

[******] PhD, Senior Researcher of the EMOGS department of the State institution "Scientific Centre for Aerospace Research of the Earth of the Institute of Geological Science of the National Academy of Sciences of Ukraine" 55–B, O. Gonchar Str., Kyiv, 01054, Ukraine; artur@casre.kiev.ua.

1. INTRODUCTION

In fact, there is no longer a separation between "nature" and "society" on planet, but there are complex man-made socio-biotic systems, which today man himself is mindlessly beginning to destroy (European Union *et al.*, 2015; Fujita, 2013). This is understandable, because technological innovations are created, used and understood, in theory, primarily by military science and the military-industrial complex. The war waged by the Russian Federation in Ukraine is being carried out by many means at the same time, which is what makes it so destructive.

Today, as before, it is the cities and their infrastructure that are the main problem area in modern wars, since war is waged simultaneously in all environments: air, land, and water. But real collisions take place in an extremely limited space. Moreover, this space includes not only the military forces of the warring parties, but also the civilian population. No matter how paradoxical it may sound, a war in the limited space of a particular city is, essentially, global.

Living in harmony with nature is one of the main principles of life on Earth. Almost every conflict has negative consequences for its ecology. Currently, this principle can be interpreted as ecocide – the man-made destruction of the ecological life on the planet, including the conditions of human existence. The interpretation of this term has the following meaning: "Ecocide is the mass destruction of plant and animal life, the poisoning of the atmosphere or water resources, as well as the commission of other actions capable of causing an ecological disaster." In recent years, a trend has emerged in international law to recognize ecocide as an international crime in its global interpretation: "Ecocide is the destruction of the country's economic space, accompanied by inevitable human casualties and the deterioration of living conditions, leading to hunger and the degradation and premature death of a large part of the population" (Crook *et al.*, 2018; Gardashuk, 2017).

Nowadays, according to the Stockholm International Peace Research Institute (SIPRI), more than 20 major armed conflicts are ongoing on the Earth, whose foundations were laid more than one decade ago (https://www.sipri.org/).

Special attention should be paid to environmental problems during military conflicts. Military operations are always accompanied by changes and the destruction of the natural environment. Depending on the scale of the used weapons and their types, military actions that destroy the natural environment can lead to an ecological disaster.

The goals, tasks, reasons and legality of the armed conflict are individual in nature. All of them circle around the idea of using different types of weapons and methods of conducting military operations. But the important moment in the regulation of legal relations between warring parties during military conflicts is that of full and unwavering compliance with international law. According to international law, in any armed conflict, the right of the parties involved in said conflict to choose the methods or means of conducting military operations is not limited (Kaplan *et al.*, 2022). International law includes the Geneva Convention of 1949 and the Additional Protocol 1 to the Geneva Convention (https://ihl-databases.icrc.org/ihl/INTRO/470). However, it is Protocol 1 that safeguards the protection of the civilian population, their property and the environment. One of the provisions concerns environmental protection. Article 35 forbids the use of weaponry that, through its very nature, may cause "excessive damage or incredible suffering", or whose usage and means of conducting military operations may cause widespread, long-term and serious damage to the natural environment.

The responsibility of the state for the destruction of entire ecosystems and damage to nature is formulated in the declaration adopted at the United Nations Conference on Environmental Problems (Geneva, 3 September 1992), during the Paris Convention on the Protection of World Cultural and Natural Heritage. Such documents, as well as other generally recognized norms and principles of international law, namely the Convention on the Prohibition of the Development, Production, Stockpiling, and Use of Chemical Weapons and on Their Destruction (https://treaties.un.org/

pages/ViewDetails.aspx?src=TREATY&mtdsg_no=XXVI-3&chapter=26), the Convention on the Physical Protection of Nuclear Material (CPPNM) and its Amendment (https://www.iaea.org/publications/documents/conventions/convention-physical-protection-nuclear-material-and-its-amendment), the Convention on Early Notification of a Nuclear Accident (https://www.iaea.org/topics/nuclear-safety-conventions/ convention-early-notification-nuclear-accident), the Convention on Assistance in the Case of a Nuclear Accident or Radiological Emergency (https://www.iaea.org/topics/nuclear-safety-conventions/ convention-assistance-case-nuclear-accident-or-radiological-emergency), the Partial Nuclear Test Ban Treaty (https://en.wikipedia.org/wiki/Partial_Nuclear_Test_Ban_Treaty), the Convention on the Prohibition of Military or any other Hostile Use of Environmental Modification Techniques (EMOD) (https://www.un.org/disarmament/enmod/), are the foundation for the regulation of environmental security issues both during peacetime, and during periods of armed conflict. The main idea of such international legal norms is the fact that conflicting parties are limited in the use of certain methods and means of conducting hostilities, so that the damage caused both to individual natural resources and objects, and ecology was decreased as much as possible.

Therefore, any war in human history is an ecological disaster, but the war in Ukraine, which began on February 24, 2022, is probably the most cynical in this regard. The actions of the Russian Federation in this conflict are characterized by the contempt shown towards the environment and the people.

Ukraine has been under constant enemy fire for more than four months. Armoured vehicles, heavy artillery, airplanes, as well as helicopters are used, mass bombardment is carried out, including by heavy artillery fire systems, guided and unguided missiles are used from sea, air and land bases. The damage to the environment is unprecedented. And such damage to the environment will eventually spread to the territory of the entire European continent and will change the balanced ecosystem not only of Ukraine, but also of Europe for at least dozens of years (European Union *et al.*, 2015). In addition to the most obvious losses from the Russian military invasion of Ukraine, such as the loss of life, the destruction of homes, and the destruction of infrastructure, all of this unfortunately leads to the deterioration of the country's economic state, threatens the environment, and worsens social living conditions. During the war, the authorities are focused on such urgent issues as financing the army, settling refugees and providing aid to the wounded. But at the same time, it is necessary to pay attention to other problems and possible future consequences of the war, and to study them comprehensively, because problems of the state of the surrounding environment can easily turn into threats of a social nature. Ukraine is now in an active gradation of military operations, that is, military operations are taking place on the territory of the state; subsequently, passive operations will follow - these are processes that are no longer under control, but they take place directly at the sites of military operations – such as demining, or the disposal of weapons. It has been concluded that war never ends in a split second, that it also has dynamic consequences, it is always associated with a risk that at any moment things can turn into a protracted ecological disaster. That is why a comprehensive approach is necessary to define the problems and consequences of the war in Ukraine and to come up with ways to solve them. Today, all environmental, social and economic problems require urgent monitoring.

In this case, it is expedient to use the obtained data of remote sensing of the Earth as a source of information for the practical instantaneous control of both the state of the natural environment and the urban environment. Many global studies have been conducted in this direction. In (Kaplan *et al.*, 2022) provides an overview of the remote sensing implementation of war activities for environmental monitoring. Other observations of the impact of armed conflicts on natural resources on a global and regional scale based on remote sensing data can be found in other country after the world wars (Welp, 2020), in South Sudan (Olsen *et al.*, 2021), in northeast Bosnia (Witmer, 2008), in Syria (Khaled Hazaymeh *et al.*, 2022), in northern Caucasus (He Yin *et al.*, 2019). It is satellite information that provides an extremely wide spatial resolution (from tens of centimetres to hundreds of meters), a significant number (dozens and hundreds) of spectral channels of various spectral resolution

(hyperspectral imaging technologies), the urgency of obtaining visual information (up to real – or almost real – time), a high geometric image quality. Wide accessibility to the market of space information, both governmental and, especially, commercial programs and systems, is important for the present time. The variety of space equipment, the types of shooting in combination with modern computer processing technologies allow for a quick study of the complex socio-ecological and economic problems. The use of satellite data for the study of environmental and socio-economic destruction caused by the conflict in conflict zones can be found in the neighboring areas Bangladesh-Myanmar border (Thiri Shwesin Aung *et al.*, 2021) and in the Polish Carpathians (Affek *et al.*, 2021). The monitoring of the state of the natural and urban environment during the military operations is one of such tasks.

The purpose of the study is to substantiate the theoretical and methodological foundations of using multispectral images for the operational monitoring of socio-ecological processes and their consequences during the period of military operations on the territory of Ukraine in 2022.

2. MATERIALS AND METHODS

The work has used remote sensing data from the Sentinel-2, Sentinel-5P, Suomi NPP satellites, as well as the image processing application Erdas Imagine, geoinformation systems ArcGIS and MapInfo Professional, as well as the open resources of Google Earth and EO Browser. To carry out the research, the authors of the article developed a chart for monitoring the socio-ecological processes and their consequences during the period of military operations on the territory of Ukraine in 2022 (Fig. 1).

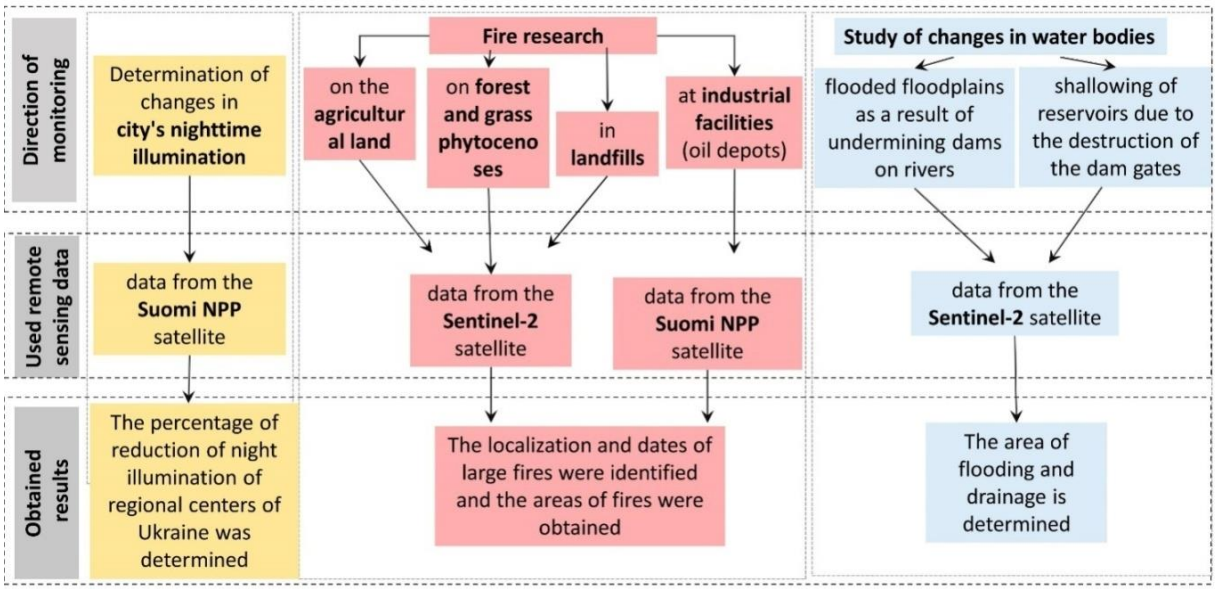


Fig. 1 – The chart for monitoring the socio-ecological processes and their consequences during the period of military operations on the territory of Ukraine in 2022.

The information garnered from the Suomi NPP satellite for March, April 2021 and 2022 was used to quantify the change in night-time illumination. It should be noted that for April 2022 there is no data for a significant territory of Ukraine. The Suomi NPP night-time illumination product has a spatial resolution of 450 meters and a physical dimension of nanoWatts/cm^2/sr. The processing of night illumination data from the Suomi NPP satellite was performed using the Erdas Imagine image processing application and consisted of the following stages: 1) the selection of the territory of

Ukraine using the outline of Ukraine in *.aoi format with the SubSet function of the Erdas Imagine package, 2) the conversion images of the night illumination of the territory of Ukraine in 2021 and 2022 into the WGS 84 / zone 36 coordinate system using the Reproject function of the Erdas Imagine package, 3) using the city vector layer for the selected cities, the average values of night illumination on the dates of the study were calculated.

Data from the Sentinel-2 satellite and the Erdas Imagine image processing application were used to establish the areas of fires. With the help of the EO Browser resource, images from the Sentinel-2 satellite were found before the start of the fire, on which the fire process itself and the consequences of the fire are observed. Using the Erdas Imagine and the Layer Stack function, 11-channels images from the Sentinel-2 satellite were formed. Image analysis was carried out helping establish the contour of the fire and calculate the area affected by the fire.

The Erdas Imagine and EO Browser programs were used to appreciate the consequences of a fire at an oil depot. First, with the help of the EO Browser resource, the image from the Sentinel-2 satellite was ascertained, which shows a fire at a warehouse for fuel and lubricants. At the same time, data from the Sentinel-5P satellite was obtained, and the change in NO_2 concentration was studied. To evaluate the change, the concentration values before and during the fire were averaged and the changes were calculated in the Erdas Imagine application.

Two images from the Sentinel-2 satellite, dating from April 10, 2021 and April 7, 2022, were used to establish the consequences of blowing up the dam that separated the Irpin River from the Kyiv Reservoir. With the help of the Erdas Imagine and the Layer Stack function, the image was formed in so-called “natural colours”. The next step was to detect the area of flooding, and create a vector layer, based on which the area of flooding was calculated.

3. RESULTS AND DISCUSSION

In peacetime, more than 60% of the inhabitants of Ukraine lived in cities, and the rate of expansion of urban territories is two times higher than the rate of growth of the population herein. A feature of the largest of them was the excessive concentration of population in relatively small areas of population, transport, industrial enterprises, and housing and municipal structures (http://www.ukrstat.gov.ua). All this has now been mercilessly destroyed.

The bombed and destroyed Ukrainian cities of Bucha, Irpin, Gostomel, Borodyanka, Chernihiv, Sumy, Okhtyrka, Kharkiv, Mariupol, Izyum, Popasna, Rubizhne and many others had not witnessed such an onslaught since the Second World War.

As the war continues, indirect methods of assessment have to be used to evaluate the scale of destruction and assess economic losses. Moreover, such methods are often used not only to study the economic situation in the region, but also to have a clearer picture of the humanitarian situation in the war zone.

Cities of different size, number, and population density were selected as model examples, among which there are cities of thousands or millions of inhabitants, satellite cities, and urban-type settlements. Among themselves, they differ in terms of the criticality of the situation caused by the military operations.

It should be noted that a city in a critical situation is a “black box” that cannot be opened immediately, nor completely, since long and dangerous work is necessary to clear such cities in the wake of military operations. The experience of the war in Yugoslavia in the mid-1990s shows that, years later, its cities are prone to the danger of exploding mines, which are found as a result of construction work on territories that are being cleared, or during natural disasters (downpours, landslides) (https://ru.osvita.ua/vnz/reports/ecology/21279).

Table 1 shows the ratio of illumination, which allows the comparison of values during March–April 2021 and 2022.

Table 1

The average value of night-time illumination (nanoWatts/cm2/sr) of Ukrainian cities for March and April 2021–2022.

N°	Ukrainian cities	Average value 2021		Average value 2022	The difference in lighting 2021/2022		
		March	April	March	April	March	April
1	Borodyanka	2.584	2.608	0.482	–	5.36	–
2	Bucha	13.837	13.07	2.122	–	6.52	–
3	Chernihiv	7.248	–	4.825	–	1.50	–
4	Gostomel	5.185	5.535	1.312	–	3.95	–
5	Irpin	15.861	13.569	6.768	–	2.34	–
6	Kyiv	22.889	23.894	9.698	–	2.36	–
7	Kramatorsk	6.11	5.909	0.348	0.416	17.56	14.20
8	Mariupol	14.659	8.474	1.271	0.807	11.53	10.50
9	Mykolayiv	8.942	8.997	0.425	0.374	21.04	24.06
10	Sumy	9.361	–	0.674	–	13.89	–
11	Kharkiv	12.335	11.356	2.197	2.026	5.61	5.61
12	Kherson	9.696	10.596	5.75	5.545	1.69	1.91

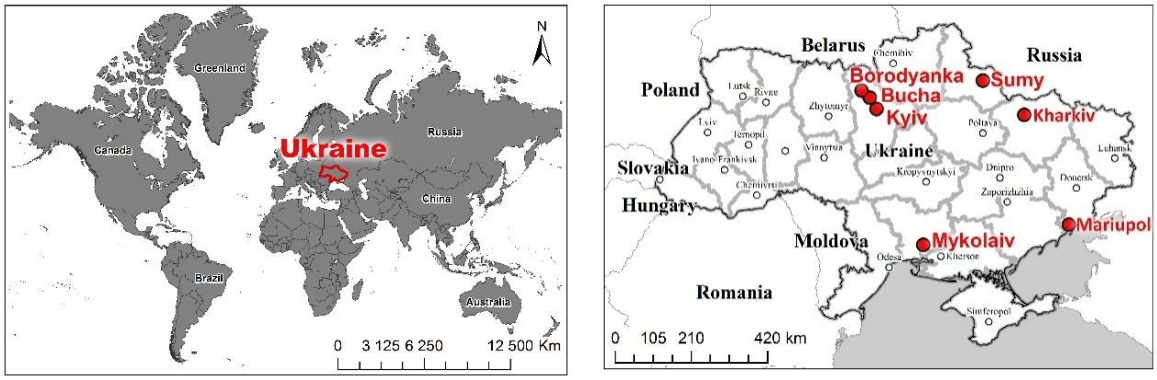
where "–" indicates the absence of night illumination values.

Analysing the data in Table 1, we may conclude that the cities of Mykolaiv, Kramatorsk, Sumy, and Mariupol were the most affected, where the values of night illumination decreased 13–20–fold and are 0.3–0.7 nanoWatts/cm^2/sr.

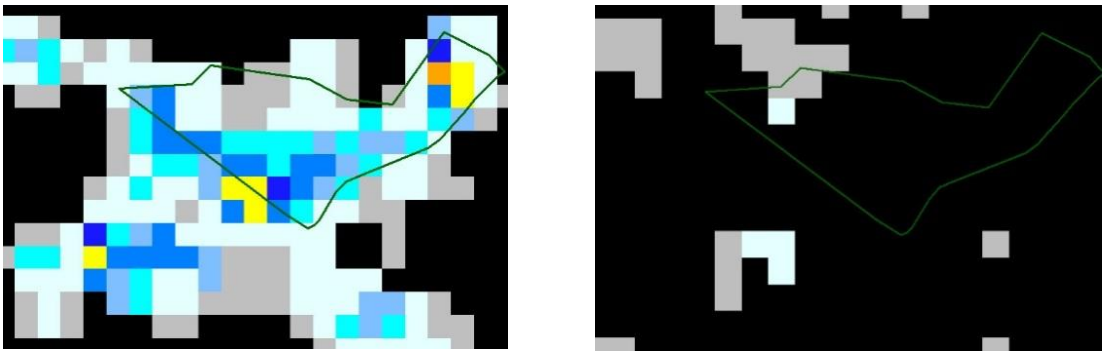
At the same time, the Henderson method was applied. According to it, a 1% decrease in night-time illumination of industrial and residential agglomerations corresponds to a 1% decrease in the economic activity of the studied region (Henderson *et al.*, 2012). At the same time, it turned out that the night illumination in industrial cities, regional centres, as well as in the cities in which fights took place, dropped by 7.78. Accordingly, economic activity probably decreased by the same amount, and this without considering the mass migration of the population from the territory of Ukraine. These indicators can give an idea of the losses suffered by the country's economy as a result of the war with the Russian Federation.

For clarification, Figure 2 shows examples of satellite images of cities for March–April 2021 and 2022.

The location of the study area

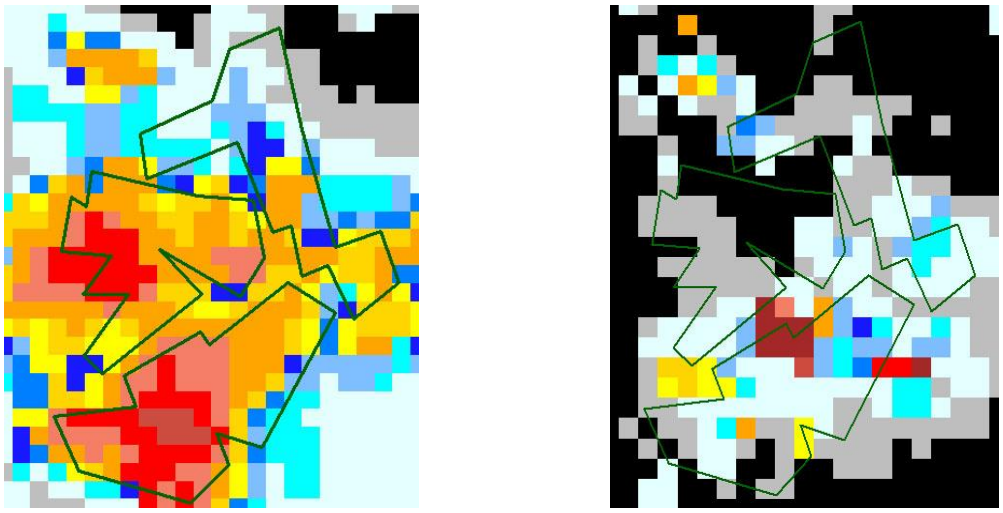


Borodyanka



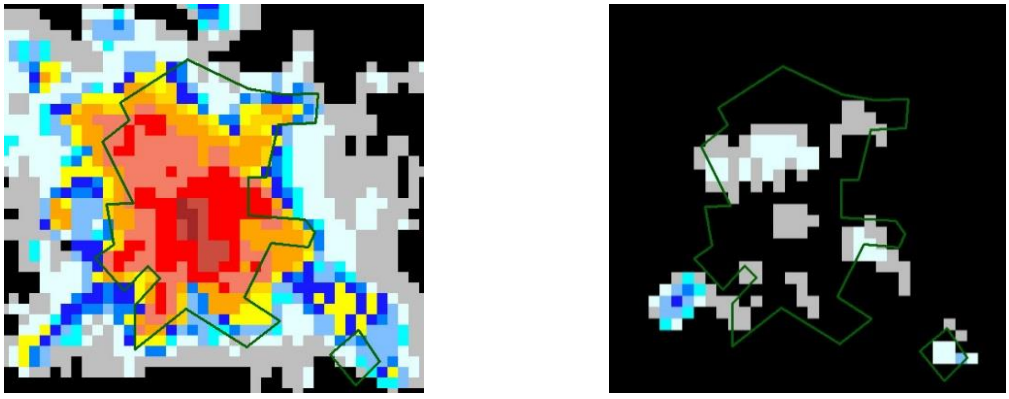
2021–03 2022–03

Bucha, Irpin, Gostomel



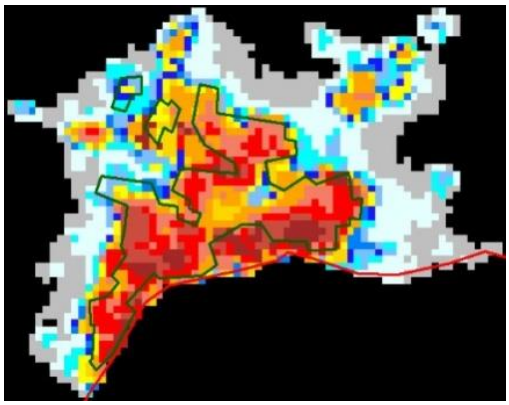
2021–03 2022–03

Sumy



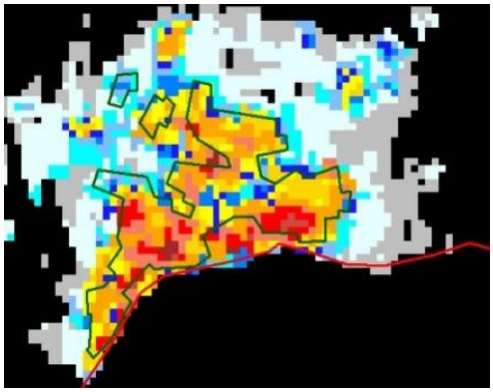
2021–03 2022–03

Mariupol

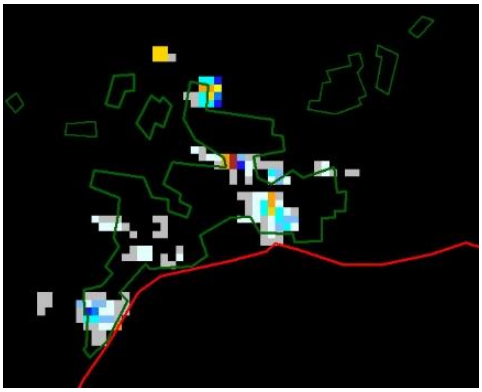


2021–03

2022–03

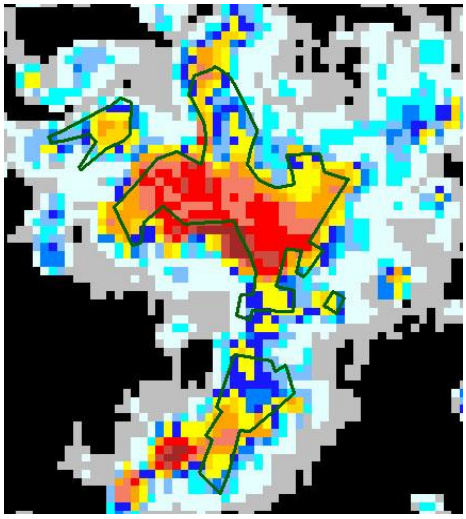


2021–04

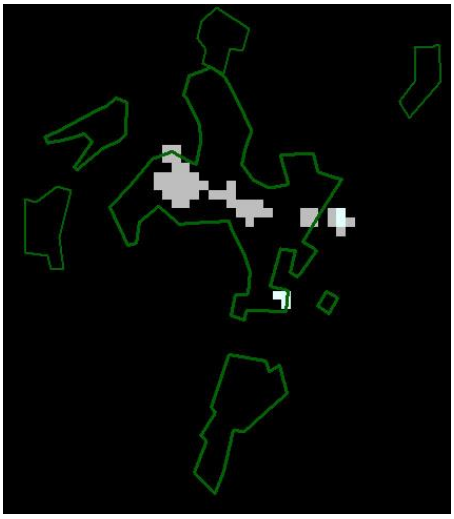


2022–04

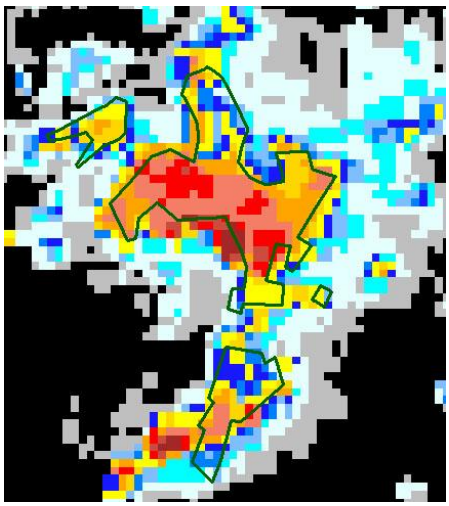
Mykolayiv



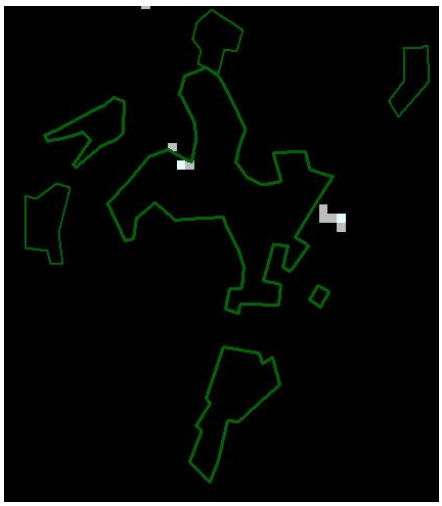
2021–03



2022–03

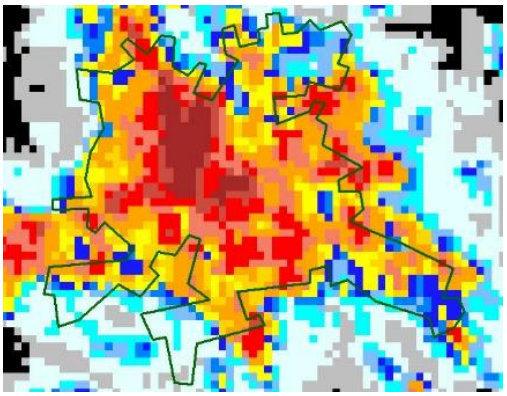


2021–04

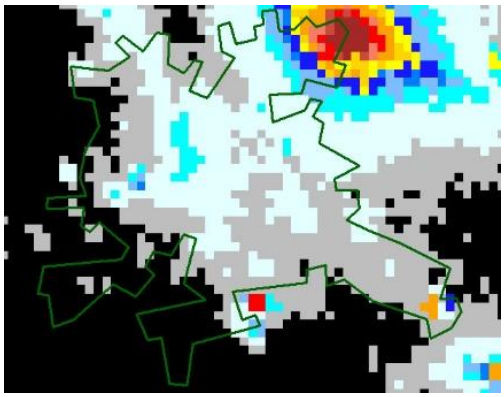


2022–04

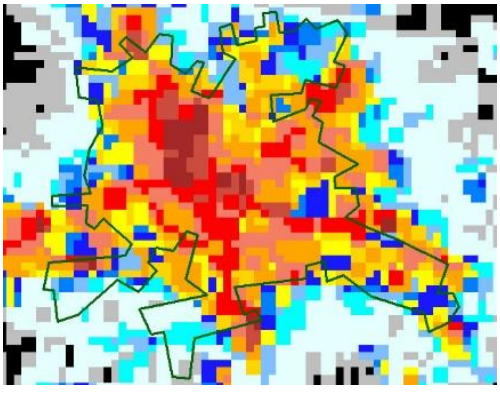
Kharkiv



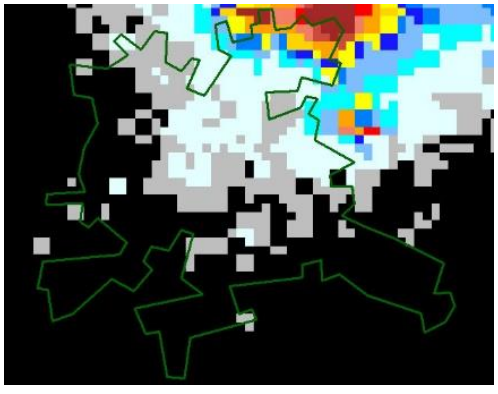
2021–03



2022–03



2021–04



2022–04

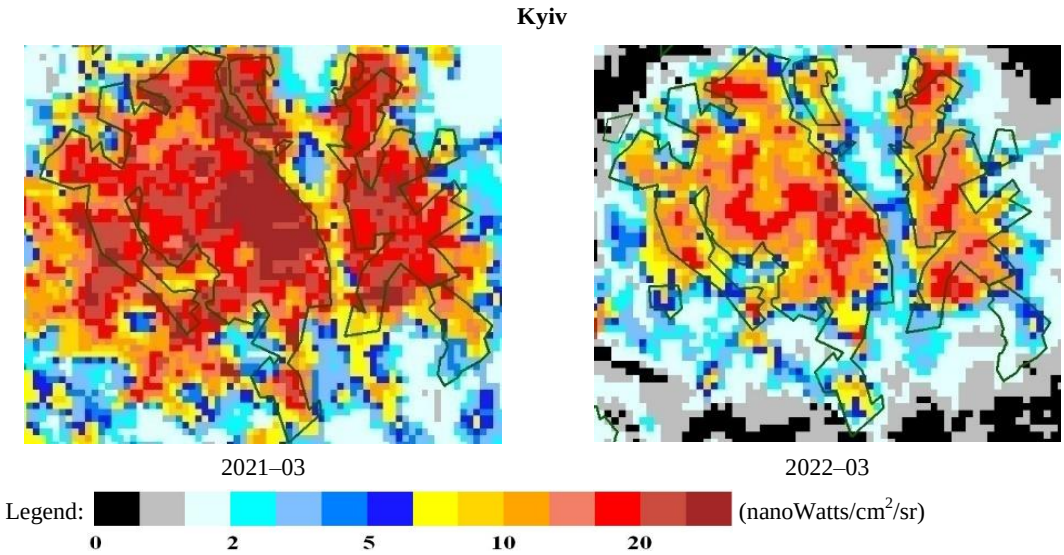


Fig. 2 – Night-time satellite Suomi NPP images of Ukrainian cities for March, April 2021, 2022 (https://eogdata.mines.edu/products/vnl/).

The images of Figure 2 show the major decrease in night illumination compared to the peace time of 2021. In all of the above-mentioned cities, the area and intensity of night-time illumination of the territory has significantly decreased.

As an example, the area and intensity of night illumination of Kyiv, the largest city in Ukraine and the seventh in Europe in terms of population, is given. Together with the suburbs, it forms the Kyiv agglomeration with a total population of over 4 million inhabitants (http://www.ukrstat.gov.ua). There is a 2.36-fold decrease in illumination in the city itself, which is most likely due to martial law.

The settlements northwest of Kyiv suffered the greatest destruction in the Kyiv region. According to our calculations, in the cities where fierce battles took place, the illumination rate dropped: for Borodyanka, from an average value of 2.584 (nanoWatts/cm^2/sr) for March 2021 to 0.482 to (nanoWatts/cm^2/sr) for March 2022, i.e., 5.36 times, for Bucha the drop in night illumination was 6.52 times, for Gostomel 3.95 times, for the city of Irpin – 2.34 times.

Cities on which the Russians continues to carry out artillery and air strikes, Kharkiv – the second largest city in Ukraine –, and Mykolaiv – a city of half a million people of regional importance – have registered a catastrophic decrease in lighting, which is a consequence of brutal battles, the destruction of civil infrastructure and the evacuation of the population. Thus, Fig. 1 shows that in the city of Kharkiv relatively large values of night illumination in 2022 are located in the north, almost beyond the city limits, and correspond to military actions (shelling and its consequences). Compared to last year's pictures for 2021, the maximum values of night illumination correspond to the central part of the city and, in numerical terms, the drop in night illumination was 5.61. For Mykolaiv, the drop in night illumination is the maximum for the studied cities and amounts to 21–24 times, while in Fig. 2 there is no night activity at all, which is a catastrophic situation for the regional centre.

Mariupol was in a critical situation. A city besieged for several months is indeed a critical situation. Here, active, non-stop fighting (shelling, bombing etc.) took place at a constant rate. In the city, the lighting completely disappeared, only the centre of light intensity was recorded in the area of Azovstal, which indicated continuous bombing by the Russian Federation.

Cities such as Mariupol, or others throughout the history of military conflicts (Aleppo, Grozny), are a typical example of a modern global-regional-local conflict on the backdrop of war.

The experience of restoring many cities of the world affected by ecological, man-made disasters shows that their former life cannot be restored primarily for economic reasons: it is much more

profitable to demolish the ruins and rebuild the city anew. Although the surviving population usually seeks to revive their settlements at least partially (Fujita, 2013).

There is no need to talk about the rapid restoration of fragile natural ecosystems, which were subject to the negative impact of modern climate changes and human activity from the consequences of war, just as in peacetime. Any war carries enormous environmental threats to the population, but hostilities in Ukraine can lead to particularly catastrophic consequences for the environment. Nuclear power plants, seaports, hazardous waste warehouses (mineral fertilizers, polyurethane foam, paint and fuel and lubricant materials etc.), industrial enterprises, including chemical and metalworking plants, are now in areas of active hostilities. Fires have been recorded at oil depots, gas stations, landfills, and there are records of damage to heat and water supply facilities (sewage pumping stations, filter stations, water pumps) (https://www.ecoleague.net).

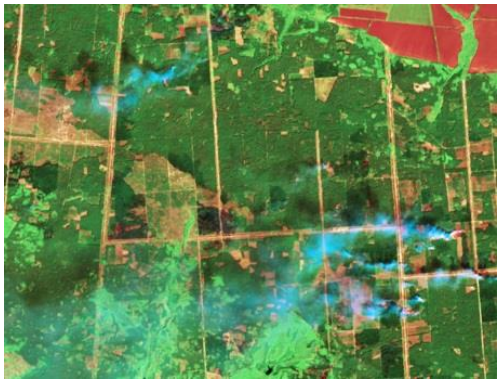
One of the serious consequences of the hostilities is a fire hazard situation. Unfortunately, fires during the war in Ukraine are not uncommon. According to the State Emergency Service, a third of all fires in Ukraine are now caused by shelling. The number of fires in Ukraine increased by 33%, compared to 2021. Previously, such fires occurred several times a year. Now, they are an every-day occurrence (https://dsns.gov.ua). During hostilities, both civilian objects and large-scale grass and forest vegetation fires take place.

Due to climate change and other factors, forest fires have been a huge problem even in peacetime. Now, when any missile may ignite a fire, Ukrainian forests are a real powder keg.

Examples of the results of the assessment of the forest and grass fire area (Figs. 3, 4) were carried out using Sentinel-2 satellite images.

Map of Ukraine showing the location of the city of Izum

April 26, 2022



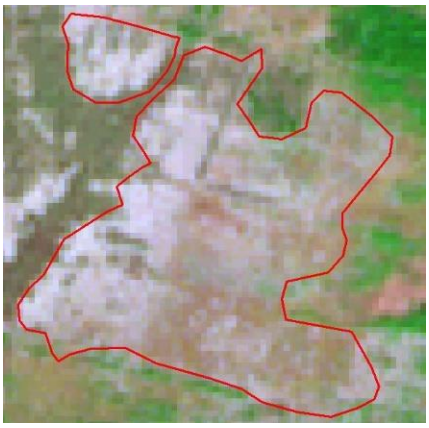
May 6, 2022

June 10, 2022

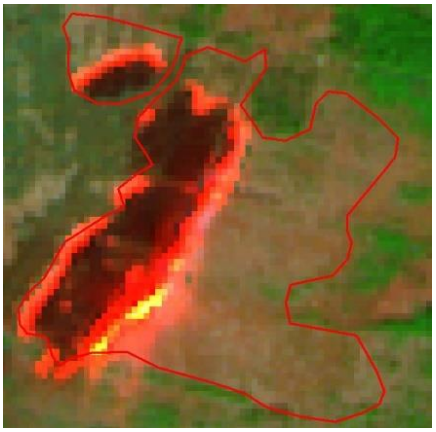
Fig. 3 – Results of forest fires west of the city of Izyum, Kharkiv region, according to data from the Sentinel-2 satellite (https://www.sentinel-hub.com).

An analysis of the images shows that there is a constant destruction of forest plantations as a result of active hostilities, as can be seen by fires and plumes of smoke for the May–June 2022 period. The final assessment of the damaged forest cover can be given only after the end of the war; at present, we are able to discuss the targeted fire areas. An example is given of the area of the fire on March 11, 2022, which is 0.38065 km^2; after 10 days, on March 21, 2022, it became 0.95681 km^2, that is, the area affected by the fire increased 2.51 times (Fig. 4).

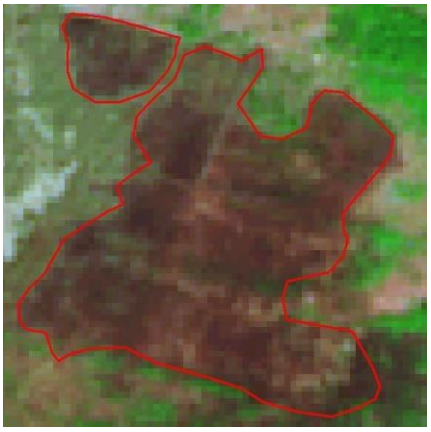
Map of Ukraine showing the location of the Chernobyl exclusion zone



March 26, 2021



March 11, 2022



March 21, 2022

Fig. 4 – Establishing the consequences of a fire on the grass of the Chernobyl exclusion zone according to data from the Sentinel-2 satellite (https://www.sentinel-hub.com).

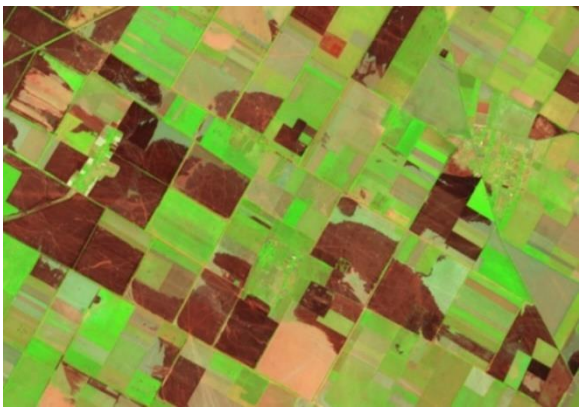
When analysing the image in Figure 4, it is revealed that the use of channel 12 of the Sentinel-2 satellite, a wavelength of 2100–2280 nm, allows for the accurate calculation of places where there are strong open fires: the yellow colour in the figure approximately 2–3 times higher than the value of the spectral brightness of normal fire (red colour) and 4-5 times higher than the value of spectral brightness for scorched earth (burgundy colour).

As a result of the military aggression on the territory of Ukraine, the field is contaminated with chemical elements. As a result of military operations, hectares of arable land are mechanically damaged, which in turn degrades the destroyed upper fertile layer of the soil, while grain fields are also burning. As a result of bombing and artillery shelling, deep craters appear in the soil layer. According to

estimates, a bomb weighing 240 kg creates a crater with a diameter of 8 m and a depth of 4 m. The soil in the crater and in its immediate vicinity becomes unsuitable for agricultural work (Libanova, 2015; https://www.ndi.org/our-stories/time-conclude-1990s-conflict-balkans; https://ru.osvita.ua/vnz/reports/ecology/21279/).

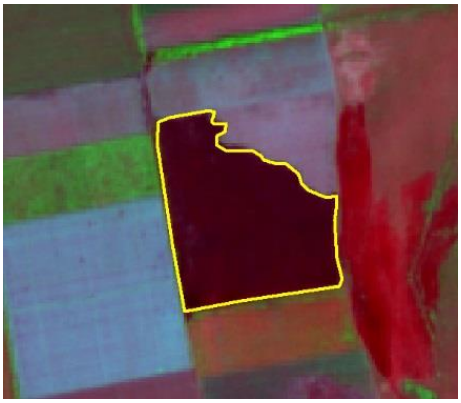
Examples of negative environmental consequences for agricultural fields based on remote sensing materials are shown in Figure 5. According to data from the Sentinel-2 satellite, the area of the fire was 0.33 km^2.

Map of Ukraine showing the location of the study area in Kherson region



General view of the territory of the Kherson region as of July 08, 2022

Before the fire as of June 3, 2022



After the fire as of June 13, 2022

Fig. 5 – Examples of fires on agricultural land in the South of Ukraine according to data from the Sentinel-2 satellite (https://www.sentinel-hub.com).

During the war, fires were also recorded in landfills. Landfills burn constantly and for a long time, garbage deposits heat up to 50–100°C. In addition to the threat of fires for nearby residential areas, it is primarily a source of poisonous substances for humans. When garbage is burned, carcinogens are released into the air, which increases the risk of developing cancerous tumours; for example, phosgene may also be released, which was known during the First World War as a combat gas (https://rethink.com.ua/uk/news-and-events/ekologichni-problemi/chim-nebezpechne-gorinnya-smittezvalishch).

One such example is the one near the village of Novi Petrivtsi, Vyshgorod district, on the territory of the landfill (total area of 7 hectares), where a fire broke out on an area of 2 hectares, as shown in Figure 6.

Map of Ukraine showing the location of the village of Novi Petrivtsi

March 16, 2022 (the start of the fire)

March 18, 2022

March 23, 2022

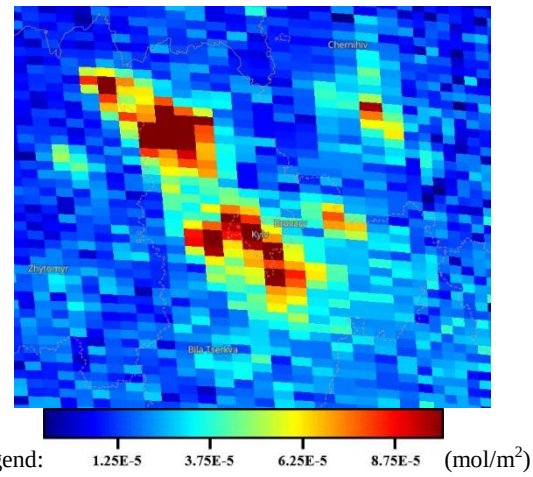
Fig. 6 – Dynamics of the development of a fire at a landfill in the village of Novi Petrivtsi, Vyshgorod district, Kyiv region, according to data from the Sentinel-2 satellite (https://www.sentinel-hub.com).

As a result of fires, combustion products pollute the atmosphere. Below are examples of observing damage to infrastructure facilities and emissions of harmful substances into the air at the same time.

Oil depots were among the first to suffer (becoming the most common category of man-made hazards in various regions that were subjected to targeted shelling). In total, at least 60 oil depots were affected, including other storage facilities for fuel and lubricants in 23 regions (https://en.wikipedia.org/wiki/Environmental_impact_of_the_2022_Russian_invasion_of_Ukraine).

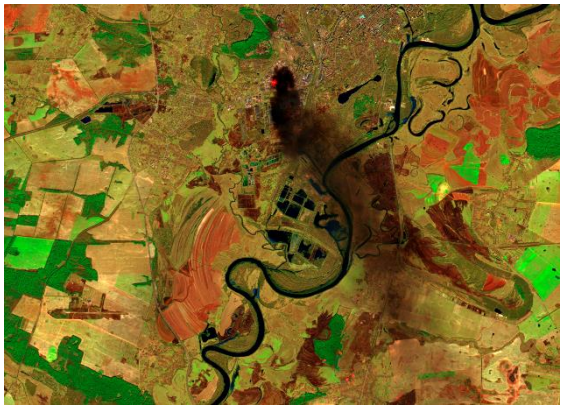
One of the largest fires at oil depots took place on March 3, on the territory of Kombinat Aistra in Chernihiv. During shelling, a shell fell on the oil depot. As a result, a tank set with a total capacity of 5,000 m^3 caught fire and the detonation and destruction of jet fuel storage facilities (4,500 t) and diesel fuel (11,000 t) took place (https://dixigroup.org/wp-content/uploads/2022/06/100days.pdf). On the afternoon of March 19, 2022, the Russian army continued shelling the western part of Chernihiv, the result of which was a fire at the warehouse of fuel and lubricants, as shown in Figure 7.

Map of Ukraine showing the location of the city of Chernihiv



Sentinel-5P data for March 23, 2022

Sentinel-2 data for March 21, 2022



Sentinel-2 data for March 23, 2022

Fig. 7 – The results of the influence of military operations on the state of the air as a result fire at a fuel and lubricants warehouse in Chernihiv., The Sentinel-5P space image shows an increase in the concentration of NO2 over the territory of active military operations around Kyiv and over a fire at a PMM warehouse in Chernihiv. The Sentinel-2 space images show the direction of the plume (https://www.sentinel-hub.com).

Military actions on the territory of Ukraine have been causing serious threats consisting of man-made emergency situations triggered by the actions of the occupiers. The risks to the population associated with damage to objects that pose an increased environmental hazard are of particular concern at this time, because in the absence of control and the possibility of eliminating their negative consequences, the scale of the negative impact potentially increases.

In Ukraine, hydroelectric power plants, dams and locks on the Dnieper Cascade may pose a danger to the population during military operations against them or air attacks: Dniprovska HPP (Dnipro HPP, Zaporizhzhya), Middle Dnipro HPP, Kakhov HPP, Kremenchuk HPP, Kaniv HPP, Kyiv HPP, small and medium hydropower plants on the Dniester cascade, dams (http://epl.org.ua/announces/vijna-pidvyshhuye-ryzyky-nadzvychajnyh-sytuatsij-na-ges).

On February 26, 2022, in the area of the village of Kozarovich, Russian troops destroyed the dam that separated the Irpin River from the Kyiv Reservoir. The total area of flooding according to remote sensing data from the Sentinel-2 satellite with a spatial resolution of 10 meters on April 7, 2022 is approximately 20 km2 (Figs. 8, 9).

According to satellite data, the distance between the “flood water” and the nearest buildings is 50–100 meters.

In the village of Demydiv, the most difficult situation occurred because of flooding. The flooding of the Kozka River actually divided the village into two parts, so that the central part of the village is free of water only on the southwestern direction. The tense situation to the east of the village, as shown in Fig. 9, where homesteads are flooded, means that the water has already reached the nearest residential buildings, and the distance to another ten residential buildings is 5–20 meters. In the village of Chervone, the direct distance to residential buildings is 200 meters. In the village of Rakivka, the distance is 210–250 meters. In the village of Huta-Mezhihirska, according to remote sensing data, 10 residential buildings have already experienced the encroaching of “high waters”.

Such a situation is catastrophic in itself, but everything is made more complicated by the consequences of military actions. Such a rise in the water level subsequently leads to a rise in the level of groundwater, which in turn leads to excessive moisture. For residential buildings, the penetration of groundwater into basements means that the communication networks laid underground will be subjected to an additional load. One negative factor of such flooding is the impossibility of using the fields for this year’s harvest.

In addition, mass flooding greatly slowed down communication within the region and neighbouring villages.

Map of Ukraine with the location of Kyiv Reservoir

February 26, 2022
(before the dam was destroyed)

March 11, 2022

March 18, 2022

Fig. 8 – The results of the dam blast on the Kyiv Reservoir according to data from the Sentinel-2 satellite short wave infrared composite (SWIR) (https://www.sentinel-hub.com).

Map of Ukraine with the location of the village of Demydiv

Blue counter from the Sentinel-2 satellite March 18, 2022 superimposed on a March 22, 2022 Maxar Technologies photo

From the satellite of Maxar Technologies for March 22, 2022

From the satellite of Maxar Technologies for March 22, 2022

Fig. 9 – Flooding locations in the village of Demydiv as a result of the spill of the Irpin River to data from the Sentinel-2 satellite and satellite image taken by the company Maxar Technologies. General view of the area and extent of the spill, highlighted in blue on the Sentinel-2 satellite image, and detailed close-up examples on the satellite images, taken by Maxar Technologies*)(https://museum.kpi.ua/map/?ns=war&d=north&l1=2022-03-22&l2=&z=13&lon=30.365094&lat=50.731245).*

The destruction of one of the sluice gates of the Oskilsky Reservoir in Kharkiv Oblast on April 2 is one of the biggest changes in the environment that occurred as a result of the Russian-Ukrainian war (Fig. 10). Approximately 355,500,000 cubic meters of water were rapidly released from the reservoirs, causing the level of the Siversky Donets River to rise and exposing about 9,000 hectares of silted riverbed. The rise in the water level of the Siverskyi Donets River, into which the Oskil flows, helped stop the advance of the Russian troops, who still cannot cross the largest river in Eastern Ukraine. However, in addition to the short-term tactical advantages important for the defence of state, there are also long-term environmental consequences. The Oskil reservoir was created to regulate the water level in the Siverskyi Donets-Donbas canal. This reservoir is connected with the water supply of the vast majority of the population of the Donetsk and Luhansk regions (https://uncg.org.ua/en/should-the-oskil-reservoir-be-rebuilt-after-the-war).

Map of Ukraine with the location of the Oskil reservoir

View before the destruction of the dam on March 29, 2022

View after the destruction of the dam May 8, 2022

View after the destruction of the dam October 18, 2022

Fig. 10 – The destruction of the Oskil reservoir in Kharkiv Oblast as a result of the destruction of the dam gates, according to the remotely sensed data (Sentinel-2) (https://www.sentinel-hub.com).

Therefore, terrorist attacks and the conduct of hostilities on the territory of Ukraine with the capture of objects of the energy structure can lead to catastrophic consequences for life and health of people, industrial objects and the natural environment.

4. CONCLUSIONS

Periodically, any country, including modern Ukraine, experiences war. In this case, the eco-destructive nature of war keeps exceeding the negative impact on the environment during the peace period of the country's life, and the issue here is not only the extremely negative direct environmental consequences of the war, but also the long-term consequences of a collateral nature. The war in Ukraine has already become an emergency situation, triggered by a violation of the ecogenic and technogenic security at the regional level with cross-border consequences. The harmful effects of many environmental problems will, in many cases, be of a supra-regional nature.

The losses have already skyrocketed. It is very difficult to evaluate them at this time when the war is still ongoing. When one thinks about environmental damage, one often thinks about qualitative characteristics. It is the use of satellite information that makes it possible to support such information with quantitative estimates. The qualitative growth of space technologies is the factor that reduces the degree of significance of traditional factors that had previously determined the success of ecological, economic and social development of countries during peacetime, especially during wartime, when

there is no possibility to operate with reliable statistical data. In particular, new approaches to the study of urban protection problems are needed. Modern and promising military and space technologies, or nanotechnologies will affect the structure and typology of urban spaces. It is thus necessary to revise the historically formed principles of fortification, which in turn will ensure the safety of cities.

The complex consequences of ecocide (the degradation of the natural environment, the destruction of economic complexes, life support systems, housing, migration, and the death of the population) indicate a man-made humanitarian disaster and a high probability for an ecological disaster. Despite the fact that the end of the military confrontation is most likely far away, all participants in the conflict should waste no time in discussing the environmental problems of military operations and come to an agreement that would at least mitigate the current and future environmental consequences of said military operations. When peace is eventually reached, the Ukrainian government will not only have to restore the destroyed economy and social sphere, but also the ecology, which had already been a most problematic aspect in Ukraine prior to the war, according to many indicators.

REFERENCES

100 days of war: consequences for the Ukrainian environment. URL: https://dixigroup.org/wp-content/uploads/2022/06/100days.pdf.

Additional Protocol to the Geneva Conventions of August 12, 1949, relating to the Protection of Victims of International Armed Conflicts (Protocol I), dated June 8, 1977. URL: https://ihl-databases.icrc.org/ihl/INTRO/470.

All-Ukrainian Environmental League URL: https://www.ecoleague.net.

Affek, A.N., Wolski, J., Zachwatowicz, Maria, Ostafin, K., Radeloff, V.C. (2021), *Effects of post-WWII forced displacements on long-term landscape dynamics in the Polish Carpathians*. Landscape and Urban Planning **214**, pages 104164.

Convention on assistance in the event of a nuclear or radiation emergency. URL: https://www.iaea.org/topics/nuclear-safety-conventions/convention-assistance-case-nuclear-accident-or-radiological-emergency.

Convention on the Physical Protection of Nuclear Material (CPPNM) and its Amendment. URL: https://www.iaea.org/publications/documents/conventions/convention-physical-protection-nuclear-material-and-its-amendment.

Convention on early notification of a nuclear accident. URL: https://www.iaea.org/topics/nuclear-safety-conventions/convention-early-notification-nuclear-accident.

Convention on the Prohibition of Military or Any Other Hostile Use of Environmental Modification Techniques (ENMOD). URL: https://www.un.org/disarmament/enmod.

Convention on the prohibition of the development, production, stockpiling, use of chemical weapons and on their destruction. URL: https://treaties.un.org/pages/ViewDetails.aspx?src=TREATY&mtdsg_no=XXVI-3&chapter=26.

Crook, M., Short, D., South, N. (2018), *Ecocide, genocide, capitalism and colonialism: Consequences for indigenous peoples and glocal ecosystems environments*. Theoretical Criminology, **22**(*3*), 298–317. DOI: https://doi.org/10.1177/1362480618787176.

Earth Observation Group. Nightly DNB Mosaic. URL: https://eogdata.mines.edu/products/vnl/.

Ecological consequences of the Russian invasion of Ukraine (2022), Wikipedia URL: https://en.wikipedia.org/wiki/Environmental_impact_of_the_2022_Russian_invasion_of_Ukraine

European Union, United Nations and World Bank Group (2015), "Ukraine. Recovery and Peacebuilding Assessment: Analysis of Crisis Impacts and Needs in Eastern Ukraine", vol. **1**, March 2015. URL: http://reliefweb.int/sites/reliefweb.int/files/resources/V1-RPA_Eng_rev2.pdf.

Witmer, F.D.W. (2008), *Detecting war-induced abandoned agricultural land in northeast Bosnia using multispectral, multitemporal Landsat TM imagery*. International Journal of Remote Sensing **29**(*13*):3805–3831 https://doi.org/10.1080/01431160801891879].

Fujita, K. (ed.) (2013), *Cities and Crisis. New Critical Urban Theory*. London: SAGE. 325 p. DOI: 10.1111/1468-2427.12350.

Gardashuk, T. (2017), *Colonialism, Postcolonialism and Environmental Crisis (Ukrainian Experience)*. Almanac of Ukrainian Studies. Kyiv: "Milenium+", **20**, pp. 21–26. https://cutt.ly/eGn52lZ.

Henderson, J. Vernon, A. Storeygard, David N. Weil. (2012), *Measuring Economic Growth from Outer Space*. American Economic Review, **102** (*2*): 994–1028. doi: 10.1257/aer.102.2.994.

How dangerous is the burning of landfills? URL:https://rethink.com.ua/uk/news-and-events/ekologichni-problemi/chim-nebezpechne-gorinnya-smittezvalishch.

Partial Nuclear Test Ban Treaty. URL: https://en.wikipedia.org/wiki/Partial_Nuclear_Test_Ban_TreatyKaplan, G., Rashid, T., Gasparovic, M., Pietrelli, A., & Ferrara, V. (2022). *Monitoring war-generated environmental security using remote sensing: A review*. Land Degradation & Development, **33**(*10*), 1513–1526. https://doi.org/10.1002/ldr.4249.

Khaled Hazaymeh, Wahib Sahwan, Sattam Al Shogoor, Brigitta Schütt. (2022), *A Remote Sensing-Based Analysis of the Impact of Syrian Crisis on Agricultural Land Abandonment in Yarmouk River Basin*. Sensors 22:10, pages 3931.

Libanova E.M. (ed.) (2015), *Revival of Donbass: assessment of socio-economic losses and priority areas of public policy: a scientific report.* Kyiv, 168 p. URL: https://iie.org.ua/wp-content/uploads/monografiyi/2015/2015_mono_Strategiya.pdf.

Namespace: war. URL: https://museum.kpi.ua/map/?ns=war&d=north&l1=2022-03-22&l2=&z=13&lon=30.365094&lat=50.73124.

Victor Mackenhauer Olsen, Rasmus Fensholt, Pontus Olofsson, Rogerio Bonifacio, Van Butsic, Daniel Druce, Deepak Ray, Alexander V. Prishchepov (2021), *The impact of conflict-driven cropland abandonment on food insecurity in South Sudan revealed using satellite remote sensing*. Nature Food 2:12, pp. 990–996.

Time to conclude the 1990s conflict in the Balkans. URL: https://www.ndi.org/our-stories/time-conclude-1990s-conflict-balkans.

The State Emergency Service of Ukraine. URL: https://dsns.gov.ua.

Thiri Shwesin Aung, Indra Overland, Roman Vakulchuk, Yanhua Xie (2021), *Using satellite data and machine learning to study conflict-induced environmental and socioeconomic destruction in data-poor conflict areas: The case of the Rakhine conflict*. Environmental Research Communications 3:2, pages 025005.

State Statistics Service of Ukraine. URL: http://www.ukrstat.gov.ua/.

Stockholm International Peace Research Institute. URL: https://www.sipri.org/.

He Yin, Van Butsic, Johanna Buchner, Tobias Kuemmerle, Alexander V. Prishchepov, Matthias Baumann, Eugenia V. Bragina, Hovik Sayadyan, Volker C. Radeloff (2019), *Agricultural abandonment and re-cultivation during and after the Chechen Wars in the northern Caucasus*. Global Environmental Change 55, pp. 149–159.

War in Yugoslavia: environmental consequences of military actions. Abstract. URL:https://ru.osvita.ua/vnz/reports/ecology/21279/.

War increases the risks of emergency situations at hydroelectric power plants. Ecology. Law. Human. URL:http://epl.org.ua/announces/vijna-pidvyshhuye-ryzyky-nadzvychajnyh-sytuatsij-na-ges/.

Welp, M. (2020). *A global analysis on impact of conflicts on long-term greening trends*. Student thesis series INES.Master thesis in Physical Geography and Ecosystem Science. 46 p.

Sentinelhub. URL: https://www.sentinel-hub.com.

Should the Oskil Reservoir be rebuilt after the war? Ukrainian nature protection group. URL: https://uncg.org.ua/en/should-the-oskil-reservoir-be-rebuilt-after-the-war.

Received October 12, 2022