ASSESSMENT AND MONITORING OF FIRES CAUSED BY THE WAR IN UKRAINE ON LANDSCAPE SCALE

OLHA V. TOMCHENKO[1], ANNA V. KHYZHNIAK[1], NATALIA A. SHEVIAKINA[2*], SNIZHANA A. ZAHORODNIA[2], LESYA A. YELISTRATOVA[1], MARIIA I. YAKOVENKO[3], IRYNA R. STAKHIV[3]

[1] State Institution "Scientific Centre for Aerospace Research of the Earth of the Institute of Geological Sciences of the National Academy of Sciences of Ukraine", Olesia Honchara Str., 55-b, Kyiv, 01054, Ukraine
[2] Institute of Telecommunications and Global Information Space of the National Academy of Sciences of Ukraine, Chokolovskiy bulv., 13, Kyiv, 03186, Ukraine
[3] Kyiv National University of Taras Shevchenko, Vasylkivska Str., 90, Kyiv, 03022, Ukraine
[*] Corresponding author email: n.a.sheviakina@gmail.com

Received: 23rd June 2023, **Accepted:** 4th September 2023

ABSTRACT

The article assesses the changes in the state of Ukraine's natural environment, namely due to the fire on its territories as a result of military operations. Remote sensing can be considered as a decision support tool for landscape management, remote sensing plays a vital operational tool in the affected areas to assess the consequences, as well as to make appropriate decisions to protect the environment and support environmental recovery programs in these areas.

This paper presented applying of remote sensing methods to assess large fires caused by military events in Ukraine war using the VIIRS spectroradiometer (375 m) on board the NASA/NOAA Suomi NPP satellite and NOAA-20 satellites, as well as NASA's Fire Information for Resource Management System (FIRMS) resource. The paper presents examples of the use of remote sensing to detect changes in territories affected by military operations, and provided estimates of the total number of fires in 2022. Authors proposed a methodology for obtaining daily data on the localization of fires in the territories of active hostilities, in particular in 15 regions of Ukraine that are closest to the front line. Results of this paper indicated the VIIRS spectroradiometer and the FIRM's resource as an effective tool for monitoring fires and assessing changes in the environment caused by them as a result of military operations in Ukraine.

The possibility of using satellite imagery for operational fire monitoring has been proven, which, in combination with traditional ground-based data, can play a crucial role in protecting civilians and providing evidence of environmental violations.

Keywords: fires, war impact to the environment, ecological monitoring, land use/land cover change.

INTRODUCTION

Any war creates enormous environmental threats that cause unprecedented destruction and devastation of the country's natural landscapes. The number of armed conflicts on Earth has not decreased over the years, and a large number of works published in recent years have been devoted to monitoring environmental changes due to their impact (Biswas, 2000). In particular, work (Ajmi & Saif, 2009) contains various aspects of the study of the environmental consequences of war, covering both general issues such as war prevention and its various consequences: environmental, legal, political and technical foundations of the impact of warfare agents on the environment and human health, as well as atmospheric transfer and release of persistent organic pollutants in war to more specific ones related to two major tragic examples: the war in the Balkans and the war in the Persian Gulf. Aspects of the Balkan War include heavy metal pollution in Serbian national parks, the impact of NATO strikes on the Danube River basin, and problems related to transuranic elements. The Gulf War in Kuwait covers other issues related to the impact of oil pollution, impacts on water resources, and soil damage to ground fortifications, among other environmental and health concerns.

Remote satellite monitoring methods are perhaps the only available tool for studying territories that are under occupation or in which direct hostilities are taking place, or are inaccessible due to mining. Researchers (Lubin & Saleem, 2019) present the possibilities of mapping based on remote sensing of the destruction of Aleppo during the civil war in Syria between 2011 and 2017, namely, the detection of temporal changes in the urban environment based on the analysis of satellite image textures. The authors of (Mohamed *et al.,* 2020) presented the results of monitoring changes in land use/land cover in Syria from 2010 to 2018 using multi-temporal Landsat images in the GIS environment. The results of integrating spatial data from multiple sources to assess the impact of the Syrian civil war on cities and the population are presented in (Deng *et al.,* 2021; Hazaymeh *et al.*, 2022). How the conflict affects land use: agricultural activities in the areas captured by the Islamic State are also described in (Eklund *et al.,* 2017). Armed conflict and changes in land use: impressions of the Iraqi-Iranian war in the Zagros forests (Beygi *et al.,* 2020). Increased deforestation in Colombian protected areas in the post-conflict period (Clerici *et al.,* 2020). The web portal of the independent group of researchers and citizen journalists Bellingcat (Scorched Earth, 2022) describes the use of FIRMS data to monitor war zones in Ethiopia, where a civil war has been ongoing since the end of 2020.

Ukrainian scientists have now also shifted the focus of peaceful research to military topics, and there are a number of publications on this topic, in particular, (Rawtani *et al.*, 2022) describes the use of remote sensing data to study the environmental consequences of the Russian invasion of Ukraine in 2022. Multispectral data from NOAA-2, Suomi NPP, Aqua and Terra satellites, as well as multispectral data from Sentinel and Landsat were used for a more detailed visualization of the consequences of the Russian invasion. Paper (Yaimaiti *et al.,* 2022) provides visual results of environmental damage such as air pollution, destruction of dams on water bodies, forest and grass fires, including the destruction of agricultural land on Sentinel-2 and 5P images, and changes in night lighting according to Suomi NPP/VIIRS data. Paper (Cardil *et al.,* 2023) presents the results of combining Sentinel-1 radar data with Sentinel-2 optical data to assess damage in the regions around Kyiv, the capital of Ukraine, at the beginning of the war in 2022. Based on the logarithmic intensity ratio algorithm on Sentinel-1 SAR images and GLCM average texture analysis on Sentinel-2 optical data, to identify damaged buildings in the first place. From this analysis, we can conclude that people suffer in any war. And, of course, in this case, the tragedy of people replaces the tragedy of nature.

In the war against Ukraine, Russia is not only killing people, destroying settlements and infrastructure. In this war, Russia is using a new type of high-tech terrorism - environmental terrorism, which is no safer than other types of terrorism, as violent actions are applied to people indirectly through the natural environment. This will lead to difficulty to eliminate consequences. For many years, and some of them may be irreversible. One of these negative consequences is fires. In Ukraine, fires have become more frequent over the past decade. The fires that are occurring now are markedly different from the past, as their environmental and economic consequences are exacerbated by the hostilities. In most cases, the scale of the natural disaster is reaching significant proportions precisely because Ukrainian firefighters have no access to these areas due to shelling. Since the beginning of the war, about 3 million hectares of forest in Ukraine have been affected (https://texty.org.ua/fragments/109583/skilky-lisiv-postrazhdalo-vid-vijny-i-yak-shvydko-yih-mozhna-vidnovyty/). Due to forest fires, burning of oil products and industrial facilities, emissions of pollutants into the air occur daily, the number of which is difficult to calculate today. But, the consequences will be dramatic and lead to an environmental disaster.

The war is also affecting territories outside Ukraine. The consequences of the impact of hostilities on the general state of the environment are discussed in (Pereira1 *et al.,* 2022*;* Yelistratova *et al.,* 2022*;* Cardil *et al.,* 2023). Researchers developed a methodology for determining the rate of fire spread using VIIRS spectroradiometer data, and established the influence of soil cover, seasonality, and weather conditions on the rate of fire spread. Paper (Trofymchuk *et al.,* 2022) presents the results of using FIRMS data to determine the localization of temperature anomalies, foci and fires in Ukraine from February 24 to June 8, 2022, and provides a more detailed analysis of the spread of fires in and near the Black Sea Biosphere Reserve.

Today, remote sensing tools allow us to accurately and clearly display the consequences and scale of the impact of military operations on the environment using the example of such a natural disaster as fires. That is why the aim of the work is to monitor fires (number, localization and their division depending on the type of surface (agricultural fields, grass, forest, settlements) and assess changes in the state of the environment as a result of military operations in the territory of 15 administrative regions of Ukraine closest to the front line for the period from March 2022 to March 2023.

To achieve the goal, the following targets: using data from the VIIRS spectroradiometer (375 m) placed on board the NASA/NOAA Suomi NPP satellite and satellites NOAA-20 NASA's Fire Information for Resource Management System (FIRMS) to obtain daily data on the localization of fires in the territories of active hostilities; Using ESA WorldCover 2021 ground cover data to determine the types of surfaces affected by fires to analyze the statistics of changes in territories and the impact on environmental components; to verify the reliability of fires on certain types of ground cover, find Sentinel-2 satellite images from the EO-browser resource on the FIRMS website for specific dates and provide an illustration of the evidence of the localization of fires.

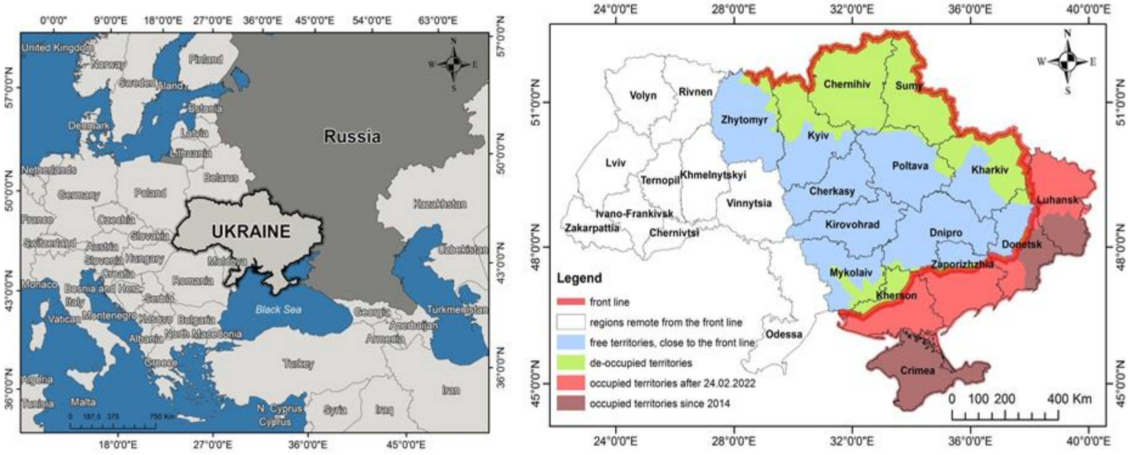
MATERIALS AND METHODS

The large-scale Russian invasion of Ukraine began on February 24, 2022. However, the occupation of Ukraine's territory began in 2014, when Crimea and parts of Luhansk and Donetsk regions were occupied (https://truth-hounds.org/ekologichna-sytuacziya-na-terytoriyi-doneczkoyi-ta-luganskoyi-oblastej/). As of February 23, 2022, 43,300 square kilometers, or 7 % of Ukrainian territory, were under russian occupation. After the beginning of the russian invasion in 2022, this area increased by 2.9 times, and amounted to 125,000 square kilometers, that is, 20.7 % of the Ukrainian territory was occupied according to Forbes Ukraine magazine published on May 24, 2022.

To analyze the impact of the war on the territory of Ukraine, the authors selected 15 regions of Ukraine (Fig. 1). This list includes 11 regions of Ukraine where the fighting was directly conducted or which were/are in temporary occupation, surrounded (blocked): Donetsk, Lugansk, Zhytomyr, Zaporizhzhya, Kyiv, Nikolaev, Kherson, Sumy, Kharkov, Chernihiv and AR Crimea. And also, 4 regions (Cherkasy, Dnepropetrovsk, Kirovograd, Poltava) are close to the front line. That is, during the analysis, the entire territory of left-bank Ukraine (where r. Dnipro is a boundary landmark).

Fig. 1: Research area. Boundaries of Ukrainian regions and occupied/affected territories, as of May 07, 2023

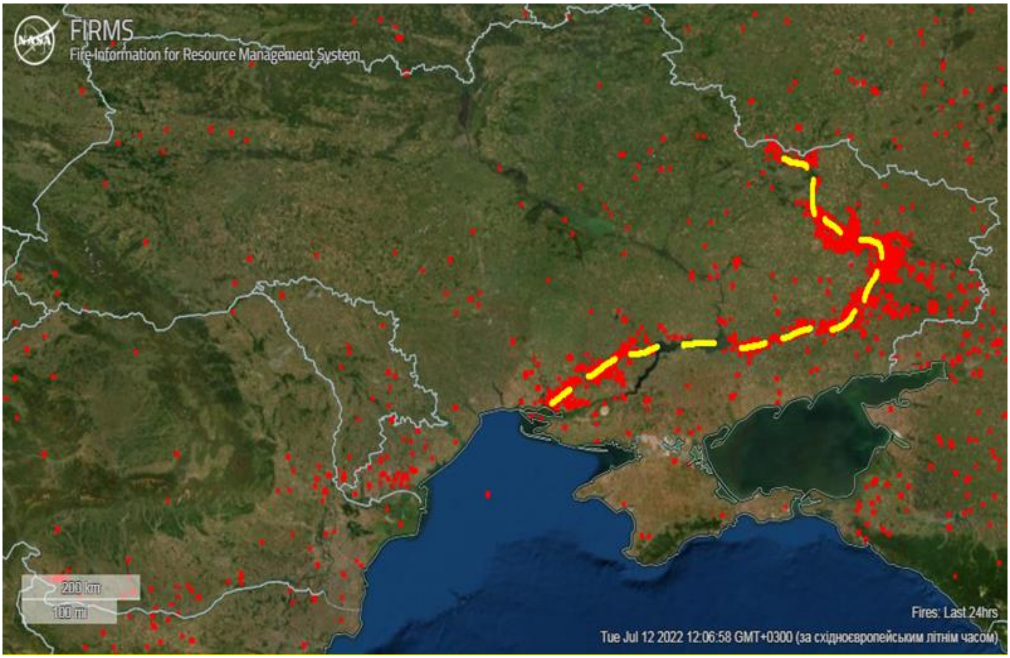
(on the map of Ukraine: 1 - front line, 2 - regions remote from the front line, 3 - free territories close to the front line, 4 - de-occupied territories, 5 - occupied territories after 24.02.2022, 6 - occupied territories after 2014)



Three input data resources were selected to obtain daily data on fire localization, monitoring and subsequent assessment of environmental changes in the areas of active hostilities for the period from March 2022 to March 2023: Fire Information for Resource Management System (FIRMS), European Space Agency (ESA) WorldCover 2021, Earth Observation (EO) Browser.

Fire localization monitoring was carried out using the FIRMS (Fire Information for Resource Management System, 2023) service developed at the University of Maryland and supported by the US National Aeronautics and Space Administration (NASA). FIRMS contains geospatial and descriptive information on fires detected by the MODIS moderate resolution spectroradiometer (1000 m) on board Terra and Aqua satellites, as well as the VIIRS spectroradiometer (375 m) on board NASA/NOAA Suomi NPP and NOAA-20 satellites. The product of the Visible Infrared Imaging Radiometer Suite (VIIRS) sensor system installed on the NASA/NOAA Suomi National Polar-orbiting Partnership (Suomi NPP) and NOAA-20 satellites has a spatial resolution of 375 m in nadir (VIIRS, 2023). VIIRS data were chosen for the study, because of the high resolution and thus increased accuracy required for mapping fires and, accordingly, tracking the analysis of their large clusters and with greater accuracy (Fig. 2).

Fig. 2: Fire localization map for two weeks in July 2022: yellow line - front line; red dots – fires



The Firms website (Fig. 2) clearly shows that a huge number of fires (red dots) in Ukraine are concentrated along the front line (yellow line). The map shows the localization of fires for 2 weeks in July 2022, when the most large-scale clashes were taking place along the entire front line. The system provides near real-time data on active fires within three hours of satellite observation, using algorithms to monitor the average infrared radiation from fires and thermal anomalies that can be visualized on a map as hotspots (Fire Information, 2023). A hotspot is a pixel in a satellite image with a high intensity of infrared radiation, indicating a heat source. One pixel can contain one or more active fires. The FIRMS data can be used not only to detect forest fires, but also thermal anomalies of various nature (FIRMS, 2023).

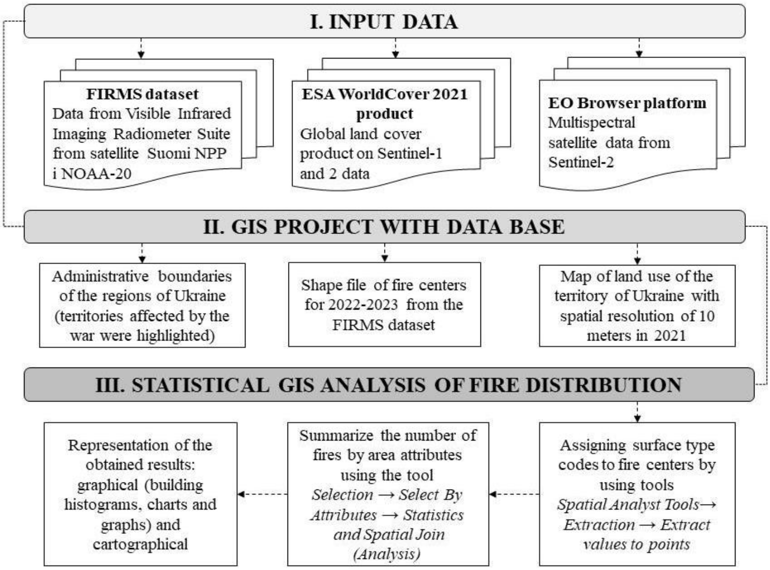
In addition to fire localization data from the FIRMS website, ESA WorldCover 2021 surface type maps were used to assign the points of fire centers to the codes of the type of land surface affected by the fire. ESA WorldCover 2021, a classification map of land cover types (Earth's surface), was created based on the experience of the European Space Agency GlobCover and CCI Land Cover (Zanaga *et al.*, 2022). ESA WorldCover is a map of the world's surface with a spatial resolution of 10 meters. This map is based on imagery acquired by Sentinel-1 and Sentinel-2 satellites with a resolution of 10 meters. The algorithm used to create ESA WorldCover products is based on the algorithm for creating the Copernicus Global Land Service annual dynamic land cover map (CGLS-LC). The ESA WorldCover 2021 data reflects 10 land cover classes and mangroves - that is, 11 classes. The legend includes 11 general classes that properly describe the land surface: «Tree cover», «Shrubland », «Grassland », «Cropland», «Built-up», «Bare / sparse vegetation», «Snow and ice», «Permanent water bodies», «Herbaceous wetland», «Mangroves» and «Moss and lichen».

After receiving the coordinates and dates of the fires from the FIRMS service, they were directly searched on Sentinel-2 satellite images in the EO Browser resource for further visualization. EO Browser is a free cloud-based tool (https://www.sentinel-hub.com/explore/eobrowser) for visualizing and downloading available medium and low-resolution images from various satellites, including those used in Sentinel-2 operations. EO Browser combines many functions: data comparison, various automatic visualization options, channel synthesis, area measurement, and statistical data in the form of graphs (EO Browser, 2023). This viewer provides the ability to export data processing results to georeferenced files.

The study used free images of Sentinel-2 satellites for 2022-2023 equipped with an optoelectronic multispectral sensor for imaging with a resolution of 10 to 60 m in the visible, near-infrared (VNIR) and short-wave infrared (SWIR) spectral bands. This ensures that differences in vegetation conditions, including temporary changes in landscapes, can be detected. In many cases, the time of satellite passage and the time of the fire do not coincide, or the images are too cloudy to see anything. Therefore, only a very small percentage of fires at the time of the fire itself with smoke can be found and visually displayed on Sentinel-2 optical satellite images. But the fires can be visually identified on the following dates, so not only open fires but also dark areas of fires are evidence of the existence and localization of the fire.

In terms of methodology, the study of fires as a result of military operations on the territory of Ukraine consisted of using data obtained from the FIRM's resource on the localization of fires for the period from March 2022 to March 2023 in the area of active hostilities. Further, ESA WorldCover 2021 land cover data were used to determine the types of surfaces affected by fires. The EO-browser resource was used to search for Sentinel-2 satellite images. The images were found for specific dates defined on the FIRMS website. Thus, the reliability was checked and illustrations of evidence of detected fires on certain types of land cover were provided (Fig. 3).

Fig. 3: Flowchart of methods for studying the distribution of fires on the territory of Ukraine as a result of military operations



The data of observations of thermal anomalies and active fires from the VIIRS sensor system from March to March 2022-2023 were downloaded from the FIRMS archive in the format of a point shapefile and further processed. ESA WorldCover 2021 data was used to assign attributes (surface type index) to the points where they were detected. The first step in working with the source materials was to analyze the administrative boundaries of Ukraine's regions. We identified the territories where military operations were actively conducted and the areas that were destroyed and affected by the war. To do this, all points from the FIRMS resource were selected within each administrative unit and grouped into a separately created shapefile of fire centers in each region from March to March 2022-2023. The 10-m resolution land use map for Ukraine based on 2021 Global land cover is presented in a color scheme of colors, each color corresponding, as noted above, to a certain type of object class represented on the territory of Ukraine (Fig. 4).

Fig. 4: Map of land cover classes on the basis of ESA WorldCover 2021 and fires obtained from FIRMS for the period from March 2022 to March 23

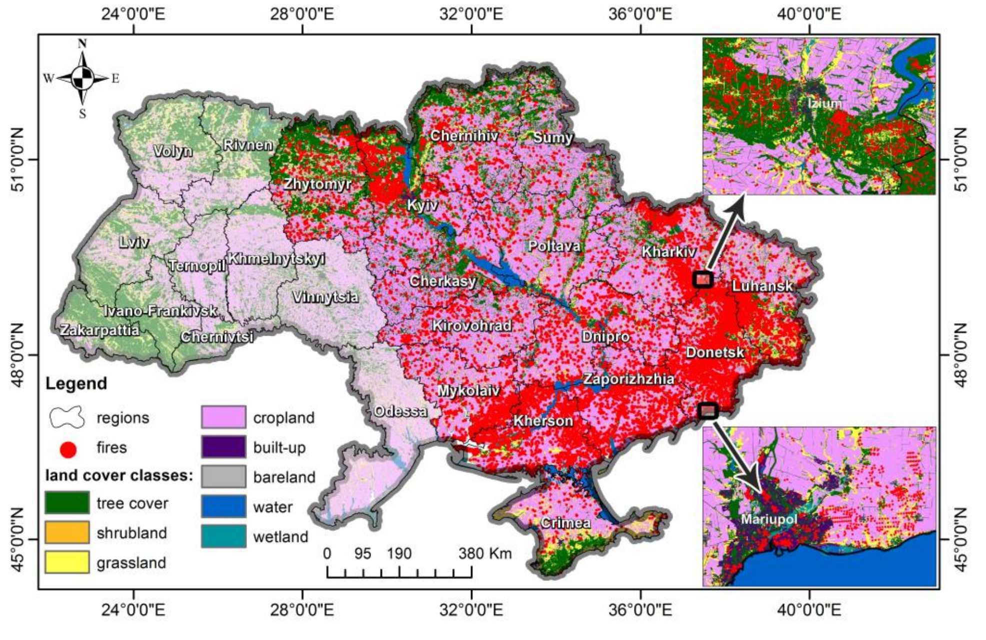


Figure 4 shows all the fires received from FIRMS for the period from March 2022 to March 2023, which are overlaid on the ESA WorldCover 2021 framework. Of all the available ESA WorldCover 2021 codes, the 4 following classes were of the greatest interest, as shown in Table 1. Namely: tree cover, grassland and herbaceous wetland, cropland, built-up. To assign surface type indices to fire centers in ArcGIS, the Spatial Analyst Tools → Extraction → Extract values to points tool was used. Each point within a particular administrative unit was assigned indices corresponding to classes. The next step was to calculate the number of fires for each region. To do this, we used the ArcGIS tool "Selection" → "Select by Attributes" and the "Statistics" utility. All data was clearly sorted by region, date (month), and type of fire surface, i.e., the index corresponding to a certain class.

Table 1: Selected surface types based on ESA WorldCover data

Land Cover Class	**Definition**	**LCCS code ***

Tree cover	forest areas dominated by trees with a cover of 10% or more	A12A3 //A11A1
		A24A3(C1(C2)-R1(R2)

Grassland and Herbaceous wetland	natural herbaceous vegetation complexes (meadows, pastures, uncultivated lands) and wetlands	A12A2 A24A2
Cropland	agricultural land (covered with annual grass crops)	A11A3(A4)(A5) // A23
Built-up	Land covered by buildings (residential and industrial), roads and other artificial structures	B15A1

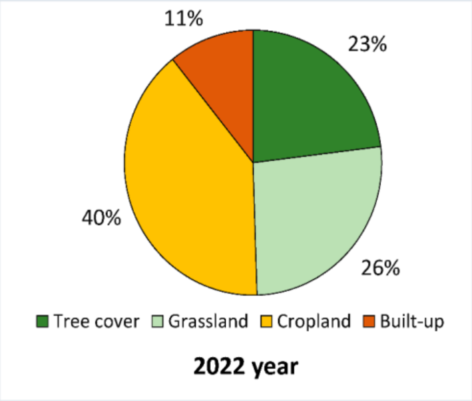
* according to the Land Cover Classification System (LCCS) developed by the United Nations (UN) Food and Agriculture Organization (FAO).

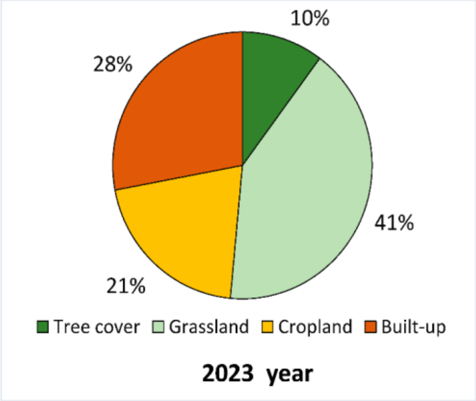
Histograms and graphs were constructed, and a cartographic representation of the results was presented. The total maps of the number of areas within each of the 4 classes of surfaces by region were constructed using the Spatial Join (Analysis) tools in ArcGIS (Sheviakina *et al.,2020*).

RESULTS AND DISCUSSION

The distribution of fires depending on the type of land cover in the war-affected regions of Ukraine from March 2022 to March 2023 was made. According to Table 1, fire distribution graphs were drawn for four types of land cover: forests; natural herbaceous vegetation complexes (meadows, pastures, uncultivated land) and wetlands; agricultural land (covered with annual herbaceous crops); land covered with buildings (residential and industrial), roads, and other artificial structures, as shown in Fig. 5.

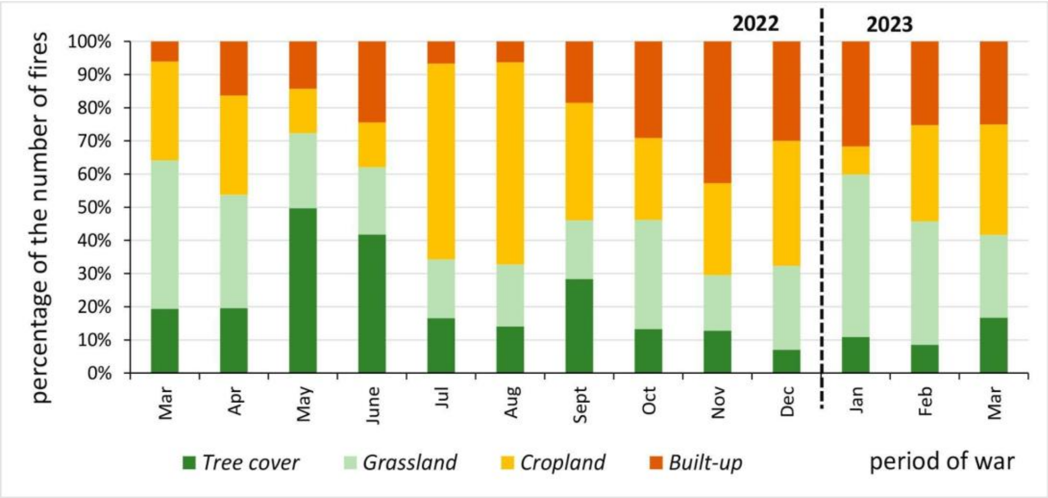
Fig. 5: The general distribution of fires depending on the type of land cover in the war-affected regions of Ukraine from March 2022 to March 23





Considering the monthly distribution of fires in 2022 (Fig. 6), a more or less constant number of them persists in natural grassy landscapes – 20-30 % of the total. For areas covered by forests, the highest number of fires was observed in May and June 2022, 50 % and 40 %, respectively, 28 % in September, and by the end of 2022, it decreased to 10 %. For agricultural lands, the maximum number of fires is observed in July-August 2022 – 60 % and by the end of the year it decreases to 20-30 % of the total. In the built-up areas, the distribution of fires changes as follows: the maximum number of fires is observed from September to November 2022, in December there is a 10 % decrease, and it remains at this level until March 2023.

Fig. 6: The general distribution of the number of fires by month, depending on the type of land cover, within all 15 occupied and frontline territories from March 2022 to March 2023



If we compare the fire rates for March 2022 and March 2023, it should be noted that the number of forest fires and arable land remains unchanged within 18-20 % and 30 %, respectively. And the number of fires in built-up areas has increased almost 4 times, while the number of fires in pastures has been halved. In addition, the number of fires in settlements in 2023 was 28 % in three months, while in 2022 this value was 11 % in ten months. This is the result of a change in the place of hostilities and their intensity, the de-occupation of northern Ukraine, which is mostly covered with forests, and the displacement/concentration of hostilities, mainly in the east and south of the country.

Fig. 7: Pareto chart of the total number of fires by region in 2022 (from March to December)

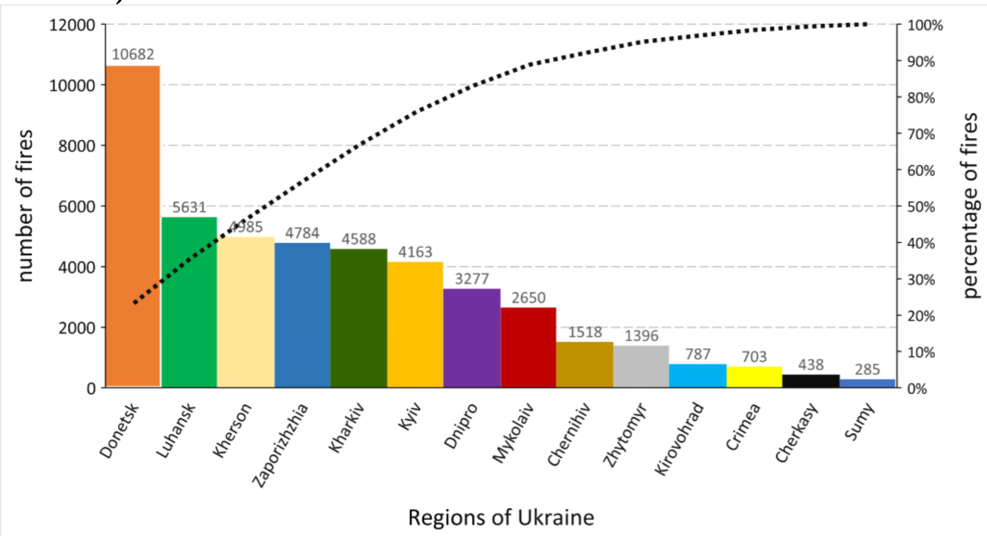


Fig. 8: Distribution of the number of fires by type of land cover by region within the occupied and frontline territories from March to December 2022

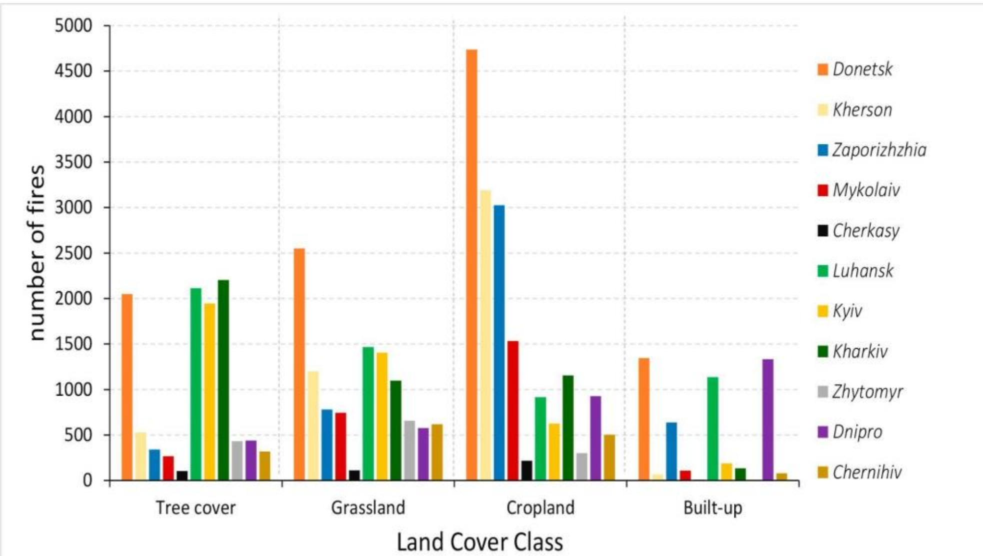
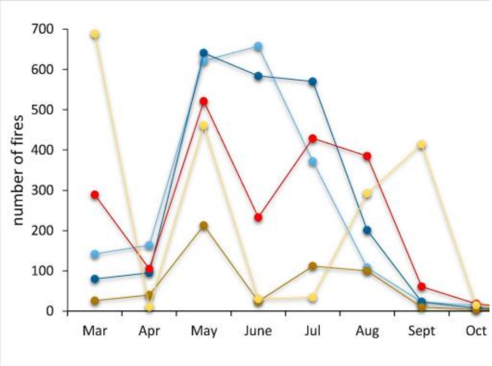


Table 2: Statistics on the number of fires obtained from FIRMS in the war-affected regions of Ukraine from March 2022 to March 2023

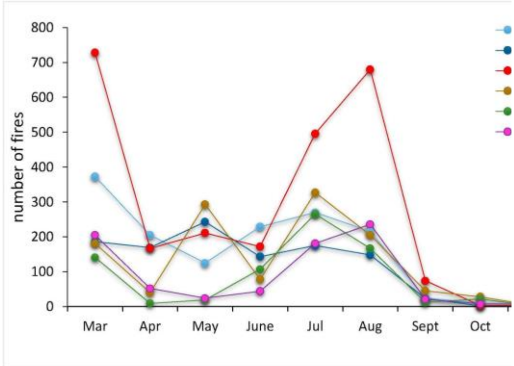
Name of region	**Type of surface (land cover)**								**Sum of fires within 4 classes in each region**	Total area of the region, km2
	Tree cover		Grassland		Cropland		Built-up			
	Number of fires	Total area of class within the region, %.	Number of fires	Total area of class within the region, %.	Number of fires	Total area of class within the region, %.	Number of fires	Total area of class within the region, %.		
Donetsk	2060	11.6	2565	14.94	4744	66.3	1374	6.11	10743	26.6
Luhansk	2121	15.9	1485	23.8	918	56.4	1160	3.5	5684	26.8
Kherson	533	3.4	1272	19.5	3203	65.8	68	2.5	5076	26.3
Zapori-zhzhia	341	2.9	798	10.6	3037	78	659	3.2	4835	27
Kharkiv	2209	24.5	1104	7.6	1158	63.8	134	3.3	4605	31.7
Kyiv	1948	32.8	1408	7.5	624	50.2	188	6.6	4168	28.8
Dnipro	449	7.8	586	7.2	936	76.4	1386	5.1	3357	31.7

Mykolaiv	267	2	755	6.1	1548	88,3	109	2.5	2679	23.6
Chernihiv	319	40.5	619	12.8	502	44.1	79	2	1519	31.7
Zhytomyr	432	45	658	5.6	300	47.2	7	2.1	1397	29.9
Kirovo-hrad	104	5.9	169	1.3	471	88.5	45	2.2	789	24.4
Crimea	106	13.5	186	37.6	321	38.3	91	3.7	704	26.6
Cherkasy	104	20.2	116	3.6	217	66.9	7	3.5	444	21.2
Sumy	43	40	96	7.7	133	50	14	2.5	286	24
Total value of fires within all regions	**11036**		**11817**		**18112**		**5321**		**46286**	

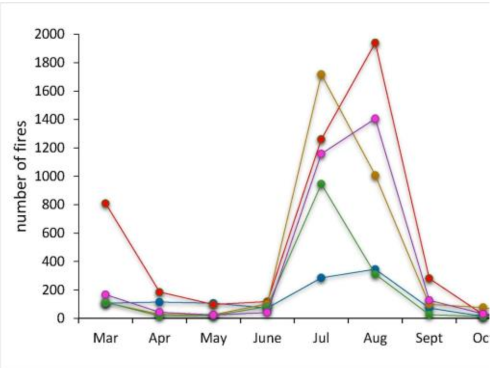
Fig. 9: Distribution of the number of fires by month depending on the land cover class by region in 2022



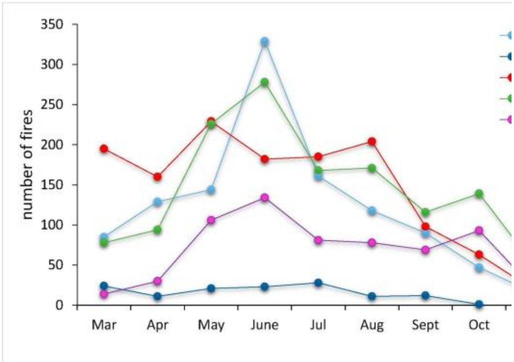
Tree cover



Grassland



Cropland



Built-up

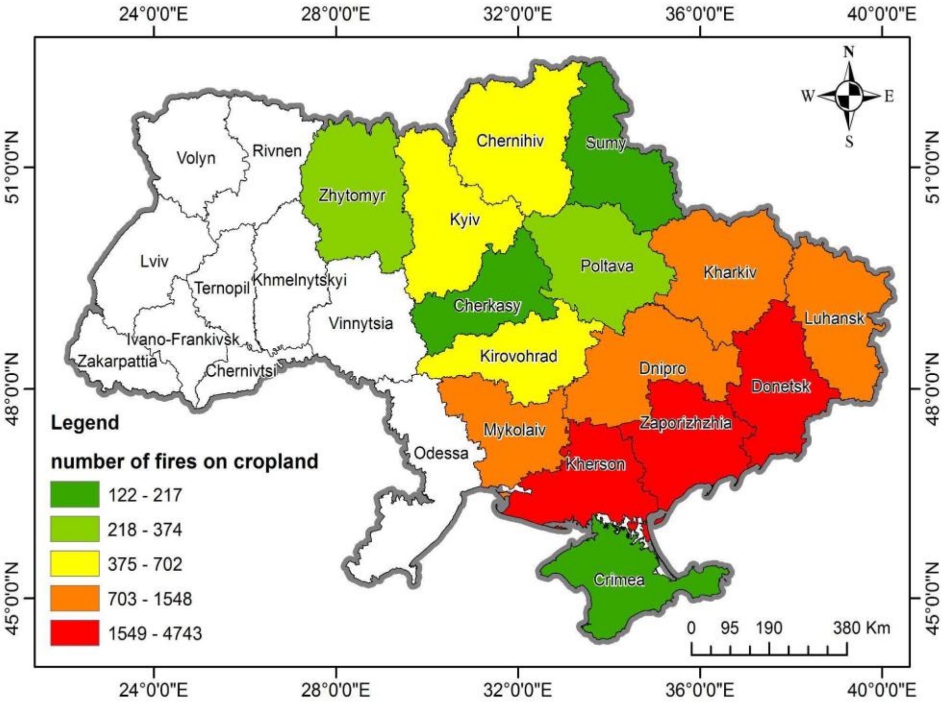
Comparing the data with respect to the territorial and administrative breakdown (Fig. 7), the largest total number of fires is recorded in Donetsk region (10682); in Luhansk, Kherson, Zaporizhzhia, Kharkiv, and Kyiv regions the number of fires varies between 4-5 thousand; in Dnipro and Mykolaiv regions the number of fires is 3277 and 2650 respectively (Table 2, Fig. 7).

For planning economic activities and assessing the loss of natural ecosystems, it will be of practical value to estimate the area of affected land by land cover type in the regions (Fig. 8.) Fig. 9 shows the monthly distribution of the number of fires by region, depending on the type of land cover. In particular, for Kyiv region, the largest number of fires is observed in areas covered by forests (forests in the Kyiv region occupy 32.8 %, Table 2), with the highest activity in March, then from mid-April to mid-June, and from mid-July to October 2022, when the northern part of the region was occupied, and intense hostilities were conducted in this area. In Kherson region, the largest number of fires is characteristic of arable land, which is predominant in this region, with fire activity observed in July and August, when Ukrainian troops launched an active offensive (de-occupation) of Kherson region (northern part of the region).

In general, agricultural land suffered the most, especially in Donetsk, Zaporizhzhia, and Kherson regions (Figures 9 and 10). In built-up areas the largest number of fires was observed in Luhansk, Dnipro, Donetsk, and Zaporizhzhia regions, with peak values in April-September 2022.

At this stage of the work, data sets were accumulated and formed in the form of a GIS database, which allows us to display total vulnerability maps for all four classes of land cover in the occupied territories. For example, the fire susceptibility of the agricultural land class for the entire study period from March 2022 to March 2023 is shown (Fig. 10).

Fig. 10: Map of the distribution of the number of fires on agricultural land for the entire study period from March 2022 to March 2023



According to the Institute of Public Administration and Scientific Research on Civil Protection (https://idundcz.dsns.gov.ua/statistika-pozhezh/analitichni-materiali)), units of territorial bodies of the State Emergency Service registered 80,654 fires in Ukraine in 2022. Compared to 2021, the number of fires increased by 1.5 %, which is mainly the result of hostilities with russian armed groups (fires associated with explosions and shelling amounted to more than 15 %). Studies published in the report "Initiative on accounting for emissions of greenhouse gases due to war" (page 35-39 of the document https://ecoaction.org.ua/vplyv-ros-vijny-na-klimat-2.html) show that from the beginning of the war, the total number of fires has increased 36 times, and the total area is 14 times, compared to this period of 2021. The number of fires in the zone of active hostilities and in the occupied territories of Ukraine has increased the most.

The study provides examples of the use of Sentinel-2 satellite imagery as a tool for detecting fires in different regions of Ukraine during the period of active hostilities in 2022-2023, on different types of surfaces, including forest fires, grass fires in nature reserves, agricultural land, fires in residential buildings and industrial infrastructure. The imagery can detect areas with fire and smoke, as well as determine the size and extent of the fire.

Forest fires in wartime have quite serious environmental consequences when there are no attempts to extinguish them by the warring parties. Forest ecosystems are disturbed, and the resulting burns create favorable natural conditions for the reproduction of insect pests and the development of fungal diseases. After fires, forest resources practically lose their water-regulating, soil-protecting, sanitary and hygienic, and environmental functions.

Fig. 11: Examples of recording forest fires on the territory of the Izyum forest, Kharkiv region, Ukraine: a) - total map of fire locations for 5 days from July 3 to 7, 2022 from the Firms website, where a huge number of fires (red dots) are clearly visible; b) - Sentinel-2 satellite image for 07.07.2022 (the burned forest is brown against the background of green undamaged forest)

a) **b)**

The State Forestry Agency reported that in 2022, 1009 forest fires were extinguished on an area of 15.5 thousand hectares, which is 1.5 times more than the number and 53 times more than the area of fires in the previous year, excluding a significant part of the forests of Zaporizhzhia, Luhansk, Mykolaiv, Donetsk, Kherson and other regions where hostilities were conducted, and part of the territories of these regions is currently under the control of the occupiers (Public report, 2022). As a result of massive shelling, the Izium forest in Kharkiv region was heavily damaged (Fig. 11), most of it burned down.

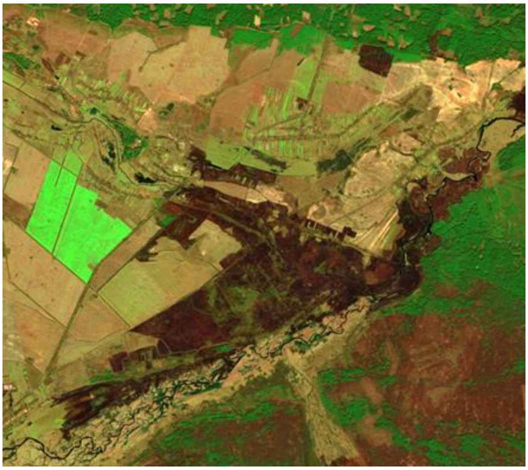
Active hostilities in the Izyum forests have caused damage to the soil cover, in particular, due to the passage of heavy equipment, compaction occurs, which means that air and moisture exchange processes are disrupted and the preconditions for forest cover restoration are deteriorating (Public report, 2022).

It should be noted that the overall degree of damage and the timeframe for restoration to the pre-fire state depend not only on the intensity of the fire itself, but also vary greatly between ecosystems. For example, the full restoration of an old oak or pine forest after a wildfire will take more than a hundred years, and the duration of such restoration will be equal to the age of the oldest dead trees. In the case of a grass fire, significant damage is caused to the grass and shrub layer. At the same time, the main tier of trees has a high chance of surviving or dying only partially, and therefore the restoration of the forest ecosystem will last from several years to several decades.

Steppe fires in wartime also cause significant environmental damage to the environment. At a temperature of 6000°C, which is usually recorded when dry grass is burned, the soil is temporarily sterilized within a centimeter layer, resulting in the death of microorganisms, insects and worms (Krushelnitsky *et al.*, 2016). The recovery time after fires is shorter for steppe ecosystems, but in such cases, the time of year during which the fire occurred is a very important factor. If it was late fall or winter, i.e. outside the growing season of steppe vegetation, the impact will be minimal. Because the root systems of steppe plants are adapted to such fires, and therefore will not be affected. At the same time, fires during the growing season often led to the death of plants and animals that are unable to quickly escape from the fire. For many steppe plants, this period of activity is early spring. Accordingly, an intense steppe fire during the spring months can destroy local populations of some steppe plant species for decades (Fig. 12). Many of these species are rare due to the shrinking steppe area and are listed in the Red Data Book of Ukraine or lists of regionally rare species (approved by individual oblasts).

Fig. 12: Examples of grass fires detection on Sentinel-2 satellite images: a) Grass fire in the floodplain of the Desna River near the village of Smolyn. Smolyn, Chernihiv district, Chernihiv region 23.03.2022; b) Grass and forest fire in the floodplain of the Uzh river near the village of Rahivka in the Vyshgorod district of Kyiv region on 21.03.2022

a)



b)

Due to climate change, Ukraine suffers from large-scale peat fires characteristic of wetlands. Large-scale peat fires most often occur within the Ukrainian Polesie, Precarpathia, Maly Polesie, where the main arrays of peat soils are concentrated. In most of the affected floodplains of small rivers surrounding Kyiv, in the swampy pristine parts of the Desna and Dnieper floodplains, the thickness of peat in places reaches 6-7 meters. The emergence of peat fires contributes to the human factor, careless handling of fire. But unlike conventional forest or steppe fires, extinguishing burning peatlands is much more difficult because the peat deposits are underground. The high flammability and nature of the occurrence turns the burning of peat into a kind of smoldering, which can last for months. As a result of peat fires, almost 10 times more biological mass burns, compared with forest fires, and a significant amount of smoke and toxic gases, "greenhouse" reactive gases CO_2, NO are released into the atmosphere. At first glance, fires do not seem to be a problem for wetland ecosystems due to the presence of significant amounts of water.

Fig. 13: Examples of recording of grass fires on the territory of the Black Sea Biosphere Reserve (Ivanovo-Rybalchansky site): a) total map of fire locations for the 3 weeks from August 8 to 29, 2022 from the Firms website, which clearly shows a huge number of fires (red dots); Sentinel-2 satellite image dated 12.08.2022 (burnt steppe vegetation is brown)

a) **b)**

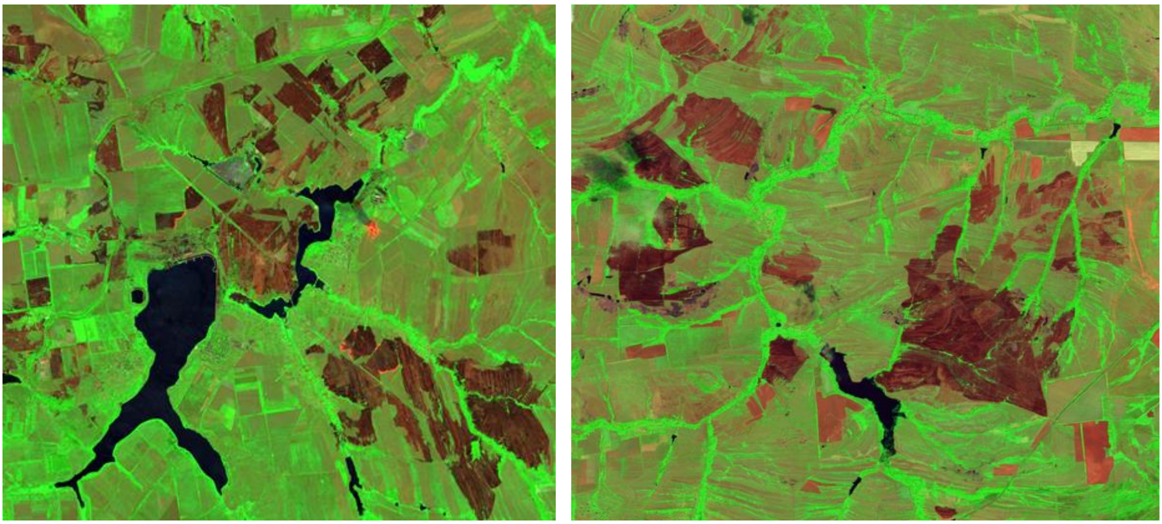
However, during dry periods, large-scale fires can also occur in marshes, destroying the above-water vegetation (Ecoaction, 2023). Fires regularly occur even in peacetime due to natural factors (for example, lightning, meteorites, ignition of flammable materials during heat and fire hazardous weather), and even more often due to people (for example, careless handling of fire or smoking in forests and other natural areas, arson, open burning of agricultural residues in the fields, technical equipment malfunctions, etc.). During the war, the number of fires and the area of land affected has increased significantly. Fires that could be caused by carelessness while relaxing in natural areas became much less due to the fact that many refugees left the country, as well as due to restrictions. At the same time, large areas of land were affected by fires caused by shelling, bombing, explosions, land mining and other consequences related to the war (https://ecoaction.org.ua/vplyv-ros-vijny-na-klimat-2.html). Fires in grassy meadows, river floodplains, and wetlands are affecting a large number of nature reserves. Figure 13 shows an example of the Black Sea Biosphere Reserve. The Black Sea Biosphere Reserve located in the conflict zone in the east of the country. This is the marine biosphere reserve of Ukraine, which is included in the World Network of UNESCO Biosphere Reserves.

Fig. 14: Examples of fires on agricultural lands near the village of Sukhyi Stavok in the Velyko Oleksandrivskyi district of Kherson region, Ukraine: a) total map of fire locations for 5 days from July 4 to 8, 2022 from the Firms website, where a huge number of fires (red dots) are clearly visible; b) Sentinel-2 satellite image for 08.07.2022

a) **b)**

Due to Russian shelling, fires have frequently broken out and continue to break out in agricultural fields throughout Ukraine. According to the Main Directorate of the State Emergency Service of Ukraine, since the beginning of July, 75 fires have been recorded in the open areas of Kherson region alone, covering an area of 297,478 hectares.

Fig. 15: Examples of recording fires on agricultural land Sentinel-2 satellite image: a) near Svitlodarsk, Bakhmut district, Donetsk region 07.07.2022; b) near Illiriya village, Luhansk district, Luhansk region 09.07.2022



a) **b)**

Due to the constant shelling, it is extremely difficult to extinguish such fires in the de-occupied territories, and on the occupied lands, the russians deliberately do not allow firefighting. Detection of fires on agricultural land is an important element in monitoring (Aung *et al.,* 2021; Yin *et al*., 2029; Affek *et al.,* 2021) the environmental condition of the territory and food security of the population (Fig. 14). Unfortunately, fires on agricultural lands were detected in most of the occupied regions that were on the front line (Fig. 15). Fires in the images are easily identified by their dark brown color against a green background.

Thus, demonstrated the effectiveness of using the FIRMS service to obtain the coordinates and dates of fires, as well as to directly search for these fires on Sentinel-2 satellite images in the EO Browser resource. Thus, in this problem, satellite monitoring provides invaluable assistance in the system of detecting fire points both in terms of the area of spread and the time of their occurrence. The use of such technologies allows us to quickly and accurately determine the location and time of fires, which is important for further control over them and for detecting and recording damaged areas remotely.

The authors of the study presented in the work (Svidzinska & Underwood, 2023) determined the correlation between fire and conflict, it was found that the level of correlation between two spatial processes at the country level is not high, since military activity is localized. This means that the relationship between military actions and fire anomalies should be studied on a regional scale, taking into account only the conflict zone. In our study, the zone of interest was represented that are directly in the zone of hostilities, or that were/are in temporary occupation, surrounded (blocked), as well as territories that are close to the front line. This made it possible to concentrate the research on the impact of war on the environment, and to distinguish classes of earth cover.

In paper (Yelistratova *et al*., 2022; Chengxin *et al*., 2023) the environmental consequences of the war in Ukraine were carried out on model examples (city, territorial community, etc.). Our study is conducted in the direction of detail on the number of fires at the level of specific classes of land cover. The study https://ecoaction.org.ua/vplyv-ros-vijny- na-klimat-2.html analyzed data on the number and area of fires for different categories of land use. In addition to agricultural land, forests and other natural landscapes were most affected. This document confirms the results of our study. In particular, regarding agricultural land on the border of administrative regions. The results of the study presented in our publication can be used as additional information not only on the environmental consequences of fires. But also the economic component, namely, will prevent and eliminate food problems in each administrative area.

The war is also affecting territories outside Ukraine. The consequences of the impact of hostilities on the general state of the environment are discussed in (Pereira1 *et al*., 2022; Cardil *et al*., 2023). Large-scale fires as a result of Russian shelling can affect global climate change. The impact of war on climate change (Kicaj *et al*., 2023; Hurzhyi, 2022) inevitable, cross-border transfer of polluting elements is already happening. The consequences of the Russian invasion are existential for Ukraine and neighboring territories. The longer the war, the greater and more global changes in the environment both locally and globally.

CONCLUSIONS

Based on the results of the research, monitored the fires. The distribution of fires depending on the type of land cover surface in the war-affected regions of Ukraine in the period from March 2022 to March 2023 was carried out. The effectiveness of using the FIRMS service to obtain the coordinates and dates of fires, as well as the direct search for these fires in the Sentinel-2 space images in the EO Browser resource, has been demonstrated and proved.

As a result of the analysis, it was established that most fires in Ukraine occur under arable land, pastures and forests, which is more than 80 % of the total number of fires. Fires occurred less frequently in built-up areas, but they can have more serious consequences on the environment and public health. The total number of fires per year within the analyzed regions is 46286, which indicates a serious problem with fires in Ukraine during the war and negative environmental consequences both now and in the future. The number of fires in built-up areas in 2023 in three months was 28 %, while in 2022 in ten months this value was 11 %. This indicates a change in the location of hostilities and their intensity. The largest number of fires in the built-up areas is noted for Lugansk, Dnipropetrovsk, Donetsk, Zaporizhzhya regions, peak values fall on April-September 2022.

The war started by Russia causes great damage to the natural environment of Ukraine. Estimates obtained from satellite observations suggest that the situation is changing for the worse. GIS and remote sensing data can be used for monitoring fire spread and identify areas of potential danger. This allows for effective planning of fire prevention and elimination measures. The data can also be used to assess changes in the environment and make decisions on its protection and restoration.

The presented results of the study are among the first scientific assessments of the environmental consequences of the war in Ukraine, which are global in nature without exaggeration. As a result of fires, the content of harmful substances is released into the air. Therefore, the results obtained may indicate the localization of contamination. Also, as additional information, they can indicate, taking into account meteorological forecasts, the possibility of cross-border movement of air pollution to countries bordering Ukraine.

Prospects: In the future, it is possible to create databases for comprehensive environmental monitoring of the state of the territories of Ukraine that are closest to the front line, have been occupied or are currently under occupation. The study also has the prospect of expanding the topic to include the boundaries of nature reserves, to obtain the appropriate number of protected areas affected by fires.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

REFERENCES

Affek, A.N., Wolski, J., Zachwatowicz, M., Ostafin, K., and V.C. Radeloff (2021). Effects of Post-WWII Forced Displacements on Long-term Landscape Dynamics in the Polish Carpathians. *Landscape and Urban Planning* 214: 104164.DOI: 10.1016/j.landurbplan.2021.104164

Ajmi, D.A., and Saif U.D. (2009). Remote Sensing: Fundamentals, Types and Monitoring Applications of Environmental Consequences of War. *Environmental Consequences of War and Aftermath*. Vol. 3. Berlin, Heidelberg: Springer Berlin Heidelberg, 41-124. The Handbook of Environmental Chemistry. DOI: 10.1007/978-3-540-87963-3_3

Aung, T. S., Overland, I., Vakulchuk, R., and Y. 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: 25005. DOI: 10.1088/2515-7620/abedd9

Beygi H.H., Shafiei, A.B., Erfanian, M., Tayyebi, A., and A., Alijanpour (2020). Armed Conflict and Land-use Changes: Insights from Iraq-Iran War in Zagros Forests. *Forest Policy and Economics* 118: 102246. DOI: 10.1016/j.forpol. 2020.102246

Biswas, A. K. (2000). Scientific Assessment of the Long-term Environmental Consequences of War (2000). *The Environmental Consequences of War*. DOI:10.1017/CBO9780511522321.017.

Cardil, A., Tapia, V.C., Monedero, S., Quiñones, T., Little, K., Stoof, C.R., Ramirez, J., and S. De-Miguel (2023). Characterizing the Rate of Spread of Large Wildfires in Emerging Fire Environments of Northwestern Europe Using Visible Infrared Imaging Radiometer Suite Active Fire Data. *Natural Hazards and Earth System Sciences* 23.1: 361-73. DOI: 10.5194/nhess-23-361-2023

Clerici, N., D. Armenteras, P. Kareiva, R. Botero, J.P. Ramírez-Delgado, G. Forero-Medina, J. Ochoa, C. Pedraza, L. Schneider, C. Lora, C. Gómez, M. Linares, C. Hirashiki, and D. Biggs. (2020). Deforestation in Colombian Protected Areas Increased during Post-conflict Periods. *Scientific Reports* 10.1: 4971. DOI: 10.1038/s41598-020-61861-y

Deng, H., Li, H., Xiao, S., and S. Li (2021). Integrating Multi-source Spatial Data to Assess the Impact of the Syrian Civil War on Cities and Population. *Arabian Journal of Geosciences,* 2021, Vol.14 (12). DOI: 10.1007/s12517-021-07476-7

Eklund, L., Degerald, M., Brandt, M., Prishchepov, A.V. and P. Pilesjö (2017). How Conflict Affects Land Use: Agricultural Activity in Areas Seized by the Islamic State. *Environmental Research Letters* 12.5: 54004. DOI: 10.1088/1748-9326/aa673a

EO Browser, (2023). *EO Browser is a free cloud-based tool*. Retrieved May 7, 2023, from https://www.sentinel-hub.com/explore/eobrowser/.

Fire Information for Resource Management System, (2023). *Fire Information for Resource Management System*. Retrieved May 7, 2023, from https://firms.modaps.eosdis. nasa.gov/map/#t:adv;d:2022-06-23..2022-07-12,2022-06-23;@35.0,47.8,6z.

Hazaymeh, K., Sahwan, W., Al Shogoor, S., and B. Schütt (2022). A Remote Sensing-Based Analysis of the Impact of Syrian Crisis on Agricultural Land Abandonment in Yarmouk River Basin. *Advances in Time Series Analysis* 3931.DOI: 10.17169/refubium-37181

Hurzhyi, V., (2022). The war in Ukraine may affect global climate change. Ecology 16. Available online at: https://nasze-slowo.pl/vijna-v-ukrayini-mozhe-vplynuty-na-globalni - klimatychni-zminy/ (Ukrainian).

Chengxin Z., Hu, Q., Su, W., Xing, Ch., Liu, Ch. (2023). Satellite spectroscopy reveals the atmospheric consequences of the 2022 *Russia-Ukraine war. Science of The Total Environment.* Volume 869, 2023, 161759 https://doi.org/10.1016/j.scitotenv.2023.161759

Kicaj, H., Polukarov, Y., Prakhovnik, N., Polukarov, O., Kachynska, N. (2023). How war in Ukraine is affecting the climate. *International Journal of Environmental Studies*, Volume 80, 2023, Pages 277-283 doi.org/10.1080/00207233.2023.2174743

Krushelnitsky, A.D., Ogorodniychuk, I.V. and O. M. Ivanko (2016). Landscape Changes in the Environment Due to Military Actions and Their Epidemic Risks. *Medychni Perspektyvy* 21.2: 103-06.DOI: 10.26641/2307-0404.2016.2.72275.

Lubin, A., and A. Saleem (2019). Remote Sensing-based Mapping of the Destruction to Aleppo during the Syrian Civil War between 2011 and 2017. *Applied Geography* (Sevenoaks) 108: DOI: 10.1016/j.apgeog.2019.05.004.

Mohamed, M.A., Anders, J., and Ch. Schneider (2020). Monitoring of Changes in Land

Use/land Cover in Syria from 2010 to 2018 Using Multitemporal Landsat Imagery and GIS. *Land (Basel)* 9.7: 226. DOI: 10.3390/land9070226 4.

Pereira, P., Bašić, F., Bogunovic, I., and D. Barcelo (2022). Russian-Ukrainian War Impacts the Total Environment. *The Science of the Total Environment* 837: DOI: 10.1016/j.scitotenv.2022.155865.

Public report, (2022). *Public report of the head of the state forestry agency resources of Ukraine (2022*). Retrieved May 4, 2023, from https://forest.gov.ua/storage/app/sites/8/publich_zvit/publichnii-zvit-za-2022.pdf.

Rawtani, D., Gupta, G., Khatri, N., Rao, P.K. and Ch. M. Hussain (2022) Environmental Damages Due to War in Ukraine: A Perspective. *The Science of the Total Environment* 850: 157932.DOI: 10.1016/j.scitotenv.2022.15793).

Scorched Earth, (2022). *Scorched Earth: Using NASA Fire Data to Monitor War Zones (2022)*. Retrieved May 4, 2023, from https://www.bellingcat.com/resources/2022/10/04/scorched-earth-using-nasa-fire-data-to-monitor-war-zones/.

Sheviakina, N., Trofymchuk, O., Zagorodnya, S., Radchuk, I., Tomchenko, O. (2020). Remote Sensing Monitoring of Biotopes Distribution within the Nature Reserve Area. *Environ. Res. Eng. Manage*. 76, 109-112.

Svidzinska, D., Underwood, E., (2023). *Using Remote Sensing to Assess Fire Anomalies in Ukraine* https://storymaps.arcgis.com/stories/e6ab84f3542f40758e7c05021a4e5dd9

VIIRS, (2023). VIIRS I-Band 375 m Active Fire Data (2023). Retrieved May 7, 2023, from https://www.earthdata.nasa.gov/learn/find-data/near-real-time/firms/viirs-i-band-375-m-active-fire-data.

YAimaiti, Y., Sanon, Ch., Koch, M., Baise, L.G. and B. Moaveni (2022). War Related Building Damage Assessment in Kyiv, Ukraine, Using Sentinel-1 Radar and Sentinel-2 Optical Images. *Remote Sensing (Basel, Switzerland)* 14.24: 6239. DOI: 10.3390/rs14246239

Yelistratova, L., Apostolov, A., Movchan, D. (2022). Using night illumination images based on remote sensing data for the socio-economic assessment of a besieged city (Mariupol City, (Ukraine) as an example). *Publishing House "Baltija Publishing*", 2022, P 82-85 DOI https://doi.org/10.30525/978-9934-26-235-7-19

Yelistratova, L.O., Apostolov, O.A., Khodorovskyi, A.Ya, Khyzhniak, A.V., Tomchenko, O.V. and V.I. Lialko (2022) Use of satellite information for evaluation of socio-economic consequences of the war in Ukraine. *Ukrainian Geographical Journal* 2022.2: 11-18. DOI: 10.15407/ugz2022.02.011

Yin, H., Butsic, V., Buchner, J., Kuemmerle, T., Prishchepov, A.V., Baumann, M., Bragina, E.V., Sayadyan, H., and V.C. Radeloff (2019). Agricultural Abandonment and Re-cultivation during and after the Chechen Wars in the Northern Caucasus. *Global Environmental Change* 55: 149-59 DOI: 10.1016/j.gloenvcha.2019.01.005

Zanaga, D., Van De Kerchove, R., Daems, D., De Keersmaecker, W., Brockmann, C., Kirches, G., Wevers, J., Cartus, O., Santoro, M., Fritz, S., Lesiv, M., Herold, M., Tsendbazar, N.E., Xu, P., Ramoino, F., Arino, O., (2022). *ESA WorldCover 10 m 2021 v200*. https://doi.org/10.5281/zenodo.7254221

Trofymchuk, O., Vishnyakov, V., Sheviakina, N., Klymenko, V., and O. Tomchenko (2022). Detection of thermal anomalies as a result of military actions in Ukraine by remote sensing methods. *International Multidisciplinary Scientific GeoConference: SGEM* 22.2: 303-13.DOI: 10.5593/sgem2022/2.1/s10.35