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Fire analysis using Sentinel-2 and Sentinel-5P data: Oil pipeline explosion near Strymba Village

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Abstract. Oil pipeline explosions pose a serious threat to environmental safety. The relevance of this study lies in examining the consequences of such incidents and their impact on the environment. The aim of the research was to assess the scale of the fire and the degree of air pollution by nitrogen dioxide and carbon monoxide following the pipeline explosion. The research methods included the analysis of satellite images using the normalized difference vegetation index, the normalized burn ratio, and the differenced normalized burn ratio, followed by the detection of burned areas using the thresholding method. The application of advanced Earth remote sensing methods, such as data from the Sentinel-2 and Sentinel-5P satellites, allowed for the analysis of the consequences of the oil pipeline explosion and the subsequent fire that occurred on 30.09.2023, near the Strymba Village in the Nadvirna District of Ivano-Frankivsk Region. Additionally, an analysis of harmful substance emissions into the air, obtained from the Sentinel-5P satellite, was conducted, followed by visualisation using the Python programming language and statistical analysis. The results obtained include the calculation of the fire area, which is approximately 2.5 ha, and the detection of elevated levels of nitrogen dioxide and carbon monoxide above the norm following the fire. Methods for converting concentration units obtained from satellite observations to ground-level concentrations were used. The validation of the obtained results with surface measurements confirms the study's findings regarding nitrogen dioxide and carbon monoxide pollution. After the fire, concentrations ranged from 0.46 to 0.58 ml/m^3 for nitrogen dioxide and 9.86 ml/m^3 for carbon monoxide. These research results are important for identifying small fires resulting from pipeline explosions and for the practical understanding of the specifics of harmful substance emissions during such fires

Keywords: satellite data; spectral indices; fire area; harmful substances; nitrogen dioxide; carbon monoxide

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Introduction

The importance of studying and monitoring the consequences of oil pipeline explosions is increasing due to their potentially serious impact on the environment. Given the limited number of studies on such explosions and their possible consequences for the ecological situation, there is a growing need to analyse the effects and use effective research methods to obtain reliable results. The use of advanced Earth remote sensing methods opens up broad possibilities for assessing the extent of the damage and analysing the environmental consequences of these incidents. In the study by D.P. Finch *et al.* (2022), aimed at developing means of identifying zones of atmospheric nitrogen dioxide (NO_2), which is an indicator of combustion, a neural network was applied. The authors successfully trained the model on a limited number of images from the TROPOspheric Monitoring Instrument (TROPOMI), achieving an accuracy of over 90%. Numerous distributions of NO_2 concentrations worldwide were identified, reflecting the locations of emission zones such as major cities, power plants, oil and gas sources, and shipping routes. The authors recommend using NO_2 as an indicator of anthropogenic emissions of carbon dioxide (CO_2) and methane (CH_4), and utilising these data to improve emission assessments. The study revealed the potential of NO_2 for detecting new hydrocarbon emission sources globally.

Researchers M. Li *et al.* (2021) found that fires have a significant impact on NO_2 emissions, especially in the western coastal regions of the USA. They constitute a substantial portion of the total NO_2 emissions in these areas, exceeding 10% of the total NO_2 volume in the region. This underscores the importance of analysing NO_2 emissions from fires to understand the overall impact of fires on air quality and atmospheric composition. Large NO_2 emissions can have serious consequences for human health and ecosystems, necessitating attention both in emission control and in the monitoring and forecasting of air pollution. The study also highlights the significant contribution of tropospheric NO_2 columns from various non-urban sources, such as soil (11.7% on average across the contiguous United States), oil and gas extraction (4.1%), fires (10.6%), and lightning (2.3%). In the study by R.J. Pope *et al.* (2021), the 2019/2020 fires in Australia were analysed, which caused large amounts of smoke, aerosols, and trace gases. The authors found that carbon monoxide (CO) emissions from these fires circumnavigated the entire Southern Hemisphere, with CO levels over the South Pacific Ocean during November 2019 to January 2020 being 30-70% higher than in the 2018/2019 season. Increases in methanol (CH_3OH) and CH_4 levels in the smoke plumes were also detected, which have important atmospheric implications. The authors emphasise the importance of future Earth observations for monitoring forest fires, which are expected to become more frequent and intense due to climate change.

Scientific studies presented in the works of M. Savenets *et al.* (2023) and S. Zibtsev *et al.* (2024) are crucial for assessing emissions of harmful substances resulting from fires in Ukraine due to the full-scale Russian invasion of Ukraine. In the study by S. Zibtsev *et al.* (2024), it was established that the Russian military aggression against Ukraine significantly increased the number and area of forest fires in the country. According to the authors, in 2022, the war was identified as the main factor in the fire situation, with about 69% of the total area damaged by fires occurring in a zone located within 60 km of the war front. Direct CO_2 emissions from fires in 2022 amounted to 5.20 million tons from all types of landscape fires. It is estimated that 749.5 thousand ha were burned by landscape fires during 2022. In the work by M. Savenets *et al.* (2023), it was found that Russian military aggression significantly affected air quality in Ukraine. Analysing data from TROPOMI, it was confirmed that during the first months of the conflict, there was a decrease in NO_2 levels in major cities by up to 35%, due to disruptions in industrial enterprises and reduced transport emissions. Amid increased military operations, NO_2 levels increased by up to 25% in the eastern and northern regions, indicating possible use of military equipment. Similarly, CO emissions significantly increased during forest fires along the front, rising by up to 8%. These results indicate the serious impact of the war on air quality in Ukraine and underscore the necessity of remote sensing for detecting and tracking changes in pollutant emissions.

Considering the available information about the location of the oil pipeline explosion from open sources, a rupture occurred near the Strymba Village, leading to an oil spill along a stream and subsequent spread of fire in areas with green vegetation (A 15-fold increase in soot..., 2023). Studying the scale of the damage will contribute to understanding the environmental consequences of such incidents, particularly the assessment of harmful substance emissions into the atmosphere. The aim of the study was to assess the scale of the fire and the degree of air pollution by NO_2 and CO following the pipeline explosion near the Strymba Village, which occurred on 30.09.2023.

Materials and Methods

Study Area. On 30.09.2023, at approximately 5:00 PM, near the Strymba Village (Nadvirna District, Ivano-Frankivsk Region, Ukraine), a rupture occurred in an oil pipeline (150 mm in diameter) resulting in an oil spill along a stream and subsequent fire spread. The area along the Strymba River features green vegetation, represented by diverse plant species. The study area includes the zone affected by the pipeline fire. The research site is located within the coordinates 48.5750°N, 24.5615°E and 48.6080°N, 24.5911°E (Fig. 1).

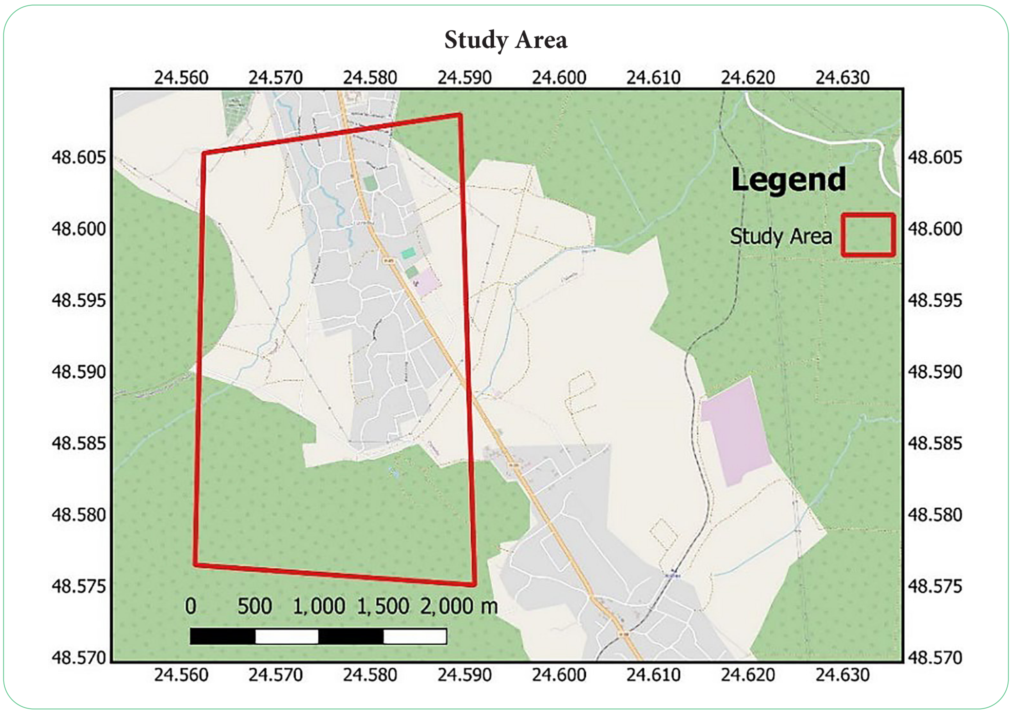

Figure 1. Study area displayed on an OpenStreetMap

Source: created by the authors

Data Collection. For this study, satellite images from the Sentinel-2 S2L2A dataset were used, specifically from the period before the onset of the fire on 30.09.2023, at 09:27 AM, and after the fire on 03.10.2023, to determine the normalized burn ratio (NBR) and normalized difference vegetation index (NDVI) in the spectral bands B4, B8, and B12. The precise time is specified for 30.09.2023, as the pipeline explosion occurred around 5:00 PM that day, and the image at 09:27 AM reflects the conditions before the fire started. The nearest available satellite images after the fire were obtained on 03.10.2023, and the exact time for this date is no longer significant. Additionally, to analyse NO_2 and CO concentrations before the fire, satellite images from the Sentinel-5P satellites on 28.09.2023 and 29.09.2023 were used, as it was not possible to obtain the necessary images for 30.09.2023. For analysing NO_2 and CO concentrations after the fire, the nearest available images were used: 02.10.2023, 03.10.2023, and 06.10.2023, for NO_2, and 02.10.2023, and 04.10.2023, for CO. All data were obtained using the Sentinel Hub platform (n.d.). The processing of images obtained before and after the fire was carried out using QGIS software (version 3.22.16).

Methodology. The study utilised Sentinel Hub, a multispectral and multi-layer service that provides access to images and fully automated archiving, processing, and dissemination of remote sensing data and relevant Earth observation products in real-time. Images from the Sentinel-2 satellite, captured by the multispectral instrument (MSI) sensor, were used, with access provided through the Sentinel Hub platform (n.d.). The research employed images from COPERNICUS/S2_SR (L2A), for which European Space Agency uses the Sen2Cor processor to apply atmospheric correction to the input Sentinel-2 L1C data with global coverage, resulting in the S2L2A data product. The chosen methodology is based on processing images selected before and after a fire by calculating the spectral indices NBR and NDVI to identify areas affected by the fire.

The NBR index is the ratio of the difference in reflectance coefficients between two spectra, expressed as an equation (Key & Benson, 2006). The NBR formula includes indicators obtained from signals at wavelengths corresponding to both the near-infrared and shortwave infrared spectra. Healthy vegetation is characterised by high reflectance in the near-infrared spectrum, while areas recently destroyed by fire are well distinguished in the shortwave infrared spectrum. NBR values range from +1 to −1. The NBR index formula is as follows:

$$NBR = \frac{(NIR-SWIR2)}{(NIR+SWIR2)}, \tag{1}$$

where $NIR(B5)$ is the near-infrared band; $SWIR2$ is the shortwave infrared band. NDVI is used to generate a vegetation cover image. This index uses the visible and near-infrared bands of the electromagnetic spectrum (Rouse *et al.*, 1973). NDVI values range from −1 to 1. The NDVI index formula is as follows:

$$NDVI = \frac{(NIR-Red)}{(NIR+Red)}, \tag{2}$$

where *Red* is the visible red light. Geographic information systems (GIS) enable the calculation of the difference between the two obtained images, NBR and NDVI, to derive pre- and post-fire data. This process is known as the differenced NBR (dNBR) and differenced NDVI (dNDVI) and can be used to assess areas with varying degrees of fire severity (Kurnaz *et al.*, 2020). To determine the difference in vegetation cover before and after the fire, the threshold method of the dNDVI was used. Initially, the image was classified using the NDVI threshold to separate the damaged vegetation area. The raster image representing these areas was converted to vector format for further area calculation. This process was repeated for the post-fire image. The difference in the areas of these sites before and after the fire represents the dNDVI value, which reflects changes in vegetation cover. Similar actions were applied to the NBR index to obtain the dNBR.

During combustion, gases and aerosols are released. The Copernicus Sentinel-5P detects concentrations of trace gases such as NO_2, CO, and formaldehyde. Sentinel-5 Precursor (Sentinel-5P) is equipped with the TROPOMI instrument, which is used for the operational retrieval of NO_2 column products in the troposphere and stratosphere. Sentinel-5P satellite data are provided at various levels of archiving, corresponding to different stages of remote sensing data processing (S5P mission, n.d.). This study utilised second-level archived data on NO_2 concentration in mol/m². Second-level archived data provide direct information on the content of chemical compounds in the air. At this level, data on NO_2 and CO are available (S5P Products, n.d.). Priority in processing is given to NO_2 and CO data, as they can diagnose the impact of the majority of emission sources (Miyazaki *et al.*, 2017). The spatial resolution of Sentinel-5P data was improved from 7×3.5 km to 5.5×3.5 km as of 06.06.2019 (S5P Mission Performance Centre..., 2023). The research methods described in this article use an input spatial resolution of 3.5×5.5 km.

Research Progress. The first stage of the NO_2 emissions study in the investigated area involved downloading data from the Sentinel Hub platform using Sentinel-5P – NO_2 satellites. The data processing began with georeferencing to a standardised regular grid. During grid alignment, all pixels falling within a defined regular grid are averaged, and the mean chemical content is calculated for each square with known coordinates. This results in the creation of new files that can be considered as third-level satellite data archival products, as they contain coordinate-referenced, statistically reliable data specific to the area of interest. The obtained results are visualised using the Python programming language and libraries such as geopandas, matplotlib, and contextily.

Subsequently, a statistical analysis of the obtained files was conducted in the QGIS environment. To enable comparisons between these two data sources, the ideal gas equation was used to convert NO_2 concentration from mol/m² to ml/m³. For processing CO concentration data, a conversion formula was implemented using the Python programming language. The obtained results were analysed to determine their effectiveness and accuracy. To verify the reliability of the obtained data, a comparison was made with data from ground measurements. The formula for the ideal gas equation is as follows:

$$C = \frac{n \times M \times P}{R \times T} \times 1{,}000, \tag{3}$$

where n is the amount of substance in mol/m²; M is the molecular mass of the substance in g/mol; P is the pressure in mmHg; R is the universal gas constant (8.314 m³ × Pa/(K×mol)); T is the temperature in K. For these calculations, the molecular mass of NO_2 (46 g/mol), the universal gas constant (8.314 m³ × Pa/(K×mol)), a temperature of 288 K (15°C), and a pressure of 760 mmHg (1,013 hPa) were used. These data were chosen to match the real conditions in the geographical areas where the measurements were conducted, ensuring the accuracy and relevance of the obtained results. The conversion formula is as follows:

$$C_{ml/m^3} = C_{mol/m^2} \times 24 \times 1{,}000, \tag{4}$$

where C_{ml/m^3} is the gas concentration in ml/m³; C_{mol/m^2} is the gas concentration in mol/m²; 24 is the conversion factor from mol/m² to ml/m³; 1,000 is the conversion factor for converting ml to m³. This method involves using conversion factors that account for both the geometric characteristics of the space (area and volume) and the physical properties of the substance (density). The conversion factor also considers the depth of the layer to which the gas concentration is applied (in m) to obtain the volumetric concentration in ml/m³.

Results

To investigate the consequences of the incident, a polygon with an area of 7.18 km² was created. This zone, which includes the area around the pipeline explosion site, has been designated as the study area for examining the spread of the fire and analysing the air pollution resulting from the incident. To identify the areas affected by the fire, the spectral indices NBR and NDVI were calculated before and after the fire within the study area, and maps were created based on these indices (Fig. 2-5).

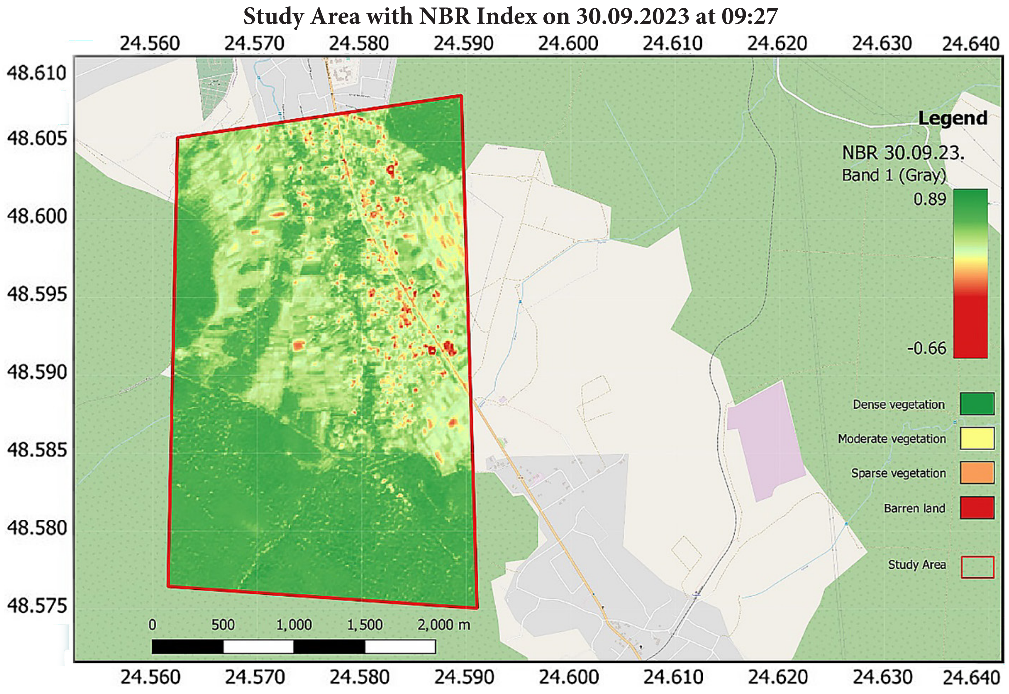

Figure 2. Map with calculated NBR index before the fire

Source: created by the authors

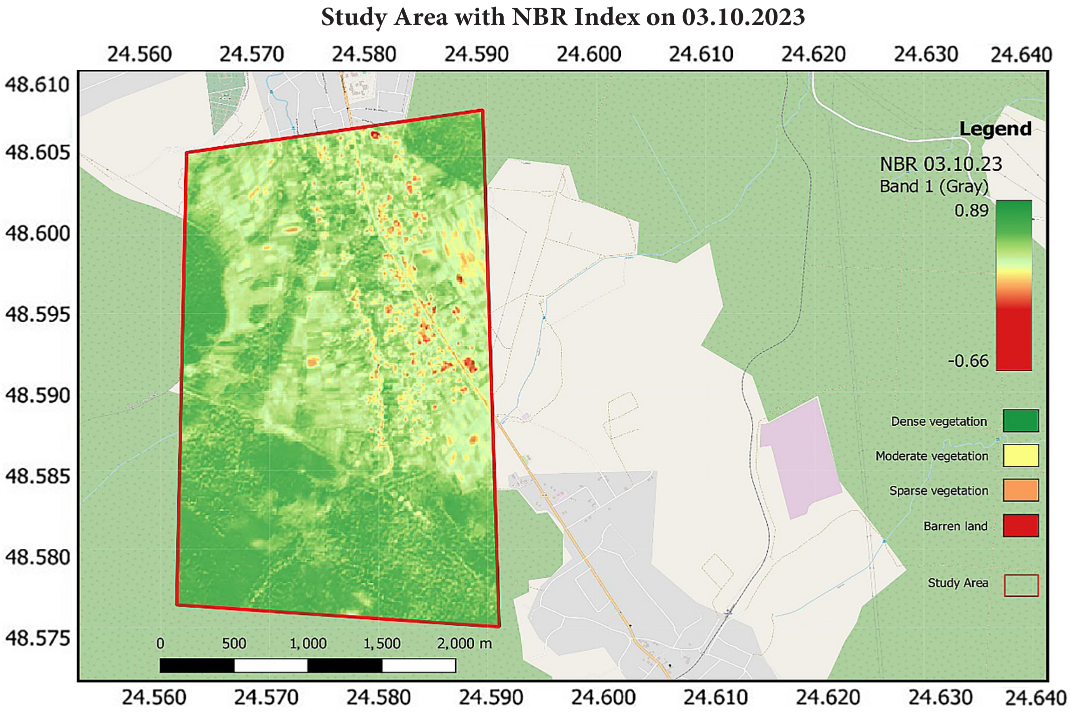

Figure 3. Map with calculated NBR index after the fire

Source: created by the authors

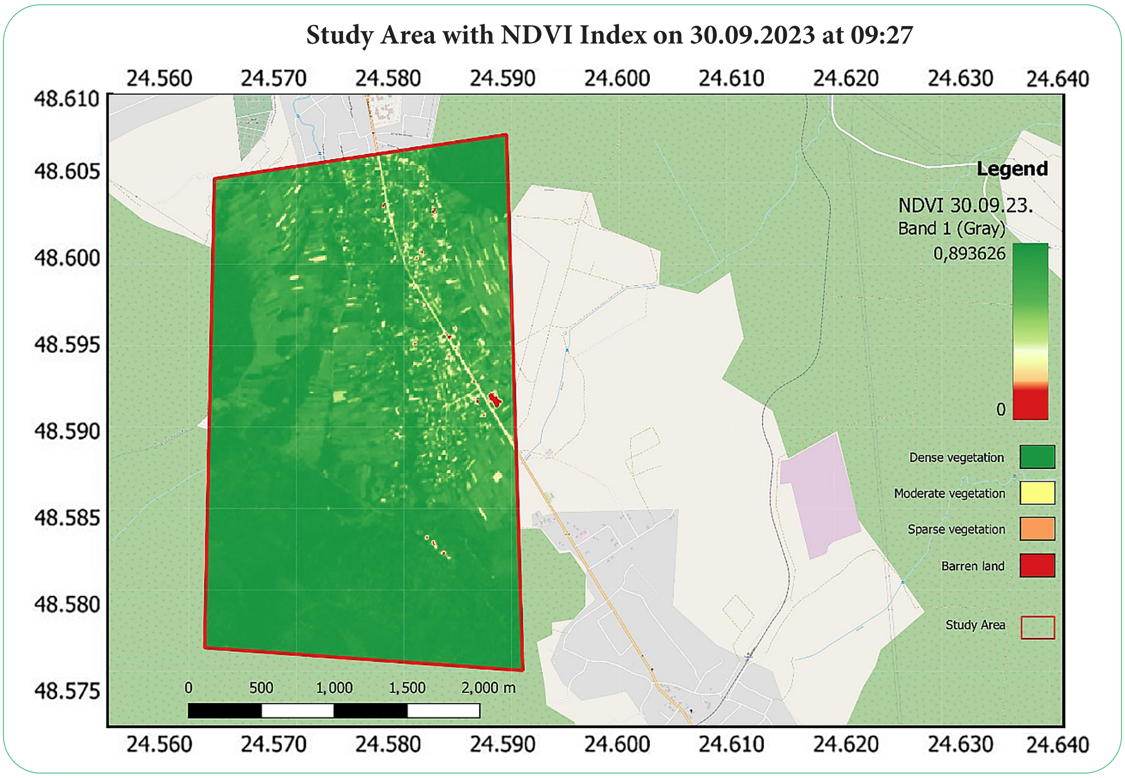

Figure 4. Map with calculated NDVI index before the fire

Source: created by the authors

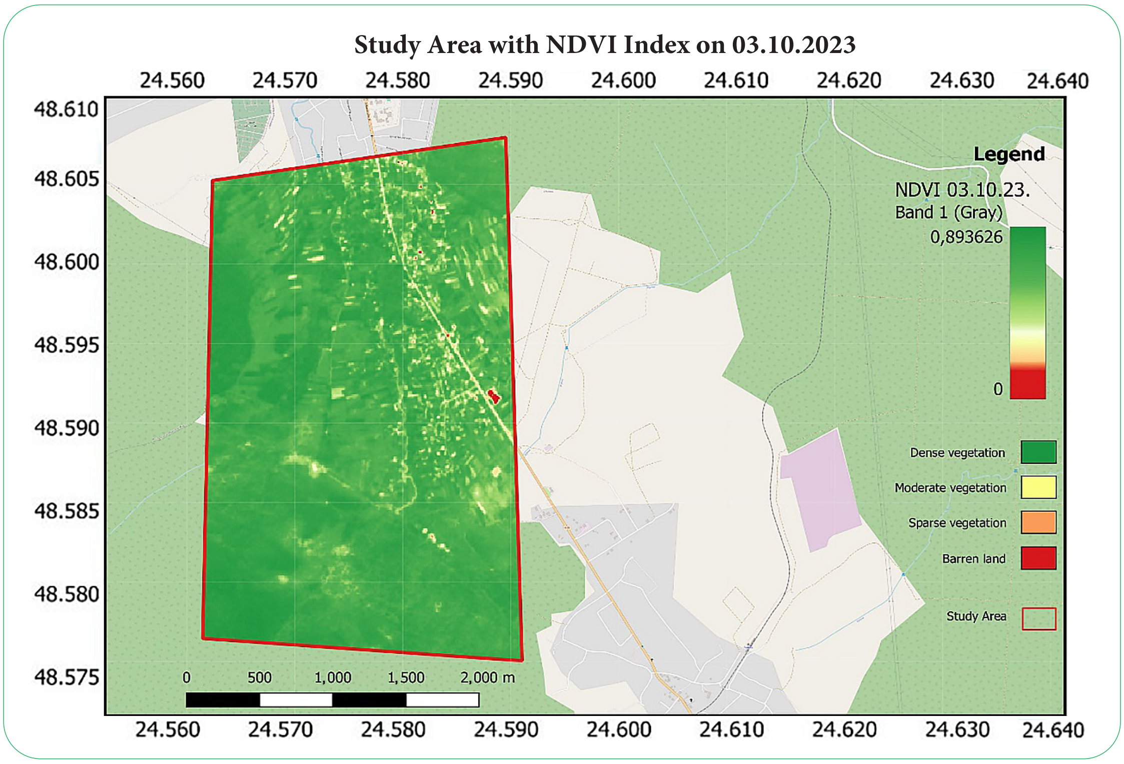

Figure 5. Map with calculated NDVI index after the fire

Source: created by the authors

Fire partially destroys land surfaces, reducing vegetation, density, greenness, and moisture, leading to changes in the spectral response of the Earth's surface (Boer *et al*., 2008). As a result of the fire, a decrease in reflectance in the visible and near-infrared ranges is observed, while reflectance in the shortwave infrared range increases (Lentile *et al*., 2006). NBR is an effective method for measuring burn severity in various types of vegetation. Maps created using the NBR indices indicate areas classified into four levels. Very low NBR values (< 0): these values correspond to areas without vegetation cover, such as transportation roads, buildings, and zones that have suffered severe degradation due to fire or other factors. Low NBR values (0-0.1): these values correspond to areas with damaged or affected vegetation, where plants may be present but have been impacted or thinned due to fire or other factors. Medium NBR values (0.1-0.3): these values correspond to areas with sparse vegetation, such as gardens, agricultural plots, and shrubs, where vegetation may be present but is sparse or damaged. High NBR values (> 0.3): these values correspond to healthy vegetation and may indicate green areas where the vegetation cover has been preserved and has not suffered serious damage from fire or other factors. This classification takes into account the specifics of the study area around the Strymba Village and the adjacent territories. Considering the diversity of the landscape and natural objects in this classification helps understand the different levels of the incident's impact on the environment. Very low NDVI values (< 0.1) indicate barren rocks, sand, and infertile areas. Soil receives low NDVI values, ranging from 0.1 to 0.2. Areas with shrubs, grasslands, and less dense vegetation exhibit values within the range of 0.2-0.5. High NDVI values (> 0.6) represent dense green areas, such as forests and cultivated lands (Dindaroglu *et al*., 2021). The maps in this study, created using the NDVI index, are also classified into four levels. Very low NDVI values (< 0.1) indicate barren areas with no vegetation cover, such as transportation roads, buildings, and infrastructure in the Strymba Village. Low NDVI values (0.1-0.2) are characterised by sparse and damaged vegetation as well as areas with exposed soil. Medium NDVI values (0.2-0.5) indicate zones with sparse vegetation, possibly gardens, agricultural plots, and shrubs around the village. High NDVI values (> 0.6) represent dense green areas, such as forests, parks, and other areas with high vegetation cover. Using the aforementioned classification and visual analysis of maps based on the NBR and NDVI indices, the polygon delineating the fire-affected area was established and detailed. It was found that this area is also located along the Strymba River, confirming information from open sources (A 15-fold increase in soot…, 2023). The results are presented in Figure 6 and Figure 7.

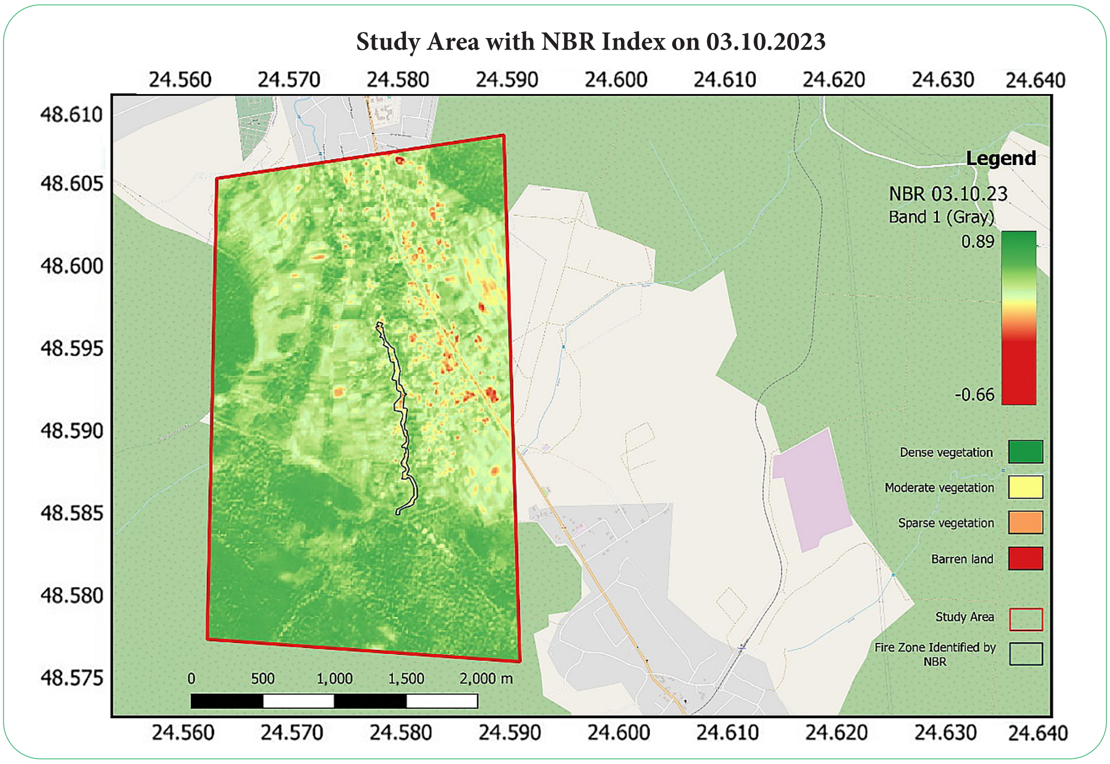

Figure 6. Map with calculated NBR index after the fire with identified fire-affected area

Source: created by the authors

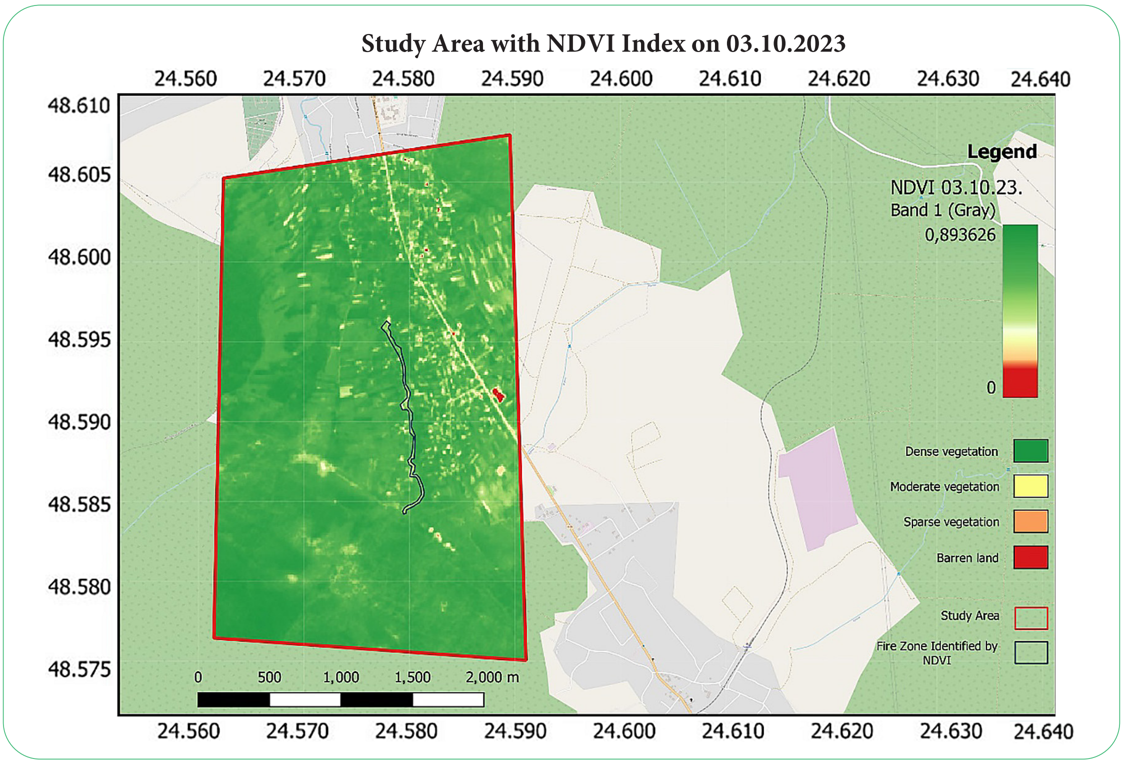

Figure 7. Map with calculated NDVI index after the fire with identified fire-affected area
Source: created by the authors

Given the specific conditions of the study area, which includes various types of land cover, the infrastructure of the Strymba Village, as well as agricultural lands and gardens, the standard methodology for calculating dNDVI and dNBR may be less effective. In the standard approach, the use of threshold values for classifying raster images can lead to inaccurate results, as low NDVI values may not only reflect damaged vegetation but also other elements such as roads, buildings, and agricultural plots. This can distort the assessment of areas affected by the fire and result in an incorrect determination of their extent. Since the main goal of the classification was to obtain the area affected by the fire, it was impractical to classify them into zones of burn severity. To determine the difference in vegetation cover before and after the incident, dNDVI and dNBR were applied. This method allowed for the separation of damaged vegetation areas from healthy ones within the detected fire-affected zone. The difference between the areas of these plots before and after the fire represents the dNDVI and dNBR values (Table 1), which reflect the fire-affected area. In this approach, the use of vector representation allows for more accurate identification of changes caused by the fire, considering the specific features of the study area.

Table 1. Vegetation damage indicators in the fire zone based on index calculations

Index	Ha
NDVI 30.09.23	0.227
NDVI 03.10.23	2.64
NBR 30.09.23	0.403
NBR 03.10.23	2.906
dNDVI	2.413
dNBR	2.503

Source: created by the authors

According to the calculations, the dNDVI value is 2.413 ha, and the dNBR value is 2.503 ha. These figures are close to each other, which confirms their reliability. The next step involves analysing the pollutant gases NO_2 and

CO within the study area before and after the fire. During data processing, a standardised regular grid is formed, ensuring coordinate referencing and reliability of the data extracted exclusively for the area of interest (Fig. 8). After creating files with the average concentration values for each grid cell, the spatial distribution of NO_2 and CO within the study area was visualised. As a result of the analysis, maps of the spatial distribution of NO_2 and CO were created (Fig. 9-10). The visualisation was performed using Python with the libraries geopandas, matplotlib, and contextily. In the visualisation of NO_2 concentration, a colour gradient scale from green to red was used. The minimum concentration value is 0, and the maximum is 1.0E-4 mol/m^2. The colours on the scale represent different levels of NO_2 concentration, with green corresponding to the lowest values and red to the highest. The detailed results allow for an assessment of the differences in air pollution levels between different dates at the time of sensing.

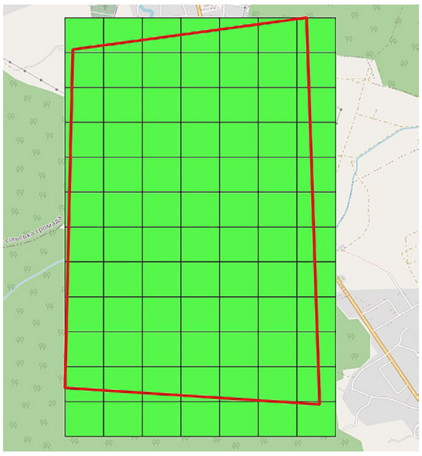

Figure 8. Created standardised regular grid
Source: created by the authors

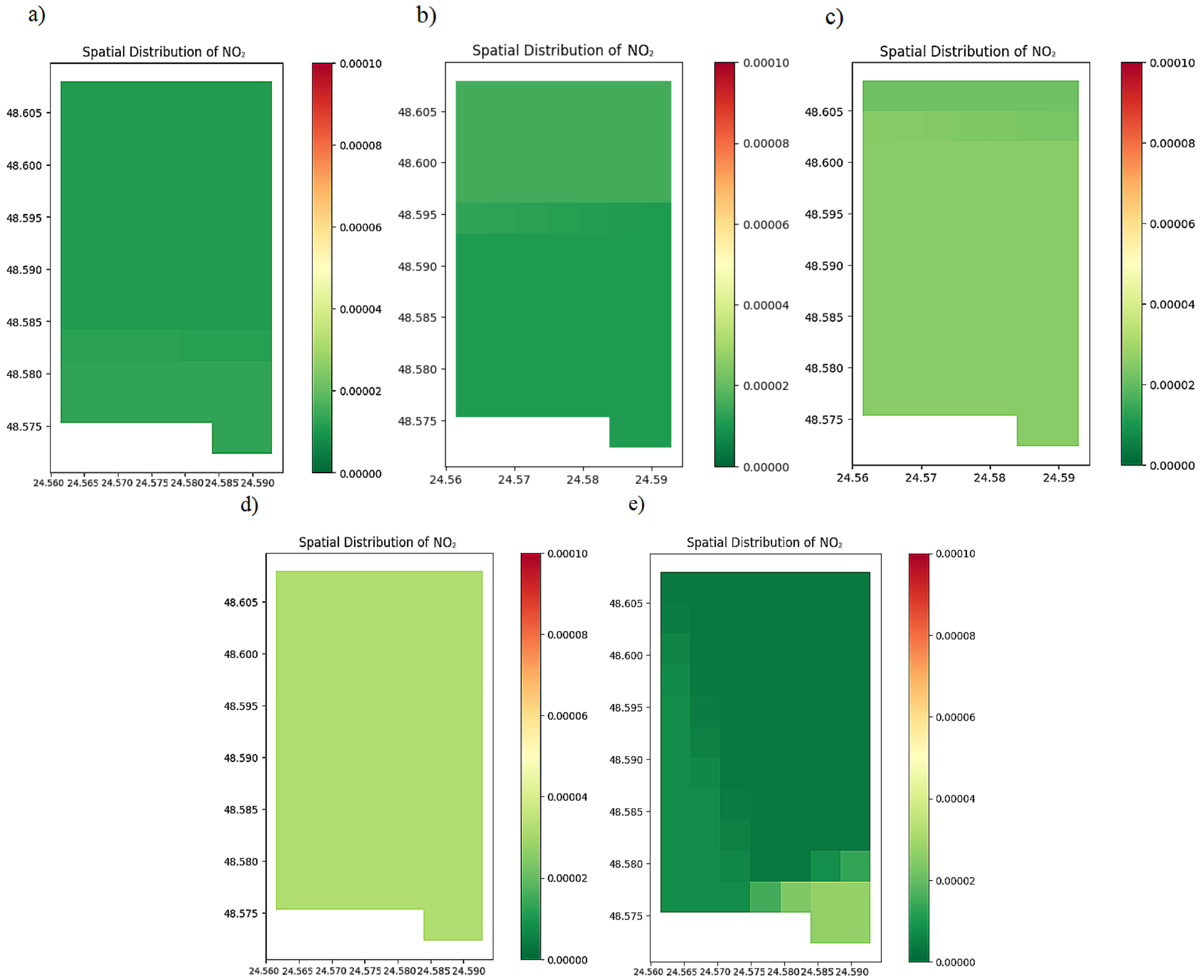

Figure 9. Average NO_2 concentrations within the standardised regular grid by dates
Note: a – 28.09.2023; b – 29.09.2023; c – 02.10.2023; d – 03.10.2023; e – 06.10.2023
Source: created by the authors

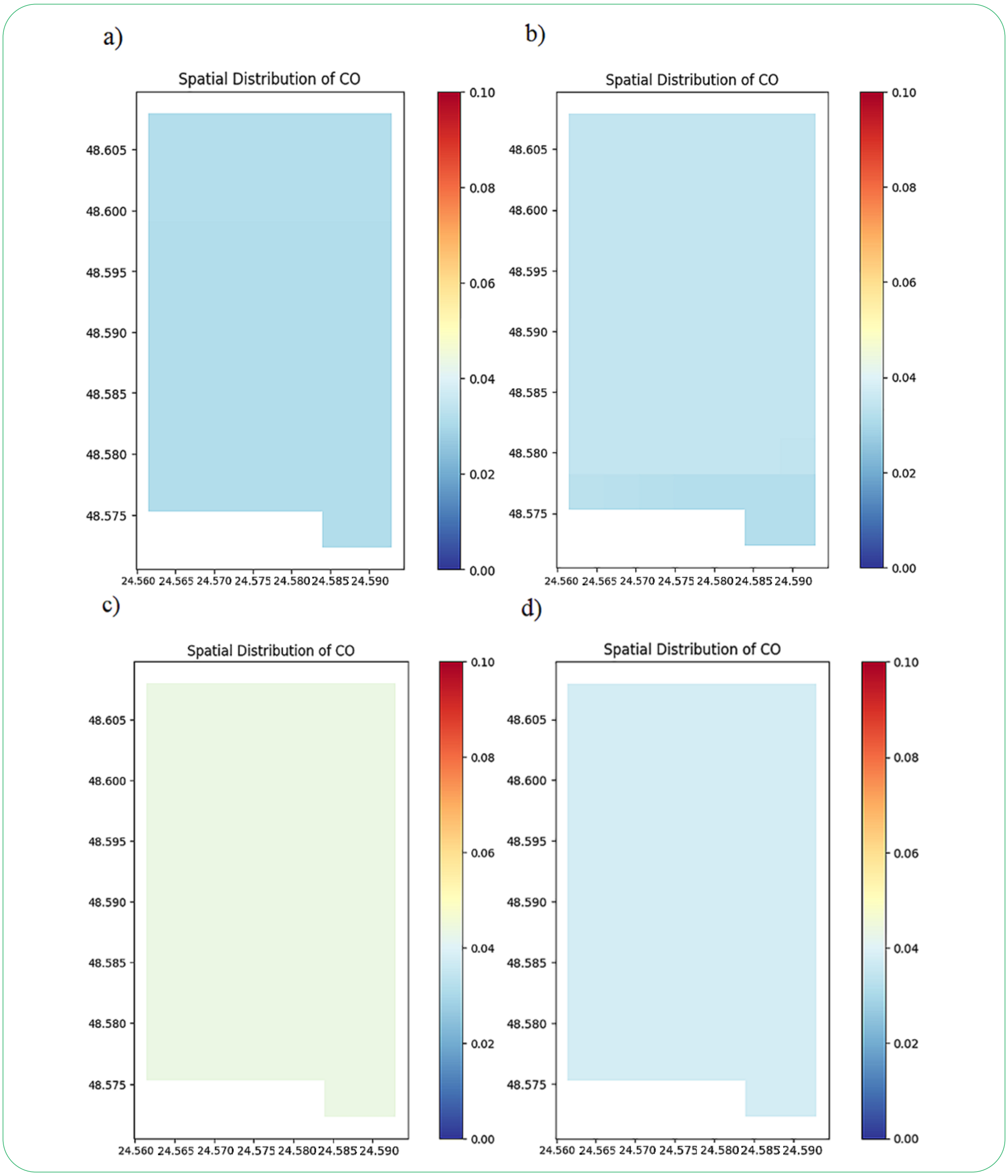

Figure 10. Average CO concentrations within the standardised regular grid by dates
Note: a – 28.09.2023; b – 29.09.2023; c – 02.10.2023; d – 04.10.2023
Source: created by the authors

In the visualisation of CO concentration, a colour gradient scale from blue to red was used. The minimum concentration value is 0, and the maximum is 0.1 mol/m^2. The colours on the scale represent different levels of CO concentration, with blue corresponding to the lowest values and red to the highest. The challenge in comparing data obtained from satellite observations with ground-level concentrations arises due to the impossibility of directly converting concentrations from satellite data to ground-level concentrations without involving additional analysis tools and meteorological data. The development of effective methods for such conversion remains a relevant task worldwide (Savenets *et al.*, 2021). Following the statistical analysis, the contents of NO_2 and CO are presented in Table 2.

Table 2. Spatial distribution of NO_2 and CO concentrations

Date	NO_2 Max, mol/m²	NO_2 Avg, mol/m²	CO Max, mol/m²	CO Avg, mol/m²	NO_2 Max, mL/m³	NO_2 Avg, mL/m³	CO Max, mL/m³	CO Avg, mL/m³
28.09.2023	1.11E-05	1.09E-05	0.0317	0.0296	0.22	0.21	7.6	7.11
29.09.2023	1.56E-05	1.18E-05	0.0346	0.0322	0.3	0.23	8.29	7.73
02.10.2023	2.55E-05	2.35E-05	0.0437	0.0411	0.5	0.46	10.49	9.86
03.10.2023	3.21E-05	3E-05			0.63	0.58		
04.10.2023			0.0376	0.0354			9.03	8.5
06.10.2023	7.81E-06	5.9E-06			0.15	0.11		

Source: created by the authors

The analysis of the spatial concentration of the pollutants NO_2 and CO within the study area showed significant differences before and after the event. Prior to the explosion, the observed average concentrations were as follows: NO_2 ranged from 0.21 to 0.23 mg/m³ and CO from 7.11 to 7.73 ml/m³. However, after the incident, there was a substantial increase in pollutant concentrations: NO_2 rose to 0.58 mg/m³ and CO to 9.86 ml/m³, representing an increase in NO_2 emissions by 176%, while CO concentration increased by approximately 39%. To avoid erroneous conclusions, it is important to note that satellite data provides information only about pollution levels in the atmospheric column, not about their vertical distribution. Therefore, the exact altitude at which the maximum pollutant concentration is observed remains unknown.

According to published information, specialists from the Ivano-Frankivsk Regional State Laboratory of the State Service of Ukraine on Food Safety and Consumer Protection conducted laboratory and instrumental studies of air quality in the Strymba Village, Nadvirna District, due to the emergency situation (Experts investigated air quality…, 2023). Air samples were taken in the Strymba Village at 112 Nizhna Str. (500 m from the incident site): NO_2 was 0.45 ml/m³, and CO was 10.0 ml/m³. Comparing the obtained results with data from open sources, the information confirms the study data on NO_2 and CO pollution. After the fire, the concentrations were 0.46 to 0.58 ml/m³ for NO_2, which is close to the ground measurements, and 9.86 ml/m³ for CO, which also corresponds to ground data. Considering the consistency between the authors' data and ground-based measurements, the reliability of the obtained results is confirmed.

Discussion

Satellite images and GIS were used to study the effects of the fire for data analysis and processing. The calculation of indices such as NDVI, dNDVI, NBR, and dNBR allowed for precise delineation of the fire boundaries. Additionally, data from Sentinel-5P satellites were used to monitor NO_2 and CO air pollution levels before and after the fire. The choice of methodology using NBR is validated by its effectiveness in creating maps of fire damage zones and assessing their impact. For instance, in the study by A. Babushka *et al.* (2021), focusing on the analysis of areas affected by fire in the Chornobyl exclusion zone, the use of the NBR methodology allowed for accurate determination of the damaged areas. The use of the NDVI vegetation index is also a crucial aspect in identifying areas affected by fires. The study by J. Digavinti & B. Manikiam (2021) aimed to analyse the post-fire effects of forest fires and vegetation regrowth using NDVI from 2014 and 2018 to assess vegetation recovery in the forest area in and around the Tirupati Region (Andhra Pradesh, India). Remote sensing methods, particularly the calculation of the NDVI index, have proven effective for mapping forest fires and analysing fire effects through change detection.

Combining the use of NDVI, NBR, dNDVI, and dNBR calculations is beneficial for enhancing the accuracy of the study. The results of determining the area of vegetation damage due to the fire and the calculation of the difference between the pre- and post-fire indices were compared with the results of the NBR and dNBR index calculations, which contributed to improving the accuracy of the obtained results. The appropriateness of calculating dNDVI and dNBR is demonstrated in the study by R. Zennir & B. Khallef (2023). Their research on fires in 2021 in the Beni-Salah National Forest, located in the Guelma Province in the extreme northeast of Algeria, confirms the relevance of using difference indices dNDVI and dNBR to estimate the forest areas devastated by wildfires.

The application of vegetation indices in research allows for the identification and mapping of areas affected by fires. In the study by F. Morante-Carballo *et al.* (2022), spectral indices such as NDVI, NBR, dNDVI, and dNBR were used to map burned areas in the La Carolina District. The NBR index enabled the quantitative assessment of areas affected by fires, while the dNBR and dNDVI indices helped determine the degree of damage to these areas. The study applied threshold values of NDVI and NBR to delineate the fire boundaries. According to the research by J.H. Walz & K.T. Weber (2021), this method demonstrates high efficiency in detecting areas of vegetation cover change after a fire, corroborating the findings of studies that used NDVI threshold values to detect actively growing vegetation. Compared to the approach by J.H. Walz & K.T. Weber (2021), which was based solely on the NDVI index, this study also considered the NBR index to obtain a more accurate assessment of fire activity and comparison with the vegetation cover, providing a comprehensive view of the fire-affected boundaries.

To accurately determine the scale of the fire on the oil pipeline, a comprehensive approach was applied, combining spectral analysis methods and pollutant gas monitoring using Sentinel-5P satellite data. Specifically, indices such as NDVI, dNDVI, NBR, and dNBR were combined with data from Sentinel-5P satellites. In the study by O.S. Yılmaz *et al.* (2023), an analysis of forest fires in the Mediterranean region of Turkey was conducted from 28.07.2021 to 11.08.2021. The use of NBR and NDVI indices based on Sentinel-2 satellite images in this study effectively determined the spread of the fire and visualised this information in the form of maps. Additionally, data from Sentinel-5P satellites were used to monitor atmospheric pollution levels after the fire. The results of the study indicate the high efficiency of using spectral indices and Sentinel-5P satellite data for analysing and visualising the consequences of fires. The Sentinel-2 satellite, part of the European Commission's Copernicus programme, consists of two satellites launched by the European Space Agency. The MSI sensor used on the Sentinel-2A and Sentinel-2B satellites has a radiometric resolution of 12 bits (Astola *et al.*, 2019). Each satellite has 13 spectral bands, with a resolution ranging from 10 to 60 m. Images obtained from Sentinel-2 satellites are noted for their better spatial and temporal resolution compared to Landsat data, which have lower resolution. Models derived from Sentinel-2 data demonstrate better efficiency compared to Landsat 8-based models for analysing forest changes, considering the root mean square error and coefficient of determination (Astola *et al.*, 2019). Low-resolution images from Landsat and other satellites have been used in many forest fire studies, including those by researchers such as Y. Hyoungjin & J. Jeong (2019), F. Pelletier *et al.* (2021), and M.J. Faruque *et al.* (2022). The higher spatial resolution of Sentinel-2 images is crucial for detecting even small fires.

The analysis of atmospheric air revealed differences in the changes in concentrations of NO_2 and CO due to the fire. Emissions of NO_2 increased by 176%, while CO levels rose by approximately 39%. According to the study by H.E. Peiro *et al.* (2022), the proportions of these emissions can vary depending on the type of fire and the specifics of the combustion, which can be useful in considering these factors when assessing the impact of pipeline fires on air quality. The high potential of S5-P TROPOMI for measuring CO emissions during forest fires was confirmed based on data obtained by C. Magro *et al.* (2021). The study found that satellite measurements of CO reflect clear trends and distributions that correspond to the behaviour and intensity of the fire. Additionally, S5-P TROPOMI demonstrates the ability to respond to changes in CO emissions depending on the specific type of fire. Satellite analysis confirmed the correlation between CO emissions and fire zones, enhancing the reliability and usability of satellite data for monitoring fire emissions. The study by C. Morillas *et al.* (2024) indicated the high efficiency of S5-P TROPOMI for monitoring NO_2 concentrations in the atmosphere. When studying the spatial and temporal patterns of NO_2 pollution in Madrid in 2022, high correlations were obtained between satellite data and surface measurements, with correlation coefficients of 0.78 and 0.81 for different analytical approaches. This correlation was particularly noticeable in urban and suburban areas, while it was less pronounced in rural zones.

Forest fires are a significant source of NO_2 and CO emissions. According to the study by N. Wan *et al.* (2023), fires in Australia emit large quantities of these pollutants. These emissions can significantly impact air quality and atmospheric composition in the regions where they occur. The use of Sentinel-5P satellite data allows for the acquisition of information on CO_2 concentration levels in the air. M.V. Savenets *et al.* (2021) described methods for real-time monitoring of air quality over Ukraine using Sentinel-5P satellite data. As a result of the study, methods for refining data were developed, enabling the analysis of chemical compound content over cities and the creation of maps showing the spatial distribution of NO_2, CO, HCHO, SO_2, and O_3 over Ukraine with detailed visualisation over specific cities. The results of the study demonstrate the high potential of remote sensing methods for investigating the scale and consequences of fires. In particular, spectral indices such as NDVI, NBR, dNDVI, and dNBR, along with the analysis of satellite data from Sentinel-5P, are effective tools for determining the boundaries of fire-affected areas and measuring atmospheric pollution levels. This is also confirmed by the results of the study.

Conclusions

The selected remote sensing methods for studying the scale of the fire caused by the pipeline explosion near the Strymba Village, Nadvirna District, Ivano-Frankivsk Region, and for assessing the degree of air pollution by NO_2 and CO after the fire, proved to be effective. In the study, data from Sentinel-2 MSI satellites were used to calculate the spectral indices NDVI, NBR, dNBR, and dNDVI to determine, calculate, and map the boundaries of the fire. Additionally, data from Sentinel-5P satellites were used to analyse NO_2 and CO levels in the air before and after the fire. Using NDVI and NBR indices, maps of the damaged vegetation cover affected by the fire along the Strymba River were created. This data is also corroborated by information published by journalists. The area of the fire was calculated using the differential indices dNBR and NDVI, applying the threshold method. According to the calculations, the fire area is 2.413 ha by the dNDVI index and 2.503 ha by the dNBR index. The similarity of the obtained values indicates the consistency of the data.

Using pollutant gas monitoring based on Sentinel-5P satellite data, an analysis of NO_2 and CO air pollution was conducted following the pipeline explosion. On 28.09.2023, the average NO_2 concentration in the air was 0.21 ml/m^3, which increased to 0.58 ml/m^3 by 03.10.2023, confirming a 176% rise in NO_2 levels over this period. An increase in CO concentration was also noted: on 28.09.2023, the average value was 7.11 ml/m^3, which rose to 9.86 ml/m^3 by 02.10.2023, indicating a 39% increase in CO levels during this time. To enable comparisons between NO_2 and CO concentration results obtained from satellite observations and ground measurements, methods for converting concentration units were used. These methods included converting NO_2 concentrations from mol/m² to ml/m³ using the ideal gas law equation and applying a conversion formula for CO concentration. The methods used for concentration conversion proved effective in this study, though further research and verification of their efficiency are necessary. Future studies should aim to improve satellite monitoring methods for pollutants, investigate the long-term environmental impacts of pipeline fires, and develop more accurate models for assessing the distribution of pollutants in various atmospheric layers.

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None.

Conflict of Interest

None.

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Аналіз пожежі за даними Sentinel-2 та Sentinel-5P: вибух нафтопроводу біля села Стримба

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Анотація. Вибухи на трубопроводах нафти стають серйозною загрозою для екологічної безпеки. Актуальність даного дослідження полягає у вивченні наслідків подібних інцидентів та їх впливу на довкілля. Мета дослідження полягала в оцінці масштабу пожежі та ступеня забруднення повітря діоксидом азоту та оксидом вуглецю після вибуху трубопроводу. Використані методи дослідження включали аналіз супутникових зображень за допомогою нормалізованого вегетаційного індексу рослинності, нормалізованого коефіцієнту горіння диференційованого нормалізованого індексу різниці рослинності та диференційованого нормалізованого коефіцієнту горіння, з подальшим виявленням горілих місць за допомогою методу порогових значень. Застосування таких передових методів дистанційного зондування Землі, як дані супутників Sentinel-2 та Sentinel-5P, дозволило провести аналіз наслідків вибуху нафтопроводу та подальшої пожежі, що сталася 30.09.2023 біля села Стримба Надвірнянського району Івано-Франківської області. Додатково проведено аналіз викидів шкідливих речовин у повітря, отриманих зі супутника Sentinel-5P, із подальшою візуалізацією за допомогою мови програмування Python та здійсненим статистичним аналізом. Отримані результати включають розрахунок площі пожежі, яка становить близько 2,5 га, та виявлення підвищення рівня діоксиду вуглецю та оксиду вуглецю вище норми після пожежі. Використано методи перетворення одиниць концентрації, отриманих за допомогою супутникових спостережень, у приземну концентрацію. Проведена валідація отриманих результатів із даними вимірюваннями на поверхні підтверджує дані дослідження щодо забруднення азотом діоксиду та оксидом вуглецю. Після пожежі концентрації складали від 0,46 до 0,58 мл/м^3 для діоксид азоту та 9,86 мл/м^3 для оксид вуглецю. Ці результати дослідження є важливими для визначення невеликих пожеж внаслідок вибуху трубопроводу та для практичного розуміння специфіки викидів шкідливих речовин під час пожеж такого типу

Ключові слова: супутникові дані; спектральні індекси; площа пожежі; шкідливі речовини; діоксид азоту; оксид вуглецю