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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).

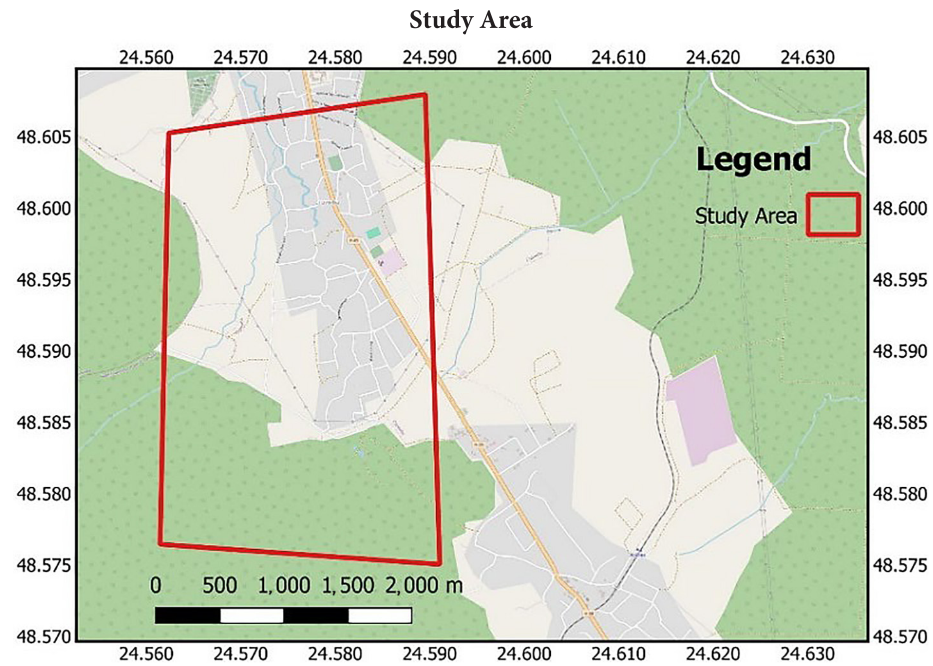

Figure 1. Study area displayed on an OpenStreetMap

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).

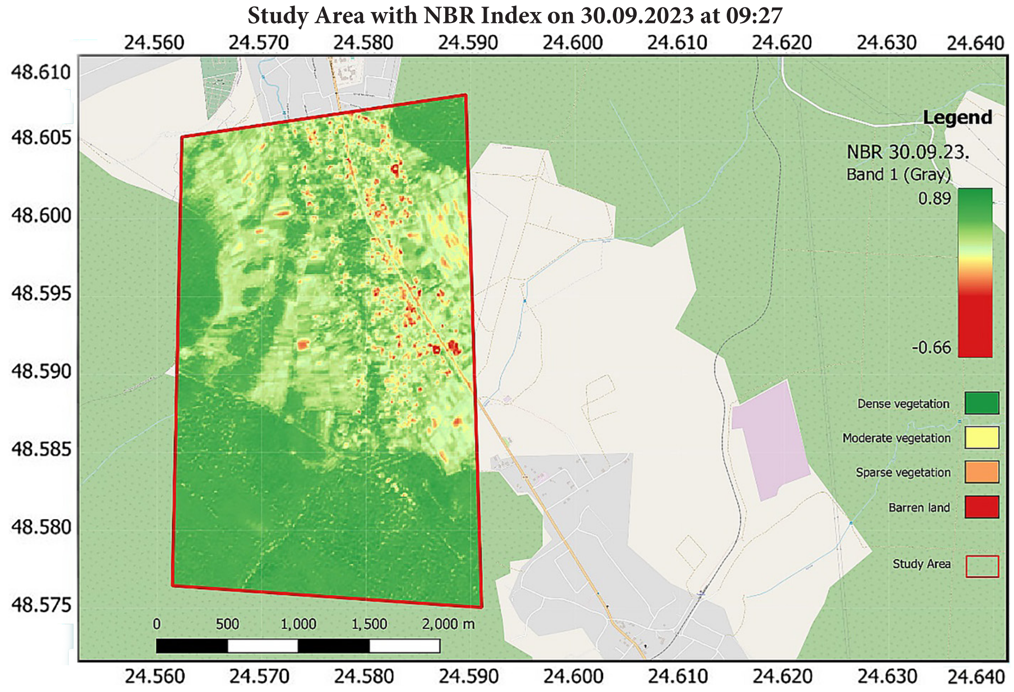

Figure 2. Map with calculated NBR index before the fire

Source: created by the authors

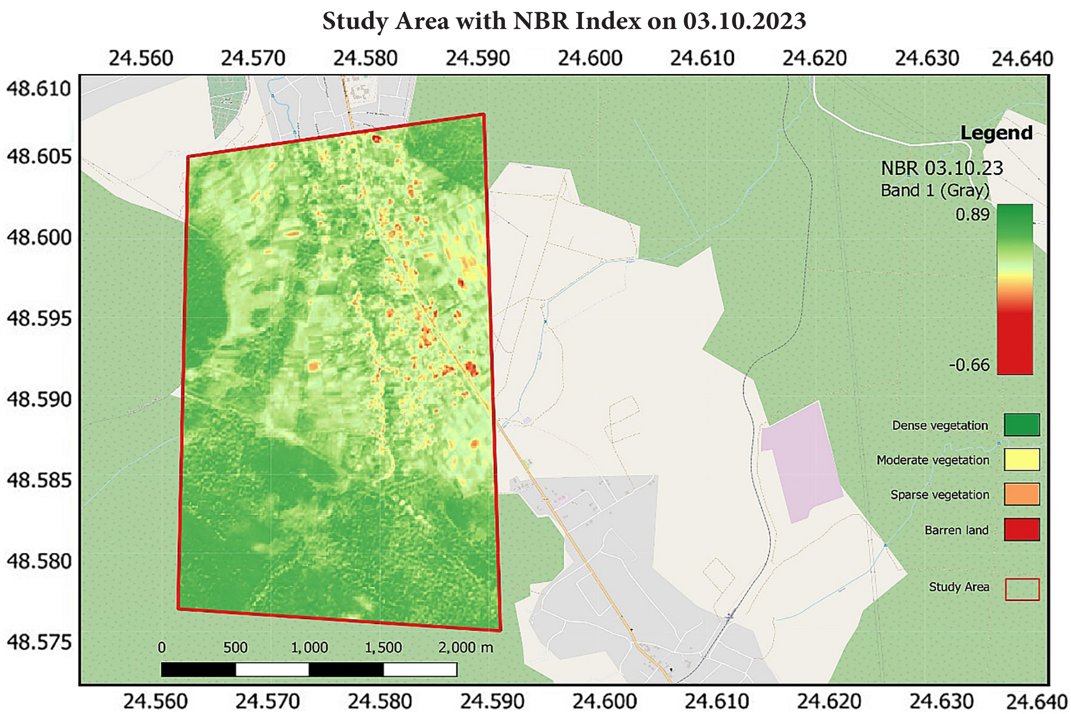

Figure 3. Map with calculated NBR index after the fire

Source: created by the authors

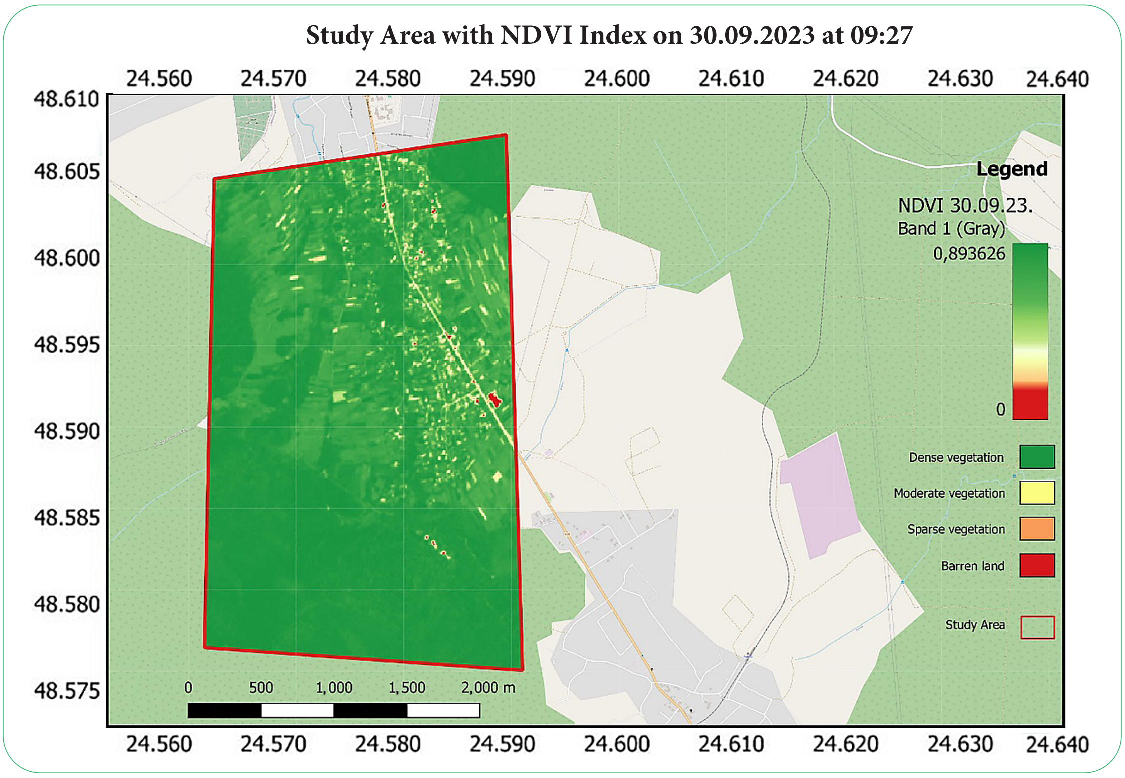

Figure 4. Map with calculated NDVI index before the fire

Source: created by the authors

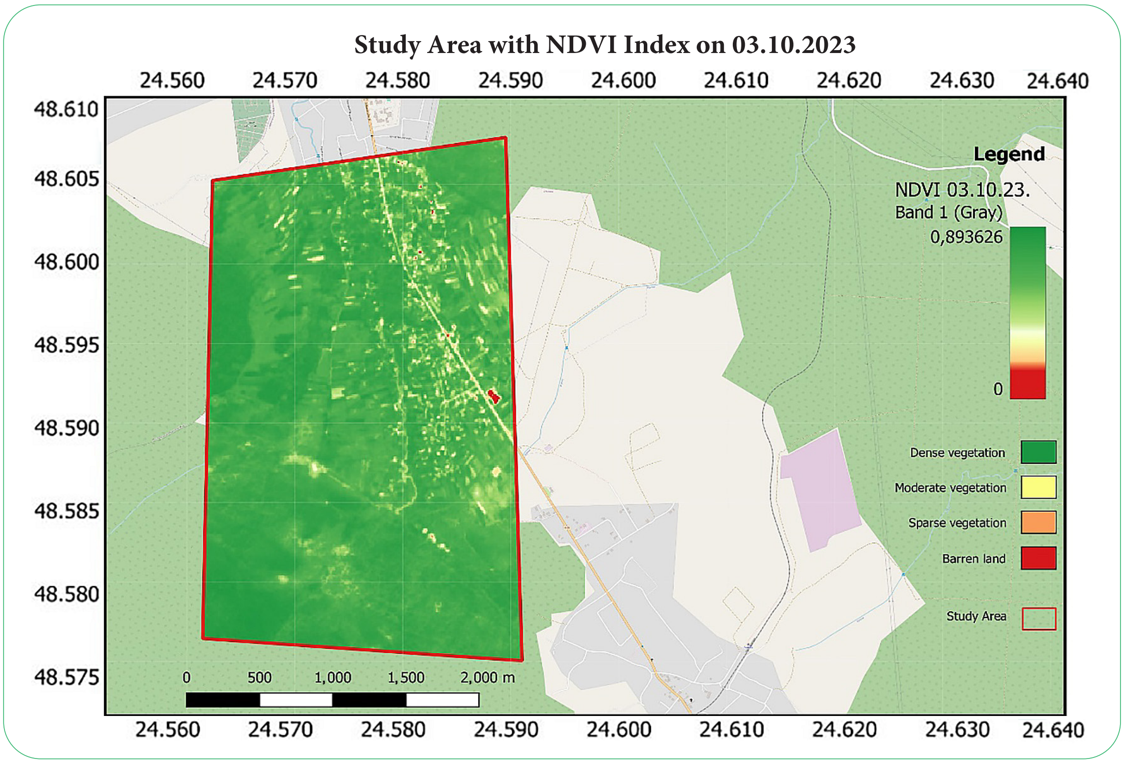

Figure 5. Map with calculated NDVI index after the fire

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.

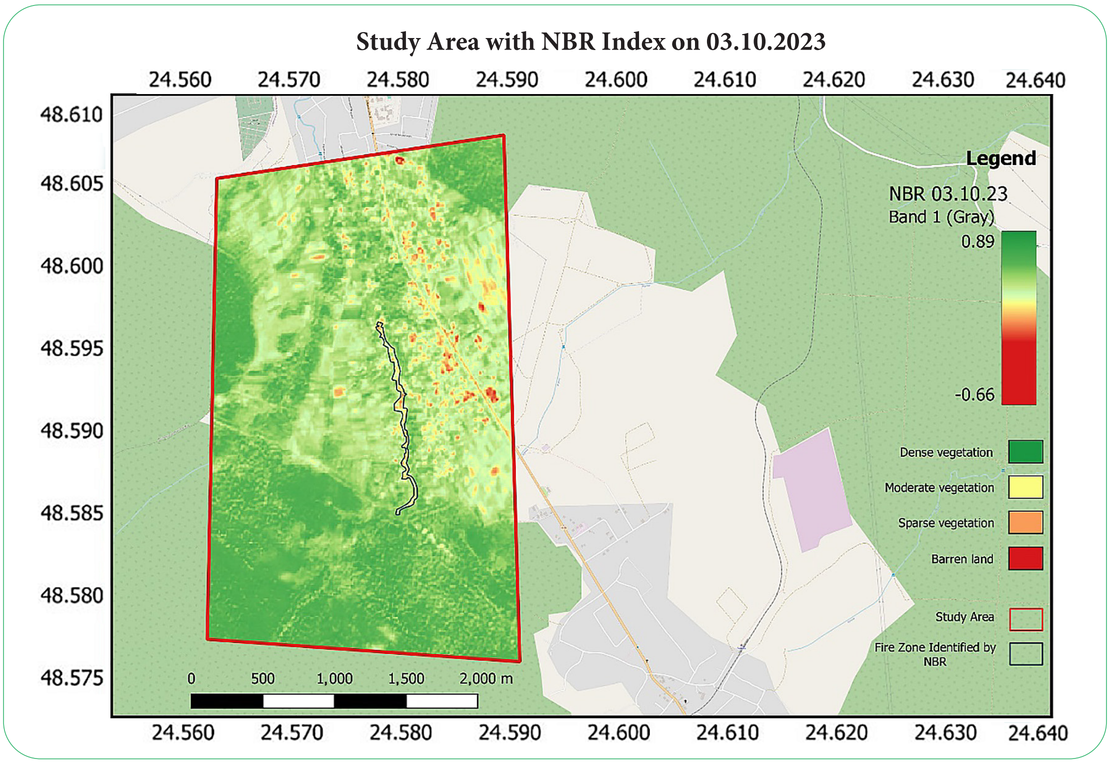

Figure 6. Map with calculated NBR index after the fire with identified fire-affected area
Source: created by the authors

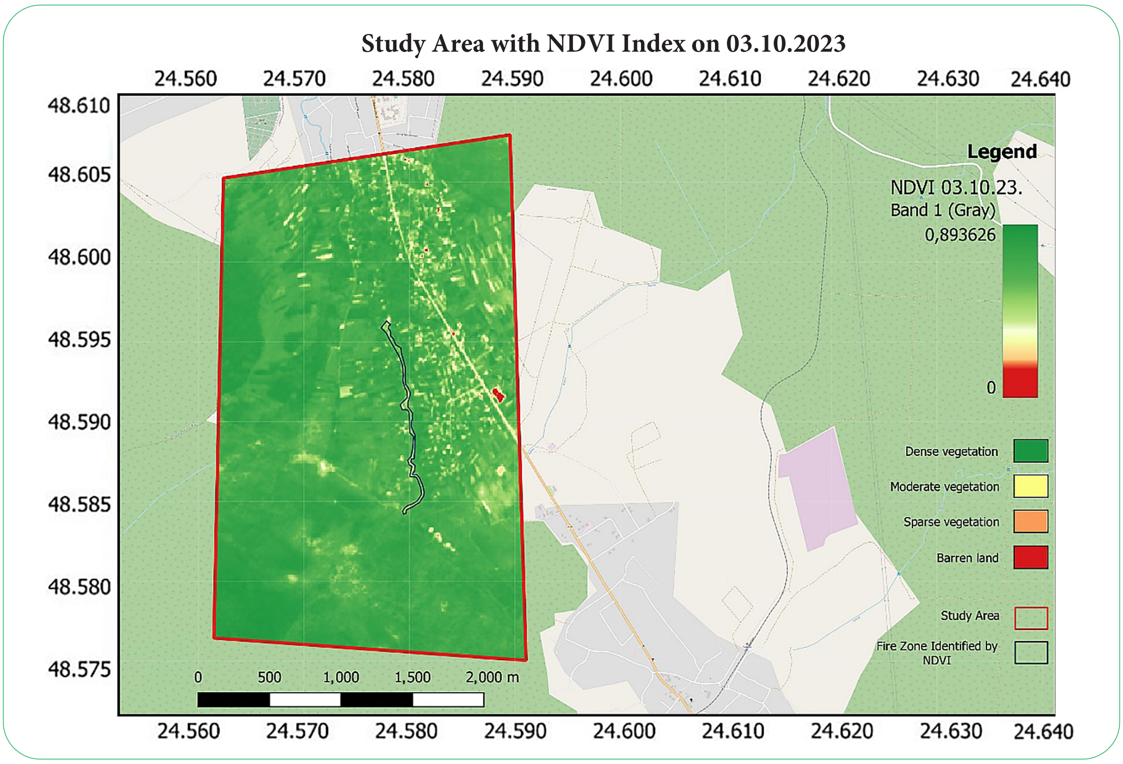

Figure 7. Map with calculated NDVI index after the fire with identified fire-affected area
Source: created by the authors

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.

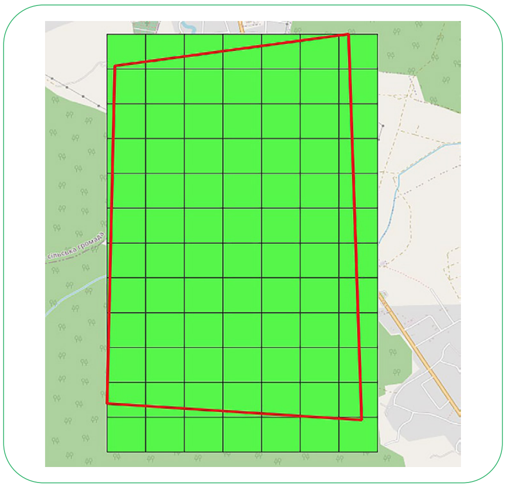

Figure 8. Created standardised regular grid
Source: created by the authors

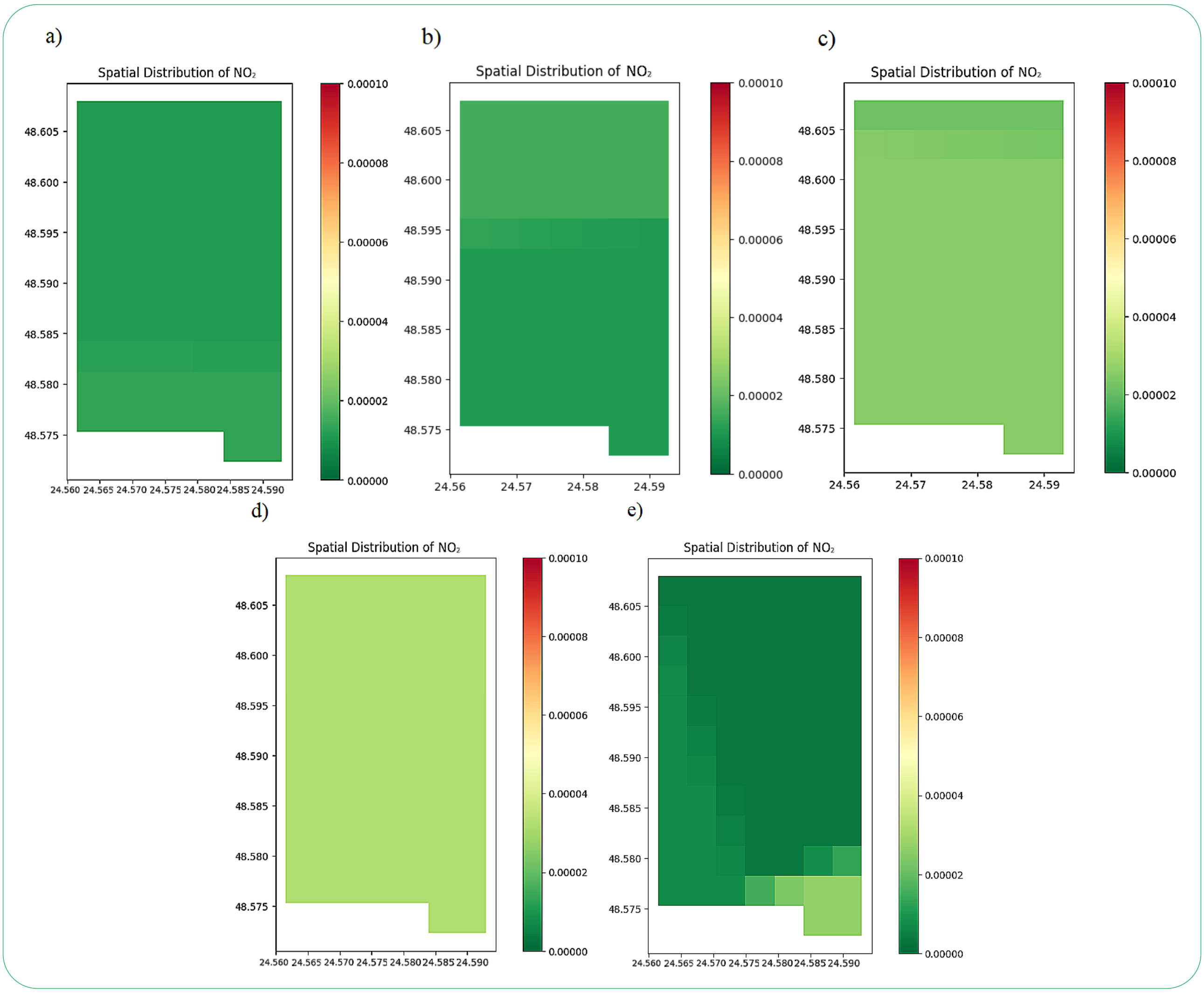

Figure 9. Average NO_2 concentrations within the standardised regular grid by dates
Note: a – 28.09.2023; b – 29.09.2023; c – 02.10.2023; d – 03.10.2023; e – 06.10.2023
Source: created by the authors

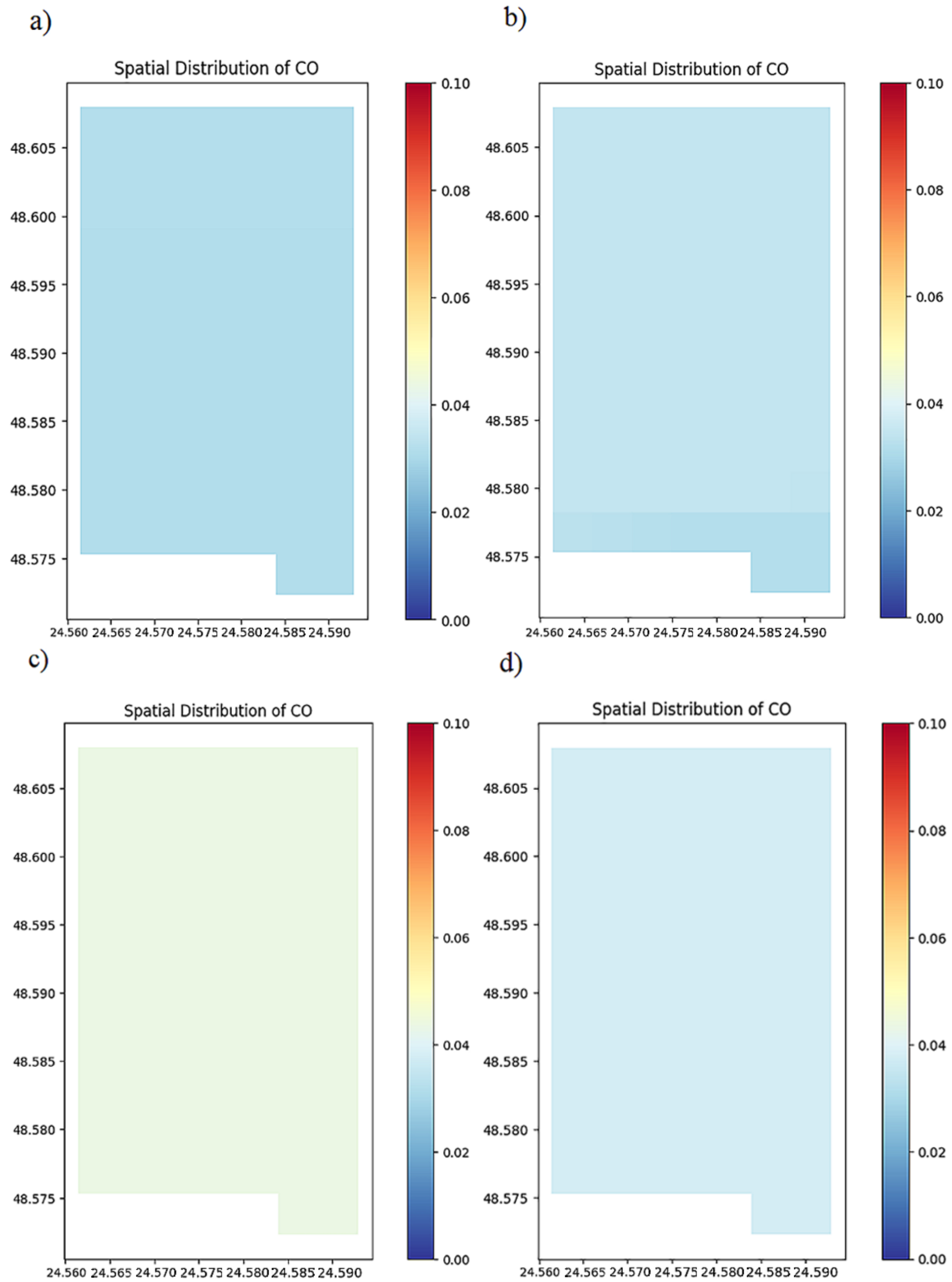

Figure 10. Average CO concentrations within the standardised regular grid by dates
Note: a – 28.09.2023; b – 29.09.2023; c – 02.10.2023; d – 04.10.2023
Source: created by the authors

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

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The efficiency of organic pollutants degradation in the process of anaerobic digestion of feedstocks with different origin

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Abstract. The study of the degree of degradation of pollutants in the process of anaerobic digestion and their content in digestate is an urgent scientific issue driven by the necessity to confirm the safety of using this product as a biofertilizer to improve the quality of agricultural land. The aim of the article was to determine the efficiency of the degradation of pollutants in the process of anaerobic digestion with the use of various additional treatment methods. A meta-analysis was conducted to establish the patterns of pollutant degradation during anaerobic digestion under different conditions and with the application of additional process intensification technologies (ultrasound, the use of chemical reagents and carbon

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cloth, interspecies electron transfer, immobilisation of microalgae, etc.). The reliability of the selected hypotheses and the statistical significance of the obtained data were determined using statistical analysis methods. It was found that additional treatment methods allow to increase in the efficiency of degradation of organic pollutants in mixed organic waste by 180% (direct interspecies electron transfer), in animal waste by 115% (alkaline pre-treatment), and in wastewater sludge by 55% (by treating them in a thermophilic aerobic reactor together with anaerobic digestion). The efficiency of the immobilisation of microalgae technology, which provides for the removal of pollutants from the liquid fraction of digestate, is 135%. The presence of a synergistic effect of additional methods of feedstock treatment has also been established, which is illustrated by an increase in the amount of methane production by 98.88-261.56%, depending on the type of waste and the treatment method. The results obtained prove the high efficiency of additional treatment technologies. The practical significance of the results obtained lies in the proven synergistic effect of using additional methods of treatment of feedstocks and digestate due to an increase in the level of degradation of organic pollutants with the production of environmentally safe fertilizer and an increase in biogas yield

Keywords: biogas production; digestate; hazardous chemicals; organic waste; pre-treatment; sustainable development; substrate

Introduction

The issue of environmentally safe handling of organic waste is quite relevant in terms of environmental safety and environmental protection technologies. The technology of anaerobic digestion of waste for the production of biogas and digestate is becoming widespread in the world as a whole. Due to its physicochemical and microbiological properties, digestate has found extensive use as a fertilizer in European countries. For Ukraine, with its developed agriculture sector, the use of digestate as an organic or organo-mineral biofertilizer and an alternative to mineral fertilizers is justified from the point of view of environmental protection, conservation of natural resources and the economic effect obtained, which is especially relevant in the conditions of martial law. However, the digestate must meet quality and environmental safety standards, therefore, it is necessary to research the content of pollutants that were originally contained in the feedstock and to study the processes of their transformation during anaerobic digestion.

According to the research of K. Chojnacka & M. Chojnacki (2023), biogas technology is quite effective and promising in terms of solving the problem of waste utilisation with the production of useful products in the form of biogas and digestate, which fits into the framework of the circular economy and ensures the production of renewable energy sources. Biogas can be used for cogeneration of thermal and electricity, as well as in gas networks as a substitute for natural gas, which is quite relevant for Ukraine and is undergoing development. K. Pilarski *et al.* (2023) note that with the help of various biogas post-purification technologies to biomethane, it is used as fuel for various types of transport in Europe. T.M. Cabrita & M.T. Santos (2023) showed in their research that a wide range of organic feedstock can be used for anaerobic digestion. Substrates should be grouped by type according to their origin: animal waste (cattle manure, pig manure, chicken manure), plant waste (corn silage, energy crops, other lignocellulosic materials), food waste, and sewage sludge. Ye. Chernysh *et al.* (2021) analysed the trends regarding prospective feedstock for biogas production in Ukraine, based on the assessment of the actual generated waste volumes and forecasts for the future, it was established that animal husbandry waste together with plant biomass will occupy leading positions. At the same time, the practice of using sewage sludge for anaerobic digestion is not developed in Ukraine, although, as noted in the work of V. Vambol *et al.* (2022), it is a quite promising and environmentally safe way of handling these types of waste in Europe.

Various technological and operational approaches are employed to enhance biogas production, including the regulation of physicochemical parameters of the process with the identification of inhibitory factors. Among these, M. Kumar *et al.* (2023) investigated the pH of the medium, the content of volatile substances, and heavy metals. V. Ripoll *et al.* (2022) noted the effectiveness of using mixed feedstock to improve the quality of digestate. Simultaneously, E. Nordell *et al.* (2022) studied the positive impact of additional digestate treatment technologies, including thermal post-treatment of digestate with simultaneous pasteurisation on the organic matter content in digestate and biogas yield. A valuable by-product of biogas technology is digestate, which is effectively used as a biofertilizer. A.M. García-López *et al.* (2023) demonstrated in their research that digestate can increase crop yields, as well as restore soils and improve their properties. Research involving R. Bouaita *et al.* (2022) indicates that depending on the type of feedstock used for anaerobic digestion, digestate may contain certain pollutants. Therefore, the issue of the environmentally safe use of digestate as a biofertilizer arises, which is regulated by relevant directives and quality standards for organic fertilizers within each state or at the level of the European Union. However, L. Hammer & L. Palmowski (2021) noted that a significant portion of organic pollutants are degraded during anaerobic digestion, which contributes to a decrease in their concentration in digestate compared to the input feedstock. At the same time, the extent of degradation of these or other substances varies depending on factors such as the chemical nature of the substance, its concentration, operational-technological parameters of the process, microbiological activity, and environmental conditions in the bioreactor, the application of additional substrate pre-treatment and digestate post-treatment technologies. Moreover, the process of anaerobic digestion, having significant potential for the degradation or binding of pollutants, can be used for the purification of polluted environments and the environmentally safe disposal of waste.

These questions are of scientific interest and relevance to the problem being studied, as the level of environmental safety of digestate and compliance with quality standards will affect its scope of application and the use of its beneficial properties. The aim of the study was to establish the patterns and effectiveness of the degradation of various pollutants in the process of anaerobic digestion of organic feedstock. To achieve this goal, the research tasks were set as follows: to conduct a meta-analysis and systematise information on the content of organic pollutants in the substrate for anaerobic digestion; to investigate the effectiveness of the degradation of various organic pollutants during anaerobic digestion, as well as with the use of various additional technologies; to analyse the additional benefits of using additional technologies and provide appropriate recommendations for the directions of further experimental research. The scientific novelty of the obtained results lies in the determination, on the basis of the conducted meta-analysis, of the high efficiency of the direct interspecies electron transfer method in the process of anaerobic digestion of mixed organic waste and the method of immobilisation of microalgae during the post-treatment of the liquid fraction of digestate in relation to the removal of organic pollutants, as well as the pre-treatment of animal waste with strong alkali and alkaline hydrogen peroxide additionally to intensify their digestion.

Materials and Methods

The methodological basis of the study was chosen as a meta-analysis, which involved searching for scientific articles on the relevant topic, a comparative-descriptive analysis of the results of various studies to establish the patterns of degradation of pollutants in the process of anaerobic digestion under different conditions and with the use of selected additional technologies for process intensification. Statistical analysis of the obtained results was also conducted to determine the reliability of the chosen hypotheses and the statistical significance of the data. At the first stage of the study, a search for relevant scientific literature was conducted, and at the same time, the focus was on articles published in the period 2015-2024 and indexed by the international scientometric database Scopus, based on the following code.

TITLE-ABS-KEY ("organic pollutant*" AND degradation AND "anaerobic digestion")

AND (LIMIT-TO (DOCTYPE, "ar"))

AND (LIMIT-TO (LANGUAGE, "English"))

As a result of the search, 136 publications were found. After analysing each article, clarifying the direction of the research and the availability of the necessary results, the sample for meta-analysis was limited to 50 original articles. The frequency of occurrence of articles on the research topic, according to the search code and the results of the extended analysis, in individual journals ranged from 8 to 1. The number of journals with more than three articles published during the study period from 2015 to 2024 was six, as shown in Figure 1, constructed using the analytical tools of the Scopus database.

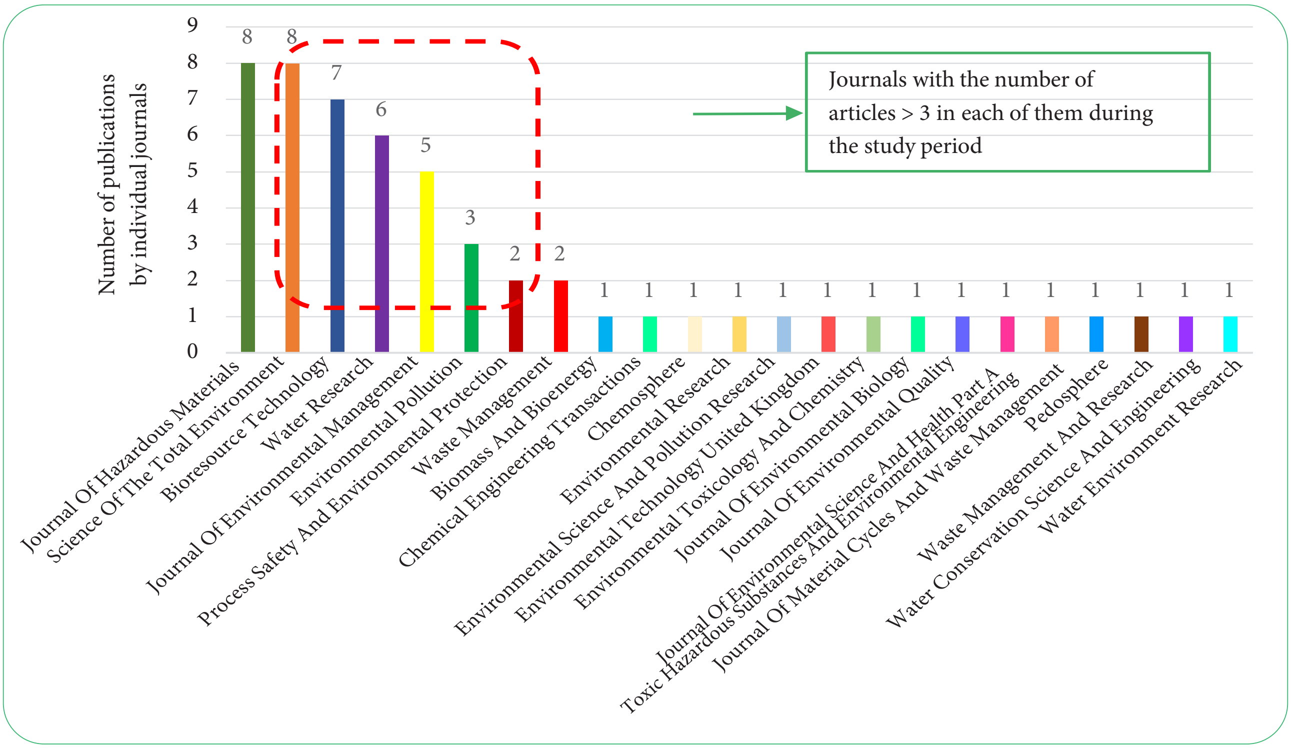

Figure 1. Quantitative distribution of articles by research topic in the context of individual journals indexed by the Scopus database for the period 2015-2024

Source: created by the authors

Based on the selected articles, a bibliometric network was constructed and visualised using the VOSviewer software (version 1.6.20). As a result of the analysis of the obtained network, clusters were identified by keywords describing four research directions (Table 1; Fig. 2). Further meta-analysis was conducted based on the identified clusters.

Table 1. Clusters of research areas on the degradation of pollutants during anaerobic digestion of waste according to keywords in articles published in Scopus in 2015-2024

Red cluster	Blue cluster	Green cluster	Yellow cluster
Anaerobic digestion of organic waste as one of the approaches to waste management (sewage sludge) and biotransformation of organic pollutants	The fate of organic pollutants during anaerobic digestion and the influence of various factors at each stage of the process	Factors, parameters and role of microbial activity for biodegradation of organic pollutants; toxicity of pollutants for metagenic bacteria	Mechanisms and patterns of organic pollutants degradation during the process of anaerobic digestion of feedstock

Source: created by the authors

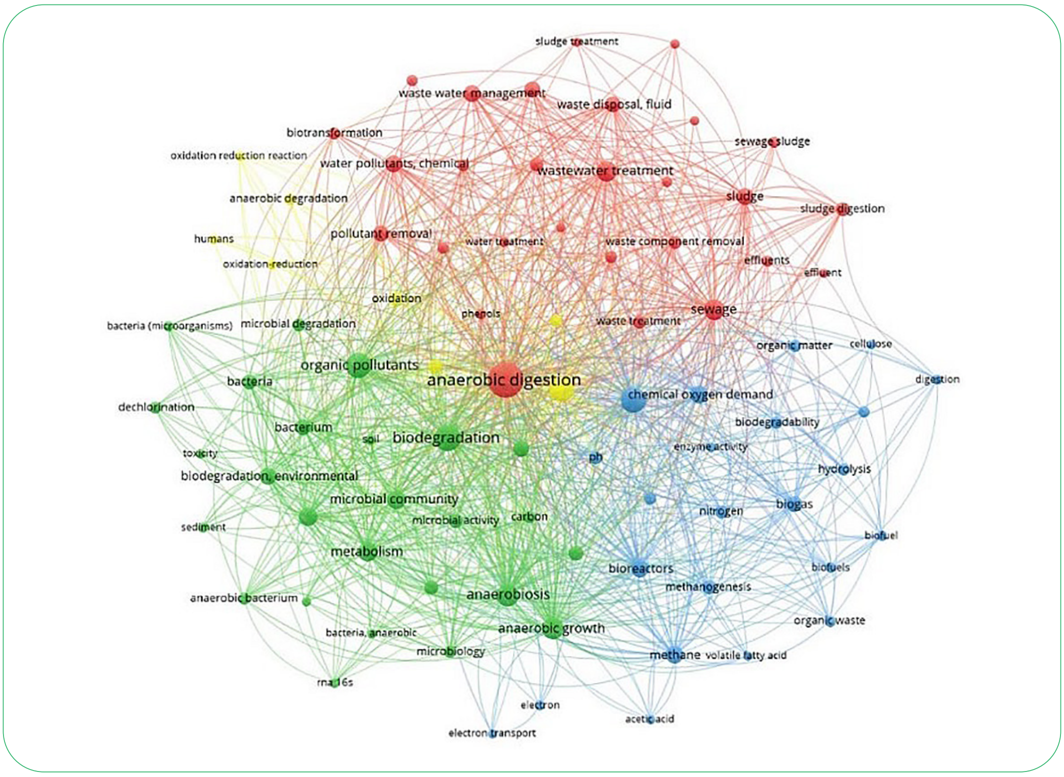

Figure 2. Visualisation of the bibliometric network based on the frequency of occurrence of > 5 keywords in articles on pollutant degradation during anaerobic digestion of organic waste published in Scopus in 2015-2024

Source: created by the authors

In the second stage of the research, based on the dataset obtained from the analysed articles, the level of removal of organic pollutants from the anaerobic digestion system was assessed, which allowed the establishment of the efficiency of substance degradation in anaerobic bioreactors. Within the framework of the analysis of the research results, the following independent factors were identified: substrate type, the chemical nature of the substance, and the peculiarity of the method (technology). The effectiveness of this process was evaluated by the absolute values of concentrations or by such an indicator as chemical oxygen demand (COD). The effectiveness of the removal (degradation) of organic pollutants in the process of anaerobic digestion of the substrate and the effectiveness of the use of additional technologies for the removal of substances in relation to anaerobic digestion (control) were evaluated in accordance with the formulas:

$$E_{rem} = \frac{C_d - C_s}{C_s} \times 100\%; \quad (1)$$

$$E_t = \frac{C_d - C_{dt}}{C_s - C_{dt}} \times 100\%, \quad (2)$$

where E_{rem} is the efficiency of removal (degradation) of organic pollutants in the anaerobic digestion process, %; C_d is the concentration of organic pollutants in the digestate, mg/g; C_s is the concentration of organic pollutants in the substrate, mg/g; E_t is the efficiency of applying additional technologies for substance removal relative to anaerobic digestion as a control, %; C_{dt} is the concentration of organic pollutants in the digestate when additional technology is applied, mg/g. The following technologies were subjected to the most thorough investigation. One of the studied technologies for the chemical pre-treatment of lignocellulosic feedstock in animal waste is alkaline treatment using strong alkali, such as NaOH and alkaline hydrogen peroxide. Alkaline pre-treatment ensures the breakdown of cellulose by an average of $14.8 \pm 0.1\%$ and prevents inhibition of anaerobic digestion by furan by-products, according to the research of J.R. Kim & K.G. Karthikeyan (2021). The method of direct interspecies electron transfer as an additional technology in the process of anaerobic digestion of substrates is used with the application of various conductive materials. This approach is based on extracellular electron exchange through physical contact between microorganisms, which replaces chemical indirect interspecies electron transfer (Hassanein & Lansing, 2022).

In the third stage of the research, the additional advantages of using technologies for the anaerobic degradation of organic pollutants were evaluated. In this process, the efficiency of anaerobic digestion for a particular type of substrate was determined based on the volume of methane produced. Theoretical values of the biomethane potential for various substrates, using literature data on the effectiveness of the aforementioned methods, were calculated using the approach described in by S. Weinrich *et al.* (2018). The elemental composition of substrates for anaerobic digestion was calculated as an average based on literature data. Statistical analysis of the dataset obtained from the meta-analysis was performed using the MS Excel and Statistical Package for the Social Sciences (SPSS) software (IBM SPSS Statistics, version 29.0.0.0). Data processing regarding the removal level of various groups of organic pollutants in the anaerobic digestion process of feedstocks of different origins and with the use of additional technologies was carried out using the analysis of variance (ANOVA) (Fu *et al.*, 2019). In this process, differences between data from different categories (substrate type, substance type, and type of additional technology or its absence) were evaluated. For post-hoc analysis, the Tukey honestly significant difference test (HSD) was used to establish a statistically significant difference between the data ($p < 0.05$). If the significance level value was $p < 0.05$, the null hypothesis, which assumed the absence of differences between the data, was rejected, and the difference between the results was accepted as statistically significant. For each value of the additional technology's efficiency compared to anaerobic digestion (control), the standard deviation was calculated.

Statistical processing of the data regarding the effectiveness of additional technologies in terms of biomethane potential was carried out using the chi-square method, which involved calculating the chi-square statistic with the consideration of the sample size and degrees of freedom (Aslam & Smarandache, 2023). The chi-square goodness-of-fit test uses sample data to test the hypothesis about the necessary proportions of the distribution of different values, and this test determines how well the obtained values within the sample correspond to the necessary proportions of values specified in the null hypothesis. In this process, the hypothesis about the distribution of technology efficiency over time depending on the stage of anaerobic digestion during the biomethane potential test was tested. The null hypothesis assumed that the distribution of effectiveness for the studied technologies over time is not uniform (normal). Calculations were performed based on the data obtained during the meta-analysis. The authors conducted scientific research within the framework of the Research Plan of the Department of Ecology and Environmental Protection Technologies of Sumy State University, Sumy, Ukraine, on the topics "Assessment of technogenic load in the region during changing the industrial infrastructure" (state registration No. 0121U114478) and "Reduction of technogenic load on the environment from oil production facilities: prospects for the use of biotechnology" (state registration No. 0121U114460) in accordance with the scientific and technical programme of the Ministry of Education and Science of Ukraine.

Results and Discussion

Characterisation of organic pollutants in groups of substrates used for anaerobic digestion

Substrates used for biogas production and derived from various waste origin contain certain contaminants that enter the feedstock through natural and anthropogenic pathways. Pollutants transfer into animal wastes from food products, including heavy metals and polycyclic aromatic hydrocarbons (PAHs) (Liu *et al.*, 2023b), or from animal husbandry practices (antibiotics, hormones, pharmaceuticals) as demonstrated in studies by X. Zhou *et al.* (2020) and L.G. Marutescu *et al.* (2022). Lignocellulosic materials can contain pesticides, heavy metals, and radionuclides due to the application of agrochemicals and mineral fertilizers. Additionally, during cultivation, transportation, processing, and other agricultural activities, films, woven bags, mesh covers, and some plastic pipes and plates are often used, and some of these may remain in agricultural waste. The study by O. Golovko *et al.* (2022) found that food waste contains heavy metals, pathogens, and organic micropollutants, including chemicals such as pharmaceuticals and pesticides, which raises concerns. Sewage sludge is the most contaminated feedstock for anaerobic digestion among other types of substrates (Gizaw *et al.*, 2024), as confirmed by the authors' literature search in the Scopus database. At the same time, this type of substrate is most often used in combination with other types of organic substrates of animal or plant origin (Malovanyy *et al.*, 2022) to balance the chemical composition of the feedstock and create favourable conditions for bacterial metabolism. The most toxic are persistent organic pollutants (Košnář *et al.*, 2023), which pose a high risk to human health (Beduk *et al.*, 2023). However, as mentioned above, pollutants are degraded in the process of anaerobic digestion, which completely or partially prevents their transition to digestate (Table 2).

Table 2. Characteristics of pollutants in feedstocks for anaerobic digestion of different origin

Type of substrate (feedstock for anaerobic digestion)	Pollutants	Presence in the digestate (yes/no)	Reference to the source of literature
Animal waste	Tetracycline, oxytetracycline, benzene, toluene	yes	Z. Liu *et al*. (2023b)
	Antibiotics	yes (10%)	W. Liu *et al*. (2023a)
	Sulfamethazine	yes	B.M. Oliveira *et al*. (2019)
	Tylosin	yes (10%)	A.G.D.O. Paranhos *et al*. (2022)
	Polychlorinated biphenyls (PCBs)	no	I. Višniauskė *et al*. (2018)
Sewage sludge	PAHs, PCBs, organochlorine pesticides (OCPs)	yes	Z. Košnář *et al*. (2023)
	Phenolic and fatty compounds from an oil	no	Y. Bouhia *et al*. (2023)
	Personal care products (fragrances, UV filters, antimicrobials, surfactants), PAHs and PCBs	yes	M. Biel-Maeso *et al*. (2019)
	Alkylphenols, phthalates, PAHs, pharmaceutical waste, hormones, perfluorinated acids, linear alkylbenzene sulfonates and PCBs	yes	D. Patureau *et al*. (2021)
	Pharmaceuticals, stimulants, antibiotics	yes	I. Gonzalez-Salgado *et al*. (2020)
	Pharmaceutical products	yes	A. Barreiro *et al*. (2022)
	PCBs and OCPs	yes	Z. Košnář *et al*. (2023)
	PCBs	yes	I. Višniauskė *et al*. (2018)
	Octocrylene	no	D. Fu *et al*. (2019)
	Microplastic (di(2-ethylhexyl) phthalate and phthalate)	no	N. Estoppey *et al*. (2024)
Agricultural residues and crops	PCBs	yes	K. Barcauskaitė (2019)
	Chlorophenol	yes	S.S. Ali *et al*. (2020)
	Hexachlorobenzene, humic acid	yes	C. Liu *et al*. (2021)
	Microplastic (di(2-ethylhexyl) phthalate and phthalate)	no	N. Estoppey *et al*. (2024)
Food waste	PLA plastic	yes	K.K. Porterfield *et al*. (2023)
	Microplastic (di(2-ethylhexyl) phthalate and phthalate)	yes	N. Estoppey *et al*. (2024)
	Bioplastics	yes	A. Kosheleva *et al*. (2023)

Source: created by the authors

Based on the data in Table 2, it was determined that there is a certain specificity regarding the content of various pollutants in digestate depending on the type of feedstock. Six groups of organic pollutants have been identified: antibiotics (sulfamethoxazole, trimethoprim, erythromycin, roxithromycin, cephalexin, ciprofloxacin, metronidazole, trimethoprim, sulphadoxine); personal care products (fragrances, UV filters, antimicrobial agents, surfactants); industrial chemicals (perfluorinated acids, linear alkylbenzene sulfonates, polycyclic aromatic hydrocarbons, polychlorinated biphenyls, bisphenol A, alkylphenols, phthalates, organochlorine compounds, azo dyes); pesticides (chlordane, dieldrin, diuron, endrin, heptachlor, hexachlorobenzene, pentachlorophenol); stimulants (caffeine); pharmaceuticals (anti-inflammatory drugs (ibuprofen, naproxen, and diclofenac), neuropsychiatric drugs (fluoxetine, carbamazepine, citalopram, and diazepam)); hormones (estrone, 17β-estradiol, and 17α-ethinylestradiol]). Moreover, a separate research area has established the application of the anaerobic digestion process for the purification of industrial wastewater contaminated with a wide range of organic compounds according to the specifics of the technological process. Given the wide range of pollutants present in the most common feedstock for anaerobic digestion in bioreactors aimed at biogas production, and the importance of environmentally safe valorisation of digestate in agriculture, there is an urgent necessity to research the degradation efficiency of these substances and assess their content levels in the final product. In addition, in the context of solving the problem of transformation of such a group of substances as persistent organic pollutants, in particular, pesticides, which have been found mainly in sewage sludge and agricultural feedstock (Table 2), the study of the possibility of using additional technologies is seen as necessary.

Removal and degradation of organic pollutants in the process of anaerobic digestion and with the use of additional technologies

Based on the conducted meta-analysis, anaerobic digestion was evaluated in terms of the efficiency of degrading various pollutants within specific substrates, which accordingly contributes to the purification of the feedstock and enables the production of environmentally safe fertilizers from digestate. Thus, a statistically significant high potential of anaerobic digestion was established for the removal of stimulants at the level of 100% and antibiotics (60%), an average level for pesticides and pharmaceuticals (30-50%), but a low level for personal care products and industrial chemicals (0-25%) on average for all types of substrates. Therefore, the challenge arises in finding additional technologies to intensify the degradation process of organic pollutants to reduce their concentration in the resulting digestate.

J.R. Kim & K.G. Karthikeyan (2021) found that strict pre-treatment conditions with strong alkali and alkaline hydrogen peroxide, as well as the impact of furane-derived lignocellulose by-products on cow manure, increased the anaerobic digestion efficiency of cow manure itself by 286%. At the same time, A.K. Rathankumar (2022) evaluated the high efficiency (up to 94%) of alkaline treatment of solid organic substrates contaminated with a wide range of concerning pollutants, in terms of removing 10 pesticides and 13 pharmaceuticals. Meanwhile, L. Wu *et al.* (2023) found that the use of direct interspecies electron transfer using various conductive materials increases the efficiency of anaerobic degradation of various persistent organic compounds in mixed organic waste by approximately 97%. At the same time, S. Mumtaz *et al.* (2023) determined the level of degradation of organic matter using the direct electron transfer method in a mixed substrate based on buffalo manure as the main co-substrate and plant waste as the additional one, and the efficiency of this process, evaluated as the level of COD removal, was 31.18%. In contrast, X. Lu *et al.* (2018) noted the positive effect of iron oxide-zeolite on the anaerobic digestion of complex organic waste, as a result of which the degradation efficiency increases by 74.8%. In addition, B.M. Oliveira *et al.* (2019) showed that the use of an additional carbon source in the form of glucose, fructose, sucrose, and meat extract during anaerobic digestion of waste contributes to an increase in biodegradation of the veterinary antimicrobial agent sulfamethazine from 39% to 54-61%, respectively.

It is worth noting that in the case of using anaerobic digestion for wastewater treatment, the effective application of additional technologies alongside the digestion process has been demonstrated. Y. Xiao *et al.* (2023) demonstrated the effectiveness of using titanium nanofibers for the degradation of organic pollutants in feedstock based on chicken manure and wheat straw waste, using the dynamics of volatile fatty acid indicators, COD, and decolourisation rate, the removal levels of which were 72.9%, 59.1%, and 66.8%, respectively. D. Feng *et al.* (2022) noted that the use of carbon cloth has a positive effect on the anaerobic digestion of high-concentration organic wastewater under different mixing conditions, increasing the efficiency of this process by 23%. K.-H. Phan *et al.* (2024) noted the high efficiency of anaerobic degradation of various azo dyes under thermophilic conditions, in particular, the removal of the azo dye mixture under thermophilic conditions was 6.7% higher than under mesophilic conditions. Instead, C. Liu *et al.* (2021) argue that the use of hydragric acrisol together with humic acid and urea increases the efficiency of anaerobic degradation of hexachlorobenzene by 71.3%. W. Gong *et al.* (2019) demonstrated the high efficiency (94.05%) of purification of the liquid fraction of digestate obtained after anaerobic digestion of waste using various technologies that involve the immobilisation of microalgae. In the study involving S.S. Ali *et al.* (2020), it was found that bacteria from the *Methanosataceae* family can have a positive effect on the anaerobic breakdown of woody biomass, as well as the detoxification of chlorophenols, increasing the efficiency of these processes by 113.7%.

Thus, the above-mentioned studies noted the positive role of applying various technologies in relation to increasing the efficiency of anaerobic degradation of a specific organic compound. Accordingly, there is a task of systematising and determining effective pre-treatment or post-treatment technologies depending on the type of feedstock used for anaerobic digestion. In the process of studying the effectiveness of degradation (removal) of organic pollutants, additional technologies are divided into 3 categories in relation to anaerobic digestion: pre-treatment of the substrate, compatible with digestion, and post-treatment of digestate (Fig. 3). When evaluating digestate post-treatment technologies, differences were found depending on the processed fraction.

Pre-treatment of the substrate	Compatible with anaerobic digestion	Post-treatment of the digestate
• ultrasound	• direct interspecies electron transfer	• immobilisation of microalgae
• mechanical impact	• addition of iron oxide-zeolite	• pyrolysis of solid fraction to produce biochar
• pasteurisation	• thermophilic aerobic reactor	• ultrasound
• thermal hydrolysis	• addition of polymers	• mechanical impact
• alkaline treatment	• addition of enzymes	• pasteurisation
		• composting

Figure 3. Systematisation of methods to intensify the process of pollutant degradation during anaerobic digestion of organic waste

Source: created by the authors

Based on the meta-analysis, the average efficiency of additional technologies for the removal of substances during the anaerobic digestion process itself was calculated. All the investigated methods and approaches were systematised within three types of fermentable substrates: mixed organic waste, waste of animal origin, and sewage sludge. The efficiency of specific methods was investigated for each type of substrate with the identification of the technology type, as per Figure 3, for the identified groups of organic pollutants: antibiotics; personal care products; industrial chemicals; pesticides; stimulants; and pharmaceuticals. Table 4 presents the results of the study on the identified methods and provides the effectiveness values of the relevant technologies in addressing the problem of anaerobic degradation of a complex of various organic compounds.

Table 4. Systematisation of methods that increase the efficiency of anaerobic degradation of a complex of different organic compounds

Type of substrate	Group of pollutants	Name of the applied technology	Type of technology	Technology efficiency*, %
Mixed organic waste	AB, IC	Direct interspecies electron transfer	Compatible with AD	180.00 ± 43.2
	P	Addition of iron oxide-zeolite		14.00 ± 4.3
		Immobilisation of microalgae	Post-treatment	135.00 ± 14.6
		Composting		31.15 ± 6.8
Waste of animal origin	PP, AB	Alkaline treatment	Pre-treatment	114.65 ± 28.7
		Pasteurisation	Pre- and post-treatment	−6.00 ± 5.5
Sewage sludge	PP, AB	Thermal hydrolysis	Pre-treatment	50.62 ± 12.2
		Mechanical impact		21.62 ± 6.9
		Ultrasound		20.33 ± 3.6
	PP, AB, S	Thermophilic aerobic reactor	Compatible with AD	54.76 ± 10.7
	PCP, IC, P, PP, S	Adding polymer		40.00 ± 4.8
	PP	Adding enzymes		5.03 ± 0.5
		Addition of enzymes + mechanical impact	Post-treatment	38.35 ± 4.7
		Mechanical impact		12.16 ± 3.5
		Ultrasound		10.36 ± 4.6

Notes: **M* ± *SD*; AB – antibiotics; PCP – personal care products; IC – industrial chemicals; P – pesticides; S – stimulants; PP – pharmaceutical products; AD – anaerobic digestion
Source: created by the authors

Thus, based on the results obtained (Table 4), the most effective additional technologies for the anaerobic degradation of various organic compounds were direct interspecies electron transfer using various conductive materials and immobilisation of microalgae, which are used for the degradation of mixed organic waste, and pre-treatment with strong alkali and alkaline hydrogen peroxide for waste of animal origin.

Synergistic effect of anaerobic digestion intensification of organic feedstock for pollutant degradation and increasing biogas yield

Among the studied methods for substance degradation, some also showed effectiveness in increasing biogas yield, particularly direct interspecies electron transfer using various conductive materials and alkaline pre-treatment. Based on a theoretical calculation using averaged literature data, it was established that 1 kg of mixed organic waste produces an average of 400 l of biomethane during normal anaerobic digestion. Whereas, with the application of the direct interspecies electron transfer method, the biomethane yield from 1 kg of this waste increases to an average of 790 l, i.e., by 98.88%, which almost corresponds to the data in the study by L. Wu *et al.* (2023). Meanwhile, 1 kg of cow manure typically yields an average of 295 l of biomethane. However, with the alkaline pre-treatment of waste of animal origin, the biomethane yield from 1 kg of cow manure increases to an average of 1,140 l, i.e., by 261.56%, which is consistent with the data presented in the study by J.R. Kim & K.G. Karthikeyan (2021). Based on the literature data within the conducted meta-analysis regarding the cumulative biomethane potential for anaerobic digestion alone (control) and with the application of direct interspecies electron transfer using various conductive materials and alkaline pre-treatment, graphs of the dependence of technology efficiency on time were constructed (Fig. 4-5).

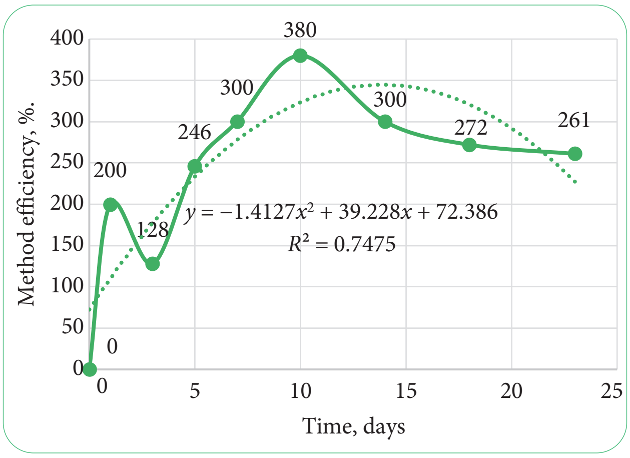

Figure 4. The efficiency of the method of pre-treatment with strong alkali and alkaline hydrogen peroxide in anaerobic digestion of cow manure in relation to time

Source: created by the authors

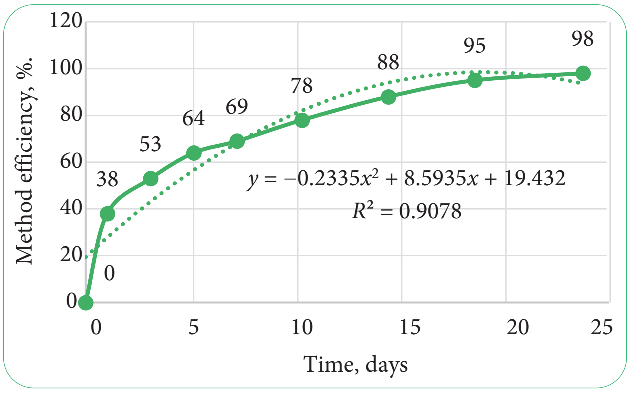

Figure 5. Efficiency of the method of direct interspecies electron transfer in the anaerobic digestion of mixed organic waste in relation to time

Source: created by the authors

During the anaerobic digestion of animal waste with alkaline treatment (Fig. 4), the cellulose in the lignocellulosic biomass of cow manure is broken down. Accordingly, a higher biomethane potential is observed. However, a sharp increase in efficiency is noted on Day 1 followed by a decrease on Day 3. This may be associated with the formation of a bacterial consortium involved in hydrolysis and the facilitation of lignocellulosic biomass hydrolysis treated with alkali. This is followed by a gradual increase in efficiency up to Day 10, followed by a decrease to Day 23. This pattern may be due to the increased availability of nutrients for bacteria, followed by gradual inhibition by volatile compounds and a change in the pH of the medium. The application of the direct interspecies electron transfer method during anaerobic digestion of mixed organic waste (Fig. 5) is implemented simultaneously with anaerobic digestion, unlike the previous one. Therefore, the patterns of efficiency distribution over time differ. There is a gradual increase in the efficiency of the technology in terms of biomethane potential without significant fluctuations, as the method's impact is manifested at all stages of digestion in a cumulative manner. However, the efficiency in terms of biomethane yield is lower compared to alkaline pre-treatment, although the results were the opposite for the degradation of organic pollutants.

By performing statistical analysis using the chi-square method, it was found that all the results obtained were reliable and accurate. The chi-square value for the increase in methane yield when using the direct interspecies electron transfer method during anaerobic digestion of mixed organic waste is 0.13, which is less than the chi-square value of 16.919 ($p > 0.05$) and indicates that the null hypothesis is accepted and the deviations are quite small. At the same time, the chi-square value for the increase in methane yield during anaerobic digestion of cow manure, pre-treated with strong alkali and alkaline hydrogen peroxide, is 0.15, which is also less than the chi-square value of 16.919, so the null hypothesis is accepted and the deviations are quite small. Thus, the results are reliable and quite accurate and indicate that the use of different additional technologies during the anaerobic digestion of different substrates does indeed increase the efficiency of the anaerobic digestion process itself for these substrates.

Based on the conducted meta-analysis, it was established that the application of additional technologies allows not only to increase in the efficiency of pollutant degradation during the anaerobic digestion of feedstock but also to increase in biogas yield. This pattern is associated with the intensification of anaerobic degradation of organic feedstock. As shown in the study by E. Nordell *et al.* (2022), thermal post-treatment of digestate with simultaneous pasteurisation can achieve more complete conversion and mineralisation of organic matter, thereby increasing the volume of biogas produced. Physical-mechanical pre-treatment methods such as grinding (Karuppiah & Azariah, 2019) or extrusion (Olatunji *et al.*, 2021) improve the porosity, flowability, and bulk density of the substrate. All this increases the surface area of fermentable particles, promoting a more efficient breakdown of organic components while simultaneously boosting biogas yield, as noted in the study by K. Obileke *et al.* (2024). The principle behind these studied methods involves biochemical or physical impacts on the structure of organic compounds, leading to the breakdown of chemical bonds and the formation of new substances, including inorganic ones, as highlighted by B. Lee *et al.* (2019) and T. Llano *et al.* (2021). These processes form the basis for the mineralisation of organic matter, as a result of which methane and carbon dioxide are formed in anaerobic conditions as the main components of biogas. Therefore, the transformation of organic matter leads to a synergistic effect in relation to the transformation of pollutants and biogas yield.

Another positive effect of applying digestate post-treatment to intensify the degradation of polluting organic matter is the production of other useful products.

It has been established that the most promising and environmentally safe product is biochar, obtained as a result of pyrolysis of the solid fraction of digestate, which is consistent with the results of research by S. Ghysels *et al.* (2022) on an integrated system of anaerobic digestion and slow pyrolysis of mixed feedstock of plant and animal origin. A systematic approach to the use of biochar involves the purification of the liquid fraction of digestate using biochar, in which the content of pollutants is reduced by more than 95% due to pyrolysis. This approach is justified, since according to the results of the study by A.M. Ali *et al.* (2019) on the content of new organic pollutants in feedstock of various origins (mainly sewage sludge, food waste, and mixed feedstock based on food waste) and two fractions of digestate, sun protective octocrylene and acetaminophen (paracetamol) were found in the highest concentrations in the liquid digestate, while octocrylene and antipyrine TCPP (tris(1-chloro-2-propyl) phosphate) were identified in the highest concentrations in the solid digestate. In addition, biochar can be used for bioremediation of soils contaminated with heavy metals due to the sorbing properties of the porous structure of biochar. On the other hand, digestate binds heavy metals in the soil, based on the complexing properties of organic matter, depending on the ratio of fluorescent components, as shown by the authors P. Skvortsova *et al.* (2024).

It is worth noting that along with traditional, widely used substrates for anaerobic digestion, grouped according to different categories of organic waste, unexplored feedstock, such as coal, also has significant biomethane potential, as shown in the study by P.H. Fallgren *et al.* (2021). In addition, understudied and local feedstock is of particular interest, as its use for biogas and digestate production is a promising way to handle specific types of organic waste, such as sugarcane and solid household waste (Tshemese *et al.*, 2023). The high potential of the fertilizing properties of digestate from local plant feedstock was noted by the authors W. Czekała *et al.* (2020), which ensures compliance with the principle of nutrient recovery in the circular economy and has a positive impact on greenhouse gas emissions (Kowalczyk-Juśko *et al.*, 2023). In addition, the production of biogas from solid household waste landfills is becoming promising due to the installation of degassing systems, as shown in a recent study by I. Vaskina *et al.* (2024). Since this type of waste also contains a wide range of pollutants, the possibility of using the developed technologies increases the scientific interest and practical significance of the research results in this direction. Moreover, mixtures of different wastes used for co-anaerobic digestion, as shown above, differ in the content of pollutants compared to mono-feedstock. Accordingly, the processes of pollutant degradation during anaerobic digestion will have their own specifics due to different microbiological and physicochemical conditions, which require further research and may be one of the directions for further research.

Thus, as a result of the meta-analysis conducted, it was established that the feedstock used for anaerobic digestion to obtain biogas is usually formed from waste with an organic component, which determines the presence of a wide range of pollutants in it. The anaerobic digestion process itself rarely ensures complete degradation of the corresponding groups of pollutants according to their biodegradability and resistance, therefore additional methods of intensification of anaerobic degradation are quite relevant. The maximum synergistic effect for the degradation of pollutants and the increase in biomethane yield was established in the case of the use of direct interspecies electron transfer methods on the example of feedstock from mixed organic waste and alkaline pre-treatment of animal waste. However, these methods require testing on other types of substrates with different properties, chemical composition, and the nature of the impact on the process parameters, including microbiological ones.

Conclusions

The analysed methods for improving the efficiency of anaerobic digestion of different substrates have shown their effectiveness, indicating their great importance and potential for application in biotechnology. The main substrates that are most often contaminated with various organic substances and require the application of effective technologies to improve the result of their anaerobic digestion are sewage sludge, animal waste, and mixed organic waste. As a result of the conducted research, it was found that such a method as direct interspecies electron transfer allows increasing the efficiency of pollutant degradation in mixed organic waste by 180%. In the case of animal waste, it is worth applying alkaline treatment, which will increase the efficiency of degradation of organic pollutants by almost 115%. The degradation of organic compounds in sewage sludge can be increased by 55% by treating it in a thermophilic aerobic reactor in combination with anaerobic digestion. Additional treatment technologies allow not only to ensure the effective degradation of pollutants during fermentation but also to increase the overall efficiency of anaerobic digestion by increasing methane yield. The results obtained indicate that when using direct interspecies electron transfer from mixed organic waste, it is possible to obtain 98.88% more methane, while pre-treatment of animal waste with strong alkali and alkaline hydrogen peroxide makes it possible to obtain 261.56% more methane from this waste. This significantly increases not only the environmental but also the economic component of the application of these treatment technologies.

The results of the study have scientific and practical significance, as they demonstrate the high efficiency and synergistic effect of additional technologies for improving the process of anaerobic digestion and increasing the degree of degradation of organic matter contained in the three most common substrates (mixed organic waste, animal husbandry waste, and sewage sludge). At the same time, this allows for identifying directions for further research aimed at evaluating the efficiency of the studied technologies for environmentally safe management of local feedstock in the context of waste utilisation for bioenergy purposes with the production of biogas and in agroecological purposes through the use of digestate as biofertilizer. Further research will be aimed at developing a laboratory stand and testing the investigated methods on local feedstock with the determination of the efficiency of degradation of organic pollutants for the production of environmentally safe fertilizer from digestate, which will ensure the prevention of chemical pollution of environmental components, including soils.

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Conflict of Interest

None.

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Ефективність руйнування органічних забруднювальних речовин у процесі анаеробного зброджування сировини різного генезису

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Анотація. Дослідження ступеня деградації забруднювальних речовин у процесі анаеробного зброджування та їх вмісту в дигестаті є актуальним науковим питанням, яке продиктовано необхідністю підтвердження безпечності застосування цього продукту як біодобрива для покращення якості сільськогосподарських земель. Мета статті – визначення ефективності руйнування забруднювальних речовин у процесі анаеробного зброджування із застосуванням різних методів додаткової обробки. Для встановлення закономірностей деградації забруднювальних речовин у процесі анаеробного зброджування за різних умов та зі застосуванням додаткових технологій інтенсифікації процесу (ультразвук, застосування хімічних реагентів та вугільної тканини, міжвидове перенесення електронів, іммобілізація мікроводоростей тощо) було застосовано мета-аналіз. Визначення достовірності обраних гіпотез та статистичної значущості отриманих даних було проведено методами статистичного аналізу. Було визначено, що додаткові методи обробки дозволяють підвищити ефективність деградації органічних забруднювачів у змішаних органічних відходах на 180 % (пряме міжвидове перенесення електронів), у відходах тваринного походження – на 115 % (лужне попереднє оброблення), а в осадах стічних вод – на 55 % (шляхом їх обробки в термофільному аеробному реакторі сумісно з анаеробним зброджуванням). Ефективність технології іммобілізації мікроводоростей, що забезпечує видалення забруднювальних речовин із рідкої фракції дигестату, становить 135 %. Також було встановлено наявність синергетичного ефекту додаткових методів оброблення сировини, що ілюструється зростанням кількості виділеного метану на 98,88-261,56 % залежно від виду відходів і методу обробки. Отримані результати доводять високу ефективність додаткових технологій обробки. Практичне значення одержаних результатів полягає в доведеному синергетичному ефекті від застосування додаткових методів обробки сировини та дигестату за рахунок підвищення рівня деградації органічних забруднювачів з одержанням екологічно безпечного добрива та збільшенням виходу біогазу

Ключові слова: виробництво біогазу; дигестат; небезпечні хімічні речовини; органічні відходи; попередня обробка; стійкий розвиток; субстрат

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Assessment of the ecological status of soil cover and design of environmental monitoring in the Ivano-Frankivsk urban community

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Abstract. Due to the increasing technogenic load on the environment, it is necessary to determine the degree of influence of industrial production on the environment. Conducting environmental monitoring of the Ivano-Frankivsk urban amalgamated territorial community will allow for further ecological assessment and forecasting of the environmental status of the studied territory. The aim of the study was to assess the condition of the soil cover of the Ivano-Frankivsk urban community and its surroundings, to determine the relevance of using geographic information systems (GIS) in environmental monitoring. The research used: a statistical method for collecting and analysing databases on the environmental situation with pollution of environmental components; and GIS mapping to identify and display the spread of pollutants using the Kriging interpolation method. A detailed analysis of various methods for monitoring the environmental status has been conducted, including remote and chemical methods. This allowed for identifying the most effective approaches for collecting and processing environmental data. Important aspects of creating an environmental monitoring system for tracking the state of the environment have been considered. Based on the collected data, maps have been created that reflect the distribution of chemical elements in the territory of the Ivano-Frankivsk urban amalgamated territorial community. These maps are an important tool for visualising and analysing the ecological status of soils. A variant of building an environmental monitoring system has been proposed and a project cartographic model has been developed. This will allow for more effective environmental monitoring and planning of measures to improve the ecological status of the area. The use of MapInfo and Surfer software allowed for a detailed analysis of the environment and the creation of a geographic information system for environmental monitoring of the Ivano-Frankivsk urban community. The results of the study have significant practical implications for various fields of environmental management and planning, including for conducting further environmental monitoring, for the spheres of state and local environmental management, public initiatives, and educational programmes

Keywords: geographic information systems; cartography; technogenic impact; field research; concentration coefficient

Introduction

Environmental protection issues are becoming increasingly urgent and pressing. The growth of industrial production, technogenic load, and other anthropogenic impacts negatively affect the environment, especially in cities. Therefore, conducting environmental monitoring and assessing the impact of anthropogenic factors on the urban environment is an extremely important task. Environmental monitoring is a system of continuous monitoring of all environmental components in space and time, accumulating geographic information data on the past and current state of the

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environment. Forecasting changes in environmental parameters under anthropogenic influence using a territory's ecological monitoring system allows for identifying and analysing the state of the environment, which is crucial for biota. Modern challenges associated with climate change, land degradation, and water and soil pollution require new approaches and solutions to preserve the environment and ensure sustainable development. Environmental monitoring using geographic information systems (GIS) and modern technologies is an important research direction that is actively advancing worldwide.

Various international and national institutions, such as UNESCO, the European Environment Agency (EEA), and the National Aeronautics and Space Administration (NASA), actively use satellite data and GIS for monitoring the ecological status (Copernicus, n.d.; Applying NASA data…, n.d.). For example, NASA employs satellite technologies to track climate change, land degradation, and the state of water resources, while the EEA focuses on analysing data on air, water, and soil pollution in Europe. In Ukraine, research in this field is conducted by scientific institutions and individual researchers, including the Research Institute of Geodesy and Cartography and the Institute of Telecommunications and Global Information Space of the National Academy of Sciences of Ukraine. Significant contributions to the development of environmental monitoring methods have been made by researchers such as V. Trysnyuk & Ye. Nahornyy (2024), studied the use of information technologies for processing radioactive contamination data, and O. Trofymchuk *et al.* (2020), analysed hazardous processes in the geological environment and issues of environmental safety.

Recent publications on the use of GIS in environmental monitoring can be found in academic journals, conference proceedings, and scientific collections. The publication by P.K. Badapalli *et al.* (2022) explores various applications of GIS in tracking and assessing the state of the environment. This is relevant due to the deepening problem of land degradation and desertification in semi-arid regions. The use of modern data collection and analysis methods, such as Landsat 8 operational land imager and thermal infrared sensor, land surface temperature, and normalised difference vegetation index, allows for efficient detection and tracking of changes in the ecological state of territories. This enables the development of strategies and measures to prevent soil degradation and desertification, as well as ecosystem restoration. The research by Y. Anpilova *et al.* (2020) reflects the relevance of using modern data analysis methods, including ground-based interferometry, for monitoring geological structures. The use of GIS allows for more accurate assessments of the impact of the Solotvyno agglomeration mines on the environment and life support systems in the transboundary basin of the Tisza River. Analysis has shown a mathematical relationship between surface deposits and their radial increase, which is crucial for risk forecasting and safety enhancement. Current research at the Institute of Telecommunications and Global Information Space covers a wide range of topics. Key research areas include the use of GIS and Earth remote sensing technologies, mathematical modelling methods and the solution of urgent environmental safety problems (Trofymchuk *et al.*, 2020). Among them, it is important to note the study of hazardous processes in the geological environment and soils, in particular, particularly issues related to landslides. The use of satellite technologies, the detection of soil degradation, and the timely response to these processes require timely information and the availability of a database. The ecological safety system aims to predict and prevent technogenic and ecological emergencies, as noted by O. Butenko *et al.* (2020).

In the Ivano-Frankivsk Region, there is a diverse soil cover consisting of natural and technologically transformed soils. General soil degradation in urban systems occurs under the influence of urban air and hydrosphere. Despite the natural capabilities of biological self-purification of the soil, its mechanisms can be seriously disrupted by overloading with various types of pollution. A particular problem in the cities of Tysmenytsia and Ivano-Frankivsk is the presence of a cultural layer, which contains traces of human activity and various pollutants. These layers, as objects of historical and archaeological study, contain a large amount of various pollutants that negatively affect the soil cover and the natural environment. In this regard, conducting environmental research and monitoring the state of the soil cover is of great importance for preserving the environmental sustainability of the urban environment. In this context, this study aimed to conduct field ecological research to investigate the ecological state of the Ivano-Frankivsk urban amalgamated territorial community (UATC) and identify possible ways to improve it. In particular, the study investigated the state of the soil cover in the Ivano-Frankivsk urban community and the application of GIS in further monitoring of this region.

Materials and Methods

To determine the technogenic impact, it is necessary to first understand the scale of the study; in this research, it is the Ivano-Frankivsk UATC. Considering the specific features of the geological structure, geomorphology, distribution of different soil types, landscape structure of the territory, and the requirements for the scale of research, an environmental monitoring network was established comprising 6 profiles and 117 geo-ecological polygons – observation points on a plot of about 265 km^2. These points are evenly distributed across the entire study area. The scale of the research is 1:100,000 (Fig. 1). The geographic coordinates and absolute heights (altitudes) of the points were determined using a GPS device eTrex 30, which used Garmin Custom Map user maps and satellite imagery. The operating modes of the eTrex 10 allowed for the creation of accurate routes to simplify orientation on the terrain, as well as the use of 3D mode.

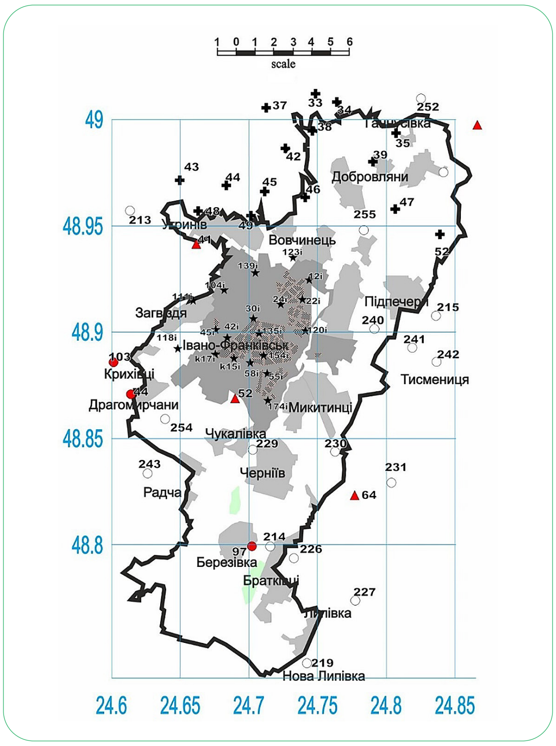

Figure 1. Map of the factual material
Source: created by the author

The goal of the field ecological studies was to create geographic information maps and study soil disturbances based on analysis and observation to compile maps of soil pollution distribution. During the routes, soil samples were collected. The main focus was on enterprises with discharges and emissions, railways and motorways, etc. Field studies were carried out using parallel routes and loops, which were linked to the type of landscape. Ecological studies of parallel routes were used to create ecological maps with pollution zones that have a north-south orientation in the study area. Therefore, the research routes were laid out from the southeast to the northwest and vice versa, as well as from the southwest to the northeast. These routes were laid out along forest clearings, paths, field boundaries, and other objects on the map. The essence of the radial-loop method lies in the fact that the route polygon was divided into parts that were studied in circular and radial directions. The radial-loop method allows for a detailed study of the soil cover, studying complex landforms, digitising the impact of pollution sources, and degradation of the geological environment. Thus, with the help of field expeditionary research, the entire territory of the studied polygon within the Ivano-Frankivsk urban community was evenly studied.

Sampling points for various analyses were located on profile lines of routes every 0.5-2 km. Samples were taken at three sites to determine the input of pollutants into the soil. The sampling procedure was carried out in a network corresponding to the district-level study scale (1:100,000). A mandatory condition was the indication of geocoordinates, physical and geographical characteristics, date, and time of sample collection. Samples were collected using an envelope scheme measuring 5×5 m and combined into a single sample, whenever possible, at least 50 m from the road in an open area. On intact soils, sampling was carried out from a depth of 10-20 cm. On anthropogenically altered soils where undisturbed lands were absent, samples were taken at a depth of 20-30 cm. Rock fragments, aboveground and root parts of plants were removed from the sample. The weight of the soil sample was 1.5 kg. Samples were taken using a drill with a 50 mm diameter metal cup in accordance with the use of landscape, geomorphological, and soil maps to cover all types of zonal soils with an appropriate grid. In total, 117 soil samples were taken at geo-ecological polygons. Analyses of the samples were carried out in the universal laboratory of Ivano-Frankivsk National Technical University of Oil and Gas, at the Department of Ecology, using Fourier IR spectrometer FSM 1201 (Ukraine) designed for measurements and scientific research in the mid-infrared spectral region. The pedosphere was assessed from two positions: from an ecological standpoint, characterised by changes in soils, their degradation, and pollution, and a general characteristic that covered the spatial distribution of the main soil types according to D. Zorin (2023).

Based on the obtained analysis results, databases were created in Microsoft Excel and then in MapInfo Professional, which are needed for the interpolation of ecological maps in Surfer. The first step was to calculate all isoconcentrates in Microsoft Excel to determine anomalous and background concentrations in soils to assess the degree of pollution relative to the clarke concentration. To determine background concentrations *B*, the contents of elements C_i are grouped by characteristic intervals into columns of the table, and for each ranked row of the column, the average content of all intervals of the element is calculated. The background was determined for each chemical element in the soil. To do this, it is necessary to determine the nature of the content of the pollutant in most (2/3) of the samples, that is, 66.6%, after which the average content of these indicators is determined. Anomalous values of C_a are concentrations that are 3 times higher than the background. Based on the background values, the total pollution indices (TPI) are calculated. TPI is the sum of the concentration factors, and the concentration factor is the ratio of the concentration to the background or maximum permissible concentration (MPC) (Zhou & Li, 2021; Arkhypova *et al.*, 2021; Adamenko *et al.*, 2022):

$$Z_c = \sum_1^n \frac{C_i}{C_f}, \qquad (1)$$

where Z_c is the TPI; *n* is the number of indicators used for calculating the index; C_i is the concentration of the chemical element; *B* is the background level. These calculations enable the construction of interpolation maps of soil contamination according to the corresponding isoconcentrates. Anomalous content is defined as anything that exceeds the background level by three times.

$$C_a = C_i - B - C_c, \qquad (2)$$

where C_a is the anomalous content; C_i is the concentration of the chemical element in the soils; B is the background level; C_c is the clarke concentration. The interpolation of ecological maps showing the distribution of a particular element in the soils of the Ivano-Frankivsk urban community was plotted on the map with isoconcentrate lines – *ik*. The average content of the ranked series of concentrations in each characteristic interval corresponds to the arithmetic mean value of that interval. This value can be used to characterise the average level of concentration of a chemical element within a defined range.

Results

In the Ivano-Frankivsk Region, there is a developed soil cover, which consists of natural and technogenically transformed soils. The soils of urbanised areas are subject to the same negative impacts as urban air and hydrosphere. Even though the soil has certain capabilities for biological self-purification, it breaks down and mineralises the waste that enters it. The mechanism of this process can be disrupted due to its overload (physical, chemical, mechanical), which leads to degradation. In the Tysmenytsia and Ivano-Frankivsk, the so-called cultural layer (transformed soils) is most common, in which traces of human activity are found: broken bricks, glass, plastic products, construction debris, fragments of concrete, clay shards, and wood. Cultural layers in cities are objects of historical-archaeological and geological study. They also concentrate mechanical, chemical, biological, and radioactive pollution. Therefore, cultural layers should also be mapped and studied by soil scientists and ecologists. Such soils are characterised by compaction, which worsens air exchange, leads to nitrogen starvation of green spaces, and suppresses the activity of soil microorganisms. A large amount of technogenic material is characterised by increased drainage, deteriorates the nourishment of plants, especially trees, and disrupts the water environment. Burning leaves can harm the functioning of park phytocenoses, as it disrupts the main geochemical cycle of nutrient return to the soil. The results of the analysis of 117 soil samples by the Ivano-Frankivsk Regional Sanitary and Epidemiological Station are summarised in the database (Table 1).

Table 1. Database of soil sample analysis in the Ivano-Frankivsk UATC

No.	Sample No.	Element content, mg/kg, C_i						TPI
		gross			mobile		gross	
		Hg	Cd	Pb	Cu	Zn	Ni	$Z_c = \sum_1^n \frac{C_i}{C_f}$
	Background→	0.001	0.011	1.5	0.44	3.5	0.24	
	MPC →	2.1	1.0	20.0	3.0	23.0	4.0	
1	● 22	0	0	0	0	0.001	0	0.00013
2	○ 201	0.9	1.2	20.3	3.6	18.4	0	403.8864
3	▲ 50	0	0	0	0.001	0.006	0	0.006665
4	● 23	0	0	0.001	0	0.04	0	0.006392
5	○ 202	–	0.001	0.007	0	0.03	0	0.262147
6	○ 203	2.2	1.3	16.4	.1	16.2	0	0.262147
7	○ 204	–	–	–	–	0.3	–	0.262147
8	○ 210	0	–	0.04	–	0	0	0.047059
9	○ 211	0	–	0.1	–	0	0	0.117647
10	● 32	0.007	–	0.2	0.01	0	0	1,587.398
11	○ 212	2.5	1.6	24.2	3.5	24.1	4.6	510.6136
12	○ 213	0	–	0.3	0.03	0.004	–	0.529933
23	○ 243	0.03	0.004	0	0.03	–	1.70	25.8352
24	○ 254	0.007	0.001	4.75	0.07	1.30	1.70	216.4139
25	● 44	0.01	0.004	0	0	0.2	0	1,001.098
26	▲ 52	0.04	0.003	0	–	–	0	245.334
27	○ 206	0.001	0	0	–	–	0	0.007143
28	▲ 42	0.06	0	0	–	–	0.57	2,614.204
29	○ 207	–	–	4.90	0.30	3.50	0.57	11.6524
30	○ 208	0.01	–	0.03	–	0	0	0.106723
31	○ 209	0.003	–	0.06	–	0	0	0.092017
32	★ K17i	2.3	0.9	14.2	2.8	24.3	5.6	708.8843
33	★ 111i	1.6	2.1	12.8	1.9	18.9	4.9	3,892.35
34	★ 139i	2.1	1.4	24.6	3.2	16.6	7.2	1,754.929
35	★ 12i	2.4	1.2	31.2	4.2	29.2	8.4	744.0283
36	★ 24i	0.8	0.8	36.6	1.9	24.4	5.4	748.1308

Table 1. Continued

No.	Sample No.	Element content, mg/kg, C_i						TPI
		gross		mobile			gross	
		Hg	Cd	Pb	Cu	Zn	Ni	$Z_c = \sum_1^n \frac{C_i}{C_f}$
	Background→	0.001	0.011	1.5	0.44	3.5	0.24	
	MPC →	2.1	1.0	20.0	3.0	23.0	4.0	
37	★ 45i	1.6	1.1	24.9	2.8	19.6	4.6	2,560.304
38	★ 174i	1.4	1.3	41.2	3.1	18.1	4.9	5,081.288
39	★ 58i	0.7	1.2	46.3	3.5	24.7	9.2	1,184.39
41	★ 104i	0	0	0	0.1	0.03	0.001	5.597702
42	★ 42i	0	0	0	0.4	0.06	0.009	32.41076
43	★ 22i	0.001	0.004	0.001	0.7	0.2	0.006	25.18538
44	★ K15i	0.003	0.001	0.004	0.03	0.9	0.01	5.625501
45	★ 55i	0	0	0.001	0.001	0.2	0.04	50.25536
46	★ 154i	0	0	0.01	0.07	0.8	0.06	100.8612
47	★ 120i	0	0	0.06	0.2	0.004	0.003	16.26425
48	★ 123i	0.009	0.003	0.9	0.1	0.001	0.001	22.46703
49	★ 30i	0.04	0.001	0.4	0	0	0	46.0063
50	★ 118i	0.01	0.01	0.03	0	0	0	52.60672
96	+ 40	0	0.01	1.4	0.2	1.1	0	5.466945
97	+ 41	0	0	0.3	0.6	1.3	0	4.051844
98	+ 42	3.6	1.4	18.4	6.8	39.7	3.9	2,614.204
99	○ 248	–	–	0	0	0.04	0	
100	+ 47	0	0.01	1.4	0.6	1.5	0	7.872038
101	+ 52	2.0	0.06	31.7	2.6	30.8	4.4	1.035714
102	○ 249	–	0.001	0	0	0	0	0.47858
103	○ 250	–	0.004	8.05	0.2	2.4	0.23	13.73774
113	○ 251	0.006	–	3.8	0.23	1.6	0.73	10.63055
114	+ 27	0	0.05	1.6	0.2	0.6	0	15.63705
115	+ 28	0	0.03	1.3	0.1	0.5	0	9.682836
116	○ 252	2.4	0.001	16.8	2.9	24.3	–	122.3846
117	○ 253	0.004	–	2.6	< 0.005	2.2	1.06	9.792527
	isoconcentrates (*ik*) for interpolating pollution on maps	0	0	0	0	0	0	
		0.003	0.002	0.005	0.004	0.003	0.004	
		0.009	0.004 *B*	0.05	0.09	0.047	0.05	
		0.014 *B*	0.008	0.54	0.17 *B*	0.93	0.18 *B*	
		0.042 *a*	0.012 *a*	0.82 *B*	0.42	4.0	0.54 *a*	
		0.15	0.03	2.3	0.51 *a*	7.67 *B*	0.66	
		1.4	0.9	2.46 *a*	1.4	18.3	2.0	
		2.1 MPC	1.0 MPC	11.5	2.5	23.0 *a* MPC	4.0 MPC	
		2.6	1.4	20 MPC	3.0 MPC	30.3	5.8	
		–	–	30.7	4.1	–	–	

Note: ○ 253 sampling points of the Tysmenytsia Environmental Monitoring System (EMS); + 47 sampling points in the territory of Private joint stock company "Ivano-Frankivskcement"; 97 sampling points of the Bohorodchany gas transportation node; ▲ 52 sampling points of the Ivano-Frankivsk Regional EMS; ★ 22i sampling points of the Ivano-Frankivsk urban EMS; B – background values; a – anomaly
Source: compiled by the author

The worst soils have an unsatisfactory ability to remove toxic chemical elements such as Hg, Cu, Pb, F, Mn, and others. These elements gradually spread throughout the soil cover and accumulate, especially near industrial emission sources. For instance, in areas near superphosphate and mercury plants, 1 kg of soil can contain from 1.3 to 5.6 mg of mercury. In soils with a pH below 5.0, the mobility of elements such as Cu, Cd, and other heavy metals increases. Some microorganisms found in the soil can convert heavy metal salts into various forms – soluble or insoluble, which affects the disruption of trophic links and can lead to the disappearance of invertebrates. Negative impacts on soils are caused by radionuclides, phenols, petroleum products, and pesticides. On private and summer cottage plots, excess mineral fertilisers quickly spread throughout the territory, significantly worsening the conditions for the development of plant plantations. Significant loading of soils by vehicles, as well as the impact of anthropogenic influence, lead to their compaction: if the norm is 10 kg/m^2, then in places of active recreation it increases to 30-40 kg/m^2 and reaches a depth of 30 cm, which leads to a deterioration in soil quality. During ecological studies of the soil cover of the Ivano-Frankivsk urban community, all these features should be taken into account. The determination of anomalous and background concentrations in the soils was carried out. Table 2 shows the calculations of *B*, and C_a for the interpolation of C_i.

Table 2. Calculations of *B*, C_a for interpolating C_i
of eco-technogeochemical soil maps with isolines of equal concentration levels

Intervals of content					
0	**0.001-0.005**	**0.006-0.01**	**0.02-0.1**	**0.2-2.0**	**> 2.0**
0	0.001	0.01	0.03	0.9	2.2
0	0.004	0.007	0.04	1.6	2.3
0	0.003	0.01	0.04	0.8	2.1
-	0.001	0.009	0.06	1.6	2.4
-	0.003	0.01	0.06	1.4	2.3
-	0.001	0.01	0.03	0.7	2.5
-	0.003	0.007	0.9	1.9	3.4
-	0.003	0.01	0.02	1.6	2.2
-	0.002	0.01		1.6	2.3
-	0.001	0.01		1.4	3.6
-	0.003	0.01		1.9	2.4
-	0.001			1.7	3.9
-	0.004			2.0	
0	0.003			1.6	
0	0.006			0.9	
0	0.004				
$\sum_{n=1}^{47} = 0$	$\sum_{n=1}^{16} = 0.043$	$\sum_{n=1}^{11} = 0.103$	$\sum_{n=1}^{8} = 1.18$	$\sum_{n=1}^{15} = 21.6$	$\sum_{n=1}^{12} = 31.6$
$\overline{x} = \frac{0}{47} = 0$	$\overline{x} = \frac{0.043}{16} = 0.0027$	$\overline{x} = \frac{0.103}{11} = 0.009$	$\overline{x} = \frac{1.18}{8} = 0.15$	$\overline{x} = \frac{21.6}{15} = 1.4$	$\overline{x} = \frac{31.6}{12} = 2.6$
$ik = 0$	$ik = 0.003$	$ik = 0.009$	$ik = 0.15$	$ik = 1.4$	$ik = 2.6$
B (82 out of 117 parameters, i.e., 66.6%) $= \frac{0+0.043+0.98}{47+16+9} = 0.014$ $a = 3 \times B = 3 \times 0.014 = 0.042$ *ik* for map interpolation: $0 - 0.003 - 0.009 - 0.014 - 0.042(B) - 0.15(a) - 1.4 - 2.1(\text{MPC}) - 2.6$					

Source: created by the author

Technogenic impact and environmental pollution lead to the transformation and changes of landscapes. By quantitatively assessing these changes, it is possible to determine the ecological state of individual components of the ecosystem (landscape), or its entirety, by analysing geochemical coefficients (Moss *et al*., 2020; Bilas *et al*., 2022). Several methodological approaches to assessing the ecological state have been proposed by various authors, but they all depend on the amount of analytical material that characterises the degree of geochemical research of a specific territory. The more analyses of soils, water, air, and vegetation are carried out, the more accurately the ecological state of the landscape can be assessed. Indicators of such an assessment include concentration factors, pollution indices, and other parameters. Calculating these quantitative indicators allows for evaluating the degree of environmental changes, which can be categorised as normal (favourable), satisfactory, tense, complex, unsatisfactory, pre-crisis, critical, or catastrophic (Lysytsia & Mudrak, 2022).

In each component of the landscape (for example, soil, water, air, etc.), various chemical elements can be found, which at certain concentrations are not harmful to humans, and are even beneficial and necessary. The average concentration of elements in the Earth's crust (lithosphere) is considered a clarke value (Table 3). Similar clarke values are calculated for soils, water, etc. However, in each region, depending on the geological structure, soil type, geographical zoning, and other factors, there will be its own, characteristic only for this region, average content of elements. Such average content is known as a regional background. It can be greater or less than the clarke values, depending on specific conditions (Adamenko *et al.*, 2022).

Table 3. Clarke values of the lithosphere

Element	Clarke values	
	%	mg/kg
Hg	8.3×10^{-6}	0.0083
Cd	1.3×10^{-5}	0.13
Pb	1.6×10^{-3}	16
Cu	4.7×10^{-3}	47
Zn	8.3×10^{-3}	83
Ni	5.8×10^{-3}	58

Source: compiled by the author based on I. Klymchuk *et al.* (2022)

Therefore, if there is an excess of the clarke values, and subsequently the background, the concentrations will be anomalous and harmful to the normal development of ecosystems. Toxic, i.e. harmful to the human body, contents of a particular element in the Ivano-Frankivsk urban community are values that exceed the MPC. Clarke concentrations are the ratio of the average content of a particular chemical element in the environment, or any object in nature, compared to some standard or baseline value. Clark concentrations are represented by known data (Table 3), while the background was calculated based on specific factual material, which is reflected in Table 2.

For accurate interpolation of elements on maps of geochemical environmental pollution, isolines are drawn through characteristic intervals, rather than arbitrarily. This approach allows for more accurate and representative results by accounting for concentration variations within defined ranges. Only such a construction of cartographic material will convey the nature of the distribution of the element in the environment. The map must necessarily include isolines of a ranked series, background, anomalous values, MPC, and maximum concentrations from the database to justify the characteristic distribution of the concentration of a particular element in its intervals. Such interpolation must be carried out for each element in order to study all the features of their distribution in soils and accumulation in the studied area. Elemental eco-geochemical maps of the content of various elements in soils and maps of TPI are generated using data interpolation in automatic mode on a PC, using the Surfer (Fig. 2-8).

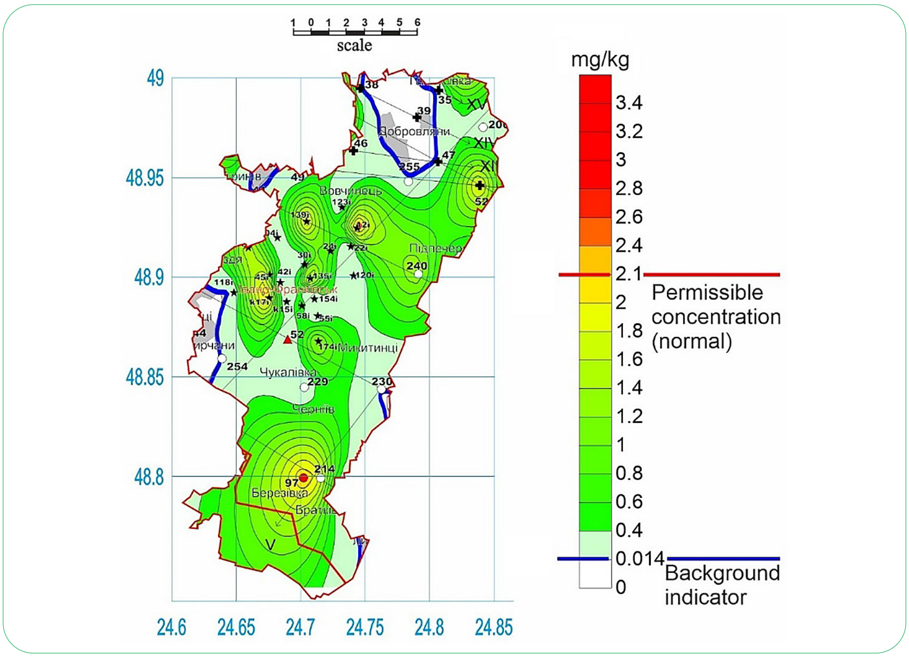

Figure 2. Hg concentration, mg/kg of soil

Source: created by the author

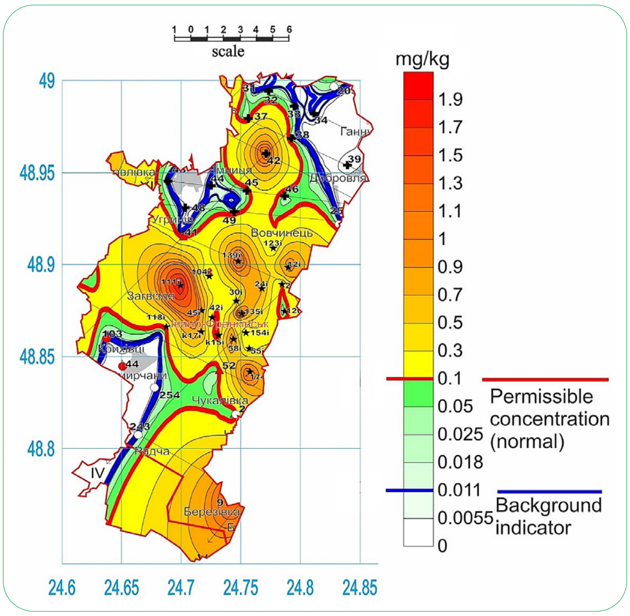

Figure 3. Cd concentration, mg/kg of soil

Source: created by the author

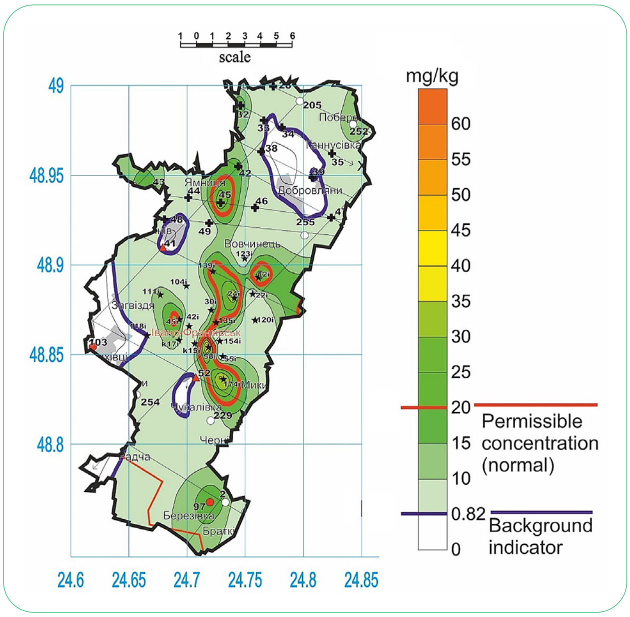

Figure 4. Pb concentration, mg/kg of soil

Source: created by the author

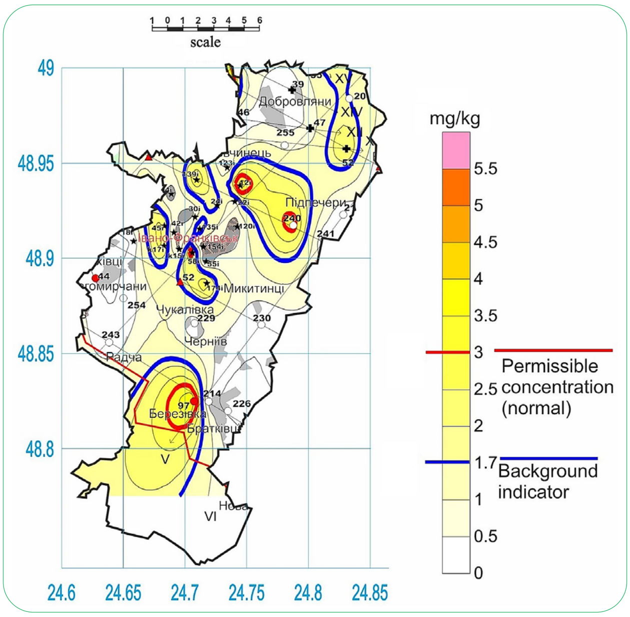

Figure 5. Cu concentration, mg/kg of soil

Source: created by the author

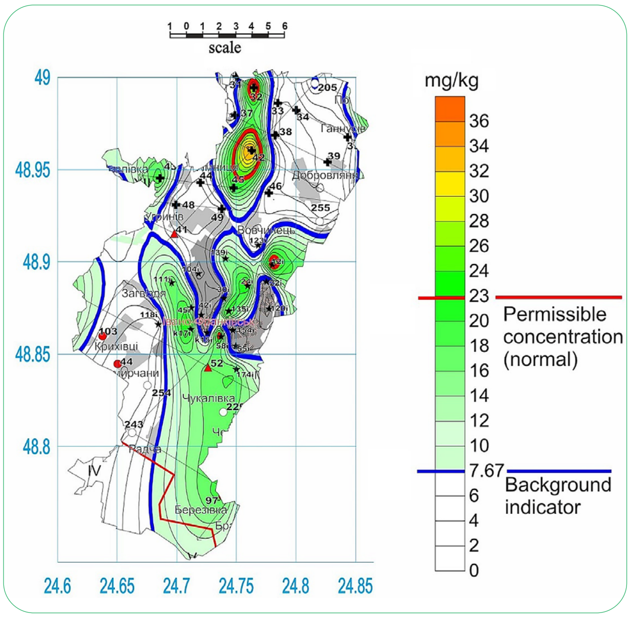

Figure 6. Zn concentration, mg/kg of soil

Source: created by the author

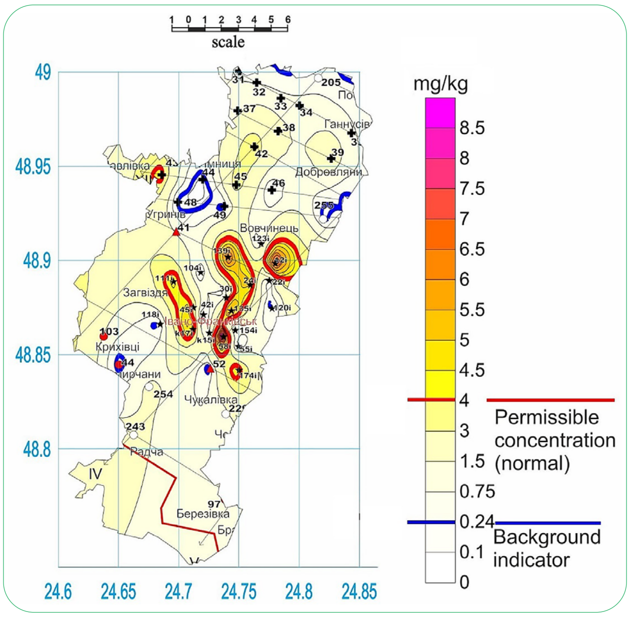

Figure 7. Ni concentration, mg/kg of soil

Source: created by the author

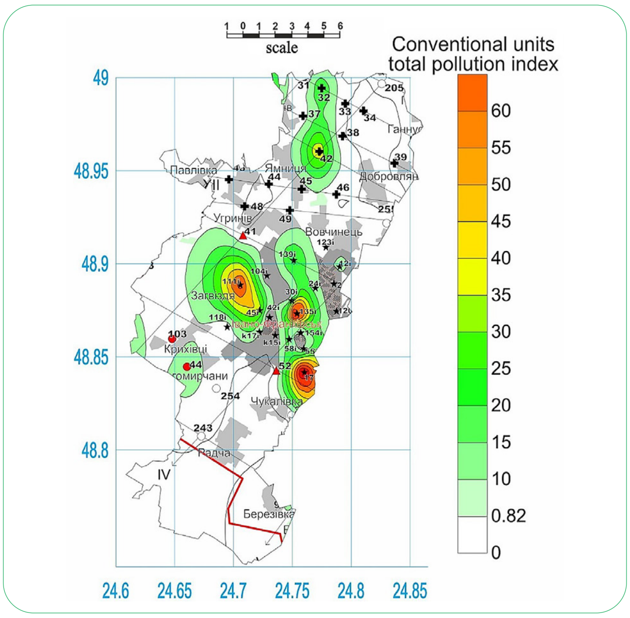

Figure 8. Soil TPI

Source: created by the author

The map of soil TPI (Fig. 8) shows the distribution of zones within the Ivano-Frankivsk UATC where there is an excess of background values and where the MPC is exceeded. Interestingly, when comparing these zones with the routes of main gas pipelines, the locations of compressor stations, and underground gas storage facilities, their interconnection can be detected. However, there are such pollution zones where technogenic sources are unknown. The authors of the study believe that for final conclusions about the impact of technogenic objects on the environment, it is necessary not only to study soils but also to study all other components of the landscape. Soil TPI is an indicator that takes into account the combination of various pollutants in the soil, including the presence of toxic metals, chemicals, radionuclides, etc. (Trigub & Domuschi, 2023). This indicator provides a general assessment of the degree of soil pollution and allows for a comparative analysis between different territories. It is measured in units that correspond to certain standards or pollution norms.

According to the obtained results, the construction of a design geoinformation map for environmental monitoring of the Ivano-Frankivsk urban community should be based on the following principles. Data collection: the first stage is the collection of relevant data on the state of the environment, such as the concentration of various pollutants in soils, water, air, etc. This data can be obtained from various sources, including laboratory measurements, satellite imagery, monitoring sensors, etc. After data collection, geoinformation analysis is carried out, which includes data processing and analysis using GIS technologies. This may involve creating digital maps, using analytical methods to detect patterns and trends in pollution, identifying pollution hotspots, and so on. Visualisation of results: one of the main aspects of a design geoinformation map is the visualisation of the obtained results. This can be done by creating thematic maps, graphs, and charts that illustrate the distribution of pollutants, their concentration, trends of change, etc. Interpretation and analysis: the final stage is the interpretation and analysis of the obtained results to formulate conclusions and recommendations. This may include identifying potential risks to human health and ecosystems, establishing the causes of pollution, assessing the effectiveness of monitoring measures, and increasing public environmental awareness.

Overall, the construction of a design geoinformation map for environmental monitoring (Fig. 9) is based on the integration of GIS data, its analysis, and visualisation to obtain a comprehensive understanding of the state of the environment and develop strategies for conservation and environmental protection. According to the specified functions for administrative management bodies of the Ivano-Frankivsk UATC, the geoinformation map of environmental monitoring should include the following interrelated structural elements: databases and data banks of element concentrations in all landscape components; forecasting the spread of chemical elements in the natural-anthropogenic system based on calculation-graphic methods; determination of MPC zones of harmful substances in the studied area; interpolation of pollution and modelling the distribution of pollution; reporting the results of the conducted work to determine the environmental status of the study area and measures for its improvement; social development programmes aimed at increasing the environmental safety of the population of the area. These elements interact with each other, providing the necessary information for making management decisions regarding the environmental safety of the population. The geoinformation map should reflect these functions in the corresponding layers and combine them for convenient analysis and use by management bodies.

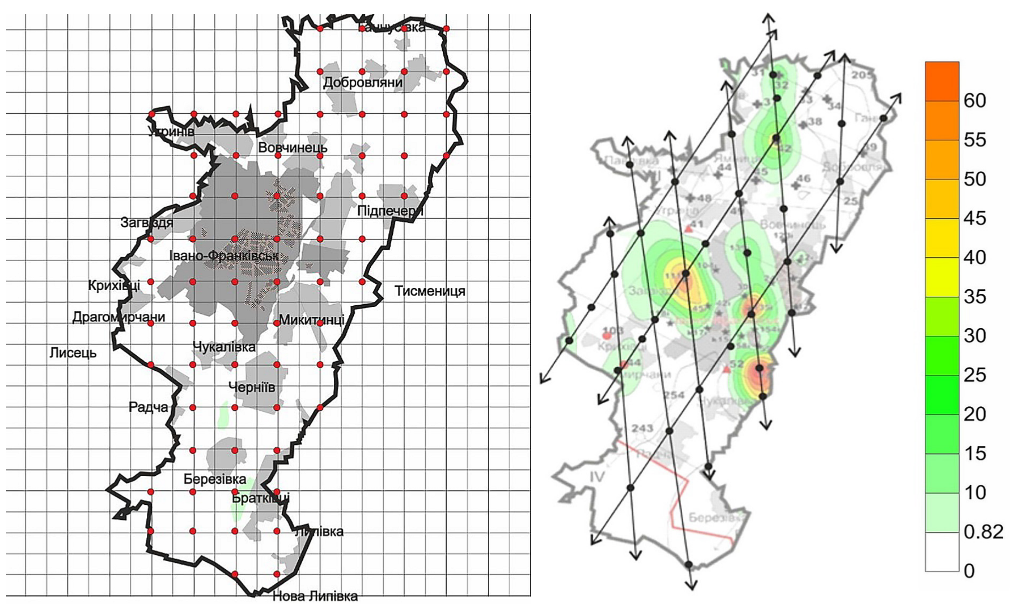

Figure 9. Design map of environmental monitoring of the territory (parallel routes and loops)
Source: created by the author

A GIS for environmental monitoring can be effectively organised by dividing it into problem-oriented blocks and thematic layers of information according to their functional purpose. The geoinformation support of such a system should contain the following thematic layers of information. General physical-geographical information, which includes hydrological networks and water bodies; settlements; administrative boundaries; relief; characteristics of the phytosphere; communication routes (land and underground transportation highways, heat pipelines); power transmission lines, etc. Sources of negative environmental impact, such as discharges and emissions; and household waste. Geo-ecological polygons, which include: sampling points and research routes. Natural protected areas, which may include: water protection zones and historical monuments, etc. Environmental characteristics, containing layers of pollution by various chemical elements in all landscape components: atmosphere; hydrosphere; lithosphere; geomorphosphere; geophysics sphere; pedosphere. Health protection and socio-domestic conditions, including demography and disease incidence of the population, etc. Categorising information in this way ensures convenient access to data and their analysis for making effective management decisions regarding environmental safety.

Collecting information about the state of the soil cover is an important component of the environmental monitoring system. For this purpose, laboratory analyses are used, or special automatic devices that can check the level of harmful substances. After obtaining the results, they are entered into a Microsoft Excel database for further analysis and use in solving environmental problems. The database containing information about the soil cover includes data on environmental pollution. The data bank should reflect the geographical coordinates of sampling points, stationary posts, or the locations of mobile laboratories, as well as the time of measurements and physical-geographical references. This database includes data on production and processing facilities, such as enterprises, workshops, as well as information on emissions or discharges. Planning databases on soil cover or other monitoring objects is carried out in accordance with the above principles (Table 2).

Thematic layers in GIS related to the analysis of major pollution sources should be represented using appropriate cartographic material. Databases containing information about the object under study, along with the corresponding cartographic material, allow obtaining answers to the following queries: the physical-geographical characteristics of the study area (location, length of communication routes, the area of the catchment basin, altitude, etc.); which area is polluted with harmful substances; which zones exceed MPC levels; which zones do not exceed background indicators (natural contents, clean unpolluted areas); which objects emit specific harmful substances and which harmful substances are distributed in the study area can be determined using databases with corresponding cartographic material; which enterprises negatively impact the environmental condition. By overlaying thematic layers in GIS, it is possible to conclude the source of environmental hazards to make appropriate management decisions. For example, by overlaying concentrations of Cd, Zn, Ni, or the TPI on physico-geographical thematic layers, a map of the current ecological situation of the study area is created.

Discussion

Within the framework of environmental monitoring of the Ivano-Frankivsk urban community and the analysis of geochemical mapping, it is necessary to emphasise the significant contribution of a number of recent studies that consider the main tools of geochemical mapping. In particular, J. Wang *et al.* (2024) in their article on mapping geochemical anomalies taking into account the instability of mineralisation-related element associations, consider the fundamental tools of geochemical mapping for studying the distribution and behaviour of economically significant elements and providing useful information about geological processes. However, the quantitative assessment of uncertainty associated with geochemical mapping has recently become a subject of general concern. This study proposes a procedure that involves defining homogeneous clusters, recognising element associations for each cluster, and identifying geochemical anomalies to account for the uncertainty of element associations in geochemical mapping. In the current study, GIS and pollution interpolation have indeed become key tools for analysing and visualising environmental data. The use of GIS allows not only to collection and analysis of pollution data but also to integration of it into a spatial context, which contributes to a better understanding of the distribution of pollution in the environment.

B. Zhou & X. Li (2021) developed software and wrote an original project. The project aims to understand the situation of agricultural environmental pollution by chemical pesticides based on GIS, understand the situation of agricultural crops and the main situation of the use of agricultural crops, and provide instructions and recommendations for monitoring environmental pollution. In their research, T. Kozlowski *et al.* (2023) developed information technology projects aimed at developing intelligent environmental monitoring systems. These projects are based on standardised requirements for software development defined in ISO 25010. These requirements are used as a primary tool for creating business-oriented "smart" environmental monitoring systems. The research methods in these articles describe artificial intelligence algorithms and models used for data analysis and the development of digital solutions. The authors of the current study propose solving these problems through monitoring and sampling the quality of all environmental components and analysing pollutants using statistical analysis, data collection, and processing to create cartographic material. In other words, it is proposed to study all components of the natural and anthropogenic environment. In previous studies, D. Zorin (2022) developed electronic cartographic GIS models of the environmental state of the Dniester Canyon, which describe the assessment of all environmental components.

In the research of L. Arkhypova *et al.* (2021), the idea of expanding the potential use of renewable energy sources in the Carpathian region by creating a set of maps in the GIS MapInfo for each type of renewable energy is considered. For comparison, this article describes obtaining accurate interpolations of elements; the maps should use characteristic intervals, rather than arbitrarily from polygon to polygon. This will allow for obtaining more accurate and representative results, as it will be able to take into account variations in concentrations within defined ranges. Only such an approach to constructing cartographic material will convey the nature of the element's distribution in the environment, according to the methodology described in this article above. Also, data on the state of vegetation and water resources in different territories can be obtained using modern technologies such as studying satellite images of degraded areas, GIS, and the differential vegetation index, the normalised differential humidity index, and the differential water index. A. Dzyba & V. Kyriienko (2024) assessed biomass growth in the Kakhovka Reservoir using these methods. A strong correlation between plant growth rates and their moisture availability was revealed by studying the relationships between indicators; a comparable study was conducted by M. Kutia *et al.* (2023) in Changsha, China.

Interpolation of data on soil or air pollution allows obtaining an estimate of the pollution distribution over the entire study area, even in places where samples were not collected. The application of interpolation methods, such as Kriging, can provide accurate results that are useful for making decisions on environmental protection and developing pollution reduction strategies. However, it is important to remember the limitations of interpolation methods, such as dependence on the location of the original data and the possibility of artefacts occurring as a result. In addition, the accuracy of interpolation can depend on the uniformity of the location of data points and the consideration of various factors that affect the distribution of pollution. In the future, for further development of research in this area, it may be useful to combine GIS interpolation methods with other analytical and statistical methods to obtain more accurate and reliable results.

The research of V. Trysnyuk & Ye. Nahornyy (2024) highlights the importance of using information technologies, particularly interpolation methods, for processing radioactive contamination data. Taking errors into account in measurements and utilising interpolation methods allow for accurately describing fields of radiation contamination in the area. This helps to ensure effective monitoring and protection of the population after nuclear events, contributing to the preservation of public health and safety. In the study by I. Krasovska *et al.* (2020), the ecological state of the border territories of Poland and Ukraine is considered, focusing on water pollution in rivers and its potential negative consequences. Through a comprehensive analysis, the main environmental factors have been identified. The study supports the necessity of an interdisciplinary approach that considers the diversity of monitoring data and applies modelling to predict pollution trends in river systems, facilitating timely interventions to prevent adverse ecological impacts.

The relevance of using GIS in environmental monitoring lies in its ability to provide a comprehensive analysis and visualisation of environmental data on a geographic map. GIS allows the integration of a variety of information about pollution, natural resources, terrain, transportation networks, and other environmental parameters, which allows the making of objective conclusions about the environmental state of a territory. In addition, GIS contributes to more effective monitoring of changes in the environment and the development of strategies for preserving natural resources and preventing pollution. The use of GIS in environmental monitoring is a key tool for making informed decisions in the field of environmental protection and sustainable development. It is advisable to further integrate into the GIS monitoring system modules for monitoring all components of the environment, their spatial distribution, a module for forecasting potential landscape changes, a module for remote sensing of the Earth, and based on relief isolines analysis, develop 3D models of the studied territory. Thus, the application of GIS provides the opportunity to create a unified information space for territorial management services, which contributes to increasing the efficiency and convenience of data processing and analysis (Adamenko *et al.*, 2022).

Comparing older technologies with modern innovations, including open cloud solutions that allow for the analysis and visualisation of large volumes of heterogeneous geodata and time series of observations of dynamic parameters, as shown by L. Davybida *et al.* (2021), it can be seen that the use of GIS in environmental monitoring is becoming a key factor in solving current problems. By analysing the methods and principles of GIS construction, one can observe significant advantages in creating cartographic models, analysing the distribution of chemical elements, and making management decisions for environmental safety. According to E.D. Kuzmenko *et al.* (2020), the use of GIS allows for the collection, processing, and analysis of large volumes of data, which contributes to eliminating environmental problems and improving the quality of the environment.

The combination of GIS and Earth remote sensing is the toolkit that allows solving most environmental monitoring tasks. This confirms that the development and implementation of new technologies in the field of ecology is an important step towards the sustainable development of our society. Given the relevance and importance of this topic, this article considers the possibilities of using GIS for environmental monitoring at the local level, in particular for assessing the condition of the soil cover in the Ivano-Frankivsk urban community. The authors analyse various monitoring methods, including remote and chemical methods, and propose options for building an environmental monitoring system based on GIS technologies.

Conclusions

As a result of the conducted research, significant results were obtained indicating the state of the environment and soil cover in the Ivano-Frankivsk Region. The analysis showed that the most common cultural soil layer in Tysmenytsia and Ivano-Frankivsk is the one containing the remnants of building materials and other human waste. It was found that these cultural soil layers have increased degradation, caused by excessive pollution with various types of waste and toxic substances. A particular problem is the insufficient ability of these soils to remove toxic chemical elements, leading to their accumulation and spread. The results of the analysis of 117 soil samples showed that the soils of urbanised areas are subject to the negative impact of the same factors as urban air and hydrosphere. Such conclusions emphasise the need to create and implement an effective environmental monitoring system to identify and manage environmental problems. Such a system would enable the development and implementation of informed measures to conserve the environment.

One of the key tasks is the implementation of an environmental monitoring system using GIS software such as MapInfo and Surfer. This will allow for systematic tracking of changes and trends in the distribution of chemical elements and other environmental parameters and timely response to potential environmental threats. In addition, the research opens up opportunities for the introduction of new methods and technologies, such as GPS and GIS software, in the field of environmental monitoring. This will contribute to increasing the accuracy and efficiency of monitoring measures aimed at preserving the environment. The study paves the way for further research in the field of environmental monitoring and the application of GIS technologies to solve complex environmental problems. It also highlights the importance of cooperation between research institutions, local authorities, and the public to create integrated approaches to environmental protection and sustainable urban development.

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Conflict of Interest

None.

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Визначення екологічного стану ґрунтового покриву та проектування екологічного моніторингу Івано-Франківської міської громади

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Анотація. Через зростання техногенного навантаження на довкілля необхідно визначити ступінь впливу промислового виробництва на навколишнє середовище. Проведення екологічного моніторингу Івано-Франківської міської об'єднаної територіальної громади дасть можливість подальшої екологічної оцінки та прогнозування стану довкілля досліджуваної території. Мета роботи – оцінити стан ґрунтового покриву Івано-Франківської міської громади та її околиць, визначити актуальність використання геоінформаційних систем (ГІС) в екологічному моніторингу. У дослідженні використовувалися: статистичний метод для збору та аналізу баз даних екологічної ситуації зі забруднення компонентів довкілля; ГІС картографія для виявлення та відображення поширення забруднюючих компонентів за допомогою інтерполяції методом Kriging. Проведено детальний аналіз різних методів моніторингу стану навколишнього середовища, включаючи дистанційні та хімічні методи. Це дозволило визначити найбільш ефективні підходи для збору та обробки екологічних даних. Розглянуто важливі аспекти створення системи екологічного моніторингу для відстеження стану навколишнього середовища. На основі зібраних даних створено карти, що відображають розповсюдження хімічних елементів на території Івано-Франківської міської об'єднаної територіальної громади. Ці карти є важливим інструментом для візуалізації та аналізу екологічного стану ґрунтів. Запропоновано варіант побудови системи екологічного моніторингу та розроблено проектну картографічну модель. Це дозволить більш ефективно здійснювати екологічний моніторинг та планувати заходи щодо покращення екологічного стану території. Застосування програмного забезпечення MapInfo та Surfer дозволило провести детальний аналіз навколишнього середовища та створити геоінформаційну систему екологічного моніторингу для Івано-Франківської міської громади. Результати дослідження мають значне практичне значення для різних сфер екологічного менеджменту та планування, зокрема для проведення подальшого екологічного моніторингу, для сфер державного та місцевого екологічного управління, громадських ініціатив та освітніх програм

Ключові слова: геоінформаційні системи; картографія; техногенний вплив; польові дослідження; коефіцієнт концентрації

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Analysis of alternative approaches to stormwater management and prospects for their implementation in Ukraine

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Abstract. Due to aging infrastructure, frequent wastewater network overflows, and potential charges for stormwater disposal, there is a need to find alternative approaches to stormwater management. Rain gardens and rainwater harvesting systems are widely used in local areas such as private homes, small businesses, and parking lots. Therefore, the aim of this study was to conduct an economic analysis of two alternative solutions – a storage tank with water reuse and a rain garden. The cost-benefit analysis was based on an evaluation of the effectiveness of each approach in reducing stormwater runoff volume and decreasing stormwater disposal fees in the wastewater network. The precipitation regime used for the calculations was selected based on data from 2014 to 2023 for the Kyiv. In the study, technical and economic aspects were considered as key factors in the decision-making process. The results of the economic sustainability analysis of both options using an example of an impermeable surface showed that both systems have an effective service life of approximately two years. The storage tank is an effective solution, reducing stormwater overflows and allowing the collected water to be reused for various purposes. However, the costs of construction and maintenance of the tank exceed the savings on stormwater disposal fees to the sewer system by almost twice, therefore the project is not economically viable in the initial period. The implementation of a rain garden design to reduce stormwater disposal fees to the wastewater network is the most cost-effective solution. Assuming that the effective use period of a rain garden design is 8-10 years, the accumulated savings on tariffs can range from €606.8 to €848.2. The introduction of financial incentives will help promote the implementation of alternative stormwater control solutions, leading to a range of environmental and economic benefits, such as reducing the impact of stormwater on the environment, protecting water resources, and potential savings in the construction and management of stormwater systems

Keywords: green infrastructure; rain garden; water storage tank; cost analysis; economic impact

Introduction

Stormwater management in the context of sustainable development is becoming a serious problem in developed cities. The modification of the Earth's surface associated with urbanisation includes the reduction of vegetation cover and

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the replacement of permeable areas with impermeable surfaces, leading to the disruption of the natural hydrological cycle of surface runoff, increases the volume of stormwater runoff, and increases the speed of peak flows. The Intergovernmental Panel on Climate Change has reported that the number of intensive precipitation events has increased significantly in many countries around the world (Climate change indicators…, 2024). As noted by K. Puczko & E. Jekatierynczuk-Rudczyk (2020), climate indicators for recent decades show a generalised statistical increase in the maximum amount of precipitation in many cities, including cities in Ukraine (Khokhlov *et al*., 2022). Traditional approaches based on the principles of "gray" infrastructure are criticised for their inefficiency, especially in cases of extreme meteorological situations, which according to X.-J. Qiao *et al.* (2018) are associated with outdated equipment and financial and budgetary constraints.

Different countries use a combination of different financing instruments. Stormwater sewer usage fees are considered to be the most effective and environmentally sustainable, as they allow for long-term planning and informed decision-making due to their high political visibility. In the USA, the Water Quality Act (1987) mandates the implementation of a comprehensive stormwater management programme through the introduction of fees. F.A. Tasca *et al*. (2018) note that other countries, such as Canada, the United Kingdom, and Australia, have similarly introduced stormwater fees. In European countries, mandatory fees for stormwater runoff into the general wastewater network have been introduced for many years for all categories of consumers. In most German cities, this payment is determined based on the area of the impermeable surface. In Hamburg, for example, the fee is calculated based on the total costs associated with impermeable areas connected to the public sewer system and amounts to €0.73/m^2 of impermeable surface, as noted by W. Dickhaut & M. Richter (2020). In Italy, there is currently no specific stormwater management fee. The cost of water services is covered by the integrated water tariff, which is paid to local organisations responsible for all types of water supply work – from water delivery to collection and purification – based on the registered volume of water consumption. In the Lithuanian city of Klaipeda, private homeowners are required to pay almost €1/m^3 of rainwater if precipitation from their property enters the general sewerage system (WaterTime, n.d.).

According to J. Boguniewicz-Zabłocka & A.G. Capodaglio (2020), the stormwater fee in Poland is included in the price of water supply services and requires payment for the discharge of rainwater or meltwater in order to encourage users to manage water resources rationally. The fee consists of a fixed and a variable component. The fixed part (subscription) is determined based on the maximum allowable discharge of rainwater, specified in the water permit. The base fee is 0.75 PLN/m^3 (approximately €0.17) per year, but can be significantly reduced if water retention systems with a capacity of more than 30% of the annual runoff are installed on the property. In areas with combined sewer systems, the fee includes the costs of wastewater collection. In areas with separate sewer systems, the fee is determined based on the volume of collected runoff or the area of the impermeable surface. In the latter case, the fee can range from 0.31 to 7.06 PLN/m^2 (approximately €0.07 to €1.63/m^2).

European integration and the implementation of priority directions of Ukraine's water protection policy require the introduction of alternative approaches to the stormwater management system as a modern mechanism for protection, rational use, and restoration of water resources under conditions of significant anthropogenic impact. The first attempts to introduce the European practice of paying for rainwater drainage to the municipal sewerage system in Ukraine were provided for in the initial version of the Order of the Ministry of Housing and Communal Services of Ukraine No. 190 "On Approval of the Rules for the Use of Centralised Communal Water Supply and Sewerage Systems in Settlements of Ukraine" (2008). As of 2024, only private entrepreneurs and legal entities pay for rainwater drainage. For instance, for the drainage of stormwater in March 2024, entrepreneurs in Kalush had to pay 98 UAH for a small store with an area of 130 m^2, 270 UAH for a shopping centre with an area of 360 m^2, and 1,600 UAH for a large warehouse with an area of 2,200 m^2 (In Kalush…, 2024).

Due to the lack of distinction between drinking and domestic water in the Ukrainian water supply system, this leads to the inefficient use of drinking water. The implementation of alternative approaches to stormwater management has an indirect economic impact on water conservation scenarios. According to the principles of "green" infrastructure and similar practices, rainwater should be retained as much as possible at or near the place of precipitation. As I. Nowogoński (2021) argues, this can be achieved through surface or underground retention, as well as infiltration processes into the soil. This article considered two simulation studies on stormwater management in the context of sustainable development: rainwater harvesting in on-site tanks with subsequent reuse; the implementation of rain garden designs to reduce stormwater volume. The aim of the study was to analyse these two approaches and evaluate their effectiveness based on two factors: reducing stormwater runoff volume and reducing sewage discharge fees into the wastewater network.

Materials and Methods

To study the precipitation pattern in a specific area, it is necessary to have up-to-date data on their amount for at least the last 10 years. Studying the precipitation regime is a key factor in confirming that a water collection system can be an alternative method of improving stormwater management. Thus, the average monthly precipitation data in Kyiv for the period from 2014 to 2023 were obtained from the Borys Sreznevsky Central Geophysical Observatory (Table 1).

Table 1. Average monthly precipitation in Kyiv from January 2014 to December 2023

Characteristics	Period	Months												Year
		1	2	3	4	5	6	7	8	9	10	11	12	
Average monthly precipitation, mm	2014-2023	37	40	43	47	65	77	68	56	59	45	46	47	**630**

Source: created by the authors based on Climate data for Kyiv (2024)

Analysis of precipitation data for the past 10 years in Kyiv (Fig. 1) shows that most of the precipitation occurs from May to September, with a total of 325 mm. The peak precipitation occurs in June when the average amount is 77 mm, and the least precipitation is observed in January, with a monthly indicator of 37 mm. From October to April, approximately 305 mm of precipitation falls. The total annual average precipitation is about 630 mm. The design of a soil retention system is based on an assessment of the volume of rainwater and meltwater that is generated on the site. For small solutions (e.g., single-family homes, commercial construction, small businesses), as in the case of the examples considered in this work, complex dynamic flow calculations are not required, unlike situations involving large-area watersheds (Liu *et al.*, 2020). The potential volume of stormwater runoff is estimated based on the total catchment area, the average annual precipitation, and the runoff coefficient and can be determined using the equation:

$$Q = P \times A \times \psi, \tag{1}$$

where Q is the annual volume of stormwater runoff, m^3; P is the average annual precipitation, mm/year; A is the area of the watershed surface (roof, parking lot), m^2; ψ is the runoff coefficient (dimensionless). The ψ values used in this study are 0.8 for a tiled roof and 0.85 for an asphalt concrete parking lot. Average values of ψ for other roof materials and surface types can be found in Table 2.

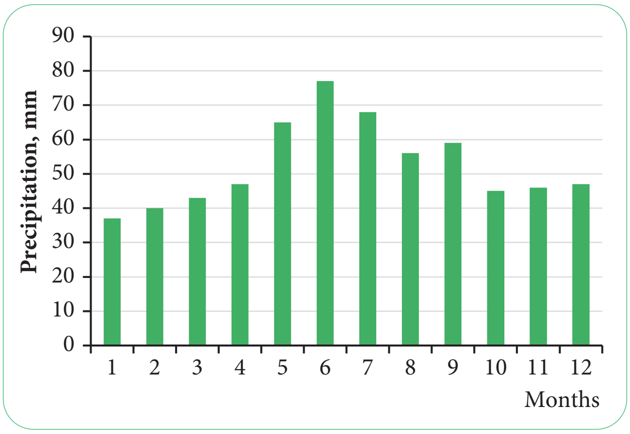

Figure 1. 10-year average monthly precipitation in Kyiv

Source: created by the authors based on Climate data for Kyiv (2024)

Table 2. Average values of the ψ for different coatings

Surface type	ψ
Roof covering:	
◉ galvanised iron	> 0.9
◉ tiles	0.6-0.9
◉ asbestos	0.8-0.9
◉ organic materials	0.2
Asphalt concrete road surfaces	0.85
Paving	0.60
Cobblestone paving	0.45
Macadam pavement not treated with binders	0.40
City blocks without pavement, small squares, boulevards	0.2-0.3
Lawns	0.10
Blocks with modern buildings	0.4-0.5
Midsized cities	0.4-0.5
Small towns and villages	0.3-0.4

Source: created by the authors based on DSTU 8691:2016 (2016), K.K. Kuok & P.C. Chiu (2020)

In most cases, to determine the size of a rainwater harvesting tank, an approach based on consumer demand for alternative water supply is used (Abdulla, 2020). This method depends on the water demand for a specific building object. The tank volume is determined as the total water demand for this object over a certain period of time (for example, during the dry season). The study discusses the volume of stormwater discharged into the wastewater network with corresponding payment rates. Therefore, to determine the size of the rainwater harvesting tank, it is advisable to take into account the maximum intensity of the precipitation event in recent years, which is repeated with a certain periodicity. The maximum precipitation rate can be calculated using the following formula for 15-minute events and areas with annual precipitation $P < 800$ mm (Boguniewicz-Zabłocka & Capodaglio, 2020):

$$q = \left(6{,}631 \times \sqrt[3]{P^2 \times C}\right)/t^{2/3}, \quad (2)$$

where C is the recurrence interval of the rain event lasting for duration t and intensity q, years; P is the average annual precipitation, mm. The volume of the storage tank is calculated by the formula:

$$VR = 0.06 \times (q_{max}(t) - q_{out}) \times t_d \times f_a \times f_z \times F_{zr}, \quad (3)$$

where VR is the volume of the storage tank, m^3; $q_{max}(t)$ is the maximum precipitation intensity, dm^3/ha, for a certain duration t_d, min; q_{out} is the amount of water that can leave the tank when overflowing, dm^3/ha; f_a is reduction coefficient, typically equal to or less than 1, and depends on the time it takes for water to pass through the system and the frequency of precipitation; f_z is a coefficient that takes into account the possibility of exceeding the water storage volume (1.1-1.2); F_{zr} is the area from which water enters the collection system, ha. The amount of the fee for centralised wastewater disposal within the discharge requirements (P_{vc}) is calculated using the formula:

$$P_{vc} = T \times Q_d, \quad (4)$$

where T is the tariff established for providing centralised wastewater disposal services to consumers within the respective category, UAH/m^{-3}; Q_d is the volume of wastewater discharged by the consumer within the limits specified by the contract, m^{-3}. To calculate and select the optimal dimensions for the rain garden design, a universal hydrological model developed by M. Kravchenko *et al.* (2024a) was used. This model is based on Darcy's law, which allows describing dynamic processes within the system at a specific moment in time using equation:

$$y_i(\tau) = \frac{A_{bassin}}{A_{sponge}} \times \left(\int_0^\tau v_r \times d\tau\right) - \\ - \frac{\sum_{j=1}^{m-1}(w_{sat,j} \times \delta_j)}{w_{sat,m}} + \sum_{i=1}^{m-1} \delta_j, \quad (5)$$

where $y_i(\tau)$ is the level of rainwater infiltration and saturation of the rain garden design at the current time step τ; A_{bassin} is the area of the watershed basin, m^2; A_{sponge} is the area of the rain garden, as a sponge tool, m^2; v_r is the average rate of rainfall onto the surface of the rain garden design, m/s, over time $d\tau$; w_{sat} is the water holding capacity of the rain garden soil media, m^3/m^3; δ_j is the thickness of the rain garden soil layers, m; i, j, m are the layers of the rain garden design, starting from the first ($j = 1$) and ending with the layer ($m - 1$), in which saturation occurs at a specific moment in time. The number of these layers can vary from 1 to i. The developed hydrological model was implemented in the Scilab software.

Results and Discussion

Many systems for rainwater harvesting have been proposed over the past few decades. In most cases, the main task of the design solution is to evaluate the tank capacity in accordance with the required level of system performance. There is a considerable amount of scientific research dedicated to the methodology for evaluating the effectiveness and determining the size of rainwater harvesting systems. According to M.G. Di Chiano *et al.* (2023), the capacity of the tanks cannot be standardised, since it significantly depends on various variables characteristic of a particular geographic region, such as local rainfall, the area of the catchment basin (roof, parking lot, etc.), drinking water needs, and the number of people in the household.

Example 1. Collecting rainwater in a storage tank and then reusing it. For the first considered case, it should be assumed that the total area of impermeable surfaces on the property of a private house or enterprise is 700 m^2, of which the roof area is 400 m^2 and the parking lot area is 300 m^2. Next, it should be assumed that initially stormwater from the site was discharged directly into the wastewater network. In addition to environmental considerations, one of the main factors that motivates the search for alternative stormwater management solutions is the fee for their discharge. Therefore, it must be assumed that during the redevelopment of the territory, the drainage system was redesigned with the introduction of a storage tank to reduce the amount of stormwater entering the sewer system from the property.

According to V. Ovcharuk *et al.* (2020), climate change has led to an increase in the frequency and duration of droughts, as well as a change in the pattern and intensity of precipitation over the past few decades in Ukraine. This highlights the importance of local rainwater storage as a key element in stormwater management. The total average runoff of 201.6 and 160.6 m^3/year, thus, were calculated using equation (1) for the roof and parking area, respectively. Equation (1) correlates with the widely used Polish standard (complies with European standards) PN-EN 75, which suggests a similar formula for calculating the runoff rate for surfaces < 10,000 m^2 (Boguniewicz-Zabłocka & Capodaglio, 2020). Researchers K.K. Kuok & P.C. Chiu (2020) propose using the value of the daily precipitation amount (mm) in the equation. The authors also suggest not collecting the first flush in the tank, which contains dust, bird and animal droppings, leaves and other debris from adjacent areas that have accumulated on the roof surface. Based on the maximum intensity value of 2.8 mm calculated for a 15-minute event using formula (2), the volume of the storage tank was calculated using formula (3). The volume of the storage tank for collecting stormwater from a roof with an area of 400 m^2 was calculated as 24.2 m^3. The volume of the tank for the parking area of 300 m^2 is 19.3 m^3. Excess stormwater during more intense events will be discharged to the sewer system.

Thus, stormwater management can be organised as follows: direct the runoff from the roof to a storage tank with a volume of 24.2 m^3, and runoff from the parking area is directed to a tank with a volume of 19.3 m^3. According to Ukrainian legislation, when discharging water that flows from the parking area into the sewer system, it is necessary to ensure that the content of petroleum hydrocarbons does not exceed 10 mg/dm^3 (Order of the Ministry of Regional Development, Construction, Housing and Communal Services of Ukraine No. 316, 2017). In view of this, a cleaning system can be provided at the inlet to the tank to help reduce the content of harmful substances. One solution could be to install an oil separator, which effectively separates petroleum hydrocarbons from water or to use a sorption filter with activated carbon or other absorbing materials capable of capturing petroleum hydrocarbons. The results of the calculated economic effect of stormwater management in Example 1 are presented in Table 3. The tariff for discharging stormwater into the wastewater network was calculated for the Kyiv using formula (4).

Table 3. The economic impact of stormwater management in Example 1

Costs	Without a drainage system		With a drainage retention system	
	Roof	Parking area	Roof	Parking area
Water reuse from collected wastewater (approximate average), m^3/year	0	0	201.6	160.6
Costs of tank construction, €	0	0	3,191	3,191
Maintenance and operation costs, €/year	20		75	
Tariff for wastewater disposal in Kyiv (0.34 €)/m^3 × (201.6 + 160.6) m^3, €/year	68.5	54.6	0	0
Payment for discharge to the wastewater network, €/year	68.5	54.6	0	0
Total annual costs, €/year	**143.1**		**75**	

Note: *1 € = 42.3 UAH (average as of May 1, 2024); this exchange rate will be used for all subsequent cost indicators presented in the article
Source: created by the authors

Considering that the projected lifespan of a rainwater harvesting tank is 20 years, the savings on water bills in the 20th year will be about €1,362, assuming no tariff fluctuations. Given that the construction costs of the tank exceed the savings on the fee for stormwater discharge into the sewer system by almost half, the project is not economically viable in the initial period. The advantages of such a system are the possibility of using stormwater accumulated in the tank for local non-potable reuse and meeting domestic needs, such as watering green spaces, washing surfaces or cars, flushing toilets, cleaning premises, etc. In addition, the volume of the tank may be sufficient for the irrigation of a green area of about 1,000 m^2, especially during dry seasons.

Overall, such a stormwater harvesting system is capable of: reducing and delaying runoff into the sewer system, retaining rainwater on-site, ensuring water infiltration into the soil, increasing evaporation from biologically active surfaces, reusing residual water for local needs, and lowering water bills. It can also optimise the operation of stormwater sewers, reducing the risk of flooding of neighbouring areas and pollution of receiving waters. The disadvantages of such a system, in addition to the high cost, include the need for periodic cleaning of the tanks from debris. It is recommended to use the water accumulated in the tank within a month to avoid microbiological contamination and reduce the risk of the proliferation of bacteria, fungi, and other microorganisms that can occur during long-term storage of water without proper treatment or circulation.

Example 2. Rain garden design. A rain garden is a type of "green" structure that is installed along the roadway, near residential buildings, gas stations, parking areas and is designed for infiltration of runoff, temporary retention, and preliminary purification of rainwater. They consist of perennial plants that accumulate and return rainwater to the ecosystem thanks to a special drainage system (Kravchenko *et al.*, 2024b). A rain garden is created in a shallow depression in the terrain, where it receives rainwater, for example, from the roof using gutters and downspouts. Immediately after precipitation, water can temporarily flood the surface of the garden, but for most of the year, it remains dry and functions as an ordinary garden without additional irrigation. The design of a rain garden consists of several layers, using soil materials with high hydraulic permeability and porosity. These materials ensure rapid water penetration into the recessed drainage pipes, which can be connected to the stormwater sewer system or the underlying aquifer. This helps to effectively manage stormwater, reducing the risk of flooding and promoting natural water infiltration into the ground. The design of a rain garden consists of three main layers: a soil layer for planting vegetation; a transition layer or infiltration layer; a gravel layer for temporary water retention (Kravchenko *et al.*, 2024b). The correct choice of soil and vegetation can perform not only water storage functions but also pollutant removal functions. A rain garden is specially designed to collect wastewater from roofs and asphalt surfaces, temporarily store it, and infiltrate it into underground drainage pipes.

The construction of a rain garden begins with digging a trench 1.3 m deep, the bottom of which is filled with a 30 cm layer of gravel (fraction 2-8 mm). A perforated drainage pipe (90 mm in diameter) wrapped in geotextile is laid on this layer. A vertical overflow pipe (also 90 mm in diameter), connected to the drainage system, protrudes about 10 cm above the decorative surface of the garden, ensuring rapid infiltration in case of high-intensity rainfall events. The space above the drainage gravel layer is filled with a medium-grained sand mixture, which serves as the basis for the intermediate infiltration layer. According to the results of further modelling, the depth of the infiltration layer is 60 cm. The top layer for planting plants, 40 cm thick, consists of a fertile soil mixture, which is selected according to the physicochemical composition of the corresponding type of vegetation. The drainage pipe is connected to the general stormwater sewer system to avoid overflow and local flooding in case of extreme events. Plants for the construction of rain gardens are selected depending on their functional purpose. For example, as R. Dudrick *et al.* (2024) state, shrubs, bushes and trees contribute to the improvement of the hydrological process through transpiration and improve the ability of the soil to accumulate water, especially in combination with herbaceous plant species.

The optimal area of a rain garden design is considered to be 4-7% of the area from which runoff will be collected (watershed area) (Rinchumphu *et al.*, 2023). Similar recommendations are proposed in Rain garden (n.d.), according to which the rain garden structure should be from 5 to 10% of the watershed area. The initial simulation data on the area of the watershed surface and the amount of precipitation remain the same as in Example 1. The recommendations indicate that the corresponding required area of the garden should be at least 4% of the effective watershed area. The total watershed area is 700 m^2, of which the roof area is 400 m^2 and the parking area is 300 m^2. Based on the characteristics of the site, the total calculated area should be at least 16 m^2 for the roof and 12 m^2 for the parking area. Rain garden designs, each with an area of 8 m^2, can be placed on opposite corners of the building so that each of them receives runoff from different parts of the roof according to the slope.

To calculate the depth of the layers (top soil, intermediate sandy, and lower gravel) of rain garden designs, using a developed simplified mathematical model taking into account Darcy's law, which allows for analysing the dynamic processes of water passage and saturation of the layers of the rain garden design at a specific moment in time (Kravchenko *et al.*, 2024a; 2024b). The authors implemented the model in the Scilab software based on the simulation of a real rainfall event, during which a record amount of precipitation of 36 mm/h or 36 dm^3/m^2×h was recorded in Kyiv on July 22, 2023, the highest in the last 10 years. Using the developed model and Scilab software with the given values of the water retention capacities of the soil layers of the rain garden (0.33/0.33/0.1 m^3/m^3), the hydrological efficiency of the design was calculated, depending on the change in the ratio of areas (ratio of the watershed area to the area of the rain garden), at which the rain garden design allows for the complete retention of water runoff at a given precipitation intensity (Fig. 2).

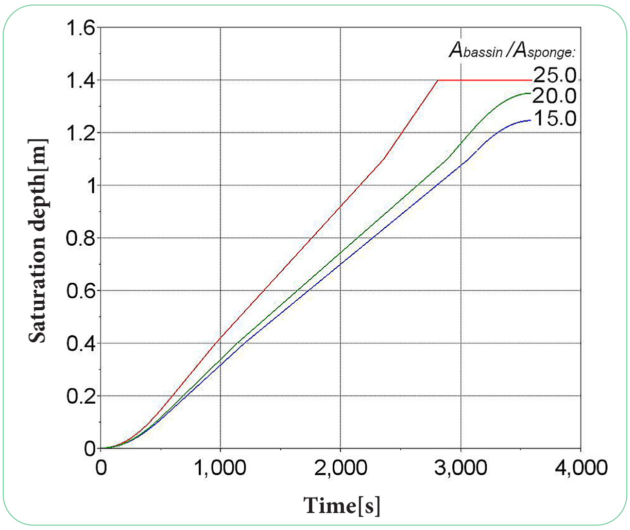

Figure 2. Curves of changes in the depth of saturation of the layers of the rain garden design in time depending on the ratio of A_{bassin}/A_{sponge}

Source: created by the authors

The modelling results showed that with the depth of the layers (0.4/0.6/0.3 m), the full saturation of the rain garden design begins with a threshold value corresponding to an area ratio of 25 for the time $\tau = 2{,}296.16$ s. In other words, if a rain garden design with an area of 16 m^2 and a depth of 1.3 m is arranged at a roof area of 400 m^2, it will allow to retain rainfall of critical intensity (36 mm/h or 576 m^3) avoiding overflow of the design in 38 minutes (2,296.16/60). As can be seen from Figure 2, the rain garden design is fully capable of retaining rainfall with an area ratio of 15 and 20, i.e., with an area of the rain garden of 26 and 20 m^2, respectively, for the roof. For the parking area, which has an area of 300 m^2, the rain garden designs will fully retain rainfall with an area of 20 and 15 m^2, respectively. Since the total average runoff, as in Example 1, is 201.6 and 160.6 m^3/year for the roof and parking area, respectively, the calculated dimensions of the rain garden design for the critical rainfall intensity will allow all rain events throughout the year to be retained without overflow. Before the construction of the rain garden, the cost of discharging stormwater into the sewer system involved a fee of €123.1 per year. According to the data of the authors J. Boguniewicz-Zabłocka & A.G. Capodaglio (2020), the average construction cost of a rain garden is €12.3/m^2 (excluding vegetation). Based on research conducted during the first year of operation, the annual maintenance and operation costs are estimated at approximately €0.5/m^2 per year (Boguniewicz-Zabłocka & Capodaglio, 2020). The economic effect of stormwater management in Example 2 is presented in Table 4.

Table 4. The economic impact of stormwater management in Example 2

Costs	Without a rain garden		With a rain garden	
	Roof	**Parking area**	**Roof**	**Parking area**
Costs for the construction of a rain garden design, €	0	0	196.8	147.6
Maintenance and operation costs, €/year	0		8	6
Payment for discharge to the wastewater network, €/year	68.5	54.6	0	0
Total annual costs, €/year	**123.1**		**14.0**	

Source: created by the authors

The results presented in Table 4 are based on the calculated maximum precipitation volumes and the hydrological efficiency of the rain garden design. Similarly to Example 1, it can be noted that all investments in the construction of a rain garden will be paid off within three years. If assumed that the effective period of use of the project will be 8-10 years (after which some intervention may be needed to restore soil permeability), the accumulated savings on tariffs would be from €606.8 to €848.2. In both presented simulation studies, the advantages of the alternative approach to stormwater management are due to two factors: a reduction in the volume of stormwater runoff and a reduction in discharge fees due to the implementation of mitigation measures. In addition to economic benefits, the implementation of such solutions brings such environmental benefits as the possibility of using water for irrigation (Example 1), which allows for improving the care of green spaces even during prolonged periods of drought. The use of a tank to reduce the load on the storm sewer during heavy rainfall can prevent network overload and local flooding. Stormwater harvesting is a profitable solution despite its high cost. However, as the calculation results show, the rain garden design is more economically viable and effective in stormwater management (Table 5).

Table 5. Comparison of the economic effect of using a rainwater harvesting tank and a rain garden design for the entire area of the impermeable site (roof + parking area)

Costs	With a drainage retention system	With a rain garden design
Water reuse from collected wastewater (approximate average), m^3/year	362.2	0
Construction costs, €	3,191	344.4
Maintenance and operation costs, €/year	75	14
Payment for discharge to the wastewater network, €/year	0	0
Total costs, €	**3,266**	**358.4**

Source: created by the authors

According to the analysed results, the implementation of a rain garden design to reduce stormwater discharge fees into the wastewater network is the most acceptable solution in terms of cost. However, when implementing this system in field conditions, it is necessary to take into account the soil conditions on the site, which should be favourable for rapid infiltration. In addition, this solution excludes any further local use of water, unlike the solution with a stormwater harvesting tank. The impact of alternative stormwater management practices cannot be underestimated, even in areas that are traditionally subject to significant rainfall. These practices successfully detain and filter a significant portion of stormwater runoff, reducing pressure on existing sewer systems and mitigating the adverse effects of runoff, such as erosion and pollutant loading. Urbanised areas of Athens, Greece, according to the results of I.M. Kourtis *et al.* (2018) demonstrate a potential reduction in peak flow in the range of 13.4-28.2% and total runoff volume in the range of 24.5-29% after the implementation of "green" infrastructure practices. A modelling study conducted by J. Leimgruber *et al.* (2019) in Graz, Austria, showed that the application of cost-effective stormwater management practices has great potential for reducing and controlling runoff, considering all aspects of the water balance and life cycle costs, including land costs. An analysis of the costs and benefits of stormwater management practices in an urban watershed in Norway conducted by C.-Y. Xu & H. Li (2020) showed that these methods reduce combined sewer overflow, and optimised solutions can be identified using hydrological modelling to maximise efficiency at minimal cost. Although neither of the cited studies conducted a quantitative assessment of the overall impact of alternative practices on stormwater sewer size requirements in urban settings, it can be assumed that their widespread implementation may have long-term benefits in terms of infrastructure design and investment costs.

A key factor in choosing the appropriate alternative stormwater management practice for a specific case is understanding the characteristics and specifics of hydrological conditions, landscape, infrastructure, and the needs of the local population. For example, rain garden design is an ideal solution for small developments (as in Example 2 of the presented research), but not for sites with large drainage areas. The results obtained within the framework of the presented study are consistent with the research conducted by L. Bortolini & G. Zanin (2018). Testing the functionality of rain gardens with three different area ratio values (10, 15, and 20), located on the campus of the University of Padua, Italy, they demonstrated that even in a small rain garden, almost all runoff volumes from the watershed area infiltrate vertically into the soil. Other authors, E. Burszta-Adamiak *et al.* (2023), showed that rain gardens can support the operation of inadequate sewer infrastructure, especially during moderately intense rainfall events.

In terms of rainwater harvesting systems, the most popular option for homeowners is the so-called "rain barrel" (or a small tank with a volume of up to 1 m^3), which does not always provide sufficient water volume, even for small irrigation needs during dry periods, and often overflows during intense rainfall events. Research shows that rain barrels, while having a certain function of demonstration and awareness raising, have little impact on runoff reduction, except in specific cases. Only larger rainwater harvesting systems (tanks), similar to the one described in Example 1 of the presented study, can significantly affect runoff reduction and replace typical household irrigation needs, as confirmed by F. Abdulla (2020). Peak flow volume and rate are important factors that influence flood risk. The use of water harvesting tanks can reduce the peak flow rate during many rainfall events, depending on the tank volume and rainfall characteristics. Case studies conducted in Italy by G. Freni & L. Liuzzo (2019) showed that runoff volume and rate were reduced by 9% to 57.7% due to the use of harvesting tanks with volumes ranging from 139 to 2,040 m^3 for rainfall of 50 mm in one rainfall event. Other authors, M.J. Deitch & S.T. Feirer (2019), found that runoff volume in Florida was reduced by more than 20% due to the installation of an 11.3 m^3 rooftop tank on a residential building.

In some developing countries with high water tariffs, rainwater harvesting systems are considered an inexpensive system that only involves installation and maintenance costs (Pala *et al.*, 2021). In addition, according to the authors J.A. Gleason Espíndola *et al.* (2018), such systems contribute to reducing dependence on the traditional sewer system and reduce water bills by up to 50% per month. An advantage of using rainwater harvesting systems is the possibility of reusing the accumulated water. Studies show that in most developed countries, such systems are implemented primarily for non-potable use. In developing countries, they are also used for potable use, often as a source of drinking water. This difference in use may be related to easy access to traditional water sources, higher average consumer income, and affordable water tariffs in developed countries. Overall, according to D. Słyś & A. Stec (2020), harvested rainwater from tanks can meet most non-potable water needs, such as toilet flushing (approximately 70% to 90%), laundry (50% to 90%), and garden watering (57%). Several studies, including S. Ali *et al.* (2020), have concluded that the cost-effectiveness of rainwater harvesting methods is closely related to local water prices and that such systems are desirable to be installed at the level of new construction districts to be economically efficient. Climatic conditions in Ukraine generally Favor the effective functioning of alternative approaches, as confirmed by the results of simulation studies.

In order for the implementation of such systems to become more relevant and widespread in the future, it is necessary to develop and implement a comprehensive programme that should include a system of measures. Among the mandatory aspects of such a programme are: the development of legislative policy (regulations, codes and standards), regulatory policy (state regulation in the field of stormwater management), incentive policy (creation of research funds, launch of financing schemes), policy of assistance at the state and regional levels (creation of associations, organisations and institutions for the study of alternative systems, provision of professional training, promotion of public awareness) and information policy (providing a platform for knowledge exchange, organising conferences of various levels, seminars, competitions, etc.). The formation of general public opinion through the use of the media, conducting surveys and excursions to study the latest alternative approaches, practices and methods are also of great importance.

Conclusions

As of 2024, the scale of implementation of alternative approaches in Ukraine is quite small, which makes the issue of sustainable stormwater management extremely relevant. One of the popular, effective and relatively simple solutions is the use of small retention or infiltration structures for individual building sites, which contributes to the increase in the use and infiltration of rainwater. As shown in this research, the implementation of such alternative approaches into practice can have significant environmental and financial benefits for property owners and local water supply and sanitation organisations. The effectiveness of such measures is largely dependent on whether there are tariff incentives. However, such solutions as rainwater harvesting tanks with the possibility of reuse can reduce costs for owners of private residential houses, small businesses and other individual water users for water purchase, as well as contribute to the conservation of water resources.

Alternative stormwater management methods are aimed at reducing the load or partially replacing traditional sewer systems. For example, rain garden designs represent an economically efficient and sustainable approach that has advantages within the framework of the sustainable development concept. However, their financial viability is limited by the lack of water reuse opportunities, as rainwater infiltrates into the drainage system without being stored. Storing (harvesting) rainwater on-site for later use can save on water supply costs, making such solutions attractive to individual users even in the short term. According to the results of the economic analysis, the implementation of rain garden designs to reduce the fee for discharging stormwater into the wastewater network is the most economically beneficial solution. According to the calculations, the total construction cost of a reservoir is €3,191, and a rain garden is €344.4. The savings on water bills over 20 years of operation of a rainwater harvesting tank will be around €1,362, assuming stable tariffs. The implementation of a rain garden design will allow savings from €606.8 to €848.2 in just 8-10 years of operation. For further research, it is important to evaluate and address additional aspects of the implementation of rainwater harvesting systems and rain garden designs that will contribute to the sustainability of water supply and wastewater disposal. In particular, it is necessary to investigate the duration of stormwater flow in distribution systems and possible water quality problems that may arise as a result.

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Conflict of Interest

None.

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Аналіз альтернативних підходів до управління зливовими водами та перспективи їх впровадження в Україні

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Анотація. У зв'язку зі застарілою інфраструктурою, частими переливами каналізаційної мережі та можливою платою за скидання дощових вод, існує потреба в пошуку альтернативних підходів до управління зливовими водами. Конструкції дощових садів та системи збору дощової води широко використовуються на таких локальних територіях, як приватні будинки, невеликі підприємства та парковки. Тому метою цієї роботи було провести економічний аналіз двох альтернативних рішень – накопичувального резервуара з повторним використанням води та конструкції дощового саду. Аналіз витрат та переваг проводився на основі оцінки ефективності кожного підходу щодо зменшення об'єму зливового стоку та зменшення плати за скидання стоків у каналізаційну мережу. Режим опадів, використаний для розрахунків, було вибрано на основі даних за період із 2014 по 2023 рік для міста Києва. Технічні та економічні аспекти в дослідженні розглядалися як ключові фактори під час прийняття рішення про вибір підходу. Результати аналізу економічної стійкості обох варіантів на прикладі імітованої водонепроникної поверхні показали, що обидві системи мають ефективний термін експлуатації приблизно два роки. Накопичувальний резервуар є ефективним рішенням, що зменшує переливи дощових вод і дозволяє повторно використовувати накопичену воду для різних потреб. Проте витрати на будівництво та обслуговування резервуара перевищують економію на оплату за скид зливових вод у каналізаційну систему майже вдвічі, тому проєкт не є економічно вигідним у початковий період. Впровадження конструкції дощового саду для зниження плати за скид зливових вод в каналізаційну мережу є найбільш прийнятним рішенням із точки зору вартості. Якщо припустити, що термін ефективного використання конструкції дощового саду становитиме 8-10 років, накопичена економія тарифів може становити від 606,8 до 848,2 євро. Впровадження фінансових стимулів сприятиме реалізації альтернативних рішень із контролю зливових вод, що призведе до ряду таких екологічних та економічних переваг, як зменшення впливу зливових вод на навколишнє середовище, захист водних ресурсів та можлива економія при будівництві й управлінні зливовими системами

Ключові слова: зелена інфраструктура; дощовий сад; резервуар для збирання води; аналіз витрат; економічний ефект

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Conceptual approach to the monitoring programme for the wetland of international importance Prut River Headwaters

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Abstract. Functioning as a flood regulator and a freshwater reservoir, the Prut River Headwaters Wetland, protected under the Ramsar Convention, is a crucial hub of biodiversity, including endemic, rare, and threatened species listed in the national and global Red Lists. There are gaps regarding site management issues, including a lack of an integrated wetland monitoring system. Therefore, the objective of this research was to organise the processes involved in the comprehensive planning of wetland monitoring. To achieve this, the study utilised the conceptual framework for monitoring developed by the expert group of the UNESCO Chair on Sustainable Management of Conservation Areas. By employing the method of information-analytical research, a model for the water monitoring programme focused on the Prut River Headwaters Wetland was developed. A combination of physicochemical and hydrobiological assessments has been designed and partly tested. The method was used to test the universality of the proposed methodology in a specific studied area that requires sustainable management, and for the purpose of studying the perspective of application to other wetlands or valuable natural complexes in nature conservation areas. For the Conceptual Phase of the monitoring programme development, the key elements of river basin management of the Water Framework Directive of the European Union were used in synergy with the provisions of the Ramsar Convention. During the Implementation Phase, field and laboratory investigations of water bodies within the testing site at seven control points were conducted (measuring physicochemical parameters with portable equipment). All parameters' values were within the limits of permissible norms. A primary database of results stored in the SMART software has been created. The practical implementation of the water monitoring plan is anticipated to contribute to the evaluation of the wetland ecosystem's condition and support the administration of the Carpathian National Nature Park in the sustainable management of the wetland area

Keywords: Carpathian National Nature Park; Ramsar site; monitoring global guideline; multilevel water monitoring programme; database

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Introduction

Wetlands are very valuable ecosystems that play a crucial role in performing a wide range of substantial benefits for human welfare, wildlife, and the maintenance of environmental stability. Some wetlands have been recognised for their international conservation importance. One of the key wetlands' ecosystem services is their capacity to maintain and improve water quality. However, this function is decreasing due to human activities and extreme weather conditions, which have a significant impact on water flows, nutrient balance, and biodiversity.

E. Duku *et al.* (2022) noted that in a rapidly urbanised socio-ecological landscape, the Ramsar site has an increasing trend of anthropogenic and natural stresses that affect the relationship between ecosystem services and human wellbeing. The researchers V. Kyyak *et al.* (2021) emphasised that intensive recreation negatively impacts the biological communities, which are located along the popular tourist trails, and systematic violations of the protection regime are observed in the Ukrainian Carpathians. The challenge is how to avoid the destruction of those landscapes from anthropogenic influence and how to retain their values in terms of ecosystem services. Governance is a very difficult task. Good governance is very much about participatory culture, and it is true that it is time and resource consuming. It is also about short term perspective. Numerous individuals and organisations have dedicated their efforts to prevent further wetland loss. It was a necessary and important first step, but a range of external pressures can lead to a decline in the natural condition of the wetlands. For instance, changes in hydrological regime, water pollution, nutrient enrichment, and invasion by weeds can lead to biodiversity degradation and threats to wetland functioning. J. Bai *et al.* (2022) recognised that water pollution occurs when pollutant concentration exceeds a water body's potential self-purification.

The particular focus of this study is the Prut River Headwaters Wetland that was designated in 2019 by the Ramsar Secretariat as a wetland of international importance. This site is located within the Carpathian National Nature Park (CNNP), Ukraine. I. Danylyk & B. Prots (2019) argued that this site is crucial for the natural functioning of the Prut River basin, playing a significant role in flood control and mitigation. It serves as an important reservoir, accumulating water seasonally for the protected areas within the park and downstream. A previous study conducted by K. Matiyiv *et al.* (2022) drew attention to numerous tourist routes passing within the wetland, causing anthropogenic pressure on certain components of ecosystems (trampling, littering, and unauthorised collection of biological resources). The most destructive effect on vegetation and soil is observed following visits from large groups of people. The collection of water parameters is intended to become the basis of regular monitoring to determine the dynamics of wetland ecosystem change. For wetland wise use and planned measures, the monitoring can be improved after revision and in accordance with the identified risks. Scientifically-based long-term monitoring is the basis for the development of management plans.

As emphasised by D. Abdul Malak *et al.* (2019), the Ramsar Convention notes that downward trends in wetlands on a global scale occur due to increased human use of wetlands and the lack of specific policy goals and objectives, particularly on a regional scale, to address wetland degradation and propose clear measures for restoration and conservation. D.T. Dalton *et al.* (2023) proved the fact that for effective site management, applied monitoring should be carried out using innovative techniques. Scientifically based monitoring is used in order to generate new knowledge and improve methodologies, instruments, and tools. In general, most of the studies implemented in Ukraine were aimed at carrying out a basic wetland inventory. Assessment and monitoring processes within the wetlands in Ukraine in the context of the Ramsar Convention are in the initial stage. This is one of the reasons for the lack of management plans that are based on the results of assessment and monitoring.

Due to international obligations under the Ramsar Convention, Ukraine is obliged to update data on the wetlands after two years following its registration. Taking into account the main stress factors for the wetlands of the CNNP, including tourism, recreation, and climate change, a water monitoring plan can significantly contribute to improving the park monitoring system and creating preconditions for wise wetland use in the future. The objective of the research was to organise the processes involved in the comprehensive planning of wetland monitoring. This study and its results indicate that the topic is relevant and important in a broad context of nature conservation through management issues, including comprehensive monitoring of water resources in valuable ecosystems. The research has scientific value and demonstrates the novelty of approaches and tools for solving a scientific task.

Materials and Methods

The following methods were used in this research: information-analytical, expert evaluation, field study, statistical analysis, measurement, and modelling. Data collection is carried out in the Microsoft Excel environment and spatial monitoring and reporting tool (SMART) software; the geographic information system (GIS) in the QGIS environment has been used for cartographic modelling. The conceptual framework for biodiversity monitoring in conservation areas of the UNESCO Chair of Sustainable Management of Protected Areas at the Carinthia University of Applied Sciences (CUAS), Austria, was applied and adapted for the water monitoring plan within the wetland, taking into account local conditions. This manual was used as the basis for developing the water monitoring plan, combining biotic and abiotic parameters. The process of monitoring plan development was provided in four phases: the Preparatory Phase, the Conceptual Phase, the Implementation Phase, the Re-evaluation Phase. The synergy of the EU Water

Framework Directive (WFD), in particular Horizontal Guideline No. 12 on the role of wetlands in the WFD, was explored, allowing the application of key elements of the river basin management plan as a tool for the development of a wetland monitoring plan. The Ramsar Information Sheet was used as an initial source of information about the Prut River Headwaters Wetland (Danylyk & Prots, 2019).

Surface water body (WB) delineation within the wetland was conducted according to the WFD approach and based on the methodological adaptation of expert guidance addressing hydromorphology and physic-chemistry for a pressure-impact analysis/risk assessment according to the EU WFD. WBs differentiation involved dividing into three types of surface waters: river (RWB), lake (LWB), and artificial WB (AWB). Surface WBs were divided into sections, taking into account hydromorphological conditions and possible anthropogenic threats. The principles of the Driver-Pressure-State-Impact-Response (DPSIR) methodology were used to recognise pressure and the possible impact of anthropogenic factors on the water ecosystem (point and diffuse sources of pollution, water abstraction, and hydromorphological alterations). Taking into account the pressure and impact on the water ecosystem identified by a group of experts, M. Korchemlyuk *et al.* (2019), the formulation of the monitoring statement has been done in order to ensure ecological stability and wise use of the wetland. A multi-level monitoring plan was developed based on the WFD approach.

Water quality testing in the Prut River at designated monitoring points was carried out by employees of the Measuring Laboratory of Analytical Control and Monitoring of the CNNP. The most representative WBs with identified anthropogenic pressure were selected for the monitoring testing programme. The following parameters were investigated: mineralisation, temperature (T), acidity (pH), dissolved oxygen (DO), biochemical oxygen demand for 5 days (BOD_5), and nitrates (NO_3^-). Four expeditions were made between May 2022 – February 2023. The research was conducted in the main hydrological seasons, covering high-water and low-water periods. For measuring parameters portable equipment has been used, such as a pH meter with an automatic temperature measurement function, a salinity meter with an automatic temperature measurement function, an oximeter, and a nitrate meter. The obtained results were entered into the SMART software database. It combines GIS with database tools and digital field assessment. The SMART system consists of three components: SMART Mobile, for a phone with the Android operating system; SMART Desktop, for a personal computer; and SMART Connect, for a server.

Results and Discussion

In the framework of the Preparatory Phase the synergy between the Ramsar Convention and the EU WFD has been studied. Both documents acknowledge the ecological significance of wetlands and their vital contribution to a range of ecosystem services, including water purification, flood regulation, and biodiversity habitat. They also emphasise the importance of adopting sustainable water management practices and incorporating environmental considerations into decision-making processes. In fact, the Prut River basin within the Hoverla Scientific Nature Protection Department of the CNNP and the Prut River Headwaters Wetland are one and the same territory. The Prut River Headwaters Wetland is a component of the hydrological continuum of the Prut River basin; therefore, it can significantly affect their condition. It means that application of both International Agreements is justified. Moreover, their synergies can assist in the development of new interdisciplinary research. The process of delineating and defining surface water bodies has involved dividing them into distinct sections and parts, considering hydromorphological conditions and potential threats based on the following criteria: WBs without any anthropogenic influence (reference conditions); WBs with known anthropogenic influence; the first-order tributaries of the Prut River; man-made/artificial ponds. Three types of 18 surface WBs were identified within the wetland and proposed for the water monitoring programme (Fig. 1): 16 RWBs – Prut River and tributaries of the first order; 1 LWB – Nesamovyte Lake; 1 AWB – the complex of the artificial water ponds for fish breeding that are on private property, but currently they are out of operation. The DPSIR methodology was used to identify the pressure and potential impacts of anthropogenic factors on the water ecosystem, including point and diffuse sources of pollution, water abstraction, and hydromorphological alterations (Table 1).

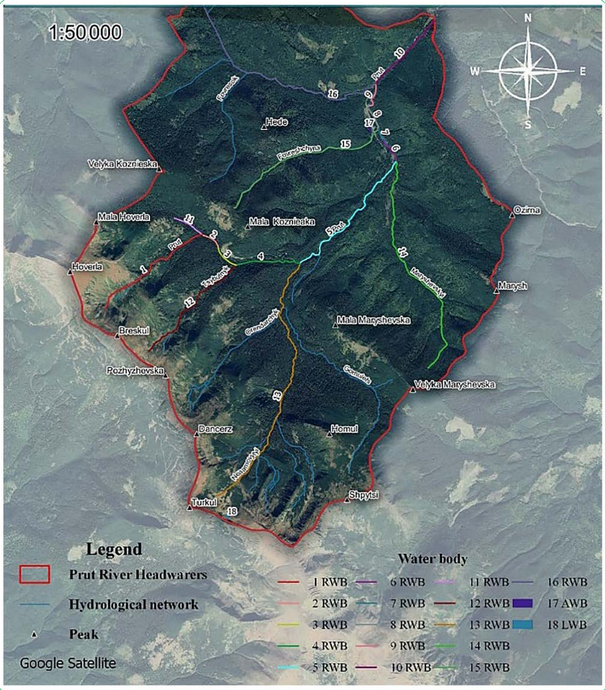

Figure 1. Water bodies delineated for water monitoring of the Prut River Headwaters Wetland
Source: created by the authors

Table 1. The DPSIR principle linking drivers and possible impacts on water bodies of Prut River basin within the wetland

Type of influence	Driver forces	Pressures	State	Impacts	Responses
Diffuse sources pollution	Tourism/ recreation	Solid waste/illegal dumping	Chemical pollution of surface water (SW) and ground water (GW)	Reduction of WB status, decreasing of biodiversity	Design of monitoring, tailor-made programme of measures
Diffuse sources pollution	Tourism/ recreation	Waste water discharges from sanitary and hygienic building	Chemical pollution of SW and GW	Deterioration of the ecological status of WBs	Tailor-made programme of measures (modernisation of waste water treatment plan (WWTP))
Point sources pollution	Tourism/ recreation	Waste water discharges from sport complex Zarosliak	Chemical and microbiological pollution of SW and GW	Deterioration of the ecological status of WBs	Tailor-made programme of measures (modernisation of WWTP)
Hydrological alteration	Water abstraction	Insufficient ecological flow	Changes the natural flow pattern and the amount of water in the environment	Deterioration of the hydrobionts' habitat	Design of monitoring programme
Hydrological alteration	Habitat continuity interruption	Altered flow conditions	Interruption of river continuity and fish migration routes	Deterioration of the hydrobionts' habitat	Design of monitoring programme

Source: created by the authors

After analysing the factors affecting the ecological status of the water resources of the wetland, the impact of tourism and recreation, which causes both point and diffuse sources of water pollution, was particularly obvious. Recognised anthropogenic impact on water resources revealed another problem – the management issues. General wetland management is carried out by the CNNP administration, but part of the land belongs to two other owners: the Vorokhta territorial community and the Vorokhta branch of the Forests of Ukraine State Enterprise. These parts of land are called "land without expropriation". These two institutions conduct their activity towards tourism and forest exploitation. Lack of cooperation between them led to the missing of very important management issues, such as prevention of point and diffuse pollution of the Prut River within the protection zone from wastewater from the Zarosliak sport base and souvenir market. As a result of Preparatory Phase, a general mission statement for water monitoring within the wetland was formulated as follows: "To enable the detection and response to changes or likely changes in wetland ecological character from anthropogenic pressure". Within the Conceptual Phase legislative base for a multi-level water monitoring programme was analysed. Taking into account the Resolution of the Cabinet of Ministers of Ukraine No. 758 "On Approval of the Procedure for State Water Monitoring" (2018), three types of monitoring were planned for the water monitoring programme within the Prut River Headwaters Wetland: surveillance, operational, and investigative (Fig. 2).

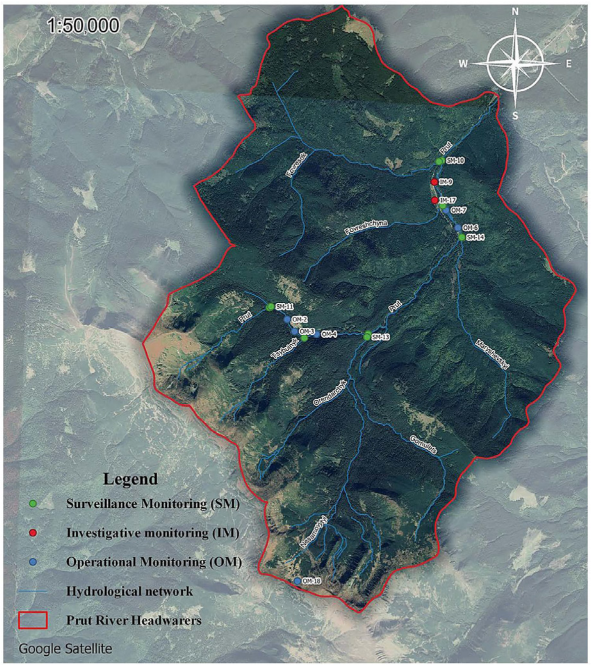

Figure 2. Multilevel monitoring sample points within the Prut River Headwaters Wetland
Source: created by the authors

For each type of monitoring, separate mission statements and monitoring sheets were developed. The example of the worksheet for the operational monitoring is presented in Table 2. The mission concept of the surveillance monitoring was proposed as next: "Supplementing and verifying of the reference condition within the Prut River Headwaters Wetland"; for the operational monitoring: "Evaluation of long-term trends (the assessment of long-term alterations in natural conditions resulting from the anthropogenic activities) within the Prut River Headwaters Wetland"; and for the investigative monitoring: "To assess the scale and degree of diffuse pollution from fish breeding ponds within the Prut River Headwaters Wetland" (in case of re-operation).

Table 2. Operational monitoring sheet for the Prut River Headwaters Wetland

Monitoring concept mission: detection of long-term trends (the assessment of long-term changes in natural conditions resulting from the anthropogenic activities) within the Prut River Headwaters Wetland					
WHY?	**WHAT?**	**WHERE?**	**WHEN?**	**WHO?**	**HOW MANY RESOURCES?**
Supplementing and validating risk assessments of the water bodies that are influenced by point and diffuse sources of pollution Monitoring outcomes: collected data of hydrochemical parameters Methods of database processing (paper, Microsoft Office ACCESS, SMART system) Monitoring results will be used for ecological assessment of the water bodies and for the data exchange with monitoring institutions	Hydrochemical parameters: temperature, dissolved oxygen, pH, conductivity, hardness, alkalinity, calcium, sodium, magnesium, colour, chlorides, sulphate, phosphates, nitrates, ammonia, total suspended solids, BOD_5, chemical oxygen demand (COD – dichromide)	Sample points: WBs 2, 3, 4, 6, 7, 8, 18	Monitoring frequency – one time/month (in the accessible period of the year); during low-water and high-water periods	The staff of the Laboratory of Analytical Control and Monitoring The Laboratory of Water Monitoring of the Western Region (Ivano-Frankivsk)	Human resources: as minimum 2 people for the field study and 1 person for conducting laboratory analyses Resources and equipment for the field trip and conducting analyses by staff of the Laboratory of Water Monitoring of the Western Region: laboratory glassware, portative equipment for parameter measurement; photoelectric colorimeter, 1 smartphone with SMART software, 1 GPS Garmins, 1 personal computer with SMART-office software Transport (1 time per month) Fuel – 30 l per trip Financial support for trainings, salary, and equipment
HOW?			**SYNERGIES/RE-EVALUATION**		
Using national standards: DSTU ISO 5667-3-2001 (2001), KND 211.1.1.106-2003 (2003)			Using the existing database of water monitoring (CNNP and other scientific institutions) Re-evaluation after 6-year period (in accordance with EU WFD and Water Code of Ukraine)		

Source: created by the authors

During the Implementation Phase field and laboratory investigations of water bodies within the testing site at seven control points were conducted (measuring physicochemical parameters with portable equipment). Water sampling points are presented in Figure 3. Case studies within the Prut River Headwaters Wetland combined field and laboratory research and presented in the next results: seven sampling sites for water monitoring, namely: No. 1, No. 4, No. 6, No. 9, No. 12, No. 16; 18 samples; field investigated parameters: mineralisation, T, pH, DO, and NO_3^-;

laboratory investigated parameter: BOD_5. All indicators of water quality did not exceed the permissible limits, except for the pH indicator in WB No. 1, which is obviously related to geological conditions because this WB is outside of any anthropogenic influence. Hydrochemical research within the wetland was entered into the SMART system (SMART-mobile and SMART-office). Collected data is available for analysis and for interdisciplinary interpretation. Figure 4 provides screenshots of the newly created database for hydrochemical monitoring within the Prut River Headwaters Wetland. After accumulating a certain database in the SMART-Desktop version, an analysis can be conducted (queries, reports based on queries, tables, or map generation) (Fig. 5).

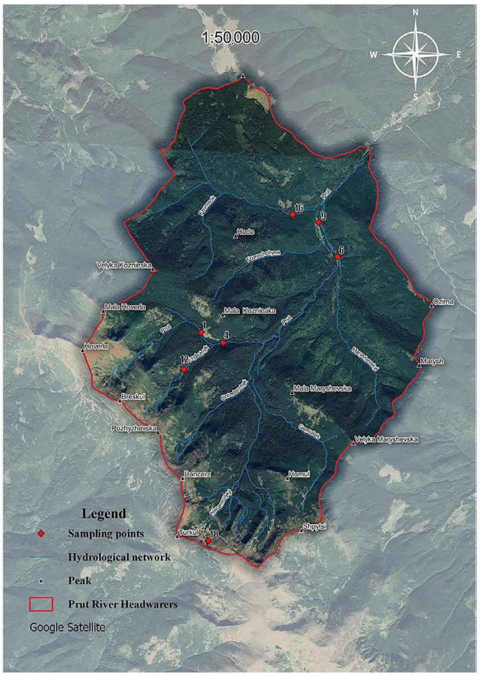

Figure 3. Testing water sampling sites within the Prut River Headwaters Wetland
Source: created by the authors

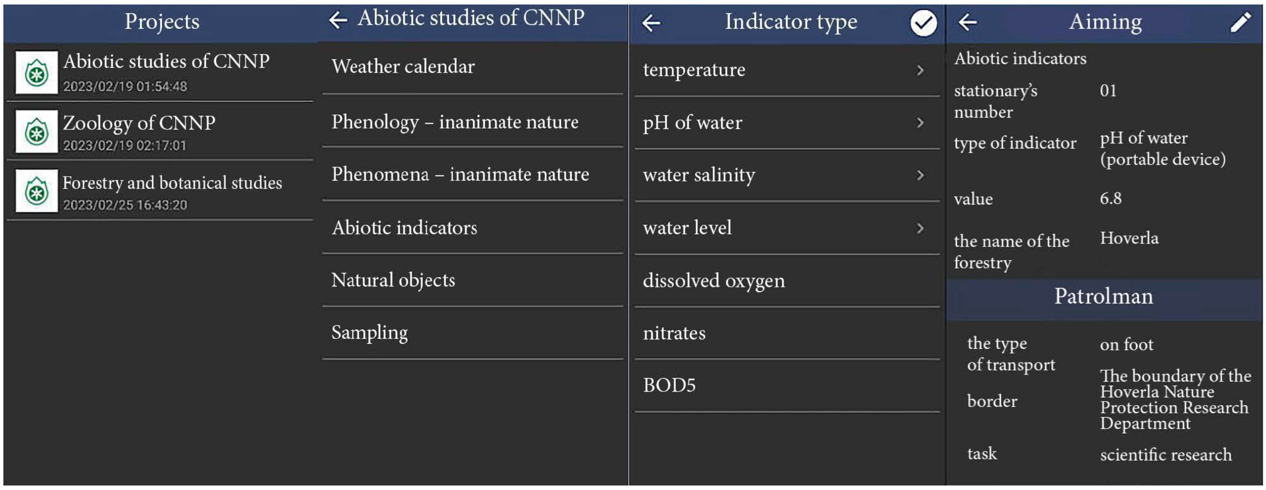

Figure 4. Example of field data collection of water parameters within the Prut River Headwaters Wetland using SMART-Mobile
Source: created by the authors

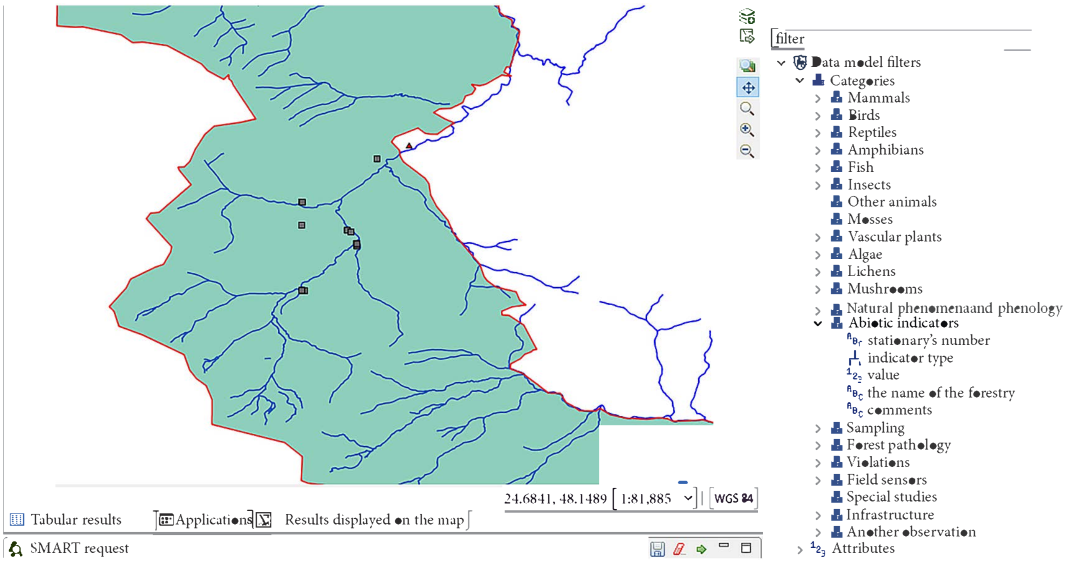

Figure 5. Examples of data request (map) within the Prut River Headwaters Wetland using SMART-Desktop
Source: created by the authors

Within the Implementation Phase the initiate database of wetland water parameters was formed. It is reliably stored in the cloud environment and can be used for various scientific or management purposes. Collected data is available as well and for interdisciplinary interpretation. Re-evaluation Phase will be conducted after long term monitoring studies. The monitoring plan can be revised and improved in the future in accordance with the identified risks or in case of estimation of implemented measures. The study showed that the planning process of wetland monitoring is not simple. N. Job *et al.* (2020) observed that in biodiversity-rich protected areas of developing nations, the management of wetlands is frequently hindered by insufficient time, personnel, and specialised knowledge, primarily due to a scarcity of data regarding the scope and characteristics of wetland resources. At the same time, as W. Kleindl *et al.* (2023) pointed out, there are more than 700 approaches to the assessment of aquatic ecology worldwide that meet the specific requirements of institutional goals. T. Dube *et al.* (2023) in their scientific paper analysed literature about wetland vulnerability that encounters numerous risks and possible deterioration, underscoring the necessity for robust monitoring and evaluation systems to safeguard their ecological and hydrological processes.

Monitoring is one of the important tools of proper management planning. Q. Demarquet *et al.* (2023) emphasised that managers and scientists require instruments to describe and oversee wetland areas, structure, and functions over extended periods, as well as at regional and global levels, and to evaluate the impacts of planning policies on their conservation status. As highlighted by P. Kumar *et al.* (2021), monitoring involves the systematic measurement, recording, and comparison of accomplishments with a predetermined set of objectives, thus providing project outcomes to managers and policymakers to aid in decision-making. D.T. Dalton *et al.* (2021) recognised new technologies as transforming the approaches of protected area managers to monitoring and implementing effective strategies that enable more efficient data collection while facilitating adherence to conservation requirements. The authors argued that choosing and using the right tools is improving options for adaptive management. H. Xu *et al.* (2019) noted that enhancing the speed and precision of monitoring changes in wetlands offers benefits for environmental protection and the scientific management of wetland resources. Ultimately, it aids in harmonising the relationship between humans and the planet. The CNNP administration is responsible for the Prut River Headwaters Wetland management in order to ensure stability of ecological character. S.L. Maxwell *et al.* (2020) highlighted that governments, policymakers, and many members of the conservation community have long held that protected areas are a fundamental cornerstone of biodiversity conservation.

Implementation of the water monitoring programme is the first practical measure that it can provide. It means that the collection of water parameters within the wetland will become the basis of regular monitoring to determine the dynamics of changes in wetland ecosystems and management issues towards wetland "wise use". The same statement was presented by S.A. Dar *et al.* (2022). They highlighted the significance of water quality monitoring in assessing the safety and appropriateness of water for different intended purposes. Most physical parameters of water quality are typically assessed through *in situ* measurements using contemporary testing equipment or field testing kits. The incorporation of hydrochemical and biological parameters within wetland ecosystems is vital. P.J. Stephenson (2020) points out that evidence-based decision-makingin natural resource management and conservation is frequently hindered by the absence of comprehensive biodiversity data. The study proved that modern technologies and tools can be very effective for data collection and storage. The SMART tool is a good example of reliable data storage and processing of information. Another example is environmental DNA (eDNA) analysis recommended by R.A. Erickson *et al.* (2019) and T. Minamoto *et al.* (2021) or GIS remote sensing images as proposed by Q. Cheng & C.N. Dang (2022). M. Boiaryn *et al.* (2023) used ArcGIS Pro for environmental mapping of the Prip-yat River basin. The CNNP experts supported the idea of inclusion in the wetland monitoring programme water biological indication, in particular, with the eDNA method. This activity is planned for 2024. Therefore, modern technologies can contribute significantly to wetland monitoring. For the hydromorphological and hydrobiological monitoring, it is necessary to invite external experts for training of CNNP staff. For comprehensive physicochemical monitoring, the Laboratory of Water Monitoring of the Western Region (Ivano-Frankivsk) can be involved in the worst season for water – during hydrological draught.

According to the International Union for the Conservation of Nature definition, monitoring is defined as the long-term collection and analysis of information that is used by management and partners in order to track progress of the implemented measures, achievement of objectives, and use of resources (Monitoring, n.d.). The monitoring concept should be part of the research concept and should be regularly updated, as well as closely relate to the conservation objectives and be linked with the management plan. Ensuring data storage, quality, and ongoing analysis must be guaranteed. A perspective for improving wetland monitoring and "wise use" is the current participation of the CNNP representatives, the author of this study in particular, with Prut and Siret Rivers Council that are responsible for development of the Prut River basin management plan with WFD requirements. Being a cross-cutting issue of this directive, the Ramsar site should be in focus of the management plan, including the monitoring programme and the elaboration of programme of measures.

Conclusions

The main focus of the study was the wetland of international importance – the Prut River Headwaters – that belongs to the CNNP. Water resources of the wetland are represented by a dense hydrological network that plays a crucial role for biodiversity and human wellbeing. Due to the fact that the site was designated relatively recently – in 2019 – proper site management has not yet been organised, and an effective monitoring programme has not been developed in order to fulfil the main Ramsar Convention goal – wetland "wise use". In order to organise the processes of comprehensive planning of water monitoring within the wetland, a conceptual monitoring framework developed by a group of experts from the UNESCO Chair of Sustainable Management of Conservation Areas from CUAS was applied. This objective was achieved by planning the monitoring programme through four consecutive phases: preparatory, conceptual, implementation, and re-evaluation. In this research, the first three stages are developed in detail, with a special focus on the Preparatory Phase.

Wetlands play a crucial role in river basin management. Analysis of the EU WFD and Ramsar Convention synergy proved that key elements of a river basin management plan can be used for conceptualisation of water monitoring for the Prut River Headwaters Wetland. Therefore, within the Preparatory Phase, delineation of surface waters was carried out, as a result of which 18 water bodies were obtained for the monitoring programme. DPSIR methodology was used to identify the anthropogenic loads on the water ecosystem, including point and diffuse sources of pollution, water abstraction, and hydromorphological alterations. Taking into account identified pressure, the monitoring statement was formulated within the Conceptual Phase as follows: "To enable the detection and response to changes or likely changes in wetland ecological character from anthropogenic pressure". This general mission can be reached through three types of monitoring: surveillance, operational and investigative. During the Implementation Phase, field studies of the seven WBs were conducted (measuring physicochemical parameters in 7 control points with portable equipment) with collecting and storing data through SMART-mobile and SMART-office software. Re-evaluation Phase was proposed to be revised after long-term implementation of the monitoring programme. In the near future, a new management plan for the CNNP will be designed for ten years. It is planned to include management of the CNNP Ramsar sites in the separate chapter with a detailed description of long-term monitoring of biotic and abiotic parameters.

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Conflict of Interest

None.

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Концептуальний підхід до програми моніторингу водно-болотного угіддя міжнародного значення «Витоки річки Прут»

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Анотація. Функціонуючи як регулятор паводків і резервуар прісної води, водно-болотне угіддя «Витоки річки Прут», що охороняється Рамсарською конвенцією, є важливим осередком біорізноманіття, включно з ендемічними, рідкісними видами, видами, що перебувають під загрозою зникнення, та занесені до національного й глобальних Червоних списків. Існують прогалини щодо питань управління ділянкою, зокрема відсутність інтегрованої системи моніторингу водно-болотного угіддя. Тому метою цього дослідження було організувати процеси комплексного планування моніторингу водно-болотного угіддя. Щоб досягти мети, використано концептуальну основу для моніторингу, розроблену групою експертів кафедри ЮНЕСКО зі сталого управління природоохоронними територіями. За допомогою методу інформаційно-аналітичного дослідження розроблено модель програми моніторингу вод водно-болотного угіддя «Витоки річки Прут». Було розроблено та частково протестовано поєднання фізико-хімічних та гідробіологічних оцінок. Метод використовувався для перевірки універсальності запропонованої методики на конкретній досліджуваній території, що потребує сталого управління, та з метою вивчення перспективи застосування до інших водно-болотних угідь, чи цінних природних комплексів природоохоронних територій. Для проміжних етапів розробки програми моніторингу використовувалися ключові елементи управління річковим басейном Водної рамкової директиви ЄС в синергії з положеннями Рамсарської конвенції. На етапі реалізації проведено польові та лабораторні дослідження водних масивів у межах ділянки в 7 контрольних точках (вимірювання фізико-хімічних показників портативним обладнанням). Усі значення параметрів були в межах допустимих норм. Створено первинну базу даних результатів, що зберігається в програмному забезпеченні SMART. Очікується, що практична реалізація плану моніторингу води сприятиме оцінюванню стану екосистеми водно-болотних угідь та підтримці адміністрації Карпатського національного природного парку в сталому управлінні водно-болотними угіддями

Ключові слова: Карпатський національний природний парк; Рамсарське угіддя; глобальна моніторингова настанова; багаторівнева програма моніторингу вод; база даних

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Greening of territories in the system of planning and improvement of the city of Ivano-Frankivsk

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Abstract. Compliance with the requirements for landscape and recreational areas in urban planning and development is a prerequisite for ensuring the sanitary well-being and comfortable living of the population. Therefore, the purpose of the presented work was to assess the green and other public landscape and recreational areas within the Ivano-Frankivsk, as well as to provide recommendations for greening the city and its improvement. Theoretical research methods were applied, including the collection and systematisation of regulatory and reporting information on public landscape and recreational areas within the Ivano-Frankivsk; analysis of compliance with the requirements of Ukrainian legislation; and generalisation of problems to provide recommendations for improving the city's amenities. It has been established that as of the beginning of 2024, the total area of existing green spaces is about 126 ha and is represented by five city parks, one dendrological park, and 58 squares. There are 5.3 m^2 of green space per person, which is almost twice as low as the norm (10 m^2/person). In 2021-2023, the city council has planned to build 41 new squares with a total area of 31.46 ha, which will increase the specific area of green spaces to 6.6 m^2/person. It was found that the average level of greenery in squares is 72%. There are seven areas and objects of the Nature Reserve Fund of Ukraine in the city, and the coverage of protected areas is less than 1%. The territory of the Emerald Network "Bystrytsia Nadvirna Valley" within the city and adjacent villages has been significantly transformed and urbanised and is used as a recreation area, which may affect protected species. The city's water bodies are only partially equipped with recreation areas. Measures to green the city and improve its amenities are proposed, including the creation of green spaces in residential neighbourhoods and along roads, the use of green elements on the walls of buildings, and the organisation of meadow parks. The practical value of the results is to highlight the current and future state of the public landscape and recreational area network in Ivano-Frankivsk and to provide reasonable recommendations for its improvement

Keywords: improvement of settlements; landscape and recreational areas; park; square; protected area

Introduction

The issue of urban landscaping is gaining new importance. In addition to the tasks set out in the current legislation of Ukraine: rational use of the territory, proper maintenance and protection, creation of conditions for the protection and restoration of a favourable environment for human life, new aspects are being added, including the preservation and improvement of the mental health of the population (Law of Ukraine No. 2807-IV, 2005). Greening the territories of

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Ukrainian cities is one of the directions of the strategy for sustainable urban development and the strategy for planning public spaces. This issue is constantly discussed not only by ordinary residents but also by the authorities and non-governmental organisations. The majority of modern Ukrainian cities are characterised by a high density of multi-story buildings and a low level of green spaces. The main ways to improve the situation with urban greenery are mostly related to the development of the existing network of parks and the arrangement of large green spaces. Insufficient attention is paid to indoor areas in city neighbourhoods and the development of lakes and riverside areas. Another equally important issue is the organisation of care for green plants, which in urban systems require special attention and directly affect the level of greenery. An interesting trend is the use of various elements of landscape design, such as hedges, lawns, curb ribbons, alley plantings, and rhododendrons for urban greening.

The importance of creating green spaces in the context of modern dense development, which is especially important for large cities in Ukraine, was considered by scientists A.V. Kodzhebash & A.P. Kodzhebash (2020), who studied the issues of vertical and modular landscaping and roof gardening. The analysis of the problem of urbanisation and development of large cities and megacities in European countries and China, conducted by V. Loiko *et al.* (2021), showed the negative impact of global urbanism on the quality of life of the population and their mental health, highlighting the main negative features. Considering the issues of urbanism in the modern and post-war space of Ukraine, N. Godz (2023) notes the importance of combining natural and urban landscapes, as well as the use of futurology in the development of urbanism. In order to solve the problem of the lack of places for recreation – green spaces within a 10-minute walk – Yu. Polianskyi & K. Shchuryk (2023) proposed the creation of a Green Line in the Riasne Micro-District of Lviv.

A number of works are devoted to the study of various aspects of green spaces in Ivano-Frankivsk. O. Tkachuk (2023), studying the degradation of vegetation in urbanised ecosystems, concluded that it is important to maintain lawn grasses taking into account climatic and environmental factors, which should improve the quality of lawns in the city. O. Lytvyn & V. Sydorka (2022) note that Ivano-Frankivsk is one of the cities in Ukraine where the greening standards are among the closest to the norms compared to other large cities in Ukraine. At the same time, they propose to create a multifunctional public space using small sensory gardens in different neighbourhoods of the city, which would be accessible and comfortable for different age groups. O. Oleshko & Yu. Petrovska (2020) studied the use of various elements of landscaping, the creation of phytocompositions, and the formation of a subject-spatial urban environment. A. Rykhlivskyi (2019) compared residential neighbourhoods built in 1960-1980 and newly built residential complexes in Ivano-Frankivsk in 2008-2018 with European analogues of urban space creation. The paper focuses on the significant increase in the building area, number of storeys, and population density, as opposed to the decrease in the area of green spaces. And the share of greenery in residential development in Ivano-Frankivsk decreased from 49.6% in the 60s-80s of the twentieth century to 16.4% in 2008-2018. V. Moroz & N. Moskalchuk (2021) also assessed landscape and recreational areas (LRAs) at the level of the inter-roads space, which covered the Park and partially the BAM and Naberezhna micro-districts. They made a map of the structural elements of the territory, calculated their areas, and calculated the percentage of greenery. I. Kavchuk & N. Riznychuk (2022) studied the species diversity of trees and shrubs in the Taras Shevchenko City Park and the memorial square in Ivano-Frankivsk.

To summarise the reviewed scientific papers, the main studies of the problem of greening urbanised areas have been carried out in the following areas: the negative impact of global urbanism on the quality of life of the population, the lack of places for recreation – green spaces within a 10-minute accessibility, the prospects for the use of vertical and modular landscaping and roof greening in densely built-up cities, assessment of visual impacts in areas with different intensity of greening, reduction of the area of green spaces and determination of the recreational load in parks in Ivano-Frankivsk, assessment of LRAs at the level of the intermunicipal territory at the city level and species diversity of tree and shrub plants in the city park and memorial square in Ivano-Frankivsk. The issue of greening urban areas covers various areas of research and is becoming increasingly relevant in modern urbanism, the formation of urban amenities, and the improvement of the quality of life and health of the population. The purpose of the study was to assess the green and other public LRAs within the Ivano-Frankivsk and to provide recommendations for greening the city and its improvement. The main tasks were to determine the adequacy of existing and projected areas of public landscaping and the level of greening of public gardens; to establish the presence and type of protected areas to organise recreation areas near water bodies; and to recommend measures to improve the city's greenery.

Materials and Methods

Ivano-Frankivsk is a regional centre located in western Ukraine in the Precarpathian Upland Region of the Ukrainian Carpathians. The theoretical research methods used in the study included systematisation of information from regulatory documents on the concept of LRAs, their structure, requirements for their planning and maintenance; collection and systematisation of data on existing and projected public LRAs within Ivano-Frankivsk; and analysis of compliance with the requirements of Ukrainian legislation regarding the size of the specific area, level of greening, etc. The paper uses the definitions of concepts and requirements from such regulatory documents as the state sanitary rules for planning and development (Order of the Ministry of Health of Ukraine No. 176, 1996), state construction norms (Order of the Ministry of Regional Development, Construction and Housing and Communal Services of Ukraine No. 104, 2019), rules for the maintenance of green spaces in settlements of Ukraine (Order of the Ministry of Construction, Architecture, and Housing and Communal Services of Ukraine No. 105, 2006), and rules for the protection of human life on water bodies of Ukraine (Order of the Ministry of Internal Affairs of Ukraine No. 301, 2017).

The sources of initial information on existing and planned LRAs within the city were open data from the Official website of the Ivano-Frankivsk (n.d.), the database of the Regulatory acts of Ivano-Frankivsk City Council (n.d.), and official websites of the City Development and Recreation Centre Municipal Enterprise (n.d.) and Blahoustrii Municipal Enterprise (n.d.), Landscaping facilities (n.d.), and the State cadastre of territories and objects of the Nature Reserve Fund (n.d.). Some important documents used in the work were: an explanatory note to the city master plan (On the approval of the changes…, 2018); an environmental protection programme for 2021-2025 (Resolution of the Ivano-Frankivsk City Council No. 396-18, 2021); and a number of resolutions of the Ivano-Frankivsk City Council on land issues in 2021-2023, which approved the technical documentation for the construction and maintenance of public gardens in the city.

The following general data about the city were used for the study: the number of available populations is 238,196 according to the Main Department of Statistics in Ivano-Frankivsk Region (Population (estimate)…, 2022). The data is as of 01.01.2022, as no up-to-date demographic information is available due to the war. The indicator was used to calculate the specific area of green space/LRAs and the ratio of the total area of green spaces/LRAs for public use to the population (m^2/person). The area of the territory within the city limits is 37 km^2 according to the city's general plan (On the approval of the changes…, 2018). The indicator was used to determine the percentage of the area of protected areas and objects in relation to the city area – the protected area indicator (%). In analysing and summarising the recommendations, it was also taken into account that since 2020 the city has been the centre of the Ivano-Frankivsk territorial community, whose territory includes 18 suburban villages. The total population of the Ivano-Frankivsk territorial community is 288,243 people, with a total area of 265.5 km^2 (Official website of the Ivano-Frankivsk, n.d.).

Results and Discussion

Planning of settlements in Ukraine is carried out in accordance with the state sanitary rules for planning and development of settlements (Order of the Ministry of Health of Ukraine No. 176, 1996). Settlement planning is based on the principle of functional zoning of the territory. The sanitary rules state that, in accordance with the current building codes and regulations, the territory of a settlement is divided into rural, industrial, and LRAs, taking into account the predominant functional use. The main purpose of the creation of rural areas and LRAs is to create favourable living conditions for the population, taking into account the quality of the environment and microclimate. The LRAs form the system of greenery and recreational areas of settlements. The main construction standards referred to in the sanitary rules are DBN B.2.2-12:2019 (Order of the Ministry of Regional Development, Construction and Housing and Communal Services of Ukraine No. 104, 2019). In accordance with them: "LRAs are a network of green and other open spaces for various purposes located both in the territories of settlements, suburban areas, and inter-settlement areas". When forming the LRAs network of settlements, it is necessary to separately allocate areas of general use, restricted use, and special purpose. Appendix D of the construction norms details the main structural elements of the network and their components depending on the location relative to the boundaries of the settlement and the type of use.

In particular, within the boundaries of settlements, the structural elements are public green spaces, which include multifunctional and specialised parks, gardens, squares, boulevards, urban forest parks, green areas of embankments and beaches, botanical gardens and zoological parks, parks-monuments of landscape art, and other natural and artificially created landscape objects. These state construction norms and sanitary rules define the basic requirements for landscaping in various zones of settlements; in particular, they oblige to comply with the requirements for the proportion of green or other LRAs within the territory of the settlement. The area of green public areas should be at least 10 m^2/person for cities and at least 12 m^2/person for rural settlements. Areas of the LRAs network may be located differently in relation to the boundaries of the settlement (its administrative boundaries). They also differ in the type of use for recreational purposes: general (access is allowed and available to all), limited (access is allowed or available to certain groups of recreationists, for example, residents of a group of residential buildings, students, or employees of an institution), or not used for recreation but have a special purpose (protected natural areas, greening of security zones, sanitary protection zones, etc.).

The normative indicators of the area vary depending on the size of the city's population, physical and geographical zoning, and the type of LRAs. According to the state building codes for Ivano-Frankivsk, the normative specific area of public LRAs within the city limits should be 11 m^2/person. According to the state sanitary rules, the specific area of public green spaces (greening norm) should be at least 10 m^2/person. According to the main type of urban planning documentation intended to substantiate the strategy of planning and development of the city's territory – the general plan (On the approval of the changes…, 2018), the area of public green spaces in the city at the beginning of 2017 was 124.26 ha. The general plan envisages 75.07 ha, which together will make up about 8.0 m^2/person. Based on the nomenclature of structural elements of the LRAs network, information from the explanatory note to the master plan of Ivano-Frankivsk, decisions of the Ivano-Frankivsk City Council on land issues for 2021-2023, information from the websites of the municipal enterprises City Development and Recreation Centre and Blahoustrii, as well as information from other sources, a summary of existing public LRAs within the Ivano-Frankivsk was formed. As of the beginning of 2024, the total area of public green spaces in Ivano-Frankivsk was about 126 ha: 5 municipal multifunctional parks with a total area of 96.6 ha; one specialised park, Druzhba Dendrological Park, with a total area of 5.0 ha (+5 ha outside the city); 58 squares with a total area of 24.3 ha. Taking into account the population of the city as of the beginning of 2022, the specific area of green public areas is 5.3 m^2/person. The calculated indicator does not meet the greening standard of 10 m^2/person and is almost half of it.

It is worth noting that the actual area of the "land" is even smaller, as 41.76 ha is water area (the total area of the water surface in three parks). In addition to public green spaces, there are no other publicly accessible LRAs within the city (urban forests, forest parks, meadow parks, hydroparks), so the specific area of publicly accessible LRAs is also 5.3 m^2/person, which does not meet the standard of 11 m^2/person.

In 2020, the environmental protection programme of the Ivano-Frankivsk territorial community for 2021-2025 was approved (Resolution of the Ivano-Frankivsk City Council No. 396-18, 2021), one of the expected results of which is to increase the area of green spaces by creating new squares and other landscaping facilities. As a result, since 2021, the number of city council decisions on the construction of new squares has increased. The information on specific objects was systematised, and it was determined that 41 new squares are planned to be arranged within Ivano-Frankivsk with a total area of 31.46 ha (Table 1). If all the squares planned for 2021-2023 are completed, the area of public green spaces could increase to 6.6 m^2/person (with the population as of the beginning of 2022). However, this will still fall short of the required amount. It is also worth noting that due to the full-scale invasion by the Russian Federation, the community's territory has become a refuge for tens of thousands of internally displaced persons. As of the end of 2023, 41,039 internally displaced persons were registered in the Ivano-Frankivsk territorial community (Assistance to internally displaced persons, 2023).

Table 1. Land sites within the Ivano-Frankivsk for which technical documentation on the inventory for the creation and maintenance of the square was approved in 2021-2023

Title	Area, ha	Transferred to permanent use
Yevhenii Konovalets Str., next to building No. 93	0.1179	Blahoustrii Municipal Enterprise
Flotska Str., near the Ivano-Frankivsk National Technical University of Oil and Gas	0.1822	Blahoustrii Municipal Enterprise
In the area of Kaluske Hwy. (near the cemetery)	2.8862	Blahoustrii Municipal Enterprise
Sukhomlynskyi Str.	0.4480	Blahoustrii Municipal Enterprise
Heroyi UPA Str.	0.1153	Blahoustrii Municipal Enterprise
Stepan Bandera Str. – Rebeta Str.	0.1321	Blahoustrii Municipal Enterprise
V. Manyukha Str.	0.0653	Blahoustrii Municipal Enterprise
Mlynarska Str.	0.1945	Blahoustrii Municipal Enterprise
O. Dovzhenko Str.	0.8041	Blahoustrii Municipal Enterprise
Hetman Mazepa Str.	0.5673	Blahoustrii Municipal Enterprise
Cardinal Lubomyr Husar Str. (Novhorodska)	0.1936	Blahoustrii Municipal Enterprise
Yevhenii Konovalets Str., in the area of buildings 130A and 136D	0.24	Blahoustrii Municipal Enterprise
Belvedere Str.	0.2830	Blahoustrii Municipal Enterprise
Halytska Str.	0.0934	Blahoustrii Municipal Enterprise
Yevhenii Konovalets Str., next to the building No. 136B	0.1151	Blahoustrii Municipal Enterprise
V. Ivasyuk Str.	0.1004	Blahoustrii Municipal Enterprise
Nearby kindergarten No. 23 "Dudaryk"	0.4903	Blahoustrii Municipal Enterprise
In the Pasichna Micro-District	2.5	Blahoustrii Municipal Enterprise
Tysmenytsia Str.	15.1932	Blahoustrii Municipal Enterprise
O. Dovzhenko Str.	0.1744	Blahoustrii Municipal Enterprise
O. Dovzhenko Str.	0.04	Blahoustrii Municipal Enterprise
V. Stus Str., near the Arsen shopping centre	0.0967	Blahoustrii Municipal Enterprise
Vovchynetska Str., next to building No. 180	0.7025	Blahoustrii Municipal Enterprise
Kakhovska Str.	0.0425	Blahoustrii Municipal Enterprise
V. Symonenko Str., near houses No. 9-13	0.25	–
Parkova Str., near the building No. 18A	0.1	–
29 Pivdennyi Blvd. – 9 Korol Danylo Str.	0.5686	–

Table 1, Continued

Title	Area, ha	Transferred to permanent use
V. Ivasyuk Str.	0.097	–
Yevhenii Konovalets Str., next to building No. 88A	0.05	–
John Paul II Str., next to building No. 18	0.4	–
Parkova Str., near the monastery of St. Joseph the Betrothed	0.3	–
V. Ivasyuk Str., in the area of buildings No. 30-44	0.7936	–
V. Ivasyuk Str., in the area of buildings No. 25-26	0.4581	–
V. Symonenko Str., next to building No. 7	0.17	–
Vovchynetska Str., in the area of buildings No. 192-198	0.5	–
11A Korolya Danyla Str. – 28 Pivdennyi Blvd.	0.2997	–
V. Chornovil Str., in the area of buildings No. 132-136	0.4843	–
Natsionalna Hvardiia Str., in the area of buildings No. 16-22	0.2018	–
V. Stefanyk Embankment Str., next to the building No. 6	0.2521	–
V. Stefanyk Embankment Str., next to the building No. 32	0.6	–
V. Stefanyk Embankment Str., next to the building No. 26	0.1567	–
Total	**31.46**	

Note: – not transferred to the balance sheet (as of 01.01.2024)
Source: compiled by the authors based on Resolution of the Ivano-Frankivsk City Council No. 184-8 (2021), Resolution of the Ivano-Frankivsk City Council No. 293-13 (2021), Resolution of the Ivano-Frankivsk City Council No. 424-18 (2021), Resolution of the Ivano-Frankivsk City Council No. 469-19 (2021), Resolution of the Ivano-Frankivsk City Council No. 55-20 (2022), Resolution of the Ivano-Frankivsk City Council No. 130-26 (2022), Resolution of the Ivano-Frankivsk City Council No. 254-32 (2022), Resolution of the Ivano-Frankivsk City Council No. 157-37 (2023), Resolution of the Ivano-Frankivsk City Council No. 125-36 (2023)

For green areas, a prerequisite is the presence of green plantings – tree, shrub, flower, and herb vegetation of natural and artificial origin (Order of the Ministry of Construction, Architecture, and Housing and Communal Services of Ukraine No. 105, 2006). According to the city council, at the beginning of 2021, the total area of green plantings in the city was 826 ha, i.e., 22% of the city's area (Resolution of the Ivano-Frankivsk City Council No. 396-18, 2021). The maps of the Global Forest Watch online platform provide a visual understanding of the real share of woody vegetation over 5 m in height (Fig. 1). State construction standards set a minimum level of greenery (percentage of green plantings in the total area of a given territory) that should be adhered to when organising green areas for public and restricted use. This figure is 65% for city parks and 75% for squares. The website of Blahoustrii, among other things, contains information on the Landscaping facilities (n.d.) maintained by the enterprise and their characteristics. It is interesting to note that the areas of the squares listed on the website differ from the areas of the same ones listed in the decisions of the Ivano-Frankivsk City Council on the transfer to the balance sheet of Blahoustrii. The level of greenery in the squares ranged from 39% to 100% (squares with 100% greenery do not have sidewalks). The average level of greenery in squares was 72%. Table 2 presents the results of determining the level of greenery in squares, which was calculated as the ratio of the area of lawns in a square to its total area. The names of the squares, their area, and lawn area are based on the data of Blahoustrii as of January 2024. The LRAs also include nature protection areas, in particular those belonging to the Nature Reserve Fund of Ukraine. The territory of the city is characterised by low coverage of protected areas (less than 1%) and the number of protected areas and objects – only 7 units (Table 3). The use of these areas and objects of the Nature Reserve Fund may be varied, but it is important to comply with the requirements of the law so that activities do not contradict their purpose and requirements for the protection, restoration, and use of natural complexes. Excursions are allowed in the Druzhba Dendrological Park, and Taras Shevchenko City Park is the main short-term recreation area of the city. Instead, natural monuments declared to preserve unique natural formations in their natural state are special purpose areas.

Figure 1. Tree cover (over 5 m high) in 2023
Source: created by the authors based on Global Forest Watch (n.d.)

Table 2. The greening levels of squares of Blahoustrii Municipal Enterprise

Name of the square location	Square area, m²	Lawn area, m²	Greening level, %
202-206 Vovchynetska Str.	112,059	10,944	91
On the corner of Vovchynetska Str. and Symonenko Str.	850	710	84
1 Dovzhenko Str.	1,300	900	69
On the corner of Mazepa Str. and Gordynskyi Str.	500	380	76
The area around the Christ the Saviour Rotunda	600	400	67
5 Kryva Str. (Piatnytsia Square)	240	170	71
97A (behind the Cosmos Cinema)	2,710	1,910	70
Knyagynia Square	3,380	1,400	41
170 Vovchynetska Str.	900	500	56
On the corner of Nezalezhnist Str. and Sukhevychi Str.	1,900	1,400	74
On the corner of Konovalets Str. and Viiskova Str.	1,400	850	61
119-121 Chornovol Str.	3,800	3,800	100
Mazepa Str., behind the medical college	1,200	900	75
Square opposite to the airport	7,000	6,200	89
Grunwaldska Str.	2,300	1,000	43
16 Mykolaichuk Str.	150	100	67
11A Korol Danylo Str. (Korol Danylo Square)	750	500	67
89A Depovska Str.	1,150	900	78
67 Halytska Str.	780	330	42
6 Botanichna Str.	600	550	92
On the corner of Petrushevych Str. and Franko Str.	380	150	39
175, 179 Hetman Mazepa Str. (behind the market)	390	250	64
73-75A/1-75A/2 Khotkevych Str. (Nebesna Sotnia Square)	2,510	2,000	80
126 Halytska Str.	1,575	1,575	100
4 Pavlo Ivan II Str.	857	586	68
30 Ukrainska Peremoha Str.	1,462	1,012	69
22 Snizhna Str.	1,602	1,090	68
13 V. Stus Str.	1,756	1,756	100
24 August, V. Stus Str.	1,868	860	46
45 V. Stus Str.	5,000	4,200	84
96 Chornovol Str.	3,829	1,490	39
2 Slava Stetsko Str.	650	450	69
Shota Rustaveli Str.	4,500	4,500	100
Grunwaldska Str. (next to the Ivano-Frankivsk City Court)	900	900	100
Total	**70,848**	**54,663**	**2,439**

Source: compiled by the authors based on Landscaping facilities (n.d.)

Table 3. Areas and objects of the Nature Reserve Fund of Ukraine in Ivano-Frankivsk

Title	Type of protected area/object	Separation by value	Location	Functional purpose of the LRA
Druzhba (named after Z. Pavlyk)	Dendrological park	National level	Ivano-Frankivsk (partially), Uhryniv Village	General use
Taras Shevchenko City Park of Culture and Recreation	The park is a monument of landscape art	Local	126 Chornovol Str.	General use
Common oak	Botanical natural monument	Local	4 Hnatyuk Str.	Special purpose
Purple beech	Botanical natural monument	Local	44 Knyahynia Str.	Special purpose
Ginkgo double-lobed	Botanical natural monument	Local	54 Vasylianok Str.	Special purpose
Centenary oak	Botanical natural monument	Local	25/1 Malanyuk Str.	Special purpose
Common oak	Botanical natural monument	Local	64 Mateyko Str.	Special purpose

Source: compiled by the authors based on State cadastre of territories and objects of the Nature Reserve Fund (n.d.)

Natural areas subject to special protection are not limited to the Nature Reserve Fund. They also include those protected under international obligations. These include the Emerald Network areas established under the Bern Convention for the conservation of species and habitats that are threatened with extinction across Europe. The site "Bystrytsia Nadvirna Valley", with a total area of 92.85 km^2, which was approved by the Bern Convention Secretariat and included in the Emerald Network in 2019, is important for the conservation of fish species listed in the Ukrainian Red List, and rare insect species found only in the Carpathian Region have been recorded here (Fig. 2). However, part of it within the city and adjacent villages has been significantly transformed and urbanised, used as a recreational area, which may affect protected species.

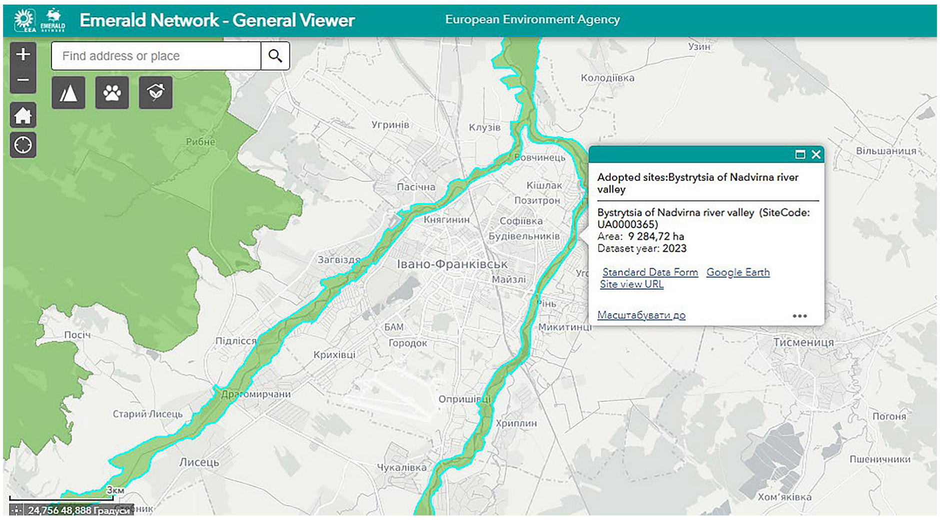

Figure 2. The Emerald Network "Bystrytsia Nadvirna Valley"

Source: created by the authors based on Emerald Network – general viewer (n.d.)

In the structure of the LRAs, water recreation areas are of great importance. According to the rules for the protection of human life on water bodies of Ukraine: "places of mass recreation on water bodies are beaches and water bodies with entertainment facilities and attractions, as well as places for physical fitness and sports activities, recreational and sport fishing" (Order of the Ministry of Internal Affairs of Ukraine No. 301, 2017). State construction standards state that within the coastal strips of rivers and lakes, beaches should be provided with a standard specific area of 8 m^2/visitor and a length of river and lake shoreline of at least 0.25 m^2/visitor. On the land and water areas adjacent to the beach zone, the coastal and aquatic zones are created. The areas of these zones are also regulated. In Ivano-Frankivsk, the beach of the City Lake, an artificial reservoir that occupies 69% of the City Lake Park with a total area of 47.93 ha, is well-equipped. It provides amenities such as umbrellas, sunbeds, changing rooms, and showers (Fig. 3). The beach is systematically maintained and cleaned. A sports ground for beach volleyball has been created in the coastal zone. However, the water area of the City Lake cannot be used for swimming due to the fact that the depth in the lake area adjacent to the beach is 2 m, not 1.5-1.75 as per safety requirements. Since Ivano-Frankivsk is located in the interfluve of the Bystrytsia Nadvirna and Bystrytsia Solotvynska rivers, residents actively use these water bodies for recreation. According to Blahoustrii, there are 9 recreational areas in the city (Table 4), with a total area of over 10 ha. Some areas of the coastal territory are equipped with changing facilities, garbage bins, and sports grounds, but mostly water recreation is unorganised. As mentioned above, this may affect species protected within the Emerald Network.

Figure 3. The beach of the City Lake

Source: compiled by the authors based on City Development and Recreation Centre Municipal Enterprise (n.d.)

Table 4. Recreation areas on the river banks of Ivano-Frankivsk

No.	Location	Total area, ha
	Bystrytsia Solotvynska River	
1	Near the pedestrian bridge from the side of Naberezhna Str. (near Flotska Str.)	0.32
2	From the pedestrian bridge to the V. Stefanyk Embankment Str. ring – Nadrichna Str.	0.18
3	Pasichna Str. near the metal depot	0.28
4	Left side from the bridge to the metal depot	3.5
5	Left side from the metal depot to Pasichnyanske Lake	3.85
6	Halytska Str. area below the bridge to the pipes	1
	Bystrytsia Nadvirna River	
7	Khotkevych Str. – Ivasiuk Str.	0.25
8	Mykytynetska Str. – Obzhodova Str.	0.727
9	Glinka Str., Mykytyntsi Village	0.101
	Total	**10.208**

Source: compiled by the authors based on Landscaping facilities (n.d.)

A recreation area in the area of Flotska Str. (near the pedestrian bridge) was arranged in 2017 on the banks of the Bystrytsia Solotvynska River. In addition to basic amenities for holidaymakers, such as trash bins, a dry closet, sun umbrellas, and changing rooms, there was also access to the river and two beach volleyball courts. The summer flood of 2018 partially destroyed it. The recreation area on the banks of the Solotvynska Bystrytsia River, near the metal depot on Pasichna Str., was developed in 2018. Sunshades, changing rooms, and garbage bins were also installed. Taking into account the current state of landscaping in Ivano-Frankivsk, the following measures are proposed to improve it. As of the beginning of 2024, the total area of green public areas within the city was about 126 ha, i.e., about 5.3 m^2/person, which is less than the established norm of 10 m^2/person. The planned expansion of the network through the creation of new squares will slightly improve the situation – up to 6.6 m^2/person, but this is not enough. This indicator of greenery in Ivano-Frankivsk is low and requires more intensive action. Particular attention should be paid to considering the possibility of organising new parks, botanical gardens, boulevards, etc.

When constructing new facilities, it is necessary to comply with the requirements for their level of greenery (the proportion of green planting to the total area), as the analysis showed that the average level of greenery in squares is 72%, while the norm is 75%, and there are squares where green spaces occupy less than half of the area. The city has 9 recreation areas along the banks of the Bystrytsia Nadvirna and Bystrytsia Solotvynska rivers with a total area of almost 58 ha, which are not well organised. Turning them into meadow parks would be a significant addition to the city's LRAs network and partially solve the problem of the lack of public areas. It is equally important to study the issue of areas of limited use, in particular the arrangement of green areas within residential neighbourhoods and city districts; study of street and road greenery and its increase, which is likely to improve air quality. Greening of residential neighbourhoods is possible through modifications of landscape design, which will include vertical and flat landscaping of residential neighbourhoods, the creation of green roofs, green bus stops, and an increase in the number of flower beds. This transformation of urban space will contribute not only to the level of greening, but also to the sustainable development of the city, addressing certain environmental issues, such as reducing air pollution and noise. Thus, it is important to create an urban space that is favourable to human activity as the basis for the improvement of a settlement. Greening of the territory is one of the mandatory components of landscaping (Law of Ukraine No. 2807-IV, 2005; Order of the Ministry of Regional Development, Construction and Housing and Communal Services of Ukraine No. 310, 2017). It must comply with the current sanitary rules and building codes and be carried out in accordance with the rules for the maintenance of green plantings in Ukrainian settlements (Order of the Ministry of Construction, Architecture, and Housing and Communal Services of Ukraine No. 105, 2006).

The joint work of J. Song *et al.* (2024) investigated the concept of urban ecological acupuncture and the possibility of applying European experience to its implementation in Korea, where there are many megacities with high population density. M. Stangel (2023) developed a strategy of ecological acupuncture on the example of the cities of Chorzów, Ruda Slenska, and Świętochłowice in Poland, which involves the use of local climate-resistant plants for vertical or roof gardening, which can also contribute to the restoration of biodiversity. Australian researchers M. Buckland & D. Pojani (2022) established the dependence of accessibility to urban greenery in Europe on the level of economic development of cities or the regional location of the city in Europe and found that urban green areas are distributed differently in different regions of Europe and have their own unique layout. The greenest cities in Europe are Prague, Stockholm, Brussels, Birmingham, and Milan. E.P. Barboza *et al.* (2021) studied the correlation between green space and mortality in 1,027 settlements in 31 European countries. It was found that the highest mortality rates due to non-compliance with the World Health Organisation recommendations on access to green spaces for different age groups in the city were in such EU capitals as Athens, Brussels, Budapest, Copenhagen, and Riga. This fact alone could prevent 20% of deaths per 100,000 inhabitants per year, or 2.3% of total mortality. The study on intensive recreational activity and the level of greenery was conducted by N. Denysyuk & V. Melnyk (2019) for the Rivne. The scientists determined that the provision of city-wide green public areas is below the standard and amounts to 6.6 m^2/person. They also found that the provision of recreational areas in different city neighbourhoods is not uniform. T. Nasteka *et al.* (2022) pay attention to the fact that when landscaping urban areas of the Kyiv Region, use evergreen representatives of dendroflora that have resistant properties to adverse environmental factors and have brightly coloured leaves in winter. An interesting area is the study of I. Zapukhliak *et al.* (2023) on the integration of sustainable development ideas into the system of training applicants in educational institutions. One of the elements is the formation of a way of thinking aimed at preserving the environment and greening the educational space.

In many regions of the world, there is a problem of insufficient greening of urban areas, which is confirmed by research by scientists from different countries. For example, D. Aly & B. Dimitrijevic (2022) assessed the level of urban greening, the condition of trees, and studied the reasons for the decline in greening in Cairo. C. Huang *et al.* (2021), having mapped the area of green spaces in 1,039 cities using satellite imagery, concluded that the density of green spaces and accessibility to them is an important element of urbanism for both large and medium-sized cities around the world. The level of urban greenery will directly affect the quality of life of the population and is an integral part of sustainable urban development. F. Tian *et al.* (2021), based on the results of studying the balance of regional ecosystems in northern China and vegetation changes using the GeoDetector method, determined that more than 94% of the region is characterised by an average rate of greening of vegetation, and, in their opinion, this is due to the intensity of urban development. V. Giannico *et al.* (2021), comparing the quality of life of the population in 51 European cities and the level of their greenery, concluded that the social component of city development, the amount of green space, and the perception of the environment are interconnected. The increase in green areas in the city will also affect the quality of the environment, which is confirmed by a number of scientists in their studies. For example, interesting are the studies by T. Iungman *et al.* (2023), which prove that it is possible to regulate the temperature balance in European cities by increasing the area of green areas. L. Xu *et al.* (2021) studied carbon dioxide emissions and the intensity of green innovations. M. Sun & J. Zhang (2020) considered the possibilities of using blockchain technology to create a smart city with low carbon dioxide levels and appropriate greening of the territory. In general, the research of S.M. Atiqul Haq *et al.* (2021) shows that city residents have a positive attitude towards urban green spaces, so this should be taken into account when designing various urban areas.

The problem of greening urban areas and their accessibility is being raised in all countries of the world. New constructive solutions are being sought for the modernisation and transformation of urban space aimed at increasing green areas. The impact of landscaping on life quality and population health is being studied. The issue of greening urban areas for sustainable urban development and the development of a "smart city" is being raised. Alternative ways to increase the area of green spaces are being sought, for example, through vertical gardening. It is also important to find plants for landscaping that are resistant to climate change and pollution. There are many progressive trends that are already being implemented in some cities, especially in the European Union. Thus, the issue of low or insufficient greening of urban areas exists in most countries of the world, so increasing the number of green areas can not only improve the quality and comfort of life but also solve environmental problems, especially in large cities. A promising area is the creation of green areas in residential neighbourhoods and the development of LRAs, which will significantly increase the level of urban greenery. Equally important is the use of landscape design elements in urban areas.

Conclusions

As a result of the assessment of green and other public LRAs in Ivano-Frankivsk, the following main results were obtained: the total area of public green spaces (parks and squares) within the Ivano-Frankivsk is about 126 ha, with 5.3 m^2/person, which does not meet the green space standard of 10 m^2/person and the public LRAs standard of 11 m^2/person. Provided that all the squares planned for 2021-2023 with a total area of 31.46 ha are arranged, the specific area of public green spaces may increase to 6.6 m^2/person. The level of greening of squares in Ivano-Frankivsk ranges from 39% to 100%. The average level of greenery was 72%, which is slightly lower than the standard of 75%. Ivano-Frankivsk is characterised by low coverage of protected areas – less than 1%. The public green spaces include the national significance Druzhba Dendrological Park and the Taras Shevchenko City Park.

A part of the Emerald Network "Bystrytsia Nadvirna Valley" within the city and adjacent villages has been significantly transformed and urbanised and is used as a recreational area, which may affect protected species. The City Lake beach with an organised lakeside area is equipped in the city. The water area of the lake cannot be used for swimming, as the depth in the lake area adjacent to the beach is 2 m. Since Ivano-Frankivsk is located in the interfluve of the Bystrytsia Nadvirna and Bystrytsia Solotvynska rivers, residents actively use these water bodies for recreation. The city has 9 recreation areas with a total area of 10.208 ha, which are mostly unequipped. Thus, promising directions for urban greening require more detailed study in the future. The most effective are vertical gardening, green roofs, the creation of green areas in residential and urban neighbourhoods, the arrangement of public gardens on the territory of educational institutions of the city, the study of the condition of trees and the city's plant fund, the development of the concept of urban ecological acupuncture, research into the accessibility of urban green spaces for all segments of the population, and the study of the relationships between green spaces and the health of the population.

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Conflict of Interest

None.

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Озеленення територій у системі планування та благоустрою міста Івано-Франківська

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Анотація. Під час планування та забудови міст необхідно дотримуватися вимог щодо ландшафтних та рекреаційних територій для забезпечення санітарного благополуччя та комфортного проживання населення. Тому метою представленої роботи була оцінка озеленених та інших ландшафтних та рекреаційних територій загального користування у межах Івано-Франківська та надання рекомендацій щодо озеленення території міста та його благоустрою. Було застосовано теоретичні методи дослідження, зокрема збір та систематизацію нормативної та звітної інформації стосовно ландшафтних та рекреаційних територій загального користування у межах Івано-Франківська; аналіз дотримання вимог українського законодавства; узагальнення проблем для надання рекомендацій із покращення благоустрою міста. Встановлено, що на початок 2024 року загальна площа існуючих озеленених територій становить близько 126 га і представлена 5 міськими парками, 1 дендропарком і 58 скверами. На одну особу припадає 5,3 м^2 озеленення, що майже удвічі нижче норми (10 м^2/особу). У 2021-2023 роках міською радою запроєктовано облаштування 41 нового скверу зі загальною площею 31,46 га, що збільшить питому площу озеленених територій до 6,6 м^2/особу. Встановлено, що середній рівень озеленення скверів складає 72 %. На території міста є 7 об'єктів природно-заповідного фонду України, показник заповідності становить менше 1 %. Територія Смарагдової мережі «Долина Бистриці Надвірнянської» у межах міста та прилеглих сіл помітно трансформована та урбанізована, використовується як відпочинкова зона, що може впливати на види, що охороняються. Водні об'єкти міста тільки частково облаштовані зонами для відпочинку. Запропоновано заходи з озеленення території міста та покращення його благоустрою – створення зелених зон у житлових мікрорайонах та вздовж доріг, використання зелених елементів на стінах будинків, організація лугопарків. Практична цінність результатів полягає у висвітленні існуючого та перспективного стану мережі ландшафтних та рекреаційних територій загального користування Івано-Франківська та наданні обґрунтованих рекомендацій щодо його покращення

Ключові слова: благоустрій населених пунктів; ландшафтні та рекреаційні території; парк; сквер; природоохоронна територія

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Pollution of the atmosphere, soil and water resources as a result of the Russian-Ukrainian war

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Abstract. Pollution of the atmosphere, soil, and water resources in Ukraine resulting from the Russian-Ukrainian war is a problem that requires immediate resolution, as the ecocide's consequences on the environment will be long-lasting and have a global impact. The aim of the study was to analyse the impact of active military actions on the atmospheric air, water resources of Kharkiv and Kharkiv Region, and the soils of the Ivory Coast of Sviatoslav National Nature Park in Mykolaiv Region by assessing their eco-geochemical state. The study of the impact of fires on the soil properties of the Ivory Coast of Sviatoslav National Nature Park using potentiometric, luminescence-bituminological, and spectrofluorometric methods revealed that the content of polycyclic aromatic hydrocarbons (PAHs) is the highest in pyrogenic areas, where low molecular weight PAHs are predominant; high molecular weight PAHs are also present, indicating recent burning of the territory. It was found that the PAH content is lower at microelevations. The aspiration method was used to investigate the atmosphere. It was shown that the level of air pollution in Kharkiv is low at all observation points, with a level of less than 5 on the scale of the air pollution index. It was found that the largest number of exceedances in the water bodies of the Kharkiv Region was recorded for such pollutants as sulphates (recorded at 17 points), ammonium nitrogen (at 16 points), biochemical oxygen demand (at 14 points), and dissolved oxygen (at 11 points). In all the most polluted water bodies, the maximum permissible concentration exceedances were recorded for 4, 3, and 2 hydrochemical indicators. The study results can be used in practice by ecologists to develop and implement measures to improve the ecological condition of the eastern and southern regions of Ukraine

Keywords: ecology; environmental consequences; economic losses; damages; national nature park; rivers

Introduction

Regular ecological pollution research plays a crucial role in maintaining a favourable ecological state in the territories of the southeastern regions and Ukraine as a whole, as one of the main ecological and economic problems of Ukraine is the environmental pollution problems of the eastern and southern regions due to the military actions of the Russian occupation forces. The concentration of various sources of pollutants in the occupied settlements is high; the impact of the Russian-Ukrainian war contributes to an increase in emissions of harmful substances, which leads to a serious impact on the natural environment. The research problem is confirmed by the fact that the war unleashed by Russia has

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caused total damage to Ukraine's environment of more than 2 trillion UAH (€55.6 billion) (The total damage…, 2023). Half of this amount is the damage from air pollution from forest fires, missile attacks, and the burning of oil products. As of October 12, 2022, emissions of pollutants into the atmosphere have been recorded, including, as noted by O. Angurets *et al.* (2023), 499,473 tonnes of combustion products released as a result of the burning of oil products.

According to the Department of Ecology and Natural Resources of Mykolaiv State Region Administration, as of August 22, 2023, 6,130 thousand hectares of land have burned in the Ivory Coast of Sviatoslav National Nature Park (Slobodianiuk, 2023). The impact of the war on the biome ecosystems of the flatland part of Ukraine includes several different aspects. Among them, the most widespread is the spread of landscape fires caused by ammunition explosions in relatively dry weather. The results of the research by T. Sak *et al.* (2022) showed that, as a result of hostilities, as of May 2, 2022, the physical volume of lost or damaged land assets amounted to 4.2 thousand hectares, and the total amount of losses were $873 million. The analytical report by Mine Action Review described the key environmental consequences of contamination with explosive ordnance and land release operations, as well as the potential impact of climate change on land release (Mitigating the environmental impacts…, 2021). The authors propose that states should have a national standard for mine action environmental management. However, the provided report only broadly addresses the issue. The pollution of water sources as a result of hostilities is more deeply analysed in the research of Ukrainian scientists O. Semenenko *et al.* (2022), where the authors consider the impact of ammunition corrosion and the decomposition of toxic substances on the pollution of groundwater in Donetsk Region.

The damage caused to Ukraine's environment by the military invasion was investigated by E. Bezsonov (2022). The author's calculations of the environmental damage caused by Russian tanks as of April 20, 2022, showed that the damage from air pollution by exhaust gases was $2.436 billion ($43.5 thousand per day), the damage to agroecosystems was $45.111 billion, and the damage to ecosystems and ecosystem services was $93.45 billion. In the study by I. Krasovska & K. Podorozhko (2022), using the spatial analysis tools of ArcGis 10.5, the authors modelled the trajectory of the movement of the cloud with nitric acid vapours. The authors compiled cartographic models of the atmospheric state, containing information about the strength and direction of the wind from April 5 to April 10, 2022. Although the topic of the impact of hostilities on the ecological state of Ukraine is now actively being researched, insufficient attention has been paid to the study of the consequences of mechanical impact during military-technogenic loads on the soil cover of environmentally protected sites, as well as the consequences of fires. The aim of the research was to establish the exceedances of the maximum permissible concentration of pollutants in water bodies of the Kharkiv Region, to establish the level of air pollution in Kharkiv, to identify the features of background areas and soils damaged by fire, and to determine the nature of the accumulation of polycyclic aromatic hydrocarbons (PAHs) in the soil cover of the Ivory Coast of Sviatoslav National Nature Park as a result of military operations.

Materials and Methods

During the soil pollution study, methodologies were regulated by the State Committee of Ukraine for Water Management (2001), the State Standard of Ukraine (hereinafter DSTU) DSTU 4287:2004 (2004), DSTU ISO 10381-2:2004 (2004), DSTU ISO 5667-6:2009 (2009), and Order of the State Emergency Service of Ukraine No. 30 "On the Approval of the Instructions for the Selection and Preparation of Water and Soil Samples for Chemical and Hydrobiological Analysis by Hydrometeorological Stations and Posts" (2016). Field investigations were conducted on sites located on the Ivory Coast of Sviatoslav National Nature Park, which is located within the Ochakiv and Berezan districts of the Mykolaiv Region. Six plots were investigated to determine the accumulation of PAHs and other characteristics of soil profiles: burned-out plots of 2023, fire-damaged areas of 2022, and background plots. These points were selected through reconnaissance routes, depending on the age of the fire. The plots were selected on different types of microrelief (microdepressions and microelevations). Sections were dug at each of the sites (30 sites in total). Soil samples were taken from each section according to soil horizons for further analytical work. The research data included field and analytical methods of research on the selected samples and the processing of the data results. Using the analytical method, the samples were analysed. Soil sampling was carried out in the first half of August 2023.

The soil samples were dried at room temperature in the shade. The soils were sieved through a sieve with holes of 0.25 mm and 1 mm, depending on the chemical analyses. During the research, the pH of the water suspension was determined using the potentiometric method on an ionometer "Expert-001" (Ekonix-Expert, RF). Total dissolved solids (TDS) were determined by the titrimetric method in a ratio of 1:5 (soil:water). Volatile organic carbon was determined by the titrimetric method using the Tyurin method with phenylanthranilic acid. The quantitative and qualitative characteristics of PAHs were studied using the luminescent-bituminological and spectrofluorometric methods. Eleven individual PAHs were determined in hexane bitumoid: diphenyl, naphthalene homologues, fluorene, phenanthrene, anthracene, chrysene, pyrene, tetraphene, perylene, benzo[*a*]pyrene, and benzo[*ghi*]perylene. Measurements were carried out by the method of spectrofluorimetric analysis at low temperature (Shpolsky spectroscopy) on the spectrofluorometric complex "Fluorat-Panorama" (Lumeks, Russia). Calculations were performed for the volatile organic carbon content by horizons and its subsequent averaging; the content of TDS by horizons and its subsequent averaging by microrelief; the content of PAHs accumulation; and the creation of graphs in the Statistica.

The methodology used for the atmospheric pollution study was regulated by DSTU 8812:2018 (2018) to determine the state and quality of atmospheric air. Sampling was carried out at measuring points in accordance with DSTU 8725:2017 (2017). Observations were carried out at stationary observation posts for air pollution (SOPAP) equipped with complete POST-1 and POST-2 laboratories. Using the aspiration method, air samples were taken in September 2023. The sampling was carried out by the Kharkiv Regional Centre for Hydrometeorology at 10 posts. Observations were carried out daily, except for Sundays. These data have been analysed in this study. Air sampling was carried out at a height of 1.5-3.5 m above the ground. Air samples were taken by pumping outside air through a special cartridge with an absorbent filter. Each substance had its specific absorbent filter. The pumping duration for determining single concentrations was 20-30 minutes. For daily average measurements, the duration was also 20-30 minutes and 24 hours for continuous sampling. Meteorological observations lasted for 10 minutes. The following devices were used for air sampling by the aspiration method: an electric aspirator (a device designed to draw air through absorbent materials) and a liquid rheometer (used to determine the volume of air sampled for analysis). Water sampling was conducted using the surface sampling method in September 2023. The analysis of the state of surface waters in the region was carried out according to the data of the Regional Office of Water Resources in the Kharkiv Region at 20 monitoring points, and the data obtained were analysed in this article. Monitoring was carried out for the content of dissolved oxygen, biochemical oxygen demand (BOD_5), ammonium nitrogen, nitrite nitrogen, chlorides, and sulphates in surface waters. The equipment, reagents, and materials used for water sampling included washed, degreased, and rinsed containers of the required volume; a Meyer's bottle; a thermometer; H_2SO_4; HNO_3; chloroform; and a pipette.

Results

Soil samples for the study were taken on the Ivory Coast of Sviatoslav National Nature Park. Soil profiles are represented by two types of soils, depending on their location in the relief. Plot 1 and Plot 2 represent the 2023 fire. Like all plots, the fire plots are represented by microdepressions and microelevations. In the plot, six sections are laid in microdepressions, and four sections are on microelevations. The plot is a flattened surface with burnt and successional vegetation. The vegetation after the fire is represented by such an herbaceous plant as feathergrass (*Stipa capillata*). Meadow grass (*Poa*) and camelthorn (*Alhagi*) are also present. Soils are represented by light humus soils post-pyrogenic and aeolian-stratified post-pyrogenic psammozem. Plot 3 and Plot 4 represent the 2022 fire. In the plot, six sections are laid on microelevations and four sections on microdepressions. Soils are represented by aeolian-stratified psammozem and light humus soils. The vegetation of the plot is represented by bromes (*Bromus*), *Stipa capillata*, *Poa*, and *Alhagi*. There is no burned vegetation on the surface of these plots. Plots 5 and 6 are background plots. In the plot, 6 sections are laid on the microelevation and 4 sections on the microdepression. Soils are represented by light humus soils. The vegetation of the plot is represented by: mugwort (*Artemísia vulgáris*), *Stipa capillata*, *Poa*, and *Bromus*. The soils of the background plots are represented by light humus soil. The profile has the following horizons: AJ-Csa (microdepression); AJ-AC-Cca (microelevation) (Fig. 1).

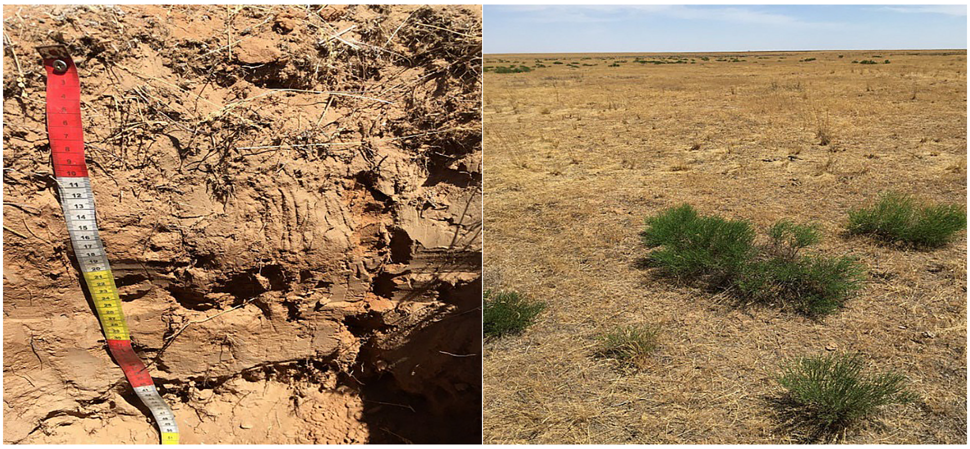

Figure 1. The soil profile of the background plots and the corresponding landscape
Source: made by the authors

The light humus soil of microdepressions is represented by AJ (depth 0-12 cm) light humus horizon: grey fawn, dry, structureless, fine sandy loam, slightly compacted, penetrated by roots (1-3 mm, medium amount), does not boil, the transition is clear in colour and structure, and the border is flat. Cca (depth 12-38 cm) soil-forming rock:

dark fawn, fresh, structureless, fine sandy loam, dense, roots (few, 1-3 mm), carbonate formations (few, loose), boils violently. The light-humus soil of microelevations is represented by AJ (depth 0-13 cm) light humus horizon: grey fawn, dry, structureless, dusty sand, poorly compacted, permeated with roots (average amount, 1-5 mm), does not boil, the transition is clear in colour and structure, and the border is slightly wavy. AC (depth 13-43 cm) transitional horizon: fawn, dry, structureless, fine sandy loam, dense, roots (1-3 mm, few), does not boil, the transition is clear in colour and structure, and slightly wavy. Cca (depth 43-60 cm) soil-forming rock: fawn, fresh, structureless, fine sandy loam, dense, single roots (1-3 mm), carbonate formations (many, loose), boiling violently. In the microdepressions of the burned site in 2023, the soil is represented by a light humus post-pyrogenic soil and has the following profile: AJpir-Acd-Cca (2004 classification) (Fig. 2). AJpir (depth 0-8 cm) light humus post-pyrogenic horizon: grey spots on fawn grey background (0.1-0.3 cm, few), dry, structureless, fine sandy loam, poorly compacted, ash (few), roots (0.1-0.2 cm, many), does not boil, the transition is clear in colour and structure, and the border is slightly wavy. ACd (depth 8-44 cm) transitional horizon on a fawn background fawn-grey spots (1-2 cm, average amount), streaks (0.5-1 cm, average amount), dry, structureless, fine sandy loam, dense, plant roots (1 mm, average amount), boiling violently, transition clear in colour, and smooth boundary. Ssa (depth 44-65 cm) soil forming rock residual carbonate: light fawn with greyish fawn spots (1 cm, average amount), fresh structureless, dense, fine sandy loam, boiling violently. The plant associations in the microdepressions of the burned site in 2023 are represented by meadow bentgrass. In the microelevations of the background site, the soil is represented by aeolian-stratified post-pyrogenic psamozem with a profile: RJae, pir-aj-D (Fig. 3).

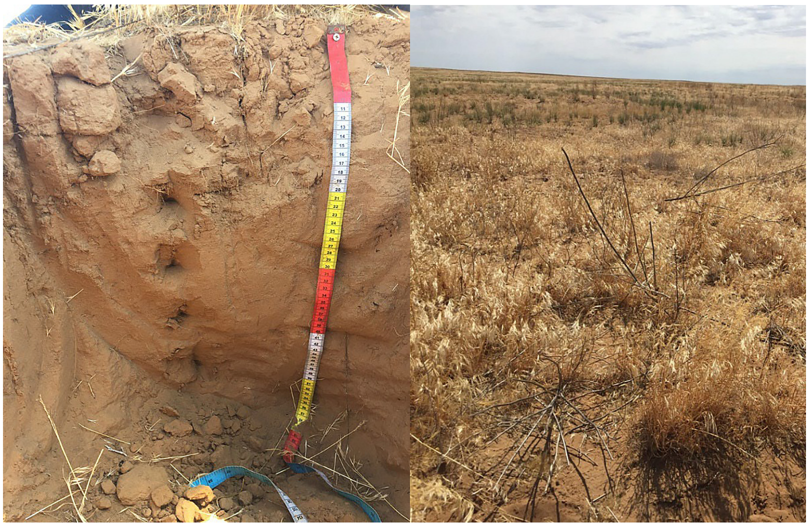

Figure 2. The soil profile of a microdepression and the corresponding landscape

Source: made by the authors

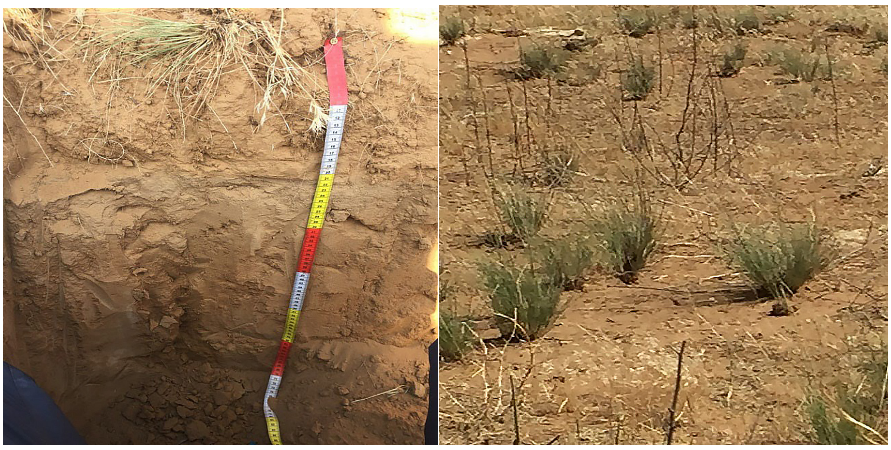

Figure 3. The soil profile of microelevations and the corresponding landscape

Source: made by the authors

RJae, pir (depth 0-21 cm) light humus stratified post-pyrogenic horizon: light fawn, dry, structureless, fine sandy loam, compacted, ash (few), roots (1-3 mm, medium), not boiling, transition clear in colour, and flat boundary. [AJ] (depth 21-28 cm) light humus horizon: light grey dry, structureless, fine sandy loam, dense, roots (2 mm, medium abundance), the transition is clear in structure, and the border is slightly wavy. [D] (depth 28-60 cm) bedrock: on an ochre-fawn background, light grey spots (3-4 cm, medium amount), dry, structureless, fine sandy loam, very dense, and single roots (1 mm, few). Plant associations in the microelevations of the background area are represented by meadow fescue grass (*Lolium pratense*). A total of 87 samples were collected from the genetic horizons of soil profiles at the key sites. Soils of the Ivory Coast of Sviatoslav National Nature Park are characterised by a neutral or slightly alkaline reaction. The measured pH values across the burn sites and background sites, mainly considering microrelief, showed the following results: in all soils, pH values range from neutral to slightly alkaline from the upper to the lower horizons. On the background sites, an increase in pH is observed in both microelevations and microdepressions towards the lower horizons. The lowest pH value was found in the upper horizons of soils in microelevations and microdepressions (7.8 and 7.9, respectively). The highest pH value on the background sites was observed in the lower soil horizons, with 8.1 in microdepressions and 8.4 in microelevations.

On the 2022 fire site, there was also an increase in the reaction of the medium to the lower horizons of the soil and a higher pH value on microelevations. The highest value is observed in the lower horizons: on microelevations, 7.55, and on microdepressions, 7.35. The minimum values are reached in the upper horizons of microelevations and microdepressions (7.38 and 7.35, respectively). On the 2023 fire sites, the pH value differed by microrelief. The minimum pH value was observed in the upper horizons (RJae and AJ). Predominantly on microdepressions, the pH is slightly higher in the upper part of the profile (7.35) than on microelevations (7.3). The maximum pH value was reached in the lower horizon of the soils (Cca or Cs) and was 7.35 on microelevations and 7.55 on microdepressions. The tendency for a decrease in pH values in post-fire soils compared to background sites is likely explained by the fact that ash water-soluble compounds penetrate the soil and saturate the absorption complex with alkaline earth elements. Electrical conductivity characterises the soil's ability to conduct electrical current by utilising the property of salts to conduct it. Thus, electrical conductivity measures the concentration of soluble salts present in the soil solution. The higher the value, the easier it is for electrical current to pass through the soil due to the higher concentration of salts.

A gradual increase in electrical conductivity was observed with the depth of the soil profile. The maximum values are reached at a depth of 45 cm and more on all considered sites. A similar pattern was observed in the background areas. The lowest electrical conductivity values in the upper soil layers are 60 mS/cm (microelevation) and 45 mS/cm (microdepression). The highest electrical conductivity values were reached on the 2022 fire site on microdepressions (500 mS/cm), and the lowest values were observed in the upper soil horizons are 50 mS/cm (microelevation) and 65 mS/cm (microdepression). On the 2023 fire sites, the minimum electrical conductivity value was observed in the near-surface part of the profile and is 50 mS/cm on microelevations and 60 mS/cm on microdepressions. The largest values are reached on microelevations 100 mS/cm and on microdepressions 300 mS/cm. On all sites, there was a gradual, small increase in electrical conductivity on microdepressions and a more pronounced, sharp increase on microdepressions.

The increase in electrical conductivity towards the lower soil horizons is directly caused by highly mineralised groundwater. The fact is that the Ivory Coast of Sviatoslav National Nature Park is located in an arid zone, and the groundwater is highly mineralised and lies at a depth of 3 meters. The analytical determination of TDS in the soil profile is directly related to the presence of salt crystals in the soil horizons. The sum of the salts was determined by the titrimetric method. On the background areas, there was no accumulation of TDS at a depth of 20 cm. The least salinisation of soils was observed in the upper horizons of microelevations and microdepressions (0.05% and 0.07%). The presence of salts in the soil profiles was noted across all studied sites. On the fire sites of 2023 and 2022, there was a presence of salts from the surface, but not in large quantities (0.05%). An increase in the sum of salts was observed along the soil profile on microdepressions at a depth of 20 cm. On the fire sites of 2023, the sum of salts at a depth of 20 cm of microdepressions is 0.25%; on the fire sites of 2022, it is 0.18%. The soils of microdepressions are slightly saline.

The presence of TDS is often observed in the soils of arid regions. Light humus soils and psammozem are directly located in the arid region of the country. The accumulation of TDS in the soil profile of arid territories is one of the main indicators of soil salinisation. The accumulation of salts in the middle of the soil profile is directly related to the insufficient amount of precipitation. Thus, the accumulation of TDS on the fire sites at a depth of 20 cm is associated with a moisture deficit. Since evaporation in this area is higher than the amount of precipitation, a moisture deficit was observed in the soil. In the process of mineralisation of organic residues, TDS were formed, which were not washed out of the soil profile, but accumulated at a depth of 20 cm.

The most important negative ecological effect of fires is the loss of organic matter by the ecosystem as a whole, including the loss of organic matter in the soil. Research has shown that there is a tendency for humus content to decrease in the 0-10 cm layer in soils that have been exposed to thermal effects. Fires have the greatest impact directly on the upper humus horizon of the soil. The organic carbon content of the background sites was decreasing before the fires. In background areas, the organic carbon values are higher than in burned areas of different ages. The maximum organic carbon value in background soils was 0.4% on microelevations and 0.7% on microdepressions. The 2022 burnt area showed a slight increase in organic carbon in the upper humus horizon of the soils, approximately 0.42% on microelevations and 0.46% on microdepressions, compared to the less recent fire. The minimum values of organic carbon are reached in the lower parts of the soil profile, approximately 0.35%. On the 2023 burnt areas, the organic carbon content is only 0.33% and 0.38% (microdepression and microelevation, respectively), decreasing down the profile to 0.1% and 0.12% (microdepression and microelevation, respectively). Thus, the decrease in organic carbon content is directly related to the impact and consequences of fires. It is most likely a consequence of the thermal impact of fires on the upper soil layer, which led to the transformation and destruction of the humus horizon of the soil.

The following results were obtained during the study of soils in the reserve that suffered from the fires of 2022 and 2023. In general, the absolute total content of PAHs in soils is low. The sum of PAHs in background areas is 6.7-37.2 ng/g; in the 2022 fire sites, 9.8-25.1 ng/g; and in the 2023 fire sites, 7.1-66.9 ng/g. The sum of PAHs changes from background areas to burned sites. The qualitative composition of PAHs changes from background areas to increasing fire age. In the background, phenanthrene (48%), naphthalene homologues (46%), diphenyl (4%), and fluorene (2%) were predominant. The presence of high molecular weight PAHs in background areas was not found. On the 2022 fire sites, the predominant groups were low molecular weight PAHs: naphthalene homologues (44%), phenanthrene (40%), diphenyl (14%), and fluorene (2%). Very small concentrations of high molecular weight PAHs such as anthracene, chrysene, and benzo[*ghi*]perylene (1%) were found. On the 2023 fire sites, the predominant groups were low molecular weight PAHs – naphthalene homologues (44%), phenanthrene (40%), diphenyl (14%), and fluorene (2%). high molecular weight PAHs (perylene, benzo[*ghi*]perylene, tetraphene, benzo[*a*]pyrene) (3%) were released in sufficiently large quantities compared to the 2022 fires. Thus, during pyrogenic damage to landscapes, PAHs in soils accumulate weakly. The differences in pollutant content between background and fire-affected soils do not exceed 1.5-2 times. This is due to the fact that free access to oxygen and high temperatures prevent the formation of PAHs during a fire. Conditions are also created for the intensive dispersion of combustion products: a convective column is formed above the fire zone – a stream of heated pyrolysis products of organic matter.

To understand the distribution and concentration of the total amount and composition of PAHs in the territory of the reserve, microelevations and microdepressions of this territory were considered separately. The total amount of PAHs on microdepressions also varied at different intervals on different sites. In the 2023 burnt areas, the total amount of PAHs ranged from 7.1 to 37.6 ng/g; on the 2022 fires, 9.8-32.5 ng/g; and in the background areas, 21.5-54.6 ng/g. The qualitative characteristics of PAHs on the sites are also different. In background areas, phenanthrene (51%), naphthalene homologues (42%), diphenyl (4%), and fluorene (3%) are predominant. On the 2022 fires: naphthalene homologues (63%), phenanthrene (24%), diphenyl (12%), and fluorene (1%). On the 2023 burned areas: naphthalene homologues (56%), diphenyl (27%), phenanthrene (14%), and fluorene (3%). An increase in naphthalene homologues, a decrease in phenanthrene, an increase in diphenyl, and the same amount of fluorene were observed from background areas to burnt areas. Also, the presence of high molecular weight PAHs was observed in the fires. During steppe fires, less material burns than during forest fires, while oxygen access remains free. These factors contributed to the lower formation of PAHs compared to forest fires, so even in soils with a high organic matter content, no intensive accumulation of polyarenes was observed. The total amount of PAHs on microelevations was characterised by different values. The largest total amount of PAHs was reached on the 2023 fires in the range of 7.1-25.7 ng/g, on the background areas 6.7-66.9 ng/g, and on the 2022 fires this value is 7.8-21.2 ng/g.

The qualitative characteristics of PAHs also differ from the values of microdepressions. In background areas, the predominant polyarenes were naphthalene homologues (52%), phenanthrene (43%), diphenyl (4%), and fluorene (1%). On the 2022 fires: naphthalene homologues (73%), phenanthrene (25%), and diphenyl (2%). On the 2023 fires: phenanthrene (48%), naphthalene homologues (39%), diphenyl (12%), fluorene (1%), and the presence of high molecular weight PAHs (1%) was also found. There was a decrease in the values of naphthalene homologues on the 2023 burnt areas and an increase in naphthalene homologues on the 2022 fires compared to background areas; an increase in diphenyl; a decrease in fluorene; a decrease in phenanthrene on the 2022 fires; and an increase in it on the 2023 fires compared to the background values. Thus, the indicators and qualitative composition of PAHs in the microrelief differ. This may be due to the uneven passage of the fire through the territory, where the soil in small areas is less disturbed and possibly less prone to fires. The formation of high molecular weight PAHs in the microrelief is directly related to the activity of fires. In total, 4549 air samples were collected and analysed in September 2023. The results of the study of the state of atmospheric air in Kharkiv are presented in Table 1.

Table 1. Indicators of the air pollution index in Kharkiv in September 2023

No.	Address	Pollution index	
		August 2023	September 2023
9	34 23 Serpnia Str. District	3.54	2.99
11	6 Teatralna Aly., Centre District	2.72	2.24
12	44 Hvardiets-Shyroninets Str., 607 Micro-District	2.43	1.83

Table 1, Continued

No.	Address	Pollution index	
		August 2023	September 2023
13	4 Pashchenkivska Str., Ivanivka District	4.12	3.39
16	4 Kholodnohirska Str., Kholodna Hora District	3.21	2.87
17	Crossroads of Derevianka Str. and Kharkivskyi Rd., Sokolnyky District	2.76	2.52
18	3 Bairon Ave. District	3.21	3.04
19	120 Saltivska Rd. District	2.14	1.97
21	53 Vrubel Str., Novobavarsk District	1.43	1.47
24	15 Municipal Hospital No. 15 at 46 Akademik Pavlov Str. District	2.2	1.85

Source: made by the authors based on Information on the ecological state of the Kharkiv and the Kharkiv Region for September 2023 (2023)

According to the observations in September 2023, the level of air pollution in the city at all stationary observation points was characterised as low (according to the Atmospheric Pollution Index (API) scale, a level of less than 5.0 is considered low). Observation data from the Kharkiv Regional Centre for Hydrometeorology indicated that the most polluted area was 4 Pashchenkivska Str., Ivanivka District (SOPAP No. 13) with an index of 3.39; the lowest level of pollution was found in 53 Vrubel Str., Novobavarsk District (SOPAP No. 21) with an index of 1.47. The reason for the increased pollution in the area of 4 Pashchenkivska Str., Ivanivka District, was the air pollution caused by the remnants of explosives (TNT, hexogen, etc.), shells containing radioactive substances, dust, and combustion products, which are related to the poor quality of roads in the area, as well as missile attacks. During September 2023, samples were taken from rivers and a reservoir in the Kharkiv Region. In total, 20 points (location of the sampling site) were investigated, and 40 surface water samples were collected (2 samples from each point of the water body). The results of the study of surface water bodies in the Kharkiv Region are presented in Table 2.

Table 2. Surface water quality indicators in the Kharkiv Region for September 2023

No.	Name of the water body	Sampling date	Measurement results, mg/dm^3					
			Dissolved oxygen	BOC_5	Ammonium nitrogen	Nitrite nitrogen	Chlorides	Sulphates
	quality standards for fishery water (mg/dm3)		6	2	0.39	40	300	100
1	Khotomlia River, Novooleksandrivka Village	September 11, 2023	6.99	2.37	0.706	0.036	34.5	116
2	Tetleha River, river mouth, Kochetok Village	September 11, 2023	8.15	0.95	0.543	0.008	37.4	122
3	Udy River, above Kharkiv	September 6, 2023	6.11	1.23	0.685	0.014	37.4	101
4	Lopan River, river mouth, Kharkiv	September 6, 2023	5.82	6.5	0.658	0.154	84.1	175
5	Kharkiv River, river mouth, Kharkiv	September 6, 2023	4.66	4.38	0.276	0.089	58.6	141
6	Murom River, river mouth	September 11, 2023	8.73	0.66	0.396	0.006	23.0	152
7	Rohan River, river mouth	September 12, 2023	8.44	1.82	0.613	0.061	45.7	299
8	Nemyshlia River, river mouth, Kharkiv	September 6, 2023	6.99	2.65	0.503	0.038	79.8	215
9	Mozh River, above Merefa	September 5, 2023	3.5	2.95	0.530	0.008	48.2	49.5
10	Mozh River, river mouth, Zmiiv	September 6, 2023	4.08	3.06	2.743	0.009	48.5	43.7
11	Kniazhna River, Brazhnyky Village	September 5, 2023	8.73	5.54	0.543	0.008	57.5	43.7
12	Lebiazha River, river mouth, Lebiazhe Village	September 11, 2023	8.73	2.68	0.348	0.021	25.9	582

Table 2, Continued

No.	Name of the water body	Sampling date	Measurement results, mg/dm³					
			Dissolved oxygen	BOC_5	Ammonium nitrogen	Nitrite nitrogen	Chlorides	Sulphates
13	Udy River, river mouth, Eskhar Village	September 12, 2023	7.27	9.40	0.947	0.123	103	236
14	Siverskyi Donets River, Pechenihy Reservoir, Pechenihy Village	September 11, 2023	7.85	2.37	0.543	0.043	34.1	103
15	Siverskyi Donets River, below the river mouth of Udy River, Eskhar Village	September 12, 2023	5.82	3	0.03	0.06	54.3	146
16	Siverskyi Donets River, Zadonetske	September 6, 2023	4.94	1.86	0.383	0.059	56.8	145
17	Orilka River, Chervona Dolyna Village	September 5, 2023	4.95	1.79	0.458	0.003	150	961
18	Orilske Reservoir, channel Dnipro-Donbas, 170 km, Orilka Village, Orilske Reservoir, sluice water outlet	September 5, 2023	5.53	2.66	0.511	0.018	163	999
19	Berestova River, Krasnohrad	September 5, 2023	11.9	8.06	1.123	0.014	44.9	202
20	Voshyva River, Kobzivka Village	September 5, 2023	3.2	2.95	1.328	0.008	152	671

Source: compiled by the author based on Information on the ecological state of the Kharkiv and the Kharkiv Region for September 2023 (2023)

The results of the study of surface waters in the Kharkiv Region showed that the largest number of exceedances were recorded for such pollutants as sulphates (at 17 points), ammonium nitrogen (at 16 points), BOD_5 (at 14 points), and dissolved oxygen (at 11 points). Exceedances of nitrate nitrogen and chloride were not detected at any of the monitoring sites. According to the results carried out in September 2023, the most polluted water bodies in the Kharkiv Region were: for 4 hydrochemical indicators Khotomlia River (Novooleksandrivka Village), Nemyshlia River (river mouth, Kharkiv), Udy River (river mouth, Eskhar Village), Siverskyi Donets River (Pechenihy Reservoir, Pechenihy Village), Berestova River (Krasnohrad); for 3 hydrochemical parameters Tetleha River (river mouth, Kochetok Village), Udy River (above Kharkiv), Lopan River (river mouth, Kharkiv), Kharkiv River (river mouth, Kharkiv), Murom River (river mouth), Rohan River (river mouth), Kniazhna River (Brazhnyky Village), Lebiazha River (river mouth, Lebiazhe Village), Orilske Reservoir (channel Dnipro-Donbas, 170 km, Orilka Village, Orilske Reservoir, sluice water outlet), Voshyva River (Kobzivka Village); for 2 hydrochemical parameters Mozh River (above Merefa), Mozh River (river mouth, Zmiiv), Siverskyi Donets River (below the river mouth of Udy River, Eskhar Village), Orilka River (Chervona Dolyna Village). The least polluted water body in the Kharkiv Region was: for 1 hydrochemical indicator, Siverskyi Donets River (Zadonetske). In the most contaminated rivers and reservoir in the Kharkiv Region, the source of the most dangerous contamination is Unsymmetrical dimethylhydrazine (UDMH) $(CH_3)_2N_2H_2$ (heptyl), a component of highly toxic rocket fuel that oxidises easily to form more dangerous compounds, including nitrosodimethylamine, a yellow liquid partially soluble in water, and many organic solvents. Thus, the highest number of exceedances of the maximum permissible concentration in water bodies of the Kharkiv Region was found for such pollutants as sulphates, ammonium nitrogen, biochemical oxygen consumption, and dissolved oxygen. The study of the atmosphere in Kharkiv showed that the level of air pollution at all observation points is low and does not pose a threat. The study of the impact of fires on soil properties showed that the content of surfactants is highest in pyrogenic areas, where low molecular weight PAHs are predominant.

Discussion

Analysing the obtained research results, it can be concluded that the pollution of the atmosphere, soil, and water resources as a result of military actions has negatively impacted natural ecosystems. All natural resources have suffered as a result of hostilities: lands from pollution of various types of waste and fires, atmospheric air from constant emissions from missile explosions and fires, water bodies, forest resources, fauna, the natural reserve fund from enemy equipment, pollution, and deliberate destruction. As a result of the ecocide, the upper fertile layer of the soil, which has been formed for centuries, was destroyed. It is known that over the past 100 years, Ukrainian soils have lost about 30% of humus (The war in…, 2022). Due to the influence of the war, this process has accelerated. Soils are losing their fertility due to changes in their physical, chemical, and physicochemical properties.

The research by R. Shaheb *et al.* (2021) focused on studying the effect of soil compaction due to the movement of heavy machinery and vehicles, which causes damage to the soil structure and degradation of the soil environment, sharing similarities with the present study. The authors' results revealed that soil compaction increases soil bulk density and strength, its porosity and hydraulic properties decrease, the growth of plant roots in crops is delayed, and the yield decreases by 50% or more, depending on the magnitude and degree of soil compaction. To improve the situation, the authors make suggestions for mitigating the effect of soil compaction, such as adhering to advanced soil management methods that help crops effectively assimilate applied nutrients, growing crops with a deep root system in crop rotation, and practising conservative soil tillage. In Ukraine, according to the authors of the study, conservation agriculture could be implemented to mitigate soil erosion; in particular, a project of a soil-protective contour-meliorative farming system could help prevent erosion in the system of soil protection tillage.

The research by R. Lasaponara *et al.* (2023) focused on studying the value of using Sentinel-1 (S1) and Sentinel-2 (S2) data together to assess fire severity in heterogeneous, fragmented ecosystems. In the study, the effectiveness of S1 and S2 fire indices was initially statistically analysed using the ISODATA clustering algorithm combined with field investigations conducted during the fire that occurred on July 13, 2019, in Sardinia. To automatically map burn areas and classify fire severity, the fire indices of S1 and S2 were integrated through multi-level classification performed at pixel and object levels. The results of the authors' research showed that the accuracy is above 94% compared to independent datasets and field investigations. The authors recommended using additional information about forest structures to improve SAR-based fire assessment. In Ukraine, the Google Earth Engine cloud service to obtain and process satellite data on forest fires and their consequences and methods for processing, analysis, and visualisation of geospatial data can be implemented, which would improve the operational efficiency of detecting hazardous areas. G. Alarcon-Aguirre *et al.* (2022) presented algorithms for mapping fire severity based on Sentinel-1 backscatter data in the southeastern Peruvian Amazon. The results of the study showed that Sentinel-1 cross-polarisation data is sufficiently accurate for detecting and quantifying fires. According to the authors, studies should also be conducted on the integration of global optical images, such as Sentinel-2 and Landsat, with synthetic aperture radar (SAR) images to assess detection and accuracy compared with independent analysis of optical images or SAR images. In Ukraine, methods for using the normalised burn ratio and supervised classification for pre- and post-fire satellite imagery could be implemented. The proposed GIS (geographic information system) technologies can be used to identify areas and calculate the areas of vegetation damaged by fires.

In the study by S. Pinakana *et al.* (2023), air pollution in South Texas was examined, establishing a correlation between human health and air pollution. The assessment was conducted for pollutants such as particulate matter, volatile organic compounds, pesticides, CO, CO_2, O_3, benzene, NO_2, SO_2, and PAHs. The results of the research showed that industry, vehicle emissions, agricultural burning, construction, and dirt roads are the major sources of pollution, causing detrimental health effects such as respiratory and cardiovascular diseases. The authors recommend increasing the number of CAMS automatic stations throughout South Texas to accurately determine the burden of air pollution on the population. In Ukraine, it is necessary to create and implement networks of automatic stations for monitoring air pollution from emissions of industrial enterprises, energy facilities, and vehicles, as well as stations for recording meteorological parameters and environmental radioactivity. For indoor and outdoor air quality monitoring, the AQMesh portable air monitoring station with small AQMesh sensors can be implemented to provide localised real-time data.

Researchers B. Ghosh *et al.* (2023) determined the distribution of heavy metals in the air and the potential health risks in three different regions of West Bengal, India. The results of the research showed that the sum of non-cancerous risks (HI) for all heavy metals exceeded the risk threshold of the U.S. Environmental Protection Agency (HI < 1) in both Kolkata and Durgapur, except for Bolpur. Kolkata had the highest estimated lifetime cancer cases compared to Bolpur and Durgapur. The authors emphasised the need for the implementation of cleaner industrial technologies, emission control norms, and sustainable urban planning. In Ukraine, it is worth implementing methods for assessing the health risk of the population from the impact of soil pollution by heavy metals by evaluating using a probit regression model. The difference between the studies is that the works analysed above consider only those pollutants and circumstances that are inherent in peacetime, while in Ukraine, the problem of pollution due to hostile actions is added to these problems.

S. Panico *et al.* (2023) examined the concentrations of potentially hazardous elements and studied the impact of metal contamination on soil quality and human health risks in three different land areas (forest, fire-prone forest, and urban area) in the Mediterranean region. The research results showed high concentrations of V, Mg, and Mn in forest and fire-prone forest soils, as well as high concentrations of Al, Fe, Ni, Pb, and Zn in urban soils. The authors propose the development of further forest management practices aimed at monitoring soil contamination. In Ukraine, it is necessary to apply biological methods of soil purification from heavy metals, such as phytoremediation, which is based on the use of plants to extract heavy metals from the soil. In the study by J. Da Gama (2023), soils under the threat of anthropogenic and climatic pressure were investigated. The author considers it advisable to implement innovative solutions such as closed-loop economy approaches and sustainable biomass use, which are necessary to reduce greenhouse gas emissions. In Ukraine, it is worth implementing bioenergy technologies and using all types of biofuels – solid, liquid, gaseous, and it is also necessary to develop a Biomass Action Plan document. N. Iliopoulos *et al.* (2023) studied smoke dispersion from a forest fire in Penteli-Attica (Greece) on July 19, 2022, which burned an area of 2,781.7 ha. According to the results of the Penteli wildfire study and the measurement of gases and particles at measuring stations near the fire, it was found that the concentrations of PM 10 and PM 2.5 (air pollutants that are particularly harmful to human life and the environment) were almost four times higher on the day after the fire, July 20. The authors propose to apply such a protective measure as the evacuation of the population from the areas affected by the wildfire. The use of monitoring equipment, including an air quality monitoring network consisting of five permanent monitoring stations installed in residential areas, could be proposed in Ukraine.

Researchers S. Stefanidis *et al.* (2023) investigated changes in soil loss rates due to rain erosion in Southern Europe during the period 1980-2018. The research results showed that the average annual soil erosion rates in Southern Europe were 6.82, 4.90, 4.89, and 5.26 t/ha/year for the decades 1981-1990, 1991-2000, 2001-2010, and 2011-2018, respectively. The authors believe that it is necessary to apply an approach that combines freely available geospatial datasets and an empirical erosion prediction model. Z. Cheng *et al.* (2023) examined the impact of different fire intensities and key environmental factors on soil microbial diversity and biomass in taiga forests in northeastern China that were damaged by light, moderate, or severe fires. The results showed that all three fire intensities significantly increased the concentrations of soil microbial carbon, moisture content, and total nitrogen content, but they significantly decreased soil available potassium content compared to unburned taiga forest. The authors suggest applying a set of measures to optimise anthropogenic landscapes by creating ecologically sustainable plant cover on them – land phytoremediation. In Ukraine, technologies for soil remediation based on plants – phytoremediation technologies – should be utilised. In the study by F. Niccoli *et al.* (2023), the consequences of a wildfire that affected a black pine forest in Central Italy in 2017 were investigated. The results demonstrated the importance of using remote sensing for accurately delineating fire-affected areas and for precise ground action planning. The authors propose to combine remote sensing analysis with ground-based forest surveys. In Ukraine, a combined approach of satellite and ground-based research could be applied to accurately determine fire-affected areas. For instance, Ukrainian researchers O. Soshenskyi et al. (2022) assessed forest damage in Luhansk Region due to severe fires using the composite burn index and the geometrically structured composite burn index methods with satellite data. Although these studies analysed various impacts of fires on soils, they did not account for heavy machinery loads on land and explosions of ammunition, which also adversely affect soils and can create or intensify fires, leading to the burning of larger territories.

In a study by H. Haller *et al.* (2023), the ability of *Amaranthus hypochondriacus* plants to extract Cd from a nutrient-poor acidic substrate to which Cd was added in different concentrations (2 and 20 mg/kg dry weight) for 180 days was investigated. The authors believe that the application of phytoremediation technologies and the use of *Amaranthus hypochondriacus* plants are important for improving ecology and human health. According to the authors of this article, plants such as switchgrass and silver grass, which are hyperaccumulators and can actively absorb heavy metals and partially accumulate them in their underground and aboveground parts, can also be used in conditions of heavy metal pollution, which can help improve the condition of soils in the post-war period. Thus, in this section, a review was conducted, and studies on soil compaction due to the movement of heavy equipment and vehicles, the severity of fires in heterogeneous, fragmented ecosystems, and so on were considered. As a result of comparing these studies with the realities of Ukraine, the modified solutions described above can be considered. Although the studies considered describe the experiences of other countries in the world, some of their results and ideas coincide with the opinions of the authors of this article.

Conclusions

The pollution of the ecosphere and soils affected by the war unleashed by Russia in Ukraine was investigated. The results of studies on the impact of fires on soil properties showed that, as a result of fires, there was a mixing of the upper horizon of microelevations with living and burnt plant roots with the soil mass, reaching a depth of 15 cm. The tendency to decrease the pH values in post-fire soils is explained by the fact that ash water-soluble compounds, penetrating the soil, saturate the absorbing complex with alkaline earth elements. The accumulation of salts at a depth of 20 cm is likely associated with the formation of TDS during the mineralisation of organic residues, which are not washed out of the soil but accumulate in it. In soils damaged by fire, there was a decrease in organic carbon, which is associated with the direct destruction of the upper horizon due to thermal exposure. The highest content of PAHs was observed in pyrogenic areas, where low molecular weight PAHs predominated, and high molecular weight PAHs were also present, which characterised the recent burning of the territory of the Ivory Coast of Sviatoslav National

Nature Park. Different total content and composition of PAHs in soils on microelevations and in microdepressions were established. The content of PAHs is lower on microelevations, probably they are less exposed to the pyrogenic factor than microdepressions. In soils from burned areas of different ages, high molecular weight PAHs are present in larger quantities than in background areas. Low molecular weight PAHs predominate on all investigated sites.

An analysis of the results of studies of water bodies in the Kharkiv Region highlighted that the largest number of exceedances of pollutants in September 2023 were sulphates and ammonium nitrogen (recorded at 17 and 16 points, respectively). Exceeding the maximum permissible concentration was also noted in the water for 4, 3, and 2 hydrochemical indicators. Exceeding the nitrate and chloride content was not detected at any observation point. An analysis of the results of studies of air pollution in Kharkiv revealed that in September 2023, the level of pollution was characterised as low, as the API scale revealed a level of less than 5.0. In Kharkiv, the most contaminated was 4 Pashchenkivska Str., Ivanivka District (SOPAP No. 13), where the pollution index was 3.39; the least polluted was 53 Vrubel Str., Novobavarsk District (SOPAP No. 21), where the pollution index was 1.47. Directions for further research may include the implementation of clear interaction between the main participants in monitoring programmes at the regional level, standardisation of regulatory norms and measurement methods, and a well-founded correction of the programme and observation sites in accordance with local conditions.

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None.

Conflict of Interest

None.

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Забруднення атмосфери, ґрунту та водних ресурсів унаслідок російсько-української війни

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Анотація. Забруднення атмосфери, ґрунту та водних ресурсів в Україні внаслідок російсько-української війни є проблемою, що вимагає негайного вирішення, оскільки наслідки екоциду для екології будуть довготривалими та матимуть глобальний характер. Метою дослідження був аналіз впливу активних військових дій на атмосферне повітря, водні ресурси міста Харкова й Харківської області та на ґрунти Національного природного парку «Білобережжя Святослава» в Миколаївській області шляхом оцінки їхнього еколого-геохімічного стану. Дослідження впливу пожеж на властивості ґрунтів Національного природного парку «Білобережжя Святослава» за допомогою потенціометричного, люмінесцентно-бітумінологічного та спектрофлуометричного методів виявили, що вміст поліциклічних ароматичних вуглеводнів (ПАВ) найбільший на пірогенних ділянках, де переважаючими групами є легкі ПАВ; також наявні важкі ПАВ, які характеризують недавнє вигорання території. Встановлено, що вміст ПАВ менший на мікропідвищеннях. Для дослідження атмосфери використано аспіраційний метод. Показано, що рівень забруднення повітря у Харкові на всіх пунктах спостереження низький, за шкалою індексу забруднення атмосфери виявлено рівень менше 5. Встановлено, що найбільша кількість перевищень у водних об'єктах Харківської області зафіксована по таких забруднюючих речовинах як: сульфати (зафіксовано на 17 точках), азот амонійний (на 16 точках), біохімічне споживання кисню (на 14 точках), розчинений кисень (на 11 точках). У всіх найбільш забруднених водних об'єктах зафіксовано перевищення гранично допустимої концентрації по 4, 3 та 2 гідрохімічним показникам. Результати дослідження можуть бути використані на практиці екологами з метою розробки та впровадження заходів для поліпшення екологічного стану східних та південних регіонів України

Ключові слова: екологія; екологічні наслідки; економічні втрати; збитки; національний природний парк; річки

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Impact of climate change on forest ecosystems in Western Polissia

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Abstract. Climate change is affecting forest ecosystems, leading to changes in the distribution of tree species, ecological relationships, and the functioning of forest plant communities. The study aimed to analyse the impact of climate change on forest ecosystems in the Western Polissia of Ukraine. To achieve this goal, in 2005-2023, the State Enterprise "Gorodetske" Research Farm studied the current state of the forest ecosystem, analysed the impact of climate change on it, and conducted detailed forest pathology reconnaissance surveys of the stands. Biodiversity indices were also determined, and the rate of degradation and death of forests was analysed using field data and satellite images. The study determined that climate change in the Western Polissia Region has a significant impact on forest ecosystems, causing changes in forest composition, the spread of diseases and pests, and a decrease in natural biodiversity. The study established that to ensure their sustainable functioning and conservation, it is necessary to take specific measures, including early diagnosis of the state of forests, adaptation to climate change, prevention of forest fires, and use of forest resources based on the principles of sustainable forestry. Implementation of such strategies can contribute to the preservation of ecological diversity and sustainable development in the region for years to come. The results obtained are of great importance for environmental management and conservation of natural resources in the Western Polissia Region, as they provide an opportunity to identify specific strategies and measures for the adaptation of forest ecosystems to climate change and other environmental challenges

Keywords: forest stand; phytopathogens; natural communities; degradation; biodiversity

Introduction

Climate change affects forest ecosystems through fluctuations in temperature and precipitation and can significantly affect the distribution of tree species in forests. Some species may be losing their natural habitat due to changing climatic conditions, while others may be expanding their range beyond their traditional range. This can lead to changes in biodiversity and ecosystem functioning. In addition, climate change can affect the production and distribution of nutrients in the forest, as rising temperatures and changes in precipitation patterns can alter the availability of water to trees and other plants, affecting their growth and development. B.D. Appiagyei *et al.* (2022) noted that the ability of plants to adapt to new climatic conditions depends on their genetic diversity and plasticity, i.e., the ability to change their physiological processes in response to environmental changes. Plants with high genetic diversity have a greater potential for adaptation, as diversity allows them to use a wide range of adaptive strategies. However, the speed and scale of climate change may exceed the ability of many plant species to adapt.

Q. Lyu *et al.* (2021) and M. Mpanda *et al.* (2021) noted that climate change can significantly affect the age structure of the forest. As temperatures rise, some tree species may grow faster, which can lead to changes in the overall structure of forest ecosystems. C. Homer *et al.* (2020) argue that it can also increase competition between different species for available resources such as light, water, and nutrients. These changes can have a significant impact on ecosystem processes and forest biodiversity. Rising temperatures can create conditions for faster growth of young trees, potentially

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changing the age structure of the forest and making it younger. Changes in age structure may have further implications for the sustainability of forest ecosystems. Young trees often require more resources to grow rapidly, which can lead to the depletion of available nutrients and water, especially in a changing climate. Climate change may change the distribution of pathogens that damage forest ecosystems. G.C. Hurtt *et al.* (2020) emphasise that this can lead to the spread of new pests and diseases or changes in the intensity of their impact. Rising temperatures can create favourable conditions for the reproduction of some pests that were not previously typical of a particular area. Climate change in forest ecosystems is leading to significant environmental changes, reducing biodiversity, and altering the dynamics of animal populations. According to L.J.R. Nunes *et al.* (2021), the decline in forest area and degradation of forest quality due to drought and rising temperatures are leading to a decline in populations of animals such as birds, mammals, insects, and others. It also affects predators that depend on these animals as food sources. Such a chain reaction can have far-reaching consequences for the ecosystem, disrupting the natural interconnections and balance between species.

Climate change is one of the world's biggest challenges and affects the forest ecosystem. Climate has a significant impact on species distribution, growth rates, and forest structure. Warming directly affects the rate of plant photosynthesis and indirectly increases the risk of phytopathogen infection (Nigatu Gebeyehu & Hailu Hirpo, 2019). The impact of climate change on the forest ecosystems of the Western Polissia Region of Ukraine is an important topic of research in ecology and natural history. The region is in the western part of Ukraine and is known for its unique biodiversity and vast forests. Any changes in climate, such as rising temperatures, changes in precipitation patterns, and the intensity of natural disasters, can have a serious impact on forest ecosystems (Kimeichuk & Kaidyk, 2022). Following V. Lavnyy *et al.* (2022), climate change requires sustainable management of forest resources to ensure their sustainability and restoration. Therefore, studying the impact of climate change on forest ecosystems in Western Polissia, Ukraine, is relevant for ensuring effective management and conservation of natural biodiversity.

Thus, climate change has a complex and multifaceted impact on forest ecosystems, which should be studied in detail and addressed when developing forest management strategies, which is the relevance of the study. Research gaps are noted in that there is a lack of precision in predicting the specific effects of these changes on different species of trees, vegetation, and animals in different ecosystems. The study aimed to address and reveal the impact of climate change on forest ecosystems in the Western Polissia Region of Ukraine. To achieve the stated goal, the following tasks were set: to conduct a detailed analysis of existing data on climate change in the Western Polissia Region; to research which tree species are typical for the region; to identify which pests and diseases are becoming more common or threatening forests due to climate change; and to develop adaptation and forest management strategies to ensure the sustainability and conservation of ecosystems in Western Polissia. These tasks will describe the impact of climate change on forest ecosystems in Western Polissia and develop appropriate management strategies to ensure their resilience and conservation.

Materials and Methods

During 2005-2023, the study of the impact of climate change on forest ecosystems in the territory of Horodets Village Council of Volodymyrets District of Rivne Region was carried out. These studies were conducted at the State Enterprise "Gorodetske" Research Farm ("Gorodetske"), which is part of the Institute of Agriculture of Western Polissia of the National Academy of Agrarian Sciences of Ukraine and is subordinated to the Ministry for Development of Economy, Trade and Agriculture of Ukraine (Fig. 1).

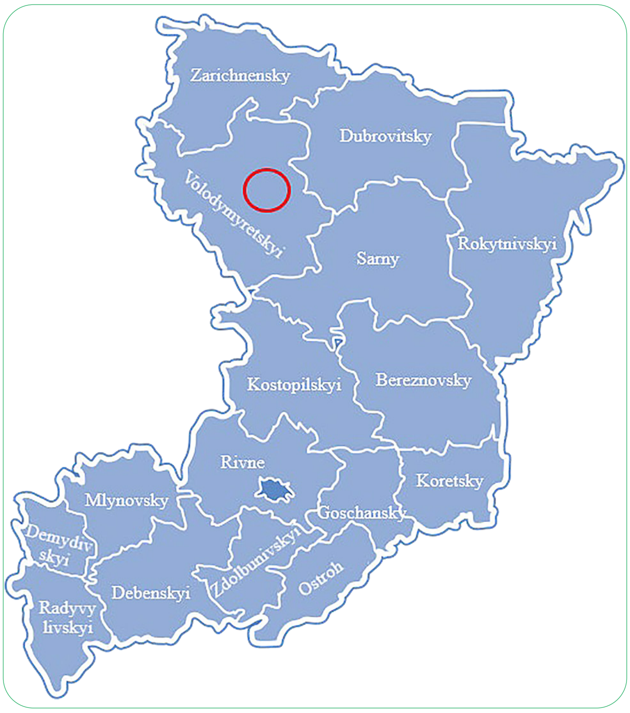

Figure 1. Territorial location of the study area
Source: compiled by the author

The study area covers 106.3 ha and is in the Ukrainian Polissia – Western Polissia Forestry District. Most of the forest plantations in this region grow in fresh subsoil conditions. The research was informed by official materials, statistics, and publications of the Ministry of Environmental Protection and Natural Resources of Ukraine (National environmental policy, n.d.), the State Agency of Forest Resources of Ukraine (General characteristics…, n.d.), and the State Statistics Service of Ukraine (Sales of forest products…, 2024). Rivne Meteorological Station (n.d.) data were used to analyse climate change, which provided a detailed analysis of changes in average annual temperature, precipitation, temperature fluctuations, and anomalous climate parameters over the period 1979-2023. Historical data from archival documents, literature, and forest management reports were studied to determine the distribution of tree species and the spread of diseases and pests, and compared with the current state (State Audit Service of Ukraine, 2020; Environmental passport of Rivne Region, 2021).

To obtain data on the current state of the forest ecosystem and the impact of climate change on it, detailed forest pathological reconnaissance surveys of stands for pests and diseases were carried out by laying out trial temporary areas. During these inspections, the plants are examined, assessing their appearance, shape, growth, and leaf colour. Any signs of damage, such as holes in the leaves, changes in the colour or texture of the bark, insect damage or nests, as well as spots, fungal fruiting bodies, or other signs of disease infestation, were inspected. Modern environmental research often involves the collection and analysis of large amounts of data (e.g., biodiversity monitoring data, climate data, satellite imagery). To simplify calculations, efficient processing and analysis of such a large amount of data, it is advisable to use programming methods. Therefore, the study used formulas to determine biodiversity indices, which were then processed by a script written in the R programming language. Simpson's index is an indicator of species diversity that considers the number of species (E) and the relative abundance of each species (p) (Somerfield *et al.*, 2008). It is calculated as:

$$E = 1 / (\Sigma\, p^2), \tag{1}$$

where Σp – the total proportion of individuals in the community belonging to a particular species. The Shannon index is an indicator of species diversity that considers the number of species (S) and the relative abundance of each species (p):

$$S = -\Sigma\, p \times \log2\,(p), \tag{2}$$

where p – is the proportion of individuals in the community belonging to a particular species. The Brillouin index is an indicator of species diversity that takes into account the number of species (H), the total number of individuals (N), and the number of individuals of each species (n):

$$H = ln\,(N!) - \Sigma\,(S \times ln\,(n_i) / N), \tag{3}$$

where N – is the total number of species; n_i – is the number of individuals of each species; S – is the number of species. The study addressed the species structure of the forest fund of Rivne Region, which is part of the Western Polissia zone, with a total area of forest plots of 374,993.5 ha. The analysis of the rates of degradation and death in forest areas was carried out by collecting and processing field research data, which included direct observation, recording, and identification of plants by route. Satellite imagery and aerial photography were also used to identify degraded areas and analyse the factors causing degradation, such as deforestation, fire, pathogens or anthropogenic factors. The obtained research results were processed for their reliability using the multivariate analysis of variance MANOVA method. Microsoft Excel and Statistica 10 software were used for this purpose.

Results

The climate indicators in the Western Polissia Region in 2000-2023 are characterised by an increase in the average annual air temperature by 2°C. The highest temperature increases are observed during the cold season, which reduces the likelihood of prolonged and severe cold weather, although short-term cold snaps are still possible. During the cold season, fog, frost, snowfall, ice, and strong gale-force winds are common, with a probability of 80-95%. The warm season is characterised by extreme heat, increased fire danger, as well as intense rain, thunderstorms, hail, and squalls. These phenomena are local in nature but manifest themselves with a certain regularity and intensity.

Since the beginning of 2000, the climatic conditions in Western Polissia have undergone significant changes as a result of global warming, which is observed in all parts of the world. Winters have become milder, and rain instead of snow in December has become a common occurrence. Since the end of 2010, spring droughts and windstorms have become more frequent, negatively impacting agriculture and forest ecosystems. Summer cold snaps are often accompanied by strong winds, heavy rains and hail, which leads to significant losses. Climate change is affecting all aspects of life in the region. Warmer winters lead to a decrease in snow cover, which is important for the water balance and prevention of spring floods. Long, hot periods in the summer increase the risk of forest fires and reduce the possibility of active photosynthetic activity. Therefore, it is necessary to adapt technologies, water management and urban planning to minimise the negative impacts and ensure sustainable development in the region.

The data show that the linear trend of climate change is increasing, which indicates that the temperature trend is positive and that the Western Polissia Region is becoming warmer due to climate change. Moreover, one can observe a complete absence of blue colour bands, which are characteristic of colder years in the chart since 2000, while there is a clear trend of red bands, which are characteristic of warmer and hotter years (Fig. 2). The amount of precipitation has been decreasing over the years, so conditions in the Western Polissia Region are becoming drier over time. In addition, drier years are becoming more and more common, with brown stripes instead of rainy ones on the chart, creating a moisture deficit for forest ecosystems (Fig. 3). The temperature anomaly for each month since 1979 indicates how much warmer or colder it was than the 30-year average air temperature between 1980 and 2010. Red months indicate warmer values, and blue months indicate colder values than the average. According to the data obtained, it is possible to state that the number of warm months has been increasing over the years, which indicates global warming associated with climate change (Fig. 4). The bottom part of the figure shows the precipitation anomaly for each month since 1979; the anomaly indicates whether the month had more precipitation than the average for the 30 years of climate observations from 1980-2010. Green months show an excess of precipitation, and brown months show a deficit compared to the norm. Thus, over the years, the trend of periods of precipitation deficit has been observed.

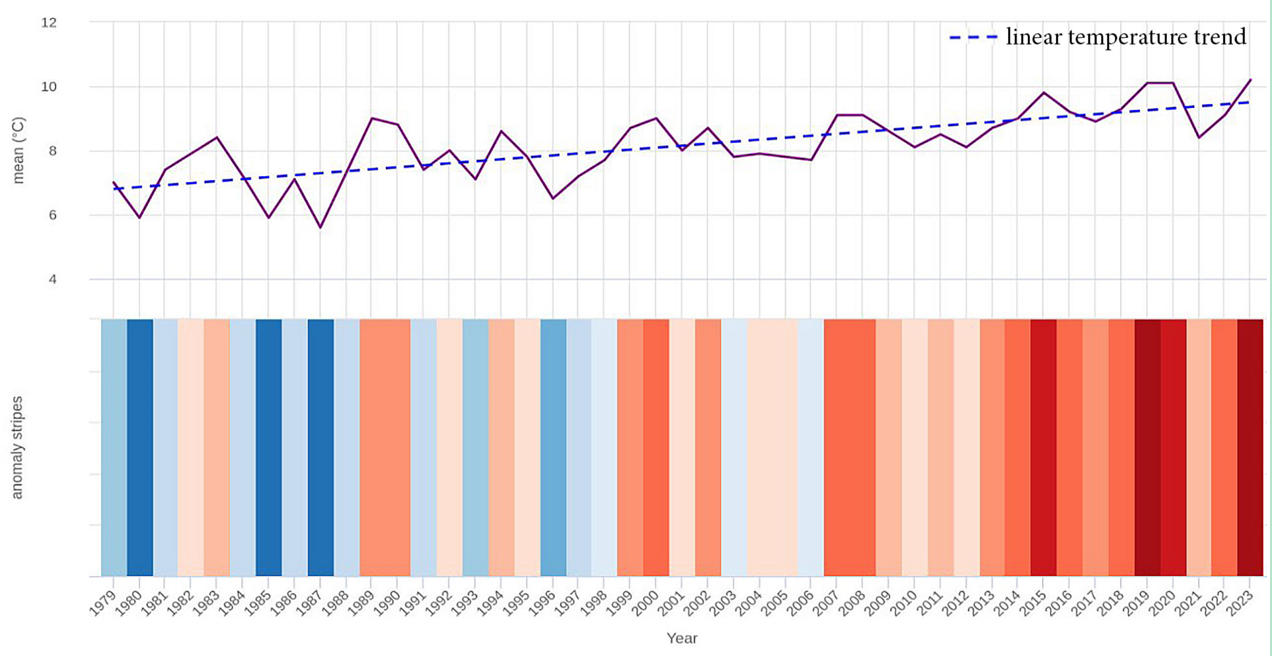

Figure 2. Annual temperature change at the Rivne Meteorological Station, 1979-2023
Source: compiled by the author based on Rivne Meteorological Station (n.d.)

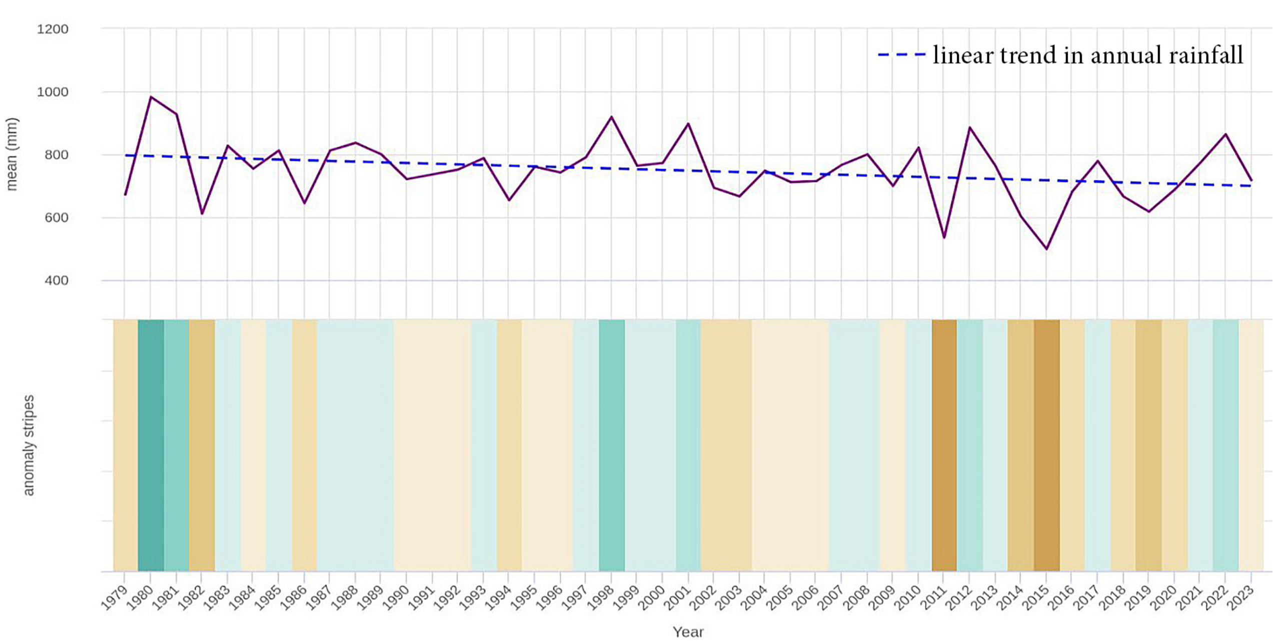

Figure 3. Dynamics of annual precipitation at the Rivne Meteorological Station, 1979-2023
Source: compiled by the author based on Rivne Meteorological Station (n.d.)

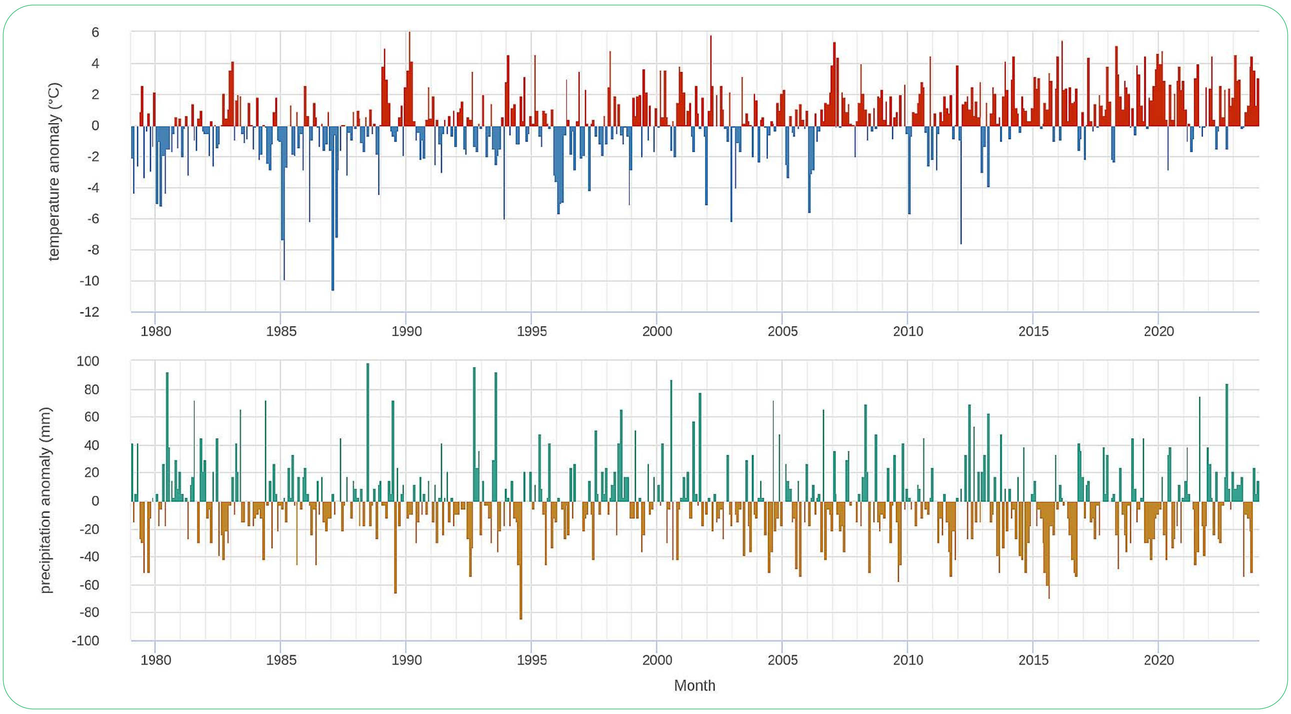

Figure 4. Deviations from the norm of average monthly air temperature and monthly precipitation at the Rivne Meteorological Station, 1979-2023

Source: compiled by the author based on Rivne Meteorological Station (n.d.)

The study established that over the past decade in Western Polissia in the example of the Rivne Region, there have been changes in the species composition of forests, which has led to a decrease in the number of valuable and productive tree species (both coniferous and hardwood) and an increase in derivative stands and less valuable forest plantations. This increase was due to the expansion of low-bonus hardwood and softwood plantations, which indicates negative changes in the quality of plantations. Such changes are considered negative due to reduced forest productivity, lower resistance to pests and diseases, and soil degradation (Lavnyy *et al*., 2022). According to the structure of forests by species groups, conifers predominate common pine, which occupies 65% of the total forest area (374,993.5 ha) (Fig. 5).

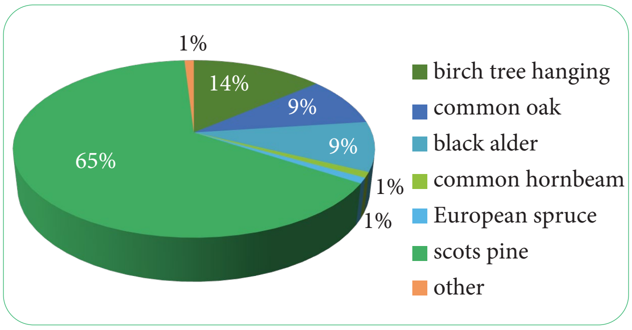

Figure 5. Species structure of the forest fund of Rivne Region

Source: compiled by the author

Other dominant forest species include hanging birch, common oak and black alder, which cover large areas: 81,658.8 ha, 52,110.9 ha and 53,892.2 ha respectively (9% each). Other species account for 3%, of which European spruce and hornbeam account for 1% each. According to the study, rising temperatures have led to the spread of diseases in forest ecosystems, in particular rust, fusarium, and pine blight. In recent years, the dry climate has contributed to the spread of root sponge, which is the most damaging to pine plantations and leads to their depletion. In addition, climate change has affected the spread of pests in forest ecosystems, such as: bark beetle, blue pine bark beetle, ribbed ragworm, goldeneye, large pine beetle, moustachioed beetle, silkworm, beetle and pine pole beetle (Fig. 6). Moreover, climate change may affect forest biodiversity. Some plant and animal species may lose their natural habitats due to changes in the growing season or soil moisture. This can lead to a disturbance of the ecological balance in forest ecosystems. The study revealed a negative trend in biodiversity loss. A script made with the R programming language was used to calculate biodiversity indices for the study plots (Table 1). In general, a downward trend can be noted for all three indices during the period under review. This may indicate a decrease in plant diversity at the "Gorodetske". The Shannon and Simpson indices, which address both the number and diversity of species, appeared to be more sensitive to changes than the Brillouin index, which takes into account only the number of species. Thus, the decline in the Shannon and Simpson index reflects not only a decrease in the number of species but also a loss of diversity. Changes in biodiversity can be caused by various factors, such as climate change, changes in land management, habitat destruction, and the loss of plant habitats. To determine in detail the causes of changes in forest ecosystems, the rates of degradation and death of forests were analysed (Fig. 7-8).

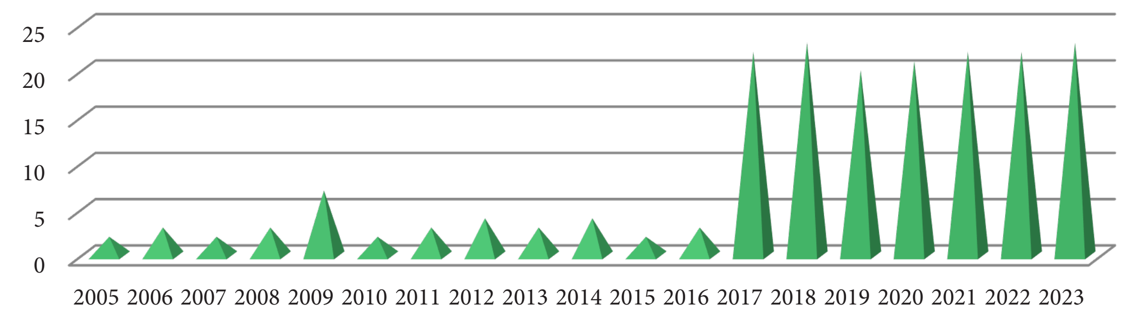

Figure 6. The presence of forest pests and diseases in the "Gorodetske", 2005-2023

Source: compiled by the author

Table 1. Plant biodiversity index at the "Gorodetske", 2005-2023, plot average

Year	Brillouin index	Shannon index	Simpson index
2005	4.5	2.8	0.65
2006	4.3	2.7	0.63
2007	4.2	2.6	0.61
2008	4.1	2.5	0.59
2009	4	2.4	0.57
2010	3.9	2.3	0.55
2011	3.8	2.2	0.53
2012	3.7	2.1	0.51
2013	3.6	2	0.49
2014	3.5	1.9	0.47
2015	3.4	1.8	0.45
2016	3.3	1.7	0.43
2017	3.2	1.6	0.41
2018	3.1	1.5	0.39
2019	3	1.4	0.37
2020	2.9	1.3	0.35
2021	2.9	1.2	0.34
2022	2.8	1.2	0.33
2023	2.7	1.1	0.31

Source: compiled by the author

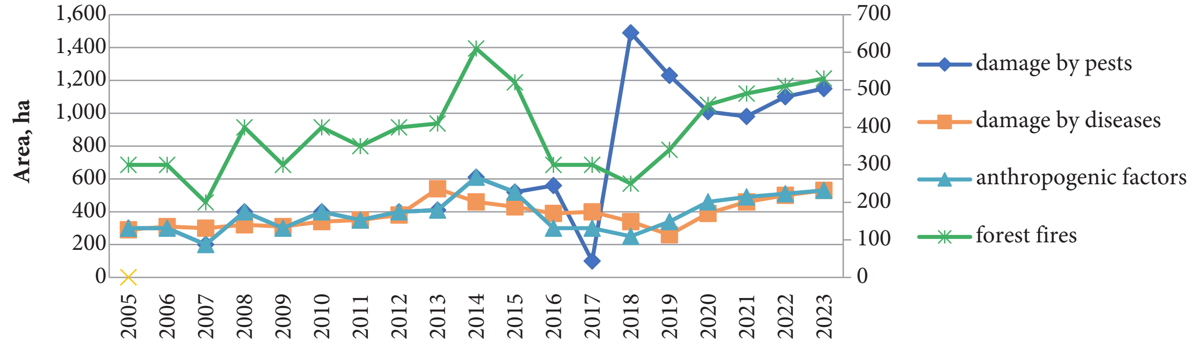

Figure 7. Dynamics of mortality of coniferous tree species, 2005-2023

Source: compiled by the author based on General characteristics of the forests of Ukraine (n.d.), Sales of forest products within Ukraine by type (2024)

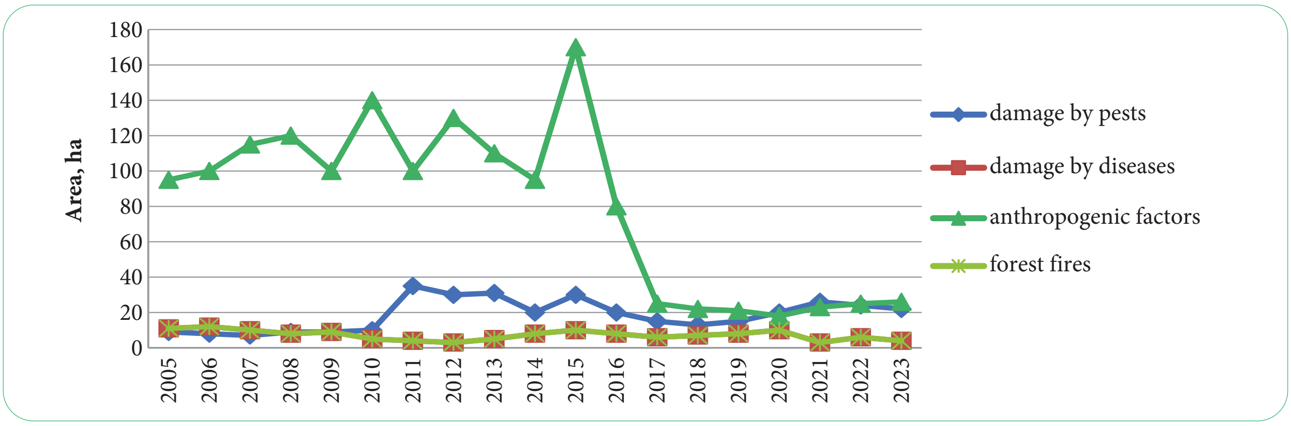

Figure 8. Dynamics of mortality of deciduous tree species, 2005-2023

Source: compiled by the author based on State Agency of Forest Resources of Ukraine (n.d.), Sales of forest products within Ukraine by type (2024)

Summarising the analysis of data for the period from 2005 to 2023, it can be determined that there is an increase in damage from diseases and pests of conifers, which indicates a deterioration in the condition of forests and their vulnerability to phytopathological factors. A stable trend of anthropogenic factors has been established for most years, including deforestation. There is also an increase in the number of forest fires, which is a result of both climate change and human activity. As for deciduous tree species, it is worth noting that in 2011 there was a sharp increase in the impact of pests. The impact of anthropogenic factors has been decreasing in most years, but high values were noted in 2007 and 2010. There is also a general trend of increasing forest fires over time, especially in 2017 and 2018.

Overall, the analysis demonstrates the threats faced by forest ecosystems and points to the need to take measures to protect and sustainably use them. In particular, the following adaptation and forest management strategies can be developed to ensure the sustainability and conservation of Western Polissia ecosystems in the context of identified impacts and threats. Monitoring and early diagnosis: establishing a system for continuous monitoring of forest conditions to detect damage from pests, diseases, climate change and forest fires in a timely manner; use of advanced technologies such as drones and satellite sensing to collect data and visualise the state of forests. Biodiversity and ecosystem restoration: preserving and restoring biodiversity by preserving natural forest complexes and regulating forestry; implementation of programmes to preserve rare and endangered species of plants and animals that are an integral part of ecosystems. Adaptation to climate change: developing and implementing climate change adaptation strategies, including protecting forests from rising temperatures, droughts, and other climate extremes; introduction of climate-resistant tree and plant species. Preventing forest fires: implementing preventive measures to prevent forest fires, such as clearing undergrowth, creating firebreaks, and educating local residents on fire safety; development and implementation of emergency and rapid response plans in case of fire. Sustainable use of forest resources: managing forest resources based on the principles of sustainable forestry, including the balanced use, restoration and conservation of forest resources; introducing forestry certification to ensure compliance with sustainable forestry requirements. These strategies are aimed at ensuring the resilience and conservation of Western Polissia ecosystems in the face of growing threats and impacts, and their implementation can help conserve valuable forest resources and ensure sustainable use for many years to come.

Discussion

Climate change is one of the biggest challenges facing the world, with a significant impact on forest ecosystems. As such, A. Zerva (2022) noted that forests are sensitive to climate change, so climate change has a huge impact on species distribution, growth rates and forest structure. Climate change is having a major impact on forest ecosystems, altering tree growth and reproduction. As temperatures rise, the chronology of tree life cycles changes, with budding, leafing and flowering occurring too early. A similar opinion is expressed by Z. Zeng *et al.* (2020), according to which climate change affects forest ecosystems both directly and indirectly, changing their structure and functioning. Rising temperatures directly affect the rate of photosynthesis and respiration of plants, and indirectly increase the risk of damage from phytopathogens. In general, climate change is seen as one of the main obstacles to sustainable development due to its impact on health, infrastructure, population, agriculture and forest ecosystems. It can also cause a deterioration in living conditions in many regions of the world (Zhang *et al.*, 2022).

According to Z. Zhao *et al.* (2021), there were unprecedented changes in the climate system during the twentieth century. These changes can be traced back to an increase in average annual temperature, changes in the quantity and quality of precipitation, and an increase in the intensity and frequency of abnormal events. It is widely accepted that climate change is closely linked to greenhouse gas emissions, especially over the past 150 years. Therefore, the term "climate change" has become synonymous with "human-induced climate change". Climate change is most adversely affected by rising air temperatures and changes in precipitation. These factors influence changes in the growing season and the composition of forest ecosystems. Analysis of the study by K. Yuan *et al.* (2021) and the modelling of changes in climate indicators confirm an increase in air temperature by 0.7°C annually. According to the study, the optimal temperature for photosynthesis in forests depends on the type of ecosystem: for deciduous trees – 17.5°C, for conifers – 16°C. Precipitation affects the intensity of photosynthesis only at low values – less than 60 mm. H. Xie *et al.* (2021), on the other hand, believe that changes in climatic parameters at the beginning of the growing season contribute to improved conditions for photosynthesis in forest plantations. However, excessively high summer temperatures can harm the condition of coniferous forests, as this factor only increases over time.

In contrast, A.A. Argiriou *et al.* (2023) suggest that reduced precipitation in August and September can negatively affect plant development. However, in the long term, the increase in the length of the growing season caused by the early onset of plant physiological activity may have a positive impact. This change can help increase the efficiency of forest ecosystems in absorbing carbon dioxide, which is important for the climate balance. In general, most authors agree that global warming is causing significant changes in the environment, which have already led to certain negative environmental impacts and may further deepen in the future. Anomalies of high temperatures alternating with coolness, prolonged absence of precipitation, as well as sudden heavy rains and other adverse weather events, lead to the degradation of forest ecosystems (Salimi *et al.*, 2021; Tian *et al.*, 2023).

Climate change harms forest ecosystems, as rising temperatures lead to changes in the composition of forest species, increase the frequency and intensity of forest fires, and promote the spread of pests and diseases, which threaten forest health. G. Forzieri *et al.* (2022) argue that these changes are affecting the ability of forests to respond to various climate factors, leading to a decrease in their resilience. Another proof of this and confirmation of the results is the opinion of M. Nigatu Gebeyehu & F. Hailu Hirpo (2019), who believe that climate change is leading to the transformation of zonal vegetation types, changes in the ratio of forest formations and forest types, as well as deterioration of forest viability and resistance to pests and diseases. In addition, they contribute to an increase in the intensity of forest drying and outbreaks of massive pest reproduction. Climate change has a significant impact on the forest ecosystems of Western Polissia, a region with many forests and rich biodiversity. Although the climate here is favourable for plant diversity, the peculiarities of the local location and atmospheric processes create conditions for the occurrence of natural meteorological events that can be catastrophic and cause significant damage (Boychenko & Karamushka, 2020). The wetland ecosystems typical of Polissia are particularly sensitive to such environmental changes. Studies point to a specific destruction of birch-rich habitats in the bogs of the left bank of Polissia, which is associated with extreme weather conditions. These ecosystems are important, and they are very sensitive to any changes in the environment, as confirmed in the study (Gautam *et al.*, 2021).

Natural climatic zones, forest species composition, and local growing conditions play an important role in how climate change will affect specific forests. According to L. Gustafsson *et al.* (2020), climate change is also causing significant changes in the biological productivity of forests, which affects the amount of available forest resources. This creates new challenges for the forestry and woodworking industries, which require the development of measures to adapt to the new conditions. These changes must be addressed to ensure forest sustainability and effective forest management in a changing climate. A comparison of the results with previous studies in this area confirms the consistency and complementarity of the findings. For instance, studies by M.M. Qaderi *et al.* (2019) and R.A. Slesak *et al.* (2022) also indicate that to effectively respond to the challenges posed by climate change and to forecast the volume of forest resources in the future, it is necessary to have a detailed understanding of forest productivity and condition in the medium and long term. L. Yang *et al.* (2022) emphasise that it is necessary to implement the principles of sustainable forestry and develop adaptation strategies that consider the natural and climatic zones and bio-ecological characteristics of forest species. This will reduce the vulnerability of forests to climate change and help preserve them for future generations.

The study confirms the opinion of Y. Li *et al.* (2020), who emphasise that the transition to sustainable forestry and the implementation of forest adaptation strategies to climate change significantly increase their resilience. Adaptation strategies should be based on the principles of sustainable forestry, addressing the natural and climatic zones and bio-ecological characteristics of forest species. This includes selecting appropriate reforestation methods, monitoring forest conditions, and integrating new technologies and approaches to forest management. In this way, the negative impact of climate change can be reduced, and forest plantations can be preserved. The findings of Q. Wang *et al.* (2023) also resonate with the present study, which found that the forestry industry reduces its vulnerability to climate change through strategic interventions. This includes implementing adaptation measures, such as developing tree varieties that are more resilient to new climate conditions and conserving biodiversity to create more resilient ecosystems. Reducing the vulnerability of the forest sector and improving its adaptive capacity has a positive impact on the environment, helping to maintain the ecological sustainability of forests (Navarro-Cerrillo *et al.*, 2023).

Thus, climate change has become a key objective of global environmental policy and a challenge for forest management strategies. Forestry managers need to be aware of their role in reducing the vulnerability of not only the forestry sector but also other sectors of the economy and agriculture. There is ambiguity regarding the development of effective mechanisms for a socially acceptable, internationally coordinated climate policy strategy that could withstand market constraints and promote appropriate institutional development. However, the forestry sector has great potential to mitigate the negative effects of climate change, but this requires the development of regional adaptation and optimisation strategies.

Conclusions

The study found that between 2000 and 2023, the average air temperature in the Western Polissia Region increased by 2°C and there is a tendency to increase the number of warm months over the years, which indicates global warming associated with climate change. In addition, conditions in this area are becoming drier over time, which creates a moisture deficit for forest ecosystems. These changes affect forests, causing a decrease in species biodiversity and disruption of ecological balance in forest ecosystems. The study also established that the decline in biodiversity is caused by factors such as climate change, anthropogenic impacts, environmental destruction, and the loss of habitat for plants due to forest fires.

An analysis of data for the period from 2005 to 2023 confirmed that in the Western Polissia Region, in the Rivne Region, there is an increase in damage from diseases and pests of both coniferous and deciduous tree species, which indicates a deterioration in the condition of forests and their vulnerability to phytopathological factors. There is an increase in climatic factors, in particular temperature risk, which negatively affects forest health. The increase in the number of forest fires can be caused by both climate change and human activity, which underscores the need to strengthen forest protection measures.

To minimise the negative impacts of climate change, it is necessary to adapt technologies, water management, and urban planning. This includes monitoring and predicting climate change, adapting forestry to new conditions, ensuring climate change resilience, and enhancing the environmental sustainability of the region. Measures must be taken to preserve forest biodiversity, prevent the spread of diseases and pests, and maintain ecological balance in the region. The results of the study are limited to the specific area of Western Polissia in Ukraine and cannot be fully generalised to other areas or climatic zones. The prospect of further research is to use models to predict the impact of future climate change on forest ecosystems.

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Conflict of Interest

None.

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Вплив кліматичних змін на лісові екосистеми Західного Полісся

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Анотація. Кліматичні зміни впливають на лісові екосистеми призводячи до змін у розподілі видів дерев, екологічних взаємозв'язках та функціонуванні лісових рослинних угруповань. Метою дослідження було проаналізувати вплив кліматичних змін на лісові екосистеми в Західному Поліссі України. Для досягнення поставленої мети впродовж 2005-2023 років на території Державного підприємства «Дослідне господарство "Городецьке"» здійснено вивчення поточного стану лісової екосистеми, проаналізовано вплив на неї змін клімату та проведено детальні лісопатологічні рекогносцирувальні обстеження деревостанів. Також визначено індекси біорізноманіття та проведено аналіз темпів деградації та загибелі лісових масивів, використовуючи дані польових досліджень та супутникові знімки. У результаті дослідження встановлено, що кліматичні зміни в зоні Західного Полісся мають значний вплив на лісові екосистеми, спричиняючи зміни в складі лісів, поширення хвороб і шкідників, а також зменшення природного біорізноманіття. Встановлено, що для забезпечення їхнього сталого функціонування та збереження необхідне вжиття конкретних заходів, включаючи ранню діагностику стану лісів, адаптацію до змін клімату, запобігання лісовим пожежам та використання лісових ресурсів на основі принципів сталого лісового господарства. Впровадження таких стратегій може сприяти збереженню екологічної різноманітності та сталому розвитку регіону на майбутні роки. Отримані результати мають вагоме значення для екологічного управління та збереження природних ресурсів у зоні Західного Полісся, оскільки надають можливість визначити конкретні стратегії та заходи для адаптації лісових екосистем до змін клімату та інших екологічних викликів

Ключові слова: деревостан; фітопатогени; природні угруповання; деградація; біорізноманіття

ЕКОЛОГІЧНА БЕЗПЕКА
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