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Geoecological assessment of the state of urban soils and their transformation under the influence of anthropogenic factors

Oksana Yehorova*
PhD in Technical Sciences, Associate Professor
Cherkasy State Technological University
18006, 460 Shevchenka Blvd., Cherkasy, Ukraine
https://orcid.org/0000-0002-7801-5582

Olga Mislyuk
PhD in Chemical Sciences, Associate Professor
Cherkasy State Technological University
18006, 460 Shevchenka Blvd., Cherkasy, Ukraine
https://orcid.org/0000-0003-0401-9836

Olena Khomenko
PhD in Chemical Sciences, Associate Professor
Cherkasy State Technological University
18006, 460 Shevchenka Blvd., Cherkasy, Ukraine
https://orcid.org/0000-0001-9329-0577

Abstract. Urbanisation and industrialisation are inextricably linked to the transformation of urban soils, posing a significant problem not only at local and regional levels but also globally. The aim of this study was to conduct a comprehensive assessment of the ecological state of soils in urbanised areas under transport and industrial pressure. The study of physicochemical soil properties was carried out using standard methods. Soil buffering capacity was assessed using the method by Professor P. Nadtochij. Key statistical characteristics were calculated, and regression analysis of the study results was performed using Pearson's correlation coefficient. A systematic analysis of the geoecological state of urban soils (urbosols) in the city of Cherkasy revealed that a low humus content (ranging from 0.9% to 7.5%, with an average of 3.0%), soil alkalisation (pH = 6.5-10.9, with an average pH = 7.9), unfavourable redox conditions (Eh values ranging from 184 to 287 mV, with an average of 239 mV), nutrient imbalance, and a significant content of toxic salts (36% of the studied soils were slightly saline, 23% moderately saline, and 10% highly saline) can have a substantial impact on the stability of the city's urban ecosystems. In terms of acid-base buffering capacity, the soils are in an ecologically stable state. The sum of buffering degrees in both acidic and alkaline ranges exceed 70-75%, with an average equilibrium constant K = 1.4. Using the SURFER software package and the Kriging method, spatial interpolation of monitoring data and cartographic zoning of the city territory was carried out based on the main physicochemical soil characteristics. A database and cartographic models of urban soil properties were developed to monitor their spatiotemporal changes, detect critical transformations, and identify zones of ecological and geochemical instability linked to technogenic impact

Keywords: physicochemical properties of soils; field research; cartographic modelling; geographic information systems; technogenic impact

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*Corresponding author

Introduction

In the context of intensive urban development, the ecological state of soils in urbanised areas has become a critical factor for ensuring the sustainable development of regions. Urbanisation is accompanied by significant anthropogenic pressure on the soil cover, leading to contamination with heavy metals, petroleum products, organic compounds, and other toxic substances. Additionally, the consequences of anthropogenic influence on soils include changes in their physical, chemical, and biological properties. Studies conducted between 2020 and 2024 documented the gradual degradation of soil cover caused by excessive anthropogenic pressure. Research by C.S.S. Ferreira *et al.* (2022) and J. Wang *et al.* (2023) identified transportation infrastructure, industrial zones, and landfills as the main sources of pollutants entering the soil. Urbanisation resulted in soil compaction, disruption of drainage properties, and erosion of the topsoil layer. These processes led to a decrease in soil biological activity, contributed to the accumulation of toxins such as heavy metals, and disrupted the nutrient balance. M. Sager (2020) reported that urban soils exhibited increased alkalinity due to construction waste, contained elevated levels of carbon and pollutants, and were characterised by high density and temperature, along with reduced moisture content caused by compaction. The presence of technogenic materials, including construction debris, significantly influenced the migration of water and dissolved substances within the soil profile. Construction activities altered the sequence of soil horizons or mixed the topsoil with underlying layers.

The study by Q. Liu *et al.* (2023*)* presented the results of mapping heavy metals in soil using various geospatial data, such as remote sensing data, climate, topographic data, and other information on the physicochemical properties of the soil. The authors compared the accuracy of Backpropagation Neural Network (BPNN) and Deep Neural Network (DNN) models for assessing heavy metal content in soil. Based on digital maps reflecting heavy metal content using the DNN model, the study examined the impact of the distance between different spatial scenes on heavy metal contamination in the surrounding soil. The model takes into account all possible combinations of analysed objects, allowing manipulation for decision-making. However, modifying the set of formal concepts may complicate the system's scalability. The work by Ș. Bilașco *et al.* (2021) presented a methodology based on geographic information system (GIS) spatial analysis for selecting the best hydromelioration solution for the development of a comprehensive gully. The proposed model is developed using spatial databases obtained from unmanned aerial vehicle (UAV) flights, flow velocity modelling, and the creation of three hydraulic analysis models using HEC-RAS software, with the primary goal of evaluating results and databases to identify the best implementation model for stabilising and reducing erosion within the analysed area

P. Shekar & A. Mathew (2024) explored the use of Revised Universal Soil Loss Equation (RUSLE), RS, and GIS models to assess soil erosion and sedimentation in the Murradu River Basin. The study utilises GIS for spatial analysis of factors affecting soil erosion, such as climate, topography, vegetation cover, and land use. This allows for the creation of accurate erosion process maps and the prediction of potential sediment yield in various parts of the basin. The RUSLE model is applied to quantitatively assess soil erosion and sediment levels, helping to identify the most vulnerable areas to soil degradation. The results obtained may serve as the foundation for developing effective water resource management strategies and soil restoration measures in the region, promoting sustainable land use and preventing further erosion. V. Melnyk *et al.* (2024) conducted a comprehensive study to assess soil contamination in Rivne, Ukraine, utilising GIS to enhance environmental monitoring. The research focused on the accumulation of heavy metals (HMs) in soils, employing indicators such as the Total Contamination Index (TCI) and Pollution Load Index (PLI) to evaluate contamination levels. The study revealed that 54% of soil samples were "significantly contaminated", while 28% were "moderately contaminated" and 18% showed "no contamination" with HMs. The researchers constructed interpolated surfaces to depict the distribution of total and accumulated HM contamination across the city. This spatial representation allowed for the identification of contamination hotspots, particularly near industrial zones, major highways, and railways. Conversely, areas near water bodies and city outskirts exhibited lower contamination levels.

V. Trigub & S.V. Domuschi (2023) conducted an ecotoxicological study to evaluate the impact of fuel stations on soil contamination with heavy metals in urban areas. The research focused on measuring concentrations of metals such as lead (Pb), cadmium (Cd), and zinc (Zn) in soils adjacent to fuel stations. The study employed various ecological indicators, including the TCI and PLI, to assess the extent of contamination. The study utilised spatial analysis techniques to map the distribution of heavy metal concentrations across the study area. By integrating soil sample data with spatial coordinates, the researchers were able to identify contamination hotspots and assess the spatial variability of pollution levels. This GIS-based approach enabled a more comprehensive understanding of the spatial patterns of soil contamination and facilitated the identification of areas requiring targeted remediation efforts.

In general, approaches to identifying quantitative direct and indirect ecosystem changes in soil under anthropogenic pressure are still limited. Important indicative parameters that characterise both direct and indirect changes in the soil ecosystem include humus content, salinity, redox potential, and the acid-base and buffering properties of the soil cover. When analysing the ecological condition of soils – as with any complex natural process – a systematic approach is required, where processing large volumes of spatially distributed and structured data is essential. In such cases, it is necessary to apply new tools and analytical methods using modern GIS technologies. This study aimed to comprehensively assess the ecological state of urban soils by examining their physicochemical properties, evaluating anthropogenic impacts, and identifying environmental risks to urban ecosystems.

Materials and Methods

The approach presented in this work includes the following stages: soil survey using standard methods; mapping of soil properties; and assessment of overall soil quality in terms of ecosystem service provision. Using the SURFER geographic information software package, the obtained data were extrapolated across the entire urban area and zoned according to key physicochemical indicators (humus content in soil, pH-water indicator, acid-base buffering capacity, content of exchangeable calcium and magnesium ammonium content) for visualisation purposes. Research sites were selected within various functional zones of the city of Cherkasy (Fig. 1). The geographical reference of the test points was carried out using a GPS navigation system. The selection of study plots was based on an analysis of natural and anthropogenic factors influencing the formation of urban landscapes in areas of permanent emissions, taking into account the indicator of cumulative environmental load (Myslyuk *et al.*, 2019). Considering that most soil-based ecosystem services in urban areas are provided by green spaces – particularly oxygen production – soil assessment and the evaluation of its related functionality were focused on the study of soils in roadside green belts.

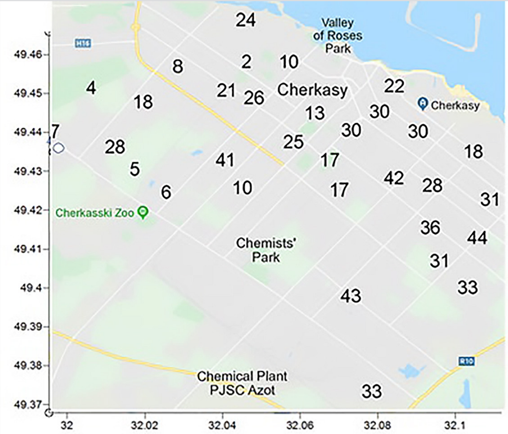

Figure 1. Map of the location of the research sites
Source: compiled by the authors

The primary objective of the field-based ecological investigations was the development of GIS-based maps and the assessment of soil disturbance through analytical and observational methods, aimed at generating spatial distributions of soil contamination. Soil samples were collected following an envelope sampling design within 5 × 5 m plots and subsequently composited into a single representative sample. In undisturbed (natural) soil conditions, sampling was conducted at a depth of 10-20 cm, whereas in anthropogenically modified soils – where intact soil layers were absent – samples were obtained from a depth of 20-30 cm. Prior to analysis, coarse fragments, above-ground biomass, and root material were manually removed. Each composite soil sample had a mass of approximately 1.5 kg. Sampling was performed using a soil auger equipped with a 50 mm diameter metal coring cup. Site selection was guided by landscape, geomorphological, and pedological maps to ensure representation across all zonal soil types within a structured sampling grid. In total, 47 soil samples were collected across geoecological monitoring plots. Analyses of the samples were carried out in the universal laboratory of Cherkasy state technological university at the Department of Ecology. Sampling of soil and plant material and their subsequent research was carried out in accordance with current regulations. Soil samples were taken from experimental plots in accordance with methodological recommendations and the State Standard of Ukraine: DSTU 4287:2004 (2004), DSTU ISO 10381-5:2009 (2009), DSTU ISO 10381-4:2005 (2009), DSTU GOST 17.4.4.02:2019 (2019).

The basic physical and chemical properties were determined for the studied soil samples. The content of mobile potassium compounds was determined by the Chirykov modification method in accordance with DSTU 4115:2002 (2002). The content of total humus was determined by the Tyurin method in the CINAO modification according to DSTU 4289:2004 (2005). The content of exchangeable calcium and magnesium – according to DSTU 7861:2015 (2015) in the modification of the Sokolovsky NNC IGA, pH-water indicator – according to DSTU 8346:2015 (2015). Ammonia content in soils was determined in accordance with DSTU 4725:2007 (2007). Soil buffering capacity was assessed using the method developed by Professor P.P. Nadtochiy *et al.* (2010), which is based on potentiometric determination of pH shifts in a soil suspension depending on changes in acid (HCl) and alkali (NaOH) concentration, following the standard water-to-soil ratio of 2.5:1 recommended by the Third International Congress of Soil Science (1935). For the studied parameters, the main statistical characteristics were calculated and regression analysis was performed using the Pearson correlation coefficient. 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. Mapping of the city area to identify spatial patterns in the formation of risk zones was carried out using Golden Software Surfer.

Results

The territory of the city of Cherkasy is entirely situated within the forest-steppe zone. According to its geomorphological and orohydrographic characteristics, the natural soil cover of the area is heterogeneous. The landscapes of Cherkasy are primarily formed by loess and loess-like loams, as well as sandy loams of various origins. The soil cover is non-uniform, characterised by a light mechanical composition and the presence of anthropogenic inclusions (e.g., fragments of construction debris and allochthonous materials). The soils are contaminated with xenobiotics, particularly heavy metals (Yehorova *et al.*, 2024). Humus is a critical factor in the resilience of soils to persistent anthropogenic pressures. It contributes to soil structuring, optimises physical properties, enhances absorption capacity and buffering ability, and facilitates the accumulation of biophilic chemical elements and energy.

Studies have shown that the soils of Cherkasy are predominantly low in humus content (Fig. 2). Humus levels range from 0.9% to 7.5%, with an average value of 3.0%, a standard deviation of 1.5, a dispersion of 2.3, and a coefficient of variation of 50%. Such low values can be explained by ongoing soil contamination and the degradation of the fertile topsoil layer. Additionally, a significant amount of sand is applied to roads during winter, and the process of humus formation is virtually absent due to the systematic removal of fallen leaves, small branches, and fruits. As a result, organic matter is not replenished, and the decomposition, humification, and mineralisation of the remaining plant residues are inhibited by the cumulative effects of anthropogenic pressures. Low levels of organic matter create unfavourable conditions for plant growth and reduce the soil's capacity to adsorb heavy metals, posing a potential threat to both the urban ecosystem and the health of the city's population.

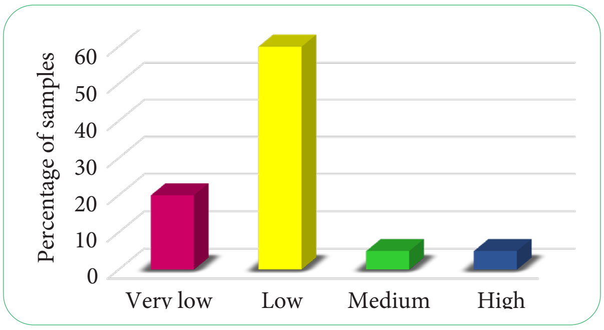

Figure 2. Humus content in soil
Source: compiled by the authors

Using the geo-information software package SURFER for data visualisation, an extrapolation of the obtained data was performed for the entire city area, followed by zoning based on humus content (Fig. 3). The modelling results revealed a significant level of and contrast in technogenic anomalies within the city's soil cover.

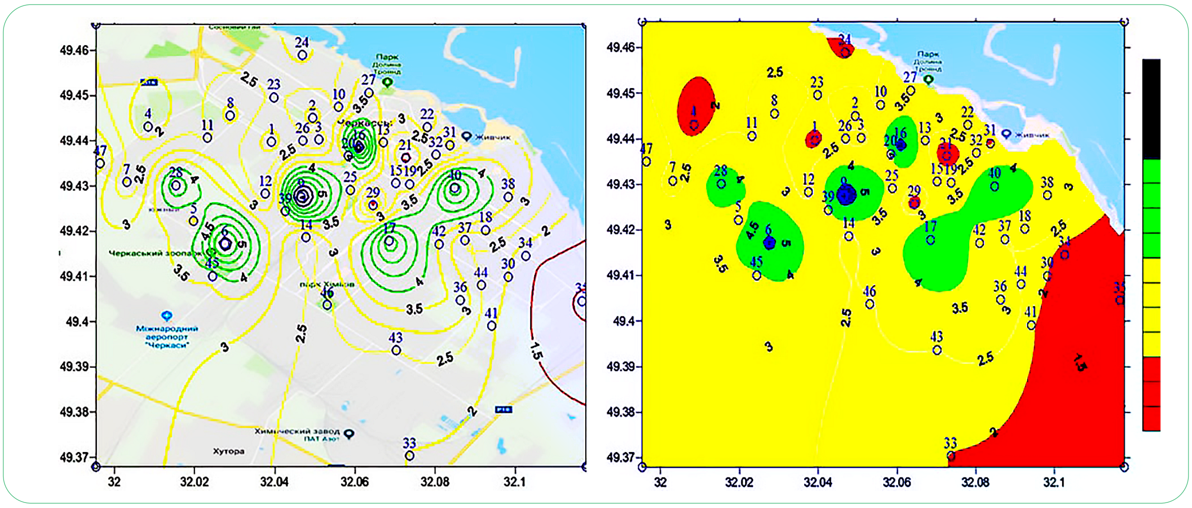

Figure 3. Zoning of Cherkasy City area based on humus content
Source: compiled by the authors

The determination of soil pH and the identification of its sources are essential for the restoration of soil fertility. Additionally, the mobility and bioavailability of heavy metals decrease with increasing pH levels. Soil acidity influences the transport of metals and plays an important role in plant development processes (Msimbira & Smith, 2020) The current soil acidity in Cherkasy ranges from 6.5 to 10.9, with an average value of 7.9, a standard deviation of 0.7, and a variance of 0.5. The studied soils, in terms of pH, are characterised as homogeneous (with a coefficient of variation of 9%), predominantly alkaline (Fig. 4), which does not support the ecosystem service of providing plants with necessary macro- and micronutrients. Soil alkalinisation in Cherkasy is likely caused by the application of sand-salt mixtures during winter to combat ice, the deposition of carbonate dust, ash, bicarbonate atmospheric precipitation, the dissolution of carbonate technogenic inclusions from construction debris in the soil, and emissions from industrial enterprises, all of which gradually enter the soil over time (Shokri *et al.*, 2024).

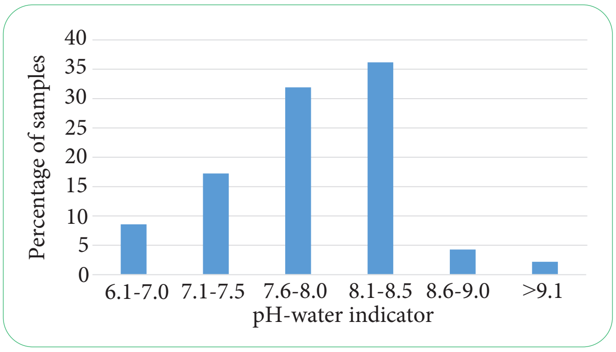

Figure 4. Distribution of soils by current acidity
Source: compiled by the authors

The conditions for plant nutrition with necessary macro- and micronutrients are suboptimal due to the current acidity levels, which can lead to the deterioration of green spaces and the failure of these spaces to perform their functions. The main centres of soil alkalinisation in urban areas are concentrated in the industrial zones of the city and along the roads of the residential areas (Fig. 5). It should be noted that in the areas of soil alkalinisation, an alkaline geochemical barrier forms, which promotes the surface accumulation of chemical elements and slows down the vertical and horizontal migration of heavy metals.

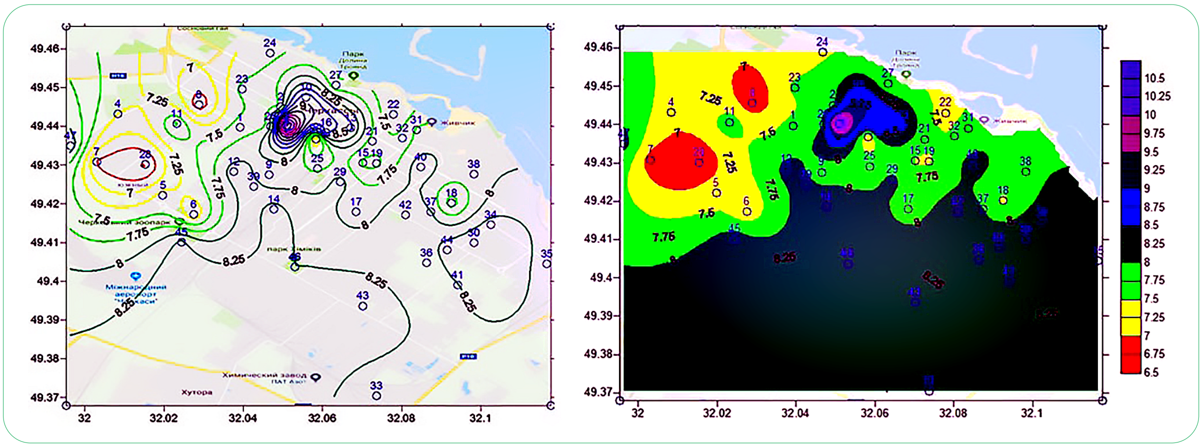

Figure 5. Zoning of Cherkasy City area based pH-water indicator

Source: compiled by the authors

According to pH values, 63% of the studied soils are only partially capable of performing the sorption function (protecting groundwater from pathogenic microorganisms), while 44% perform the sanitary function (protecting groundwater from pollutants). Many redox reactions in soils are mediated by hydrogen ions, so the redox state of soils, which is influenced by pH levels, affects soil formation processes by regulating the decomposition of organic residues, the accumulation rate, and the nature of humus substances, as well as the mobility and biological availability of nutrients (nitrogen and phosphorus compounds, microelements) in the soil-plant system. Redox conditions significantly alter the processes of soil microorganism activity, especially nitrogen-transforming microorganisms. For example, nitrogen-fixing bacteria cease growth when the Eh value exceeds 500 mV (Dayo-Olagbende *et al.*, 2020); optimal redox conditions for nitrification range from 350 to 500 mV, while denitrification occurs under conditions of less than 350 mV. The redox potential (Eh) is an integral indicator for assessing the stability of redox processes in soils, which affect its ecological properties (i.e., the ability to maintain ecological balance) in the soil-atmosphere and soil-plant systems.

The redox potential (Eh) of soils in the studied areas ranges from 184 to 287 mV, with an average value of 239 mV (standard deviation 32.9, coefficient of variation 14%). At these Eh values and pH ≥ 8.0, denitrification processes will predominate in the soil, and plants may experience a deficiency of Fe and Mn. In areas with Eh < 200 mV, the development of reduction processes is likely (Olivier *et al.*, 2021). The low redox potential of Cherkasy City soils may be due to poor soil aeration caused by compaction, moisture regime, organic matter content, and microbial activity. Graphical models of pH-buffering capacity provide a more objective assessment of the acid-base properties of soils. The buffering capacity of the studied soils in Cherkasy ranged from low to very high in the acidic range and from moderate to high in the alkaline range (Fig. 6).

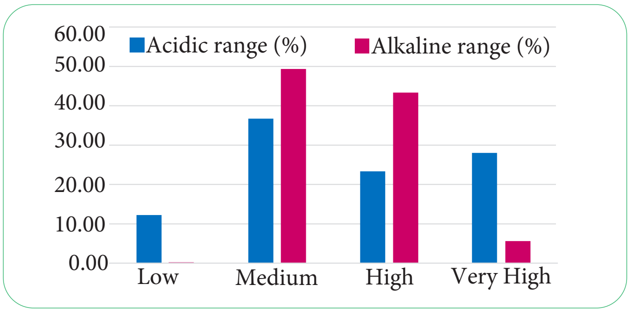

Figure 6. Soil ranking by acid-base buffering capacity

Source: compiled by the authors

A very high degree of acid-base buffering capacity in soils with respect to the action of acidifying substances is characteristic of areas located within the influence zones of such powerful sources of landscape pollution in the city as the PrAT "Azot", PraT "Cherkaske Khimvolokno" VP "Cherkaska TPP" and road transport. The research results showed that the soil ecosystems of Cherkasy function predominantly in a relatively ecologically stable mode based on acid-base buffering capacity indicators, with ecological imbalance observed only in certain areas. The equilibrium constant ranged from 0.3 to 2.7, with an average value of 1.4. Fifty-eight percent of the samples had better buffering properties in the acidic range than in the alkaline range, 20% in the alkaline range, and 22% of the samples had almost identical buffering properties against both acids and alkalis.

The sum of the buffering degrees of the acidic and alkaline ranges varied from 61% to 162%, with an average value of 113%. Soil ecosystems function in a relatively ecologically stable mode when the sum of the buffering degrees of the acidic and alkaline ranges exceeds 70-75%, and the equilibrium constant ranges from 0.6 to 4.0. Moreover, the closer this value is to 1, that is, the more symmetrical the buffering curves are in the acidic and alkaline ranges, the better the buffering mechanisms of the soil function, and the more stable the functioning of this ecosystem. The prevailing asymmetry of the buffering zones is due to the physicochemical properties of the soil. As is known, carbonate soils, due to their saturation with calcium and magnesium, possess buffering mechanisms with a pronounced asymmetric function, which is reflected in the predominance of proton (H^+) neutralisation processes. That is, these soils exhibit a significant acid-neutralising capacity. A comparative analysis of the soil's buffering properties in the acidic and alkaline ranges (Fig. 7) revealed considerable variation across the city in terms of the acid-base buffering capacity in the acidic range, which is likely due to its technogenic decalcification resulting from prolonged and intensive inputs of acidifying agents from the CHP. The correlation coefficient between the sum of absorbed bases and the degree of acid-base buffering capacity of the soils in Cherkasy in the acidic range is 0.53.

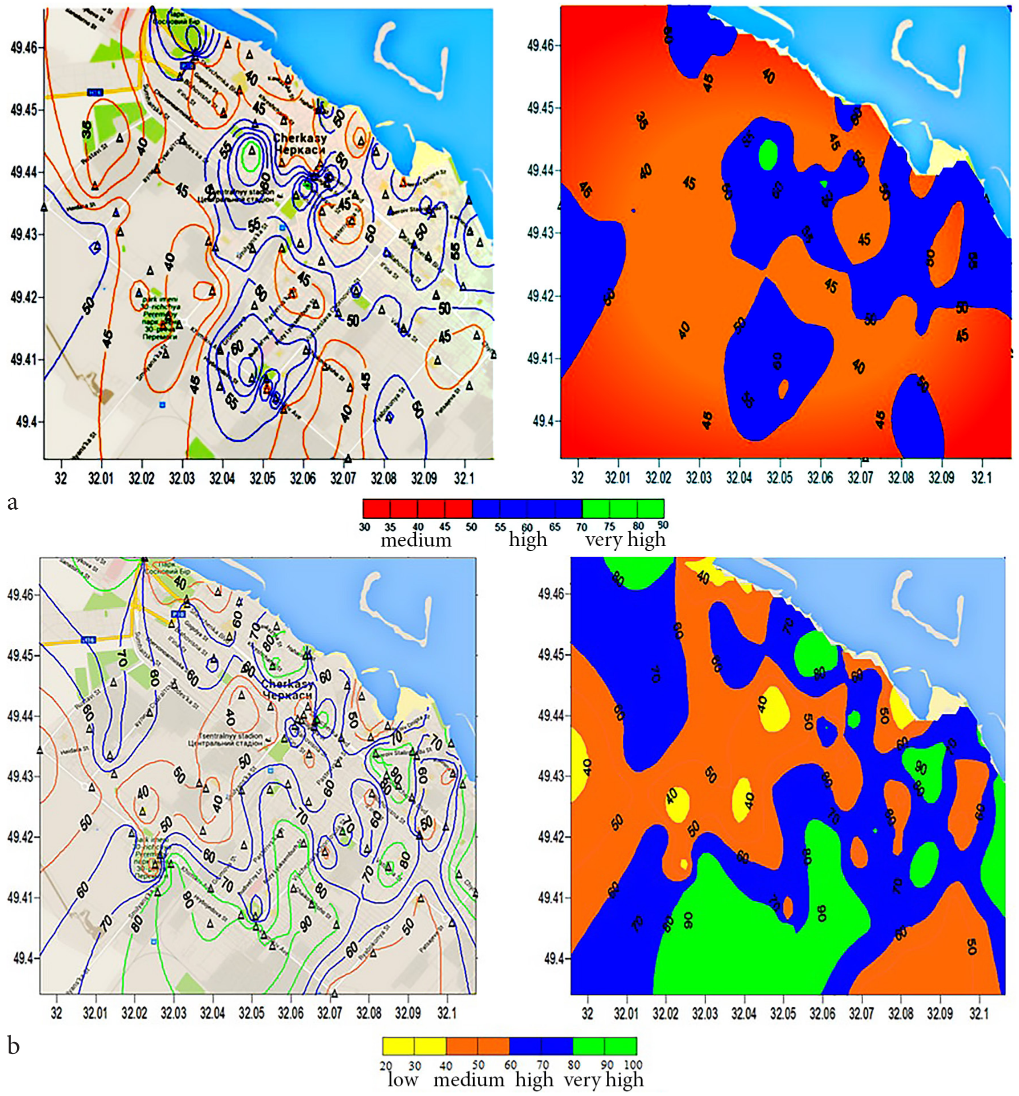

Figure 7. Soil buffering capacity

Note: a – alkaline range; b – acidic range

Source: compiled by the authors

Characteristic features of anthropogenic transformation of soils in Cherkasy include a sharp increase in the spatial heterogeneity of the anion composition of the soil cover compared to natural zonal soils, technogenic salinisation (especially in the soils of the southern and central parts of the city), and changes in the acid-base balance under the influence of a complex combination of natural self-organisation processes and various urbanogenic activities. Analysis of toxic salt content showed that almost 30% of the studied soils are non-saline, 36% are weakly saline, 23% are moderately saline, and 10% have a high salinity level (Fig. 8). It is known that even in weakly saline soils, growth inhibition is observed in 25% of woody vegetation (El Sabagh *et al.*, 2021). Statistical analysis of data using Pearson's correlation coefficient indicates that chloride ions (R^2 ranging from 0.53 to 0.85, with an average value of 0.67) and bicarbonate ions (R^2 ranging from 0.19 to 0.82, with an average value of 0.59) contribute most to the overall soil salinity. This is explained by their high concentration among leached ions and the high ionic conductivity of chloride ions. The main centres of soil salinisation are concentrated along the roads of the city's residential zones.

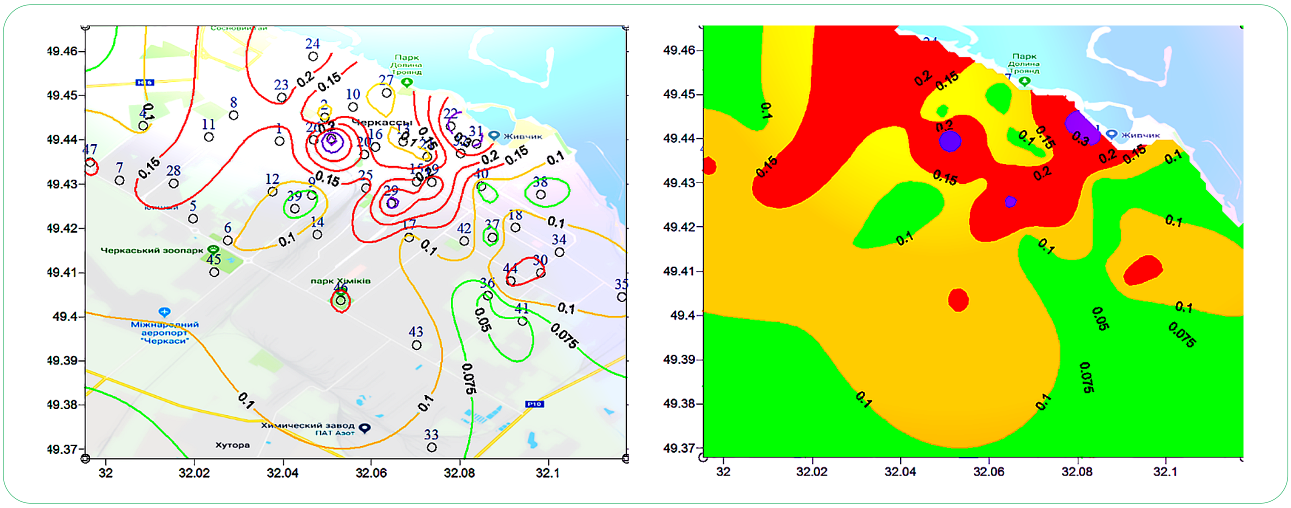

Figure 8. Zoning maps of Cherkasy urban soils based on the total toxic salts content
Source: compiled by the authors

Calcium plays an important role in soil formation processes. It is part of the soil adsorption complex (SAC), participates in exchange reactions of the soil solution, and determines the high buffering capacity of the soil in the acidic range of the environment (Jing *et al.*, 2024). The best conditions for plant nutrition are created when Ca^{2+} ions predominating in the SAC. Partial replacement of Ca^{2+} by Mg^{2+} in the SAC leads to deterioration of the soil's water-physical properties and the quality of humus, which results in reduced soil fertility. Calcium deficiency primarily affects the plant root system. Additionally, Ca^{2+} ions play an important role in altering the direction of metabolic processes in plants under stress conditions. Mg^{2+} ions are also crucial for plant growth and development, just like Ca^{2+}. At the same time, high concentrations of Mg^{2+} can negatively affect the water-stability of soil aggregates, limit the uptake of Mn by plants, and its deficiency leads to chlorosis and necrosis of leaves and stems (Ishfaq *et al.*, 2022). The conducted studies showed that the content of Ca^{2+} in the SAC varied from 1.90 to 7.25 mmol/100 g of soil with an average value of 3.60, a standard deviation of 1.18, a variance of 1.38, and a variation coefficient of 33%. The content of Mg^{2+} varied from 0.00 to 6.00 mmol/100 g of soil with an average value of 1.96 (standard deviation of 1.65, variance of 2.72, variation coefficient of 80%). For many of the studied soil samples, the content of Mg^{2+} was significantly higher than that of Ca^{2+} (Fig. 9).

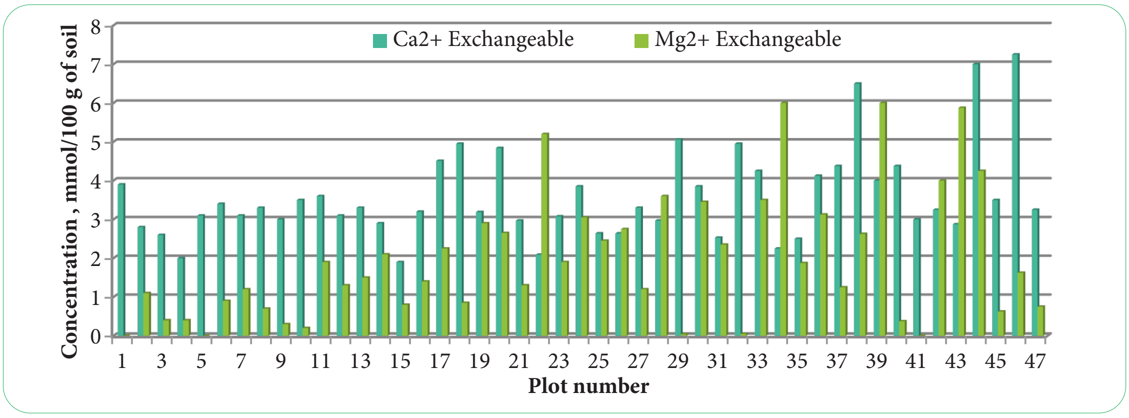

Figure 9. The content of exchangeable Calcium and Magnesium in the soils of the city
Source: compiled by the authors

A significant heterogeneity of the studied soils in terms of Mg^{2+} content was characteristic (variation coefficient of 84%), which is likely due to the use of magnesium chloride and sodium chloride mixtures in winter to combat icing, as well as the leaching of these ions from the SAC during hydrogen ion neutralisation processes. Soil classification based on the content of exchangeable calcium (Ca^{2+}) and magnesium (Mg^{2+}) revealed that a very low Mg^{2+} content was observed in 13% of the analysed soil samples. Low levels of both Ca^{2+} and Mg^{2+} were found in 11% of the samples. A medium content was recorded in 81% of samples for Ca^{2+} and in 13% for Mg^{2+}. Elevated levels were detected in 9% of samples for Ca^{2+} and in 15% for Mg^{2+}. High Mg^{2+} content was observed in 9% of the samples, while a very high content was found in 40% of the samples (Fig. 10).

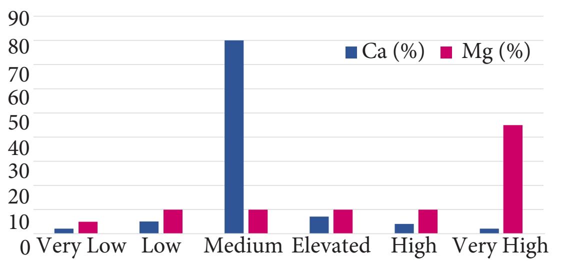

Figure 10. Grouping of soils by exchangeable Calcium and Magnesium content

Source: compiled by the authors

According to the results of soil studies conducted in the city of Cherkasy, the calcium-to-magnesium cation ratio is not optimal. In the composition of exchangeable cations in typical chernozems and meadow-chernozem soils of the forest-steppe zone, exchangeable calcium predominates. As a rule, the cation exchange capacity (CEC) is 70-85% saturated with Ca^{2+}, and only in solonetzic and solonchak-like soils is an increased content of exchangeable Mg^{2+} observed (Chaganti *et al.*, 2017). The CEC of an ideal soil should contain approximately 65% calcium and 10% magnesium. According to the results of soil studies conducted in the city of Cherkasy, the calcium-to-magnesium cation ratio is not optimal.

Potassium is classified as an essential macronutrient required for plant development, being one of the three primary nutrients needed in the largest quantities. (Hasanuzzaman *et al.*, 2018). In terms of K^+ content, the soils of Cherkasy exhibit considerable heterogeneity; however, they are generally well-supplied with this important plant nutrient. The K^+ content ranges from 0.12 to 6.20 mmol/100 g of soil, with an average value of 0.59 mmol/100 g, a standard deviation of 0.67, a variance of 1.39, and a coefficient of variation of 95%. The heterogeneity in potassium content among the studied soils can be attributed to differences in the vegetation cover of the model plots. With regard to water-soluble potassium, 89% of the studied soils are poorly supplied (<10 mg/kg), 4% are moderately supplied (10-30 mg/kg), and 7% are well supplied (>30 mg/kg) with this essential plant nutrient (Fig. 11).

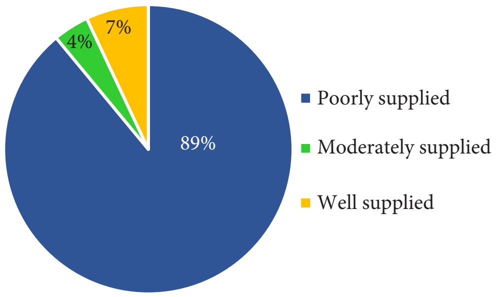

Figure 11. Grouping of soils by water-soluble potassium content

Source: compiled by the authors

Mineral nitrogen compounds are also essential for plant nutrition. The directly available forms of nitrogen for plants include ammonia (in the form of ammonium ions) and nitrates. Ammonium ions are present in soils as water-soluble salts of exchangeable and fixed (non-exchangeable) ammonium. The formation and accumulation of mineral nitrogen in the soil depends on many factors, but primarily on the quantity and quality of organic matter. The alkaline reaction of the soil increases the ability to fix ammonium ions in the CEC. The ammonium content in the soils of Cherkasy ranges from 0.000 to 0.014 (Fig. 12), with an average value of 0.003 mmol/100 g of soil (coefficient of variation – 1.01, standard deviation – 0.14, variance – 0.02). This variation can be explained by both the absorption of ammonium by plants and microorganisms and the low humus content and soil alkalisation, which is typical for urban soils in the city.

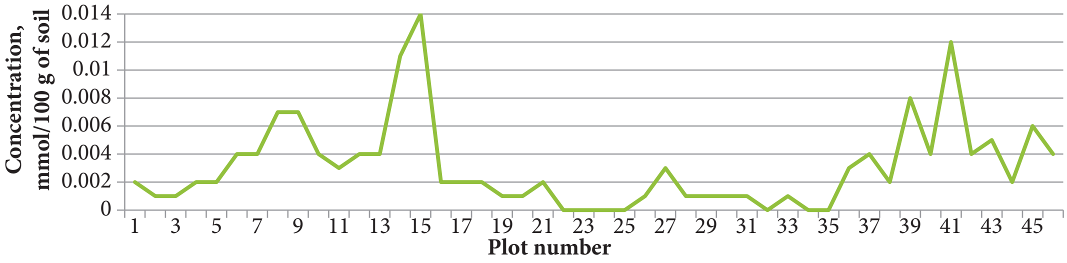

Figure 12. Exchangeable Ammonium content in Cherkasy City soils

Source: compiled by the authors

One of the primary reasons for the elevated levels of ammonium content is the specific nature of the urban soils in Cherkasy, which are characterised by low humus content and an alkaline reaction – factors that facilitate the fixation of ammonium ions within the soil complex. The alkaline nature of the city's soils enhances the ability to retain ammonium in its non-exchangeable (fixed) form, thereby reducing its availability to plants. Additionally, the formation and accumulation of mineral nitrogen in the soil is influenced by both the quantity and quality of organic matter, which is limited in urban soils due to the processes of urbanisation. In general, the low ammonium content in the soils of Cherkasy may suggest insufficient availability of this element to plants, potentially affecting the growth and development of vegetation within the city. This underscores the importance of improving soil composition – specifically by increasing humus content and managing soil pH – in order to support fertility in urbanised environments.

Discussion

In the context of environmental monitoring of urban areas and geochemical mapping analysis, it is important to highlight the valuable input of several recent studies that focus on key methodologies used in geochemical mapping. The study by J. Wang *et al.* (2024) introduced a novel approach to geochemical mapping by addressing the uncertainties inherent in defining elemental associations related to mineralisation. This methodology involves clustering the study area based on elemental similarities, identifying elemental associations within each cluster, and detecting geochemical anomalies indicative of underlying geological processes. The approach was applied to stream sediment geochemical samples from north-western Sichuan Province, China, revealing two distinct clusters corresponding to Paleozoic and Triassic lithological units. The findings suggest that the region holds significant potential for discovering gold deposits, particularly near known mineralisation sites.

From a GIS perspective, this study underscored the importance of spatial analysis in geochemical mapping. By integrating elemental data with spatial clustering techniques, the researchers were able to delineate areas with distinct geochemical signatures, enhancing the accuracy of anomaly detection. GIS tools facilitate the visualisation and interpretation of complex geochemical data, allowing for the identification of spatial patterns and relationships that might be overlooked in traditional analyses. Moreover, the incorporation of uncertainty quantification into the mapping process adds a layer of robustness, enabling more reliable decision-making in mineral exploration.

The study by F. Parsaie *et al.* (2021) focused on digital modelling and mapping the spatial distribution of topsoil total nitrogen (TN) in the Qorveh-Dehgolan plain, an area of 150,000 hectares, using machine learning algorithms. The authors applied Random Forest (RF), Decision Tree (DT), and Cubist (CB) models to predict TN concentrations based on a range of environmental covariates. These included geomorphometric attributes from a digital elevation model, spectral indices from SENTINEL-2 satellite data, soil properties, and spatial variables like latitude and longitude. The Boruta algorithm was used to select the most relevant covariates, which led to the identification of 14 key factors influencing TN distribution. Validation of the models revealed that RF provided the most accurate predictions, with the lowest root mean square error (RMSE) and mean absolute error (MAE). The study also generated uncertainty maps, highlighting areas with high prediction reliability. The findings emphasise the importance of geomorphometric variables and remote sensing indices, such as SAVI and NDVI, in soil nitrogen modelling. This research offers a robust methodology for mapping soil nutrients, supporting sustainable land management practices and precision agriculture.

T. Shi *et al.* (2021) investigated the growing issue of lead (Pb) contamination in urban topsoil, which is exacerbated by rapid urbanisation in China. The study focused on developing spatial models to map Pb concentrations in urban soils using a combination of proximal and remote sensing data. Proximal sensing reflectance spectra, along with vegetation and land-use factors derived from Landsat images, were used as landscape variables to predict Pb levels. The authors employed two hybrid statistical approaches, regression kriging (RK) and geographically weighted regression (GWR), to establish prediction models. The results showed that the use of combined proximal and remote sensing data significantly improved the accuracy of Pb concentration predictions compared to using either data source individually. Among the two methods, GWR demonstrated superior performance. This study underscored the effectiveness of using joint proximal and remote sensing data for mapping urban soil contamination, offering a timely and accessible tool for environmental monitoring.

The P. Khosravani *et al.* (2023) explored the digital mapping and spatial modelling of soil physical and mechanical (SPM) properties in the semi-arid region of Marvdasht Plain in Fars Province, Iran. This study was aimed to predict key soil properties, including mean weight diameter (MWD), geometric mean diameter (GMD), shear strength (SS), and penetration resistance (PR), using machine learning algorithms such as random forest, Cubist, and k-nearest neighbour. A total of 200 field observations were made to collect data from topsoil and subsoil, with additional environmental factors derived from topographic and remote sensing data. Two different covariate scenarios were tested, combining soil properties and environmental factors. The results revealed that soil variables, particularly clay content and soil organic matter (SOM), significantly influenced the prediction of SPM properties, with the k-nearest neighbour algorithm performing well in predicting SPM properties, and random forest providing the highest accuracy for penetration resistance at the 15-30 cm depth.

The authors G. Meza Mori *et al.* (2022) applied the MEDALUS model to assess soil degradation risks in the

Amazon region using GIS. The model takes into account factors such as climate, soil types, vegetation cover, and land use intensity, allowing for the creation of maps of ecologically sensitive areas. This enables the identification of zones requiring ecological restoration and contributes to more accurate forecasting of degradation processes. The authors emphasise the importance of a comprehensive approach to soil degradation, as it results from the interaction of various natural and anthropogenic factors. The study provides recommendations for sustainable land management in the Amazon, focusing on strategies to conserve natural resources and support local communities.

The study conducted by S. Bangroo *et al.* (2023) presented the results of spatial distribution of soil properties using both universal and ordinary kriging methods. Spatial assessment and mapping of key physicochemical soil indicators (pH, electrical conductivity, organic carbon, nitrogen, phosphorus, and potassium) were carried out using hybrid geostatistical models. However, existing environmental variables that assist in the spatial assessment and mapping of soil components face a key issue – it is difficult to obtain ecological variables with high correlation, which leads to low accuracy in the predicted models.

The author M.A.E. AbdelRahman (2023*)* examined global issues of land degradation and desertification, which pose serious threats to food security, livelihoods sustainability, and biodiversity. The use of GIS and remote sensing for monitoring and mapping land degradation allows for effective assessment of soil and water resources. The authors highlight the importance of applying technologies to analyse processes such as erosion, soil salinisation, and fertility decline, as well as to identify areas that require restoration. The authors also emphasise the need for the development of global initiatives to raise awareness about the economic consequences of degradation and promote sustainable land resource management.

The publication by B. Pradeep Kumar *et al.* (2022) addressed the geo-environmental monitoring and assessment of land degradation and desertification in semi-arid regions using satellite data and environmental indices. The study employs Landsat 8 OLI/TIRS imagery, along with Land Surface Temperature (LST) and Normalised Difference Vegetation Index (NDVI), to assess the extent and dynamics of land degradation in a semi-arid region. The authors integrate these remote sensing data to develop a comprehensive approach for monitoring land degradation processes, focusing on their impact on vegetation health, soil moisture, and overall land productivity. The findings indicate that LST and NDVI are effective in tracking desertification and land degradation over time, and the study provides a framework for using satellite-based data in environmental management. The results highlight the potential of remote sensing technologies for assessing environmental challenges in semi-arid regions and offer valuable insights for land conservation and sustainable development practices.

The integration of GIS and Earth remote sensing technologies provides a comprehensive toolkit for addressing a wide range of environmental monitoring challenges. This highlights the significance of developing and applying new technologies in ecology as a crucial step toward achieving sustainable development. Given the growing importance of this issue, the article explores the potential of GIS for local-level environmental monitoring, with a specific focus on assessing the state of soil cover in the Cherkasy Region. The authors evaluate various monitoring approaches, including both remote sensing and chemical methods, and suggest strategies for creating an environmental monitoring system utilising GIS technologies.

Conclusions

Based on the results of the conducted study, a comprehensive assessment of the geoecological state of the urban soils in Cherkasy has been provided. Analysis of 47 soil samples from different functional zones of the city revealed significant spatial heterogeneity of urban soils. The main issue is the low humus content (ranging from 0.9% to 7.5%, with an average of 3.0%) and alkalinity ($pH = 6.5$-10.9). The redox potential (Eh) of soils varies between 184 and 287 mV, with an average of 239 mV, which promotes denitrification.

According to the content of toxic salts, only 30% of the studied soils are non-saline, 36% are slightly saline, 23% are moderately saline, and 10% have a high level of salinity. A high content of exchangeable Mg^{2+} compared to Ca^{2+} may significantly affect the development of green spaces and the ecological functions of the soil. Analysis of graphical models of soil pH-buffering capacity indicates their environmentally stable condition. The total buffering capacity in both acidic and alkaline ranges exceed 70-75%, with an average equilibrium constant $K = 1.4$. The imbalance of nutrients in the soil, low humus content, and alkaline environment can significantly affect the development of urban greenery and the soil's ability to adsorb heavy metals.

The conducted research opens new possibilities for creating and implementing an effective monitoring system using a systemic approach and modern GIS technologies. The development of a database and cartographic models of the geoecological condition of urban soils will enable tracking their transformation over time and space. This will allow for the identification of early stages of significant changes and the determination of risk zones for the development of hazardous exogenous processes and unstable ecosystems, thereby contributing to the development of effective environmental protection measures.

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Conflict of Interest

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Геоекологічна оцінка стану урбоземів та їх трансформація під впливом антропогенних чинників

Оксана Єгорова

Кандидат технічних наук, доцент
Черкаський державний технологічний університет
18006, бульв. Шевченка, 460, м. Черкаси, Україна
https://orcid.org/0000-0002-7801-5582

Ольга Мислюк

Кандидат хімічних наук, доцент
Черкаський державний технологічний університет
18006, бульв. Шевченка, 460, м. Черкаси, Україна
https://orcid.org/0000-0003-0401-9836

Олена Хоменко

Кандидат хімічних наук, доцент
Черкаський державний технологічний університет
18006, бульв. Шевченка, 460, м. Черкаси, Україна
https://orcid.org/0000-0001-9329-0577

Анотація. Урбанізація та індустріалізація нерозривно пов'язані з трансформацією міських ґрунтів, що становить значний виклик не тільки на місцевому та регіональному рівнях, але й у глобальному масштабі. Метою роботи була комплексна оцінка екологічного стану ґрунтів урбанізованих територій в умовах транспортного та промислового навантаження. Дослідження фізико-хімічних властивостей ґрунтів проводилися за стандартними методиками. Буферність ґрунтів оцінювали за методикою П. Надточого. Розраховані основні статистичні характеристики та проведено регресійний аналіз результатів дослідження з використанням коефіцієнта кореляції Пірсона. Системний аналіз геоекологічного стану урбоґрунтів (урбозолів) міста Черкаси показав, що для них характерним є низький вміст гумусу (від 0,9 % до 7,5 %, при середньому значенні 3,0 %), підлуження ґрунтів (pH = 6,5-10,9, при середньому значенні pH = 7,9), несприятливі окислювально-відновні умови (значення Eh від 184 до 287 мВ, при середньому 239 мВ), незбалансованість поживних елементів та значний вміст токсичних солей (36 % досліджених ґрунтів є слабозасоленими, 23 % – помірнозасоленими та 10 % – високого рівня засоленості) можуть чинити істотний вплив на стійкість урбоекосистем міста. За кислотно-основною буферністю ґрунти перебувають в екологічно стабільному стані. Сума ступенів буферності як в кислому, так і в лужному діапазонах перевищує 70-75 %, при середній константі рівноваги K = 1,4. За допомогою програмного комплексу SURFER та методу Крігінга проведено просторову інтерполяцію даних моніторингу та картографічне зонування території міста за основними фізико-хімічними характеристиками ґрунтів. Створено базу даних та картографічні моделі властивостей ґрунтів міста для моніторингу їх просторово-часових змін, виявлення критичних трансформацій та визначення зон еколого-геохімічної нестабільності, пов'язаних із техногенним впливом

Ключові слова: фізико-хімічні властивості ґрунтів; польові дослідження; картографічне моделювання; геоінформаційні системи; техногенний вплив