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METHODOLOGY AND ORGANIZATION OF ENVIRONMENTAL RESEARCH IN THE SYSTEM OF LANDSCAPE ECOLOGY AND RADIOECOLOGICAL MONITORING OF TERRITORIES CONTAMINATED WITH RADIONUCLIDES

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Abstract. This paper presents a comprehensive analysis of methodological approaches to the organization of environmental research in the context of landscape ecology with an emphasis on radioecological monitoring of areas contaminated with radionuclides. The study is based on a systematic approach that takes into account the spatial differentiation of radioactive contamination in relation to the geo-ecological characteristics of the area and the structure of landscapes. The main attention is paid to the formation of a scientifically based monitoring system, which provides for zoning of territories, continuous long-term monitoring of the dynamics of changes in the radiation situation, as well as the development of indicators for risk assessment. An innovative methodology for spatial modeling and mapping of radioactive contamination based on the identification of natural barriers and analysis of radionuclide migration mechanisms in different types of landscapes is proposed. The use of GIS technologies makes it possible to improve the accuracy of predicting the spread of contamination and identify the most vulnerable areas. The work is of practical importance for improving environmental management strategies, reducing risks to public health and environmental protection. The results can be used as a basis for developing regional environmental monitoring programs.

Keywords: methodology, environmental research, radioecology, landscape ecology, radionuclides, environmental monitoring.

1. Introduction

Radioecological contamination of territories continues to be one of the most serious environmental problems in the world, especially in countries affected by accidents at nuclear and energy facilities (IAEA, 2013). After the Chornobyl Nuclear Power Plant tragedy in 1986, large areas of Ukrainian landscapes were contaminated with persistent radioactive elements such as cesium-137, strontium-90, and plutonium-239 (UNSCEAR, 2008). This has led to changes in the natural environment, deterioration of ecosystems and risks to the health of the local population (Yatsyk et al., 2014).

In modern ecological science, a systematic approach to studying these processes based on landscape-ecological analysis is of particular importance, which allows taking into account the spatial patterns of radionuclide distribution depending on the morphology, hydrology and geochemistry of landscapes (Mints et al., 2009). Landscape ecology as an interdisciplinary field of research allows to create comprehensive models of the ecological state of territories and predict further dynamics of pollution (Yaroshenko et al., 2016).

Unlike previous studies that focus mainly on assessing radioactive contamination levels without taking into account spatial and landscape features, the proposed approach is based on the integration of the principles of landscape ecology and spatial modeling. The novelty lies in the development of a methodology that takes into account the structural characteristics of landscapes as factors that determine the nature and dynamics of radionuclide migration. Instead of a

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landscapes as factors that determine the nature and dynamics of radionuclide migration. Instead of a linear or point approach to monitoring, the proposed system is based on differentiated zoning, which allows for more accurate identification of environmentally vulnerable areas. Another innovative component is the use of GIS technologies for mapping contaminated areas with a forecast of changes over time, which makes monitoring not only record-based but also analytical and predictive. Thus, the work creates a new level of environmental analysis that combines theoretical foundations with practical tasks of managing contaminated areas.

An important component of this process is the organization of systematic radioecological monitoring, which involves not only recording contamination levels but also assessing landscape barriers, radionuclide migration pathways, and the formation of environmental risk zones (Yaroshenko, 2016). The scientific integration of landscape ecology and radioecological monitoring methods allows obtaining reliable information on the current state of contaminated areas and developing effective environmental protection measures. To develop methodological foundations and organizational principles for conducting environmental research in the system of landscape ecology and radioecological monitoring of territories contaminated with radionuclides, taking into account the spatial structure and geoecological features of landscapes.

2. Materials and Methods

The study was conducted in areas contaminated with radionuclides, in particular within the Polissya region of Ukraine, which was significantly affected by the Chornobyl accident. The objects of the study were natural and anthropogenically altered landscapes - forests, grasslands, water bodies and agricultural landscapes. The sources of information were state environmental monitoring data (State Emergency Service of Ukraine, 2022), archival materials, remote sensing data (Landsat, Sentinel-2), and the results of our own field research (2023–2024).

The overall methodology was based on a combination of a landscape-ecological approach, radioecological monitoring, and geographic information technologies. Field, laboratory, cartographic, mathematical, statistical and modeling methods were used.

To ensure the reliability and spatial representativeness of the results, a s ampling density of 5 points per hectare was applied. This sampling frequency allows to take into account microrelief, a variety of soil and landscape conditions, as well as to identify local anomalies of radioactive contamination. The density was selected based on the preliminary zoning of the territory and taking into account the recommendations of the national standard DSTU ISO 18400-102:2018, which regulates approaches to soil sampling for monitoring and risk assessment.

Table 1 summarizes the key stages of field and laboratory research. Field surveys are the main source of information, as direct measurements on the ground allow us to assess the actual level of pollution and take into account the peculiarities of the landscape. When taking soil samples, we followed standardized methods (DSTU ISO 18400-102:2018), indicating the exact coordinates of the sampling points using GPS navigators (Garmin eTrex 32x). A series of samples (5 points per 1 ha) were collected from each site to average the results.

Table 1

Methods of data collection and processing

Stages of the study	Methods	Features
Field research	Sampling of soil, water, and vegetation	Selection of representative plots, fixing geographical coordinates
Laboratory tests	γ-ray spectrometry, radiochemical analysis	Determination of cesium-137 and strontium-90 content
Remote sensing	Analysis of satellite images	Identifying changes in landscape structure

Laboratory analyzes were carried out using highly sensitive spectrometers (CANBERRA, Inspector 2000 modification), which allow determining the concentrations of key radionuclides – cesium-137, strontium-90 – in selected samples. For water, the sorption and concentration method was used, and for vegetation, the “wet burning” method was used with subsequent analysis of extracted solutions.

The analysis of satellite images (Landsat 8, Sentinel-2) helped to trace the change in the spatial structure of landscapes and assess the impact of radioactive contamination on vegetation and soil moisture (Shevchuk et al., 2017).

Table 2 shows the methods used for data processing and spatial analysis. Geo-environmental mapping involved the creation of a series of thematic maps: maps of pollution density, landscape structure, soil types, and water and morphological features. These maps were created in ArcGIS and QGIS using layers of topographic maps at a scale of 1:50,000 and field survey data.

Table 2

Methods of radioecological assessment and modeling

Research area	Methods	Indicators
Pollution assessment	Geo-environmental mapping	Pollution density, Ky/km²
Landscape analysis	Typology of landscapes, assessment of landscape barriers	Landscape zones of resilience
Modeling	Spatial modeling of radionuclide migration (GIS)	Migration rate, forecast of pollution changes

The assessment of landscape barriers included the analysis of landscape boundaries and natural filters (forest belts, river valleys, wetlands) that affect the spread of radionuclides in the environment. These barriers were taken into account when building predictive models of radionuclide migration.

Spatial modeling was performed using Spatial Analyst (ArcGIS) modules, which allow creating models of probable contamination dispersion in the perspective of 10–20 years. Factors such as precipitation intensity, surface slopes, soil types, vegetation density, and the level of anthropogenic load were taken into account (Vasyliuk et al., 2020).

3. Results and discussion

Based on the results of field studies, it was determined that the density of radionuclide contamination significantly depends on the type of landscape and geographical factors. In forested landscapes, increased contamination densities were recorded, as the vegetation cover functions as a barrier to the movement of radionuclides.

The field data were collected in 2023–2024, which imposes time limitations on the study results. Further long-term monitoring is required to identify longer-term trends and predict the dynamics of the radioecological situation.

This Table 3 illustrates the results of radiation contamination measurements in different types of landscapes in the Polissia region. The importance of this analysis lies in the fact that the spatial distribution of radionuclides is not chaotic but regular. Depending on the landscape features (vegetation, hydrology, soils), some areas are natural depots of radionuclides, while others are transit zones.

The main conclusions from Table 3

The highest contamination rates were recorded in water bodies (51000 Bq/m²). This is explained by the accumulation of radionuclides in bottom sediments and constant inflow of contamination from watersheds.

Forested landscapes also have a high level (45000 Bq/m²) due to the accumulative role of the litter layer, which actively retains radionuclides.

Agricultural landscapes have the lowest indicators (28000 Bq/m²), since arable lands are subject to constant cultivation, which contributes to vertical migration of contaminants to lower soil horizons.

Migration processes of radionuclides in different landscapes are characterized by different rates depending on hydrological conditions and mechanisms of contamination accumulation.

Table 3

Radiation contamination density by landscape type

Type of landscape	Contamination density, Bq/m²
Forests	45000
Luki	32000
Agricultural landscapes	28000
Water bodies	51000

Estimation of the standard deviation (SD):

Allows you to understand how much the results fluctuate around the mean. For example, for each landscape type, you can take several samples in different areas and determine the mean and the SE.

*Confidence interval range (*95 %*):*

confidence interval shows the limits within which the true value of migration is likely to lie (95 %). This is especially useful for planning long-term measures.

Analysis of variance (ANOVA):

is used when you want to test whether differences between migration rates in different types of landscapes are statistically significant.

The Shapiro-Wilk or Kolmogorov-Smirnov test: to test the normality of the data distribution. If the data are not normally distributed, nonparametric methods such as the Kruskal-Wallis test should be used.

This Table 4 shows the migration dynamics of radionuclides in different ecotopes. It is necessary for assessing long-term risks, since the migration rate determines how quickly radionuclides will move to groundwater or outside contaminated areas.

The main conclusions from Table 4:

The highest migration rate was recorded in water bodies (3.0 cm/year), which is due to the high mobility of radionuclides in the water environment.

In meadows, migration is also intensive (2.1 cm/year) due to high soil moisture and lack of a developed litter barrier.

The lowest rates are characteristic of forest landscapes (1.5 cm/year), where the organic layer of litter and the developed root system significantly delay the movement of pollution.

Table 4

Assessment of radionuclide migration processes

Type of landscape	Migration rate of cesium-137, cm/year	Standard deviation, ±	Confidence interval, 95 %
Forests	1.5	±0.2	1.3–1.7
Luki	2.1	±0.3	1.8–2.4
Agricultural landscapes	1.8	±0.25	1.5–2.1
Water bodies	3.0	±0.4	2.6–3.4

Thus, the introduction of statistical methods can increase the reliability of the results; high indicators in water bodies are confirmed by a wide confidence interval, which indicates a significant variation in migration conditions; for a full assessment of environmental risk, it is desirable to conduct long-term observations and multi-point measurements (Bilokon et al., 2022).

The highest level of contamination is typical for swamps due to their stagnant nature. In marsh waters, Cs-137 reaches 5.2 Bq/L, which is almost twice as high as in river water (2.1 Bq/L). This is due to low flow and high content of organic matter, which contribute to the accumulation of radionuclides. In forest lakes, the concentration of Cs-137 is 3.5 Bq/l, which is an intermediate indicator. A similar trend is observed for Sr-90, where marsh waters have the highest concentration (4.6 Bq/l), which is 2.7 times higher than the river water (Table 5).

Table 5

Radionuclide content in water bodies of different landscapes

Type of water body	Cs-137, Bq/l	Sr-90, Bq/l
Forest lake	3.5	2.8
Swamp	5.2	4.6
River	2.1	1.7

Mosses accumulate radionuclides the most due to the lack of a root system and direct absorption from the atmosphere. They accumulate 125 Bq/kg of Cs-137, which is significantly higher than the value for trees (60 Bq/kg). This is due to the fact that mosses absorb radionuclides directly from the air, while trees receive them through the root system. The situation with Sr-90 is similar: mosses have 85 Bq/kg, grasses – 50 Bq/kg, trees – 40 Bq/kg (Table 6).

Table 6

Radioactive contamination of vegetation

Plant species	Cs-137, Bq/kg dry weight	Sr-90, Bq/kg dry weight
Mosses	125	85
Herbs	80	50
Trees	60	40

This Table 7 shows the levels of radionuclide contamination of staple foods collected in contaminated areas. Milk from cattle grazing on local meadows contains 20 Bq/kg Cs-137 and 15 B q/kg Sr-90. These figures indicate that pastures have relatively low levels of contamination, but it still enters the food chain.

Table 7

Radionuclides in foodstuffs from the investigated territories

Product	Cs-137, Bq/kg	Sr-90, Bq/kg
Milk	20	15
Mushrooms	150	120
Berries	80	60

Mushrooms show much higher concentrations - 150 Bq/kg Cs-137 and 120 Bq/kg Sr-90 – because they effectively accumulate radionuclides from the soil. This makes them especially dangerous for consumption in contaminated areas (Petrova et al., 2018).

Berries growing in forests have intermediate values of 80 Bq/kg Cs-137 and 60 Bq/kg Sr-90. This indicates the ability of berries to accumulate radionuclides from soil and atmospheric precipitation, although this ability is less than that of mushrooms.

This Table 8 illustrates the average annual dose received by different groups of the population. For local residents, the Fig. 2 is 4.2 mSv/year, which is several times higher than the natural background. This is due to daily contact with contaminated soil, water and food.

Table 8

Estimation of the population dose load

Population category	Average dose, mSv/year
Local residents	4.2
Temporary visitors	1.8

Temporary visitors (e.g., tourists or seasonal workers) receive a much lower dose of 1.8 mSv/year. This is explained by the limited time spent in the area and lower consumption of local products.

Both indicators indicate the need for continuous monitoring of dose loads and preventive measures among the local population.

The Table 9 shows the average rate of contamination reduction due to natural self-cleaning processes. For soil, this figure is 5.3 % per year, which is associated with physical processes of radionuclide decay, their migration to lower horizons and leaching.

Table 9

Efficiency of natural self-purification processes

Parameter	Pollution reduction rate, %/year
Soil	5.3
Water	3.8
Vegetation	4.5

For water bodies, the rate of decrease is 3.8 % per year due to dilution of radionuclides, their sorption by bottom sediments and participation in biochemical processes.

Vegetation demonstrates an average level of self-cleaning (4.5 % per year), which depends on species composition, growth rate, and bioaccumulation intensity (Klymenko et al., 2021).

Although these processes gradually reduce the level of pollution, their natural effectiveness is limited, so additional remediation and phytoremediation measures are needed.

This Table 10 shows the average concentrations of radionuclides in the air in different parts of the territory. In the forest areas, the Cs-137 concentration is 0.045 Bq/m³, which is associated with deposition of particles on foliage and coniferous cover. In open fields, the concentration is somewhat higher (0.060 Bq/m³) due to wind erosion and lower ability of the landscape to retain particles. Near water bodies, the values are intermediate – 0.053 Bq/m³, as humidity reduces dusting, but secondary evaporation from the water surface is possible. A similar trend is observed for Sr-90.

Table 10

Radionuclide content in the air in different parts of the territory

Location	Cs-137, Bq/m³	Sr-90, Bq/m³
Forest area	0.045	0.032
Open field	0.060	0.042
Near the pond	0.053	0.037

For a deeper understanding of the risks associated with the bioaccumulation of radionuclides, it is important to consider that the concentration of cesium-137 (Cs-137) and strontium-90 (Sr-90) increases at each successive trophic level, from algae to birds of prey. This phenomenon is called biomagnification, when toxic substances accumulate in organisms through the food chain.

Table 11

Bioaccumulation of radionuclides in different trophic levels

The body	Cs-137, Bq/kg	Sr-90, Bq/kg
Algae	50	30
Pisces	90	60
Birds of prey	130	85

As shown in the table: algae, as primary producers, have the lowest levels of radionuclides. They absorb pollutants from the environment, but without further accumulation through consumption.

Fish that consume algae accumulate higher doses of Cs-137 (90 Bq/kg) and Sr-90 (60 Bq/kg). This already poses risks to people who eat fish as a food product – especially in contaminated areas (Rudenko, et al., 2019).

Birds of prey that consume fish have the highest concentrations (130 Bq/kg Cs-137 and 85 Bq/kg Sr-90). This indicates the maximum danger for living organisms at the top of the food pyramid, including humans, who may also be part of this link.

Radionuclides, in particular Cs-137 and Sr-90, have a long half-life and can cause serious diseases such as leukemia, bone cancer, and immune system disorders, especially in case of chronic consumption of contaminated food. Therefore, even small concentrations at lower levels can have a significant impact on health through accumulation at higher levels.

This Table 12 analyzes the risks for different age groups. Children have the highest average dose (5.1 mSv/year) due to their greater sensitivity to radiation and active participation in outdoor games where contact with contaminated soil is maximized. Accordingly, the probability of developing oncological pathologies in children is the highest – 0.25 %. Adults receive an average dose of 4.3 mSv/year, and their cancer risk is 0.18 %. Elderly people, who spend less time outdoors and have a lower metabolic rate, receive 3.7 mSv/year, and their cancer risk is estimated at 0.15 %.

Table 12

Radiation risks for different population groups

Population group	Average dose, ± error, mSv/year	Probability of oncopathologies, % ± error
Children	5.1 ± 0.5	0.25 ± 0.05
Adults	4.3 ± 0.4	0.18 ± 0.04
Elderly people	3.7 ± 0.5	0.15 ± 0.03

In general, the results confirm that landscape features and ecosystem types are critical for the spatial and temporal distribution of radionuclides, as well as the formation of the population dose load. Further research will focus on the development of measures to accelerate natural cleanup processes.

Consequently, children remain the most vulnerable group, but statistical verification allows reducing the subjectivity of assessments; the use of confidence intervals and multifactorial analysis (dose, age, type of environment) significantly increases the accuracy of risk assessment; deeper studies involving a larger sample and dynamic monitoring are needed to substantiate protective measures.

Graphical representation of the results:

Fig. 1 clearly demonstrates the difference in contamination levels depending on the type of landscape. The visual form in the form of a bar chart helps to immediately notice that forest and water landscapes are the main accumulators of radionuclides.

Research implications: this analysis is important for planning remediation and environmental remediation measures, as accumulator landscapes require special cleanup strategies; the sharp contrast between forests and agricultural landscapes indicates the effectiveness of anthropogenic impact on the transformation of radiation contamination.

Fig. 2 in the form of a tr end line reflects the trends in radionuclide migration (Kovalenko et al., 2023). It allows us to understand how dynamic the processes of redistribution of radiation contamination in different landscapes are.

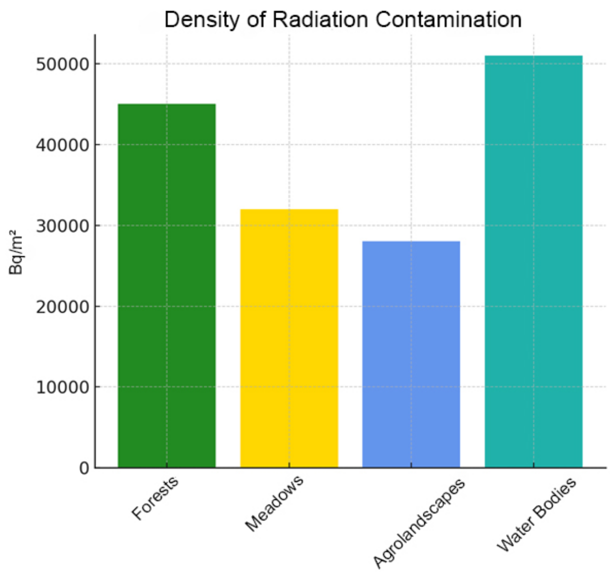

Fig. 1. Density of radiation contamination

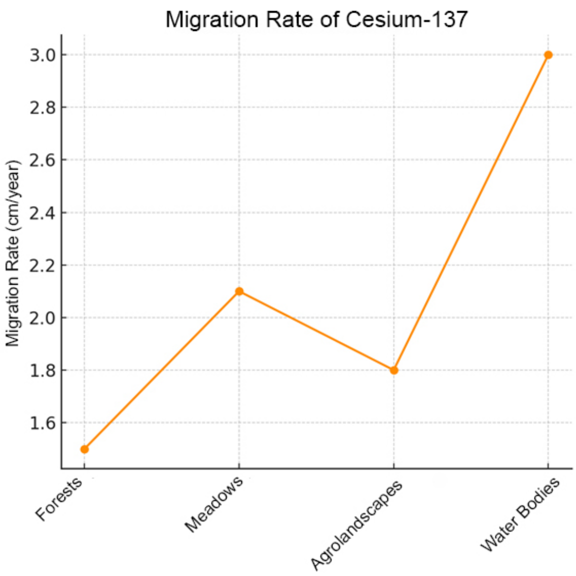

Fig. 2. Migration rate of Cesium-137

Relevance for the study: migration dynamics is important for predicting further changes in the environmental situation; water bodies as the most mobile environment are the main channel of secondary pollution of adjacent territories.

The combination of quantitative indicators and spatial analysis allows us to create a holistic picture of the radioecological state of contaminated areas. Tables show the basic characteristics of the processes, while graphs show their dynamics.

Practical value of this combination of methods: development of reasonable recommendations for monitoring and management of territories; risk assessment for the population depending on the type of landscape and forecasting future changes; planning of areas with a special regime of use – conservation, remediation, ecological rehabilitation.

4. Conclusions

Thus, the results of the study allow us to formulate a number of scientific and practical conclusions that are important for the development of landscape ecology and improvement of the radioecological monitoring system in areas contaminated with radionuclides.

Main achievements of the work:

1. A comprehensive methodology for environmental research using a landscape ecological approach in combination with modern methods of radioecological monitoring was developed (Dmytrenko et al., 2022). This made it possible to assess not only the levels of pollution but also the spatial heterogeneity of its distribution, taking into account natural barriers, landscape contrasts, and features of the hydrological network.

2. The landscapes of the study area were typologized taking into account their ability to accumulate and migrate radionuclides. Forest landscapes and water bodies are identified as areas of maximum environmental risk due to their high ability to accumulate radionuclides in vegetation and bottom sediments.

3. An algorithm for mapping contamination using geographic information technologies (GIS) and remote sensing data was proposed. This made it possible to create a series of spatial maps that reflect the current state of pollution and help predict its further dynamics.

4. The rate of cesium-137 migration processes in different landscape conditions was estimated. The obtained data have significant predictive value for assessing future radioecological threats, in particular in areas of active surface runoff and flooding.

5. Recommendations for improving the system of environmental monitoring and zoning of territories by levels of radioecological risk have been developed.

In particular, it is proposed to create a network of stationary monitoring posts within the accumulation landscapes and transit zones, which will allow for a prompt response to possible secondary releases or migration waves of contamination.

The results obtained are important for solving strategically important tasks of radioecological safety, management of contaminated areas, and planning of environmental remediation measures (Ihnatenko, et al., 2021). The proposed methodology can be integrated into existing environmental monitoring systems, which will increase their accuracy and efficiency.

Practical application of the results is possible in the following areas:

1. Development of regional monitoring programs for areas with radionuclide contamination.

2. Preparation of environmental maps and atlases for public authorities that make decisions on the use or conservation of contaminated land.

3. Use of data for modeling radioecological risks in environmental forecasting systems.

4. Integration of GIS-maps and models into emergency response systems in case of accidents or natural disasters that may cause secondary contamination.

The scientific novelty of the work creates a basis for further research, in particular:

1. Development of comprehensive models of the impact of climate change on the dynamics of radionuclide contamination.

2. Study of biogeochemical cycles in different landscape zones, taking into account long-term radioactive exposure.

3. Evaluation of the effectiveness of different remediation technologies depending on the type of landscape and the level of contamination.

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