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Assessment of radioisotope concentrations of ^{137}Cs and ^{90}Sr in the herbaceous phytocenoses plants of the Dnieper river floodplain ecosystems (northern Ukraine)

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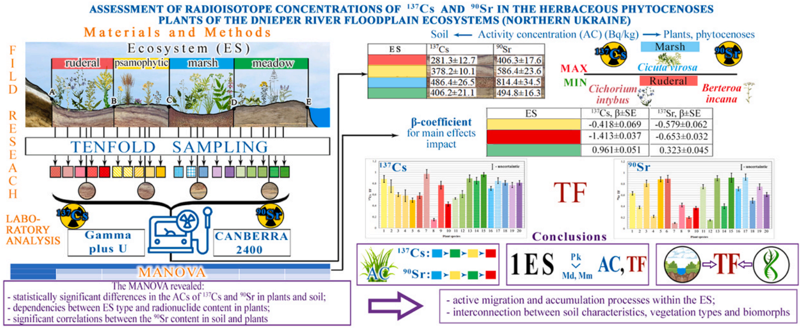
HIGHLIGHTS

- Grass stand radionuclide accumulation varies by ecosystem type and plant species.
- Transfer factors depend on plant species' biological characteristics.
- Activity concentration depends on the ecosystem proximity to the river bed.
- ^{137}Cs being most abundant in phytocenoses of ruderal ecosystems.
- ^{90}Sr effects were particularly high in ruderal and psamophytic phytocenoses.

GRAPHICAL ABSTRACT



ES	^{137}Cs	^{90}Sr
🟥	281.3±12.7	406.3±17.6
🟨	378.2±10.1	586.4±23.6
🟦	486.4±26.5	814.4±34.5
🟩	406.2±21.1	494.8±16.3

ES	^{137}Cs, β±SE	^{137}Sr, β±SE
🟨	-0.418±0.069	-0.579±0.062
🟥	-1.413±0.037	-0.653±0.032
🟩	0.961±0.051	0.323±0.045

The MANOVA revealed:
- statistically significant differences in the ACs of ^{137}Cs and ^{90}Sr in plants and soil;
- dependencies between ES type and radionuclide content in plants;
- significant correlations between the ^{90}Sr content in soil and plants

- active migration and accumulation processes within the ES;
- interconnection between soil characteristics, vegetation types and biomorphs

ARTICLE INFO

Dataset link: Accumulation by dominants and co-dominants of the ruderal, psamophytic, marsh and meadow plant communities in the

ABSTRACT

The experimental data on the ^{137}Cs and ^{90}Sr concentation in the herbaceous phytocenoses of the Dnieper floodplain ecosystems in northern Ukraine have been discussed. Different radionuclide contents in plants and soils of different ecosystems of the floodplain depends on the herbaceous phytocenoses proximity to the river bed: a higher content of radiocaesium has been found in plants and soils of the meadow and marsh ecosystems, which are close to the river bed, and radiostrontium in the marsh and psamophyte ecosystems. Besides the

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Dnieper River floodplain ecosystem (the Chernihiv Region, northern Ukraine)

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Dnieper river
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Phytocenoses
Radioactive contamination
Soil-to-plant transfer factor

intensity of radionuclide uptake by plants has been determined as by the soil and the cenotic habitat conditions so the biological characteristics of the species. The species specificity of the ^{137}Cs and ^{90}Sr accumulation by plants and the direct dependence of the soil-to-plant transfer factor from the density of the floodplain ecosystem contamination with radionuclides have been proved. Our results testified that significant differences in the caesium and strontium distribution were observed between ecosystems, likely influenced by soil characteristics, vegetation types and biomorphs. Our data suggest that the ecosystem type played a significant role, with caesium being most abundant in ruderal ecosystems and least abundant in psamophytic ecosystems, while strontium effects were particularly high in ruderal and psamophytic ecosystems compared to meadows.

1. Introduction

Floodplain ecosystems are diverse and productive. They are marked by a significant spatial and temporal variety, resulting in some of the most species-rich environments [83]. Floodplains support rich ecosystems and provide critically important benefits to people [55]. During the accident at the Chornobyl Nuclear Power Plant (NPP), the most extensive radiocaesium and radiostrontium contamination of the Dnieper river floodplain ecosystems occurred due to airborne radionuclide deposition [33,40]. The pollution of the aboveground parts of the plants with radionuclides consists of root intake into plants and deposits in the composition of dust particles on the surface of the plants [65]. Although some works [58,7,72] are devoted to studying species-specific radionuclide accumulation, the literature highlighting the need to better understand how different plant species interact and accumulate radionuclides to predict the ecosystem responses and bioaccumulation is limited [3,77].

^{137}Cs and ^{90}Sr are present in cationic forms and form stable compounds that limit both mobility and bioavailability [62]. As a result of the interrelated floodplain-river processes, the radionuclides accumulated in a floodplain may become a secondary source of the radioactive contamination of the river [14,28,34,61]. Lush herbaceous vegetation in the low-water period makes the floodplains most suitable for hay harvesting and livestock grazing. This can lead to the intensification of radionuclide flows in the trophic chains [51].

The study of the radionuclide accumulation in plant species within floodplain ecosystems is a critical area of research [30], particularly in regions such as northern Ukraine where the environmental contamination poses significant ecological and health challenges [34]. This topic remains of global relevance and continues to be of critical importance in environmental research [17,23]. The continuing challenges posed by the radionuclide contamination, particularly in fragile ecosystems, emphasise the need for sustained investigation. Understanding the effects of such contamination on both local and global scales is essential for the development of effective remediation and management strategies. Unfortunately, after more than 30 years since the radioactive fallout, the main dose-forming component of which were radiostrontium and radiocaesium, in the floodplains of some rivers of the Polesian Lowland (the Iput, Unecha, Besed rivers) it is still impossible to obtain roughage for animal husbandry with an acceptable content of radionuclides without the use of protective measures [67].

The soil – grass – livestock products pathway in floodplain ecosystems has potential importance for the radionuclide contamination of a human diet. Therefore, a floodplain as a potential pastures need to be intensively studied to determine the key radioecological parameters [15]. The problem of control of the fodder production in the territories with artificial long-lived radionuclides becomes especially important in the post-Chernobyl period [24].

The importance and continuing relevance of these studies are in several key factors for the dominant and co-dominant plant species of floodplain ecosystems [8]. These species play a critical role in maintaining the ecological balance and biodiversity of floodplains, which are dynamic environments subject to frequent disturbance. Therefore, understanding the assessment of the environmental pollution is crucial not only for the health and survival of these plant species, but also for the integrity of the interrelated floodplain-river processes [13]. This knowledge is essential for predicting how contamination may affect the complex interactions between flora and hydrological patterns, and ultimately the resilience and functionality of the whole ecosystem. Given the varying levels of radionuclides in soil across different ecosystem types, it is imperative to investigate the uptake and accumulation of this radioisotope in plant species within each ecosystem [52]. These studies provide valuable insights into the extent of the environmental contamination and the potential risks posed to both ecosystems and human health [29].

The study by McLaren [46] highlights the utility of radioactive isotopes in soil science over the past 70 years, particularly in addressing global challenges such as food security and climate change. Using the techniques such as isotope dilution and radiotracers, the study shows how these methods provide insights into soil processes and radionuclide behaviour that cannot be obtained using the conventional approaches. The results emphasise the continuing relevance of isotopes in the environmental studies and demonstrate their potential to improve our understanding of soil nutrient cycles and their response to anthropogenic impacts.

Larionova et al. [39] focused on the transfer of radionuclides, including ^{137}Cs, ^{90}Sr, ^{241}Am and $^{239+240}$Pu, from soil to vegetation at the Semipalatinsk Test Site (STS). The study found that ^{90}Sr had the highest transfer factor to sagebrush, which decreased with distance from the contamination zones. The study showed that the contamination levels were significantly higher in the vicinity of the nuclear explosion craters and emphasised the need for remediation strategies in similar regions. The comparisons with other studies showed that radionuclide transfer factors at STS were higher than those at the above-ground nuclear test sites, demonstrating the unique characteristics of the underground nuclear explosions and their environmental impacts.

Beresford et al. [4] conducted a study on the radioecology of ^{137}Cs and ^{134}Cs, focusing on the upland sheep pasture systems in the aftermath of the Chernobyl incident. Their research highlighted the mobility of radiocaesium in various soil types, specifically meadow-swamp and sandy soils, thereby providing valuable insights into the environmental behaviour of these radionuclides in the contaminated areas [4]. This study remains significant in elucidating the long-term ecological consequences of the radioactive contamination on soil and plant systems. Caesium is an alkaline element, and its chemical analogue is potassium. With an increase of the potassium concentration in soil, the ^{137}Cs accumulation by plants is decreased. The behaviour of caesium in soil is characterised by selective, irreversible absoption by micaceous clay minerals; as a result, over time, the caesium mobility decreases considerably [32,38].

Recently, many studies have been conducted on the accumulation of radionuclides by the plants of forest ecosystems. In the study published in 2023, Zarubina [81] examined the seasonal fluctuations in the circulation of ^{137}Cs within the forest ecosystems of the Chornobyl exclusion zone. Her research revealed that the concentration of ^{137}Cs in the *Pinus sylvestris* branches and needles exhibited a peak during winter months, while the wood samples showed the heightened presence of the isotope during summer.

By exploring the specific aspect of ecosystem vulnerability, this study contributes to a deeper understanding of examining plant species in psamophytic, ruderal, and meadow ecosystems, researchers can assess the vulnerability of each ecosystem type to radioisotope contamination. Differences in plant community composition, soil characteristics, and ecological processes may influence the susceptibility of ecosystems to the radionuclides contamination and subsequent impacts on ecosystem structure and function. This study addresses a critical gap in the existing literature via long-term environmental monitoring processes analysis in the Dnieper river floodplain ecosystems (northern Ukraine) after the Chernobyl accident. These studies contribute to the long-term environmental monitoring efforts aimed at tracking the persistence and dynamics of radioisotope contamination in natural ecosystems. By establishing the baseline data on the radionuclides concentrations in soil and plant tissues, researchers can monitor the changes over time, assess the effectiveness of remediation efforts, and detect any emerging environmental threats.

While the previous studies have touched on the radionuclide flows in the trophic chains [51] or the radionuclides impact of protective measures [67], there is still a noticeable gap in the scientific literature, particularly regarding the informing management strategies. The results of these studies can inform the development of targeted management strategies for mitigating the impacts of the radioisotope contamination in affected ecosystems. This may include soil remediation techniques, ecosystem restoration efforts, and guidelines for land use planning to minimize human exposure to the contaminated environments [24]. These studies are of interest not only from a local perspective, but also on a global scale. Thus, the study of the radionuclide accumulation in the selected plant species in different ecosystem types of the Dnieper river floodplain in northern Ukraine remains crucial for understanding the environmental contamination dynamics, assessing the ecosystem vulnerability, and working out the effective management and remediation strategies in the contaminated areas worldwide [17,34].

The present study has assessed the concentrations of the ^{137}Cs and ^{90}Sr isotopes in the herbaceous phytocenoses plants within the Dnieper River floodplain ecosystems in northern Ukraine. Four distinct ecosystem types – psamophytic, ruderal, meadow, and marsh – have been selected, each representing a different primary environmental influence. The research has considered four key factors that may affect radionuclide accumulation: the type of radionuclide (^{137}Cs and ^{90}Sr) present in both plant and soil samples across all ecosystems, the biomorph type [polycarpic (Pc), monocyclic monocarpic (Mm), and dicyclic monocarpic (Md)], the plant species, and the specific environmental conditions of each ecosystem. The multifactor analysis of the variance (MANOVA) method was made to investigate the influence of these environmental factors on the accumulation of ^{137}Cs and ^{90}Sr in the plant samples from these diverse ecosystems. This comprehensive analysis has revealed the intricate relationships between the environmental parameters and radioisotope uptake by different plant species. The objective of this study was to ascertain the concentrations of both ^{1} ^{37}Cs and ^{90}Sr in herbaceous plant communities situated within the Dnieper River floodplain in northern Ukraine. Furthermore, the study sought to analyse how radionuclide type, plant biomorphology, species and ecosystem characteristics influence their accumulation.

2. Materials and Methods

The methodological basis for the study was the concept of the environmental monitoring [76] and the soil to plant transfer concept [69]. The soil and plant samples were taken within the floodplain ecosystems of the Dnieper river located near the Radul village in the Chernihiv region (Fig. 1), technogenically contaminated as a result of

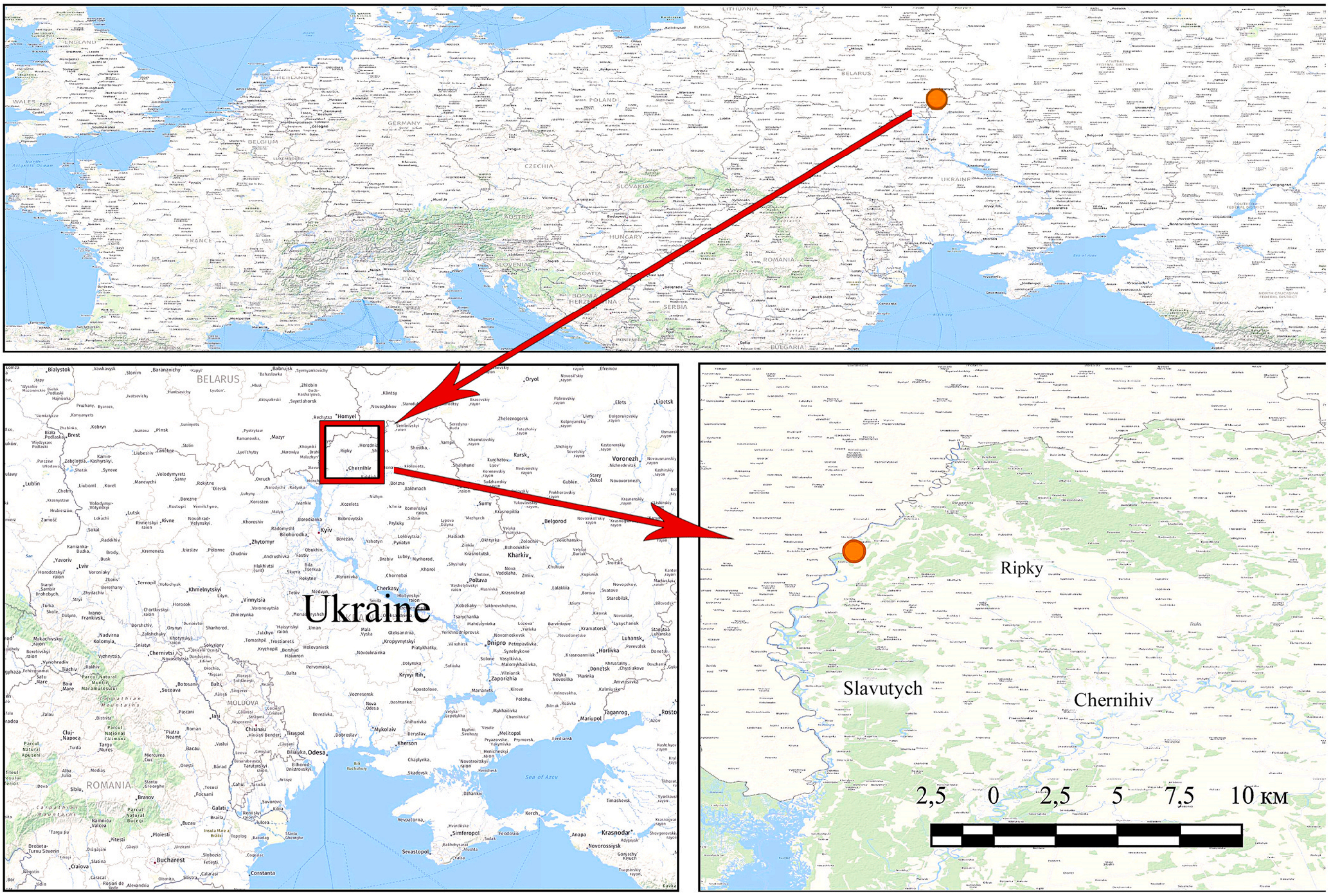

Fig. 1. Localization of the study area.

the Chernobyl accident, in 2019 after 33 years after the accident.

The study area belongs to the territories with an average level of the ^{137}Cs contamination (Fig. 2, A) and a low level of the ^{90}Sr contamination (Fig. 2, B) after the Chernobyl accident.

2.1. Field research

The phytocenoses of the Dnieper river floodplain ecosystems were studied: near-river (the meadow and marsh phytocenoses), central (the psamophytic phytocenose) and near-terrace (the ruderal phytocenose) which were located on a different distance from the riverbed. The meadow ecosystem was located from the riverbed at a distance of 14–250 m, the marsh ecosystem: 250–695 m, the psamophytic ecosystem: 695–1280 m and the ruderal ecosystem: 1280–1660 m (Fig. 3). They differed in the composition of alluvial deposits, relief, hydrology and, as a consequence, in vegetation and soil cover.

The transect across the Dnieper River floodplain was conducted in such a way that it passed through the phytocenoses with clear boundaries between them (Fig. 3, points A, B, C, D). Along the transect, the areas with maximum homogeneity of the structure of each phytocenose (plant populations more or less evenly or randomly distributed among themselves) were defined as the experimental sites (Fig. 4).

2.1.1. Geobotanical techniques

The field study of the ecosystems vegetation was carried out by the geobotanical methods [79] in particular: the vegetation relevés were taken during the optimum of the vegetation period (July) in the areas of 100 m^2; the experimental plots were homogeneous in terms of ecological conditions and plant species composition; the partaking of each species in the phytocenosis was assessed by the method of projective coverage. The syntaxa were identified according to Matuszkiewicz [45].

2.1.2. Soil type determination

The soils in the experimental sites were determined using the “Field Soil Determinant” [57] and the “Atlas of Soil Properties Maps of Ukraine” [47]. At the same time, the morphological characteristics (soil thickness and its individual horizons, color, moisture, granule size composition, structure, density, porosity, neoplasms, inclusions, distribution of plant roots, nature of the transition between horizons) and acidity were taken into account. The acidity of the soil solution in the experimental sites was determined using a portable ADWA AD12 pH meter (Hungary).

The determination of acidity was carried out in order to exclude (or detect) the effect of the possible influence of the neighboring farmland mineral fertilizers on the acidity of the studied ecosystems soils. After all, the use of fertilizers, especially those containing nitrogen, is often considered the cause of soil acidity. The literature highlights the impact of acidity on the mineralization of soil organic matter [9] and the impact of mineral fertilizers on the chemical parameters of the soil related to its acidity [73]. It is also known that the acidification, in turn, increases the rate of release of radionuclides out of soil particles [11].

2.1.3. Soil samples selected

The soil samples of the experimental plots were collected in each of the 4 sites considered. At each experimental site, the soil samples were taken in 10 replicates [50].

The sampling points within one test area were selected using the uniform selection method. For this purpose, the test area was divided into equal rectangles: 4 vertical and 5 horizontal lines were drawn. The soil samples were taken at the even intersection points of the vertical and horizontal lines (Fig. 5).

Melnyk et al. [49], analyzing numerous publications, indicate that in different periods after the Chernobyl accident, soil sampling during radioecological studies was carried out to different depths. To establish the actual levels of soil contamination with radionuclides in the first years after the accident, the soil samples were taken to a depth of 10 cm. 30 years after the accident, the main supply of radionuclides was concentrated in a 30-centimeter soil layer [36,48,49]. That is why at each experimental site we carried out the soil sampling at a depth of 30 cm with a special sampler with a diameter of 40 mm.

2.1.4. Plant samples selected

At each experimental site, the samples of plant vegetative organs were taken in 10 replicates within a plant species; 10 individual plants were selected for one sample [75]. The above-ground and underground parts of the dominant and co-dominant plants species were selected for the radiological analysis. These parts of one plant were subsequently analyzed as one sample. The samples of each plant were taken evenly from the entire area of each of the four plots in such a way that the plant sampling locations were as close as possible to the soil sampling points.

2.2. Laboratory analysis

All selected soil samples were dried in a drying stove at temperature of 105°C during 24 h. Foreign impurities (stones, plant roots and leaves, etc.) were removed by sifting through a stainless steel sieve (the diameter of 3 mm). For the radionuclide analysis, the averaged samples were selected from each dried soil sample. The homogenization of the sample was carried out using a special laboratory mill. The plant samples were also dried in a drying stove at temperature of 70°C, and then crushed and homogenized. The number of the analyzed samples of soil and each plant from each site was 10. For the ß-activity measurements of ^{90}Sr the

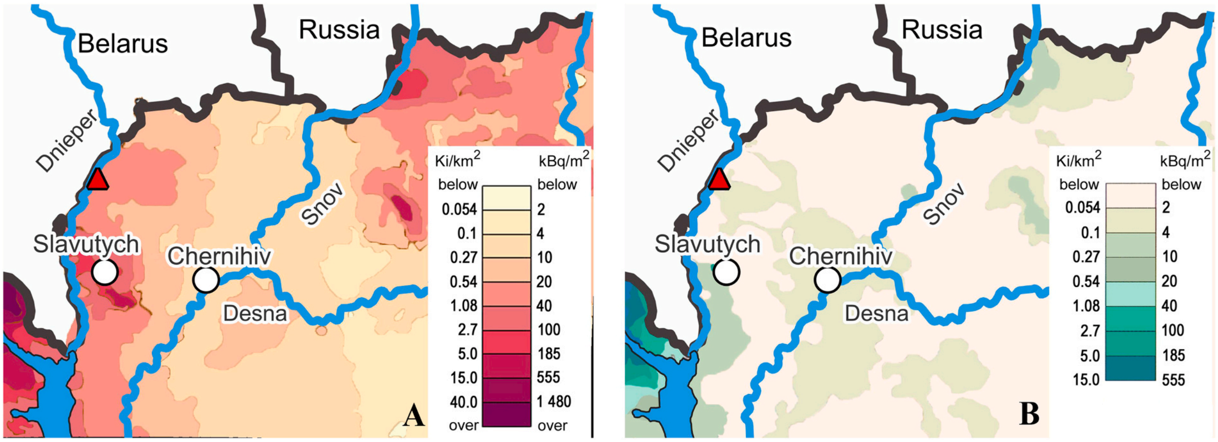

Fig. 2. The ^{137}Cs (A) and ^{90}Sr (B) contamination of northern Ukraine in the post-Chernobyl period according to Rudenko [60]. The location of the studied area is marked with a red triangle.

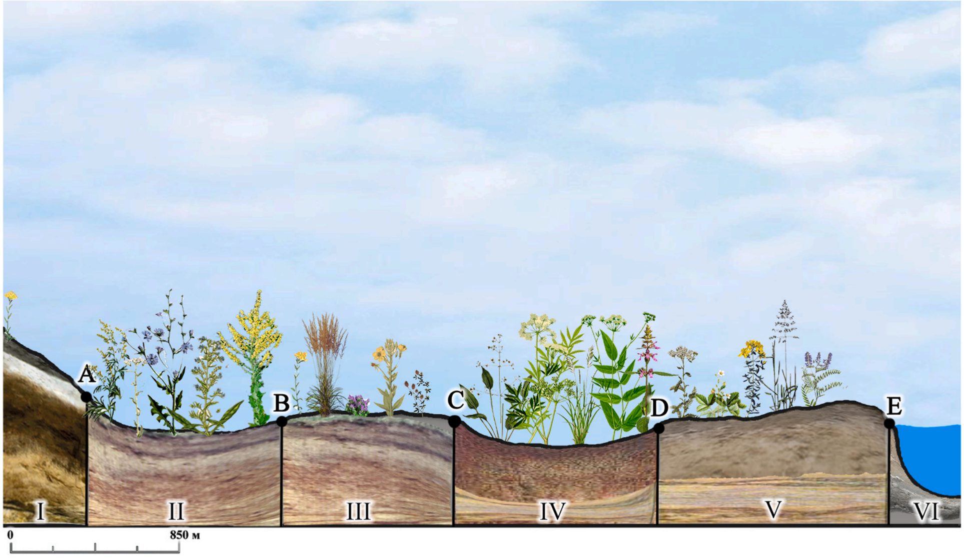

Fig. 3. Profile of the Dnieper floodplain ecosystems. Symbols: I - the slope of the pine terrace; the floodplain phytocenoses: ruderal (II), psamophytic (III), marsh (IV) and meadow (V); VI – the channel of the Dnieper river. A – N51°50’8.49", E30°43’13.48"; B – N51°50’14.69", E30°42’57.04"; C – N51°50’24.69", E30°42’31.18"; D – N51°50’31.93", E30°42’11.15"; E – N51°50’37.46", E30°42’1.93".

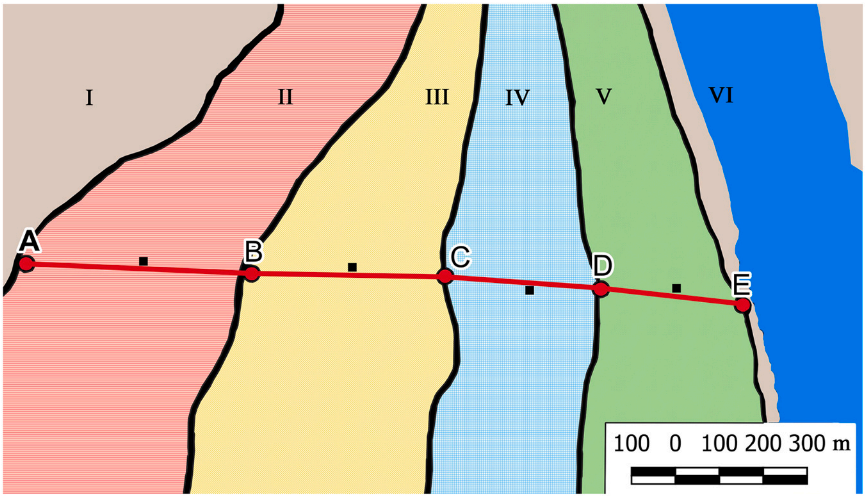

Fig. 4. Placement of the experimental sites (black squares). Symbols: see Fig. 3.

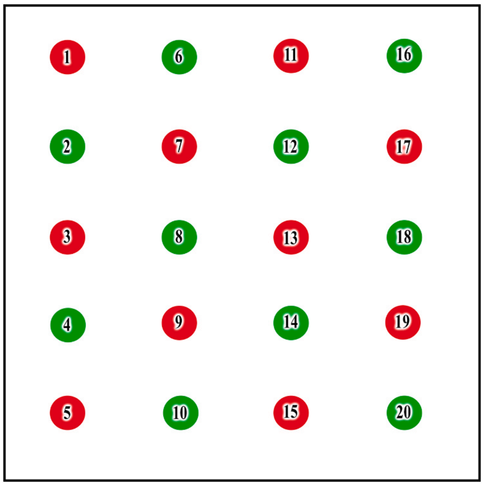

Fig. 5. Location scheme of the soil sampling points.

samples were mineralized by incineration at 450–600°C during 24 hours (for soil samples) and 48 hours (for plant samples); the obtained ash was weighed. In the ashed samples the precipitation of oxalates was carried out at pH 4 p in order to separate rare earth elements from alkaline earth elements.

The calibrated container was filled according to the calibration geometry (the sample volume fully corresponded to the volume of the calibration standard) and weighed; the container was closed; the external surfaces of the container were cleaned of the potential contamination; the container was placed on the detector and the measurements were taken. The position of the container relative to the detector fully corresponded to the position of the container at which the calibration was carried out.

The ^{137}Cs content determination in the plant and soil samples was performed using a Gamma plus U spectrometer (Expert Center, Russia), which is designed to measure the activity concentration of radionuclides according to the spectrum of gamma radiation; NaI (Tl) single crystals with a size of 63 × 63 mm are used as a detector. The spectra were analyzed using the SpectraLine software package (OOO LSRM, Russia).

The ^{90}Sr content determination was carried out with the radiochemical method with a radiometric ending at the α-β detector CANBERRA-2400 (Mirion Technologies, USA). The activity concentration measurements of ^{90}Sr were carried out in equilibrium with ^{90}Y. For this after the applied analytical procedure the samples were stored for 2.5 weeks to reach the radioactive equilibrium between ^{90}Sr and ^{90}Y. The spectra were analyzed using the program GENIE 2000 (Canberra Industries, Meriden, Connecticut, USA).

In the laboratory where the radionuclide analyses were carried out such quality control measures as metrological certification of equipment, state verification of measuring equipment, and initial comparison of sample measurement results were used.

2.3. Statistical analysis

The statistical analysis was performed using the Statistica 13.3 package (TIBCO Software, Palo Alto, CA, USA). The results were expressed as mean ± standard deviation. A multiple-range test was used to determine significant differences between means, with P values < 0.05 considered significant. The data were first assessed for homogeneity of variance using Levene's test, and normality was assessed using the Kolmogorov-Smirnov test.

The study included four different ecosystems, categorized as psamophytic, ruderal, meadow and marsh, each representing a primary type of influence. The analysis also considered four influence factors, including the type of radionuclide (^{90}Sr and ^{137}Cs) present in both plant and soil samples in all ecosystems, the type of biomorph [polycarpics (Pc), monocyclic monocarpics (Mm) and dicyclic monocarpics (Md)] and the plant species. The analyses of variance were performed to examine the effects of these factors, and linear regression coefficients (the β-coefficient and its standard deviation) were calculated to assess the relationships between variables. The β-coefficient is known to be the most important indicators of the MANOVA analysis to understand how individual independent variables affect dependent variables, as the β-coefficient is used to assess the strength and direction of the relationship between the variables in a statistical model. In addition, the sign of the β-coefficient indicates the direction of this influence: a positive β-coefficient means that the increase in the independent variable leads to the increase in the dependent variable, while a negative β-coefficient indicates the opposite relationship in which the increase in the independent variable leads to the decrease in the dependent variable. The multivariate analysis of variance (MANOVA) was carried out to evaluate the statistical significance of the parameters, and the results were compared on the basis of the relative magnitudes of their values.

The MANOVA was used to assess the effects of multiple factors on radionuclide accumulation in studied areas of northern Ukraine, providing a detailed view of how these variables interact in the context of radioactivity accumulation. The MANOVA approach involved comparing the total sum of squares (SS) model with the residual sum of squares (SS), evaluating values from the multiple correlation analysis, including the correlation coefficient (R), the coefficient of determination (R^2), and the adjusted R^2 to account for random errors. For each predictor variable, the β-coefficient was calculated to quantify both the magnitude and direction of its influence on the dependent variables, specifically the accumulation of the ^{137}Cs and ^{90}Sr radionuclides. This β-coefficient served as a key metric to assess the quality and accuracy of the regression model.

3. Results

3.1. Phytocenoses of the experimental sites

Site 1 (ruderal ecosystem). The phytocenosis of the ruderal ecosystem belongs to the *Dauco-Melilotion* Görs ex Rostański et Gutte 1971 alliance of the *Onopordetalia acanthii* Br.-Bl. et Tx. ex Klika et Hadač 1944 order of the *Artemisietea vulgaris* Lohmeyer et al. in Tx. exvon Rochow 1951 class. The phytocenosis is formed on sandy weakly nitrified soil with a neutral reaction of the soil solution (pH 7.3). It is diagnosed by such species as *Artemisia absinthium* L., *Cichorium intybus* L., *Echium vulgare* L., *Verbascum lychnite* L. *Artemisia absinthium* (the projective coverage of 35 %) and *Echium vulgare* L. (30 %) dominate in this plant community. *Berteroa incana* (L.) DC., *Verbascum lychnitis* and *Cichorium intybus* with the projective coverage of 10 % co-dominate in the ruderal phytocenosis.

Site 2 (psamophyte ecosystem). The phytocenosis of the psamophyte ecosystem belongs to the *Koelerion glaucae* Volk 1931 alliance of the *Corynephoretalia canescentis* Klika 1934 order of the *Koelerio-Corynephoretea canescentis* Klika in Klika et Novák 1941 class. The phytocenosis is formed on sandy soil with a neutral reaction of the soil solution (pH 7.1). It is diagnosed by such species as *Chondrilla juncea* L., *Helichrysum arenarium* (L.) Moench, *Hieracium umbellatum* L., *Bassia laniflora* (SGGmel.) AJScott, *Koeleria glauca* (Spreng.) DC., *Enothera biennis* L., *Otites borysthenicus* Klokov, *Plantago indica* L. *Helichrysum arenarium* (the projective coverage of 30 %) and *Trifolium arvense* L. (25 %) dominate in this plant community. *Calamagrostis epigejos* (L.) Roth (15 %), *Thymus serpyllum* L. (12 %) and *Oenothera biennis* (10 %) co-dominate in the psamophyte phytocenosis.

Site 3 (marsh ecosystem). The phytocenosis of the marsh ecosystem belongs to the *Phragmition communis* Koch 1926 alliance of the *Phragmitetalia* Koch 1926 order of the *Phragmito-Magnocaricetea* Klika in Klika et Novák 1941 class. It was formed in depressions on meadow-swamp soils with a slightly acidic reaction of the soil solution (pH 6.7). It is diagnosed by such species as *Alisma plantago-aquatica* L., *Equisetum fluviatile* L., *Iris pseudacorus* L., *Glyceria maxima* (Hartm.) Holmb.,. *Lycopus europaeus* L., *Phragmites australis* (Cav.) Trin. ex Steud., *Rumex hydrolapathum* Huds., *Sium latifolium* L. *Alisma plantago-aquatica* (the projective coverage of 40 %) dominates in this plant community. *Glyceria maxima* (15 %), *Sium latifolium* (12 %) *Stachys palustris* and *Cicuta virosa* (10 % each) co-dominate in the marsh phytocenosis.

Site 4 (meadow ecosystem). The phytocenosis of the meadow ecosystem belongs to the *Arrhenatherion elatioris* Luquet 1926 alliance of the *Arrhenatheretalia elatioris* Tx. 1931 order of the *Molinio-Arrhenatheretea* Tx. 1937 class. The phytocenosis was formed on the site with meadow sandy soils enriched with nutrients. It was the soil with a neutral reaction of the soil solution (pH 7.0). A number of species were found in the phytocenosis, which were characteristic of mesophytic meadows used for haymaking: *Achillea millefolium* L., *Campanula patula* L., *Centaurea jacea* L., *Cruciata glabra* (L.) Opiz, *Festuca rubra* L., *Lolium pratense* (Huds.) Darbysh., *Galium rubioides* L., *Galium mollugo* L., *Leucanthemum vulgare* Lam., *Pimpinella saxifraga* L., *Poa pratensis* L., *Polygala vulgaris* L., *Lotus corniculatus* L., *Plantago lanceolata* L., *Ranunculus acris* L., *Rumex acetosa* L., *Trifolium pratense* L., *Vicia cracca* L. *Poa pratensis* (the projective coverage of 40 %) and *Vicia cracca* (30 %) dominate in this plant community. *Hypericum perforatum* L., *Fragaria vesca* L. and *Achillea millefolium* with a projective coverage of 15–18 % co-dominate in the meadow phytocenosis.

3.2. Radiological analysis

The soil and plant samples collected from the herbaceous phytocenoses of the Dnieper river floodplain ecosystems (Figs. 3, 4) were analyzed in the laboratory conditions for the content of ^{137}Cs and ^{90}Sr. The results of measuring the ^{137}Cs and ^{90}Sr activity concentration in the soil and plant samples are presented in Table 1–3.

Table 1 shows that the soil of the ruderal ecosystem contains the least amount of ^{137}Cs (281.3 ± 12.7 Bq/kg) and ^{90}Sr (406.3 ± 17.6 Bq/kg). The highest content of radiocaesium and radiostrontium was detected in the soil of the marsh ecosystem – respectively 486.4 ± 26.5 Bq/kg and 814.4 ± 34.5 Bq/kg.

As it can be seen from Table 2 the lowest ^{137}Cs content was detected in the codominant species of *Cichorium intybus* in the ruderal phytocenosis (42.700 ± 5.48 Bq/kg), and the highest contamination with

Table 1

The ^{137}Cs and ^{90}Sr activity concentration (Bq/kg) in the soil and the number of plant species analyzed in each ecosystem.

Ecosystem	^{137}Cs	^{90}Sr	Number of analyzed plant species
Ruderal	281.3 ± 12.7	406.3 ± 17.6	5
Psamophytic	378.2 ± 10.1	586.4 ± 23.6	5
Marsh	486.4 ± 26.5	814.4 ± 34.5	5
Meadow	406.2 ± 21.1	494.8 ± 16.3	5

Note. All results are reported as mean ± standard error.

radiocaesium was found in the co-dominant species of *Cicuta virosa* in the marsh community (410.9 ± 26.2 Bq/kg). The plants of the ruderal ecosystem are characterized by slight contamination with ^{137}Cs: from 42.7 ± 5.5 Bq/kg to 273.1 ± 21.7 Bq/kg (Table 2). However, the plants of the marsh ecosystem, in comparison with the plant samples collected in other floodplain ecosystems, have the greatest value of the ^{137}Cs activity concentration: from 362.9 ± 19.3 Bq/kg to 410.9 ± 26.2 Bq/kg.

From Table 3 it is clear that the lowest ^{90}Sr content was detected in the co-dominant species of *Berteroa incana* in the ruderal phytocenosis (40.9 ± 4.3 Bq/kg), and the highest contamination with radiocaesium was found in the co-dominant species of *Cicuta virosa* in the marsh community (747.4 ± 43.3 Bq/kg). The plants of the ruderal ecosystem, compared to plants of other ecosystems, contain the least radiostrontium, as well as radiocaesium: from 40.9 ± 4.3 to 360.0 ± 24.5 Bq/kg (Table 3). The marsh plants have the highest content of the ^{90}Sr radionuclides: from 404.6 ± 38.6 Bq/kg to 747.4 ± 43.3 Bq/kg.

As an indicator of the ability of plants to absorb radionuclides the soil-to-plant transfer coefficient or the soil-to-plant transfer factor (TF) was used. It is the ratio of Bq/kg dry weight of the plant to Bq/kg of soil dry weight [35,69]. The transfer factors was calculated and compared for all studied plant species (Figs. 6, 7) based on the activity concentration data obtained.

3.3. MANOVA analysis

In order to assess the distribution of the strontium and caesium radionuclides in ecosystems located in the Dnieper river floodplain, which are situated not far from each other, the MANOVA analysis was used. A different set of species with a protective cover of at least 15 % was in all ecosystems, meaning they either dominated or co-dominated the plant community. In this analysis, we consider four different ecosystems categorized as psamophytic, ruderal, meadow, and marsh, each assigned to the main influence type. The statistical analysis for elucidating other factors (totalling four influence factors) included the type of radionuclide under study (strontium and caesium) in both plants and soil of the studied ecosystems, the type of biomorph (Pc, Mm, and Md), as well as

Table 2

The ^{137}Cs activity concentration (Bq/kg) by the dominants and co-dominants of the ruderal, psamophytic, marsh and meadow plant communities in the Dnieper river floodplain ecosystem (the Chernihiv Region, northern Ukraine).

Plant communite	Plant species	Biomorpha	Mean±SE	Median	Min	Max	Variance	Variation coefficient	Skewnes
Ruderal	*Artemisia absinthium*[5, 23, 40]	Pc	164.1 ± 14.7	160.5	147.0	191.0	214.8	8.93	1.08
Ruderal	*Berteroa incana*[6, 24, 41, 57, 72, 86]	Md	273.1 ± 21.7	278.0	242.0	306.0	470.1	7.94	−0.13
Ruderal	*Cichorium intybus*[7, 25, 42, 58, 73, 87, 100]	Pc	42.7 ± 5.5	45.0	35.0	51.0	30.0	12.83	−0.17
Ruderal	*Echium vulgare*[8, 43, 59, 75, 74, 88, 101, 113]	Md	215.6 ± 19.7	216.0	184.0	241.0	388.9	9.15	−0.49
Ruderal	*Verbascum lychnitis*[9, 27, 44, 60, 75, 89, 102, 114, 125]	Mm	122.5 ± 10.7	122.0	107.0	138.0	114.5	8.74	−0.04
Psamophytic	*Helichrysum arenarium*	Pc	331.7 ± 24.6	336.0	285.0	362.0	605.1	7.42	−0.69
Psamophytic	*Calamagrostis epigejos*	Pc	283.0 ± 48.9	268.0	226.0	356.0	232.9	17.29	0.32
Psamophytic	*Thymus serpyllum*[2]	Pc	225.7 ± 13.5	228.5	198.0	243.0	183.1	5.60	−0.86
Psamophytic	*Oenothera biennis*[3, 38]	Mm	219.6 ± 40.8	211.0	188.0	329.0	161.2	18.56	1.44
Psamophytic	*Trifolium arvense*[4, 22, 39, 55]	Mm	189.3 ± 15.0	188.5	167.0	211.0	223.8	7.90	0.07
Marsh	*Alisma plantago-aquatica*[15, 33, 50, 66, 81, 95, 108, 120, 131, 141, 150, 157, 165, 171]	Pc	362.9 ± 19.3	363.0	335.0	392.0	371.2	5.31	−0.10
Marsh	*Cicuta virosa*[16, 34, 51, 67, 82, 96, 109, 121, 132, 142, 151, 158, 166, 172, 177, 181]	Pc	410.9 ± 26.2	411.5	372.0	451.0	686.1	6.37	0.15
Marsh	*Glyceria maxima*[17, 35, 52, 68, 83, 97, 110, 122, 133, 143, 152, 159, 167, 173, 178, 182, 185]	Pc	391.5 ± 21.1	391.5	352.0	418.0	443.6	5.38	−0.56
Marsh	*Sium latifolium*[18, 36, 53, 69, 84, 98, 111, 123, 134, 144, 153, 160, 168, 174, 179, 183, 188]	Pc	375.6 ± 23.3	376.0	342.0	411.0	541.8	6.20	−0.04
Marsh	*Stachys palustris*[19, 37, 54, 70, 85, 99, 112, 124, 135, 145, 154, 161, 169, 175, 180, 184, 187, 189, 190]	Pc	392.9 ± 18.0	395.0	368.0	422.0	324.3	4.58	0.03
Meadow	*Achillea millefolium*[10, 28, 61, 76, 90, 103, 115, 126, 136]	Pc	213.4 ± 7.4	213.5	204.0	225.0	54.5	3.46	0.13
Meadow	*Fragaria vesca*[11, 29, 46, 62, 91, 116, 127, 137, 146]	Pc	249.4 ± 25.3	248.5	217.0	297.0	638.5	10.13	0.43
Meadow	*Hypericum perforatum*[12, 30, 47, 63, 78, 92, 105, 117, 128, 138, 147, 155]	Pc	361.7 ± 26.0	365.5	306.0	398.0	674.0	7.18	−0.94
Meadow	*Poa pratensis*[13, 31, 48, 64, 79, 93, 106, 118, 129, 139, 148, 163]	Pc	346.7 ± 25.0	343.5	302.0	382.0	624.7	7.21	−0.22
Meadow	*Vicia cracca*[14, 32, 49, 65, 80, 94, 107, 119, 130, 140, 149, 156, 164, 170]	Pc	389.1 ± 16.0	390.5	367.0	412.0	256.5	4.12	−0.10

Note. See Supplementary Material “Note to Table 2”.

Table 3
The ^{90}Sr activity concentration (Bq/kg) by the dominants and co-dominants of the ruderal, psamophytic, marsh and meadow plant communities in the Dnieper River floodplain ecosystem (the Chernihiv Region, northern Ukraine).

Plant communities	Plant species	Biomorpha	Mean±SE	Median	Min	Max	Variance	Variation coefficient	Skewnes
Ruderal	*Artemisia absinthium*[5, 23, 40, 56, 71]	Pc	360.0 ± 24.5	160.5	147.0	191.0	214.8	8.93	1.08
Ruderal	*Berteroa incana*[6, 24, 41, 57, 72, 86]	Md	40.9 ± 4.3	278.0	242.0	306.0	470.1	7.94	−0.13
Ruderal	*Cichorium intybus*[7, 25, 42, 58, 73, 87, 100]	Pc	171.3 ± 15.7	45.0	35.0	51.0	30.01	12.83	−0.17
Ruderal	*Echium vulgare*[8, 26, 43, 59, 74, 88, 101, 113]	Md	83.0 ± 6.5	216.0	184.0	241.0	388.9	9.15	−0.50
Ruderal	*Verbascum lychnitis*[9, 27, 44, 60, 75, 89, 102, 125]	Mm	149.2 ± 12.0	122.0	107.0	138.0	114.5	8.74	−0.04
Psamophytic	*Helichrysum arenarium*	Pc	370.4 ± 20.1	336.0	285.0	362.0	605.1	7.42	−0.69
Psamophytic	*Calamagrostis epigejos*[1]	Pc	222.5 ± 13.1	268.0	226.0	356.0	692.9	17.29	0.32
Psamophytic	*Thymus serpyllum*[2, 20]	Pc	472.2 ± 32.5	228.5	198.0	243.0	183.1	6.00	−0.86
Psamophytic	*Oenothera biennis*[3, 21, 38]	Mm	126.9 ± 11.2	211.0	188.0	329.0	661.16	18.56	1.44
Psamophytic	*Trifolium arvense*[4, 22, 39, 55]	Mm	516.2 ± 24.6	188.5	167.0	211.0	223.8	7.90	0.07
Marsh	*Alisma plantago-aquatica*[15, 33, 50, 66, 81, 95, 108, 120, 131, 141, 150, 158, 165, 171, 176]	Pc	576.6 ± 27.1	363.0	335.0	392.0	371.2	5.31	−0.10
Marsh	*Cicuta virosa*[16, 34, 51, 67, 82, 96, 109, 121, 132, 142, 151, 159, 166, 172, 177, 181]	Pc	747.4 ± 43.2	411.5	372.0	451.0	686.1	6.37	0.16
Marsh	*Glyceria maxima*[17, 35, 68, 83, 97, 110, 122, 133, 143, 152, 160, 173, 182, 185]	Pc	404.6 ± 38.6	391.5	352.0	418.0	443.6	5.38	−0.56
Marsh	*Sium latifolium*[18, 36, 53, 69, 84, 98, 111, 123, 134, 144, 153, 161, 168, 174, 179, 183, 186, 188]	Pc	613.8 ± 44.3	376.0	342.0	411.0	541.8	6.20	−0.04
Marsh	*Stachys palustris*[19, 37, 54, 70, 85, 99, 112, 124, 135, 145, 154, 162, 169, 175, 180, 184, 187, 189, 190]	Pc	500.3 ± 29.8	395.0	368.0	422.0	324.3	4.58	0.03
Meadow	*Achillea millefolium*[10, 28, 45, 61, 76, 90, 103, 115, 126, 136]	Pc	368.7 ± 20.7	213.5	204.0	225.0	54.5	3.46	0.13
Meadow	*Fragaria vesca*[11, 29, 46, 62, 77, 91, 104, 116, 137, 146]	Pc	72.4 ± 5.9	248.5	217.0	297.0	638.5	10.13	0.43
Meadow	*Hypericum perforatum*[12, 30, 47, 63, 78, 92, 105, 117, 128, 138, 147, 155]	Pc	445.3 ± 20.8	365.5	306.0	398.0	674.0	7.18	−0.94
Meadow	*Poa pratensis*[13, 48, 64, 79, 93, 106, 118, 129, 139, 148, 156, 163]	Pc	193.0 ± 20.9	343.5	302.0	382.0	624.7	7.21	−0.22
Meadow	*Vicia cracca*[14, 32, 49, 65, 94, 107, 119, 130, 140, 149, 157, 164, 170]	Pc	447.9 ± 42.1	390.5	367.0	412.0	256.5	4.12	−0.10

Note. See Supplementary Material "Note to Table 2".

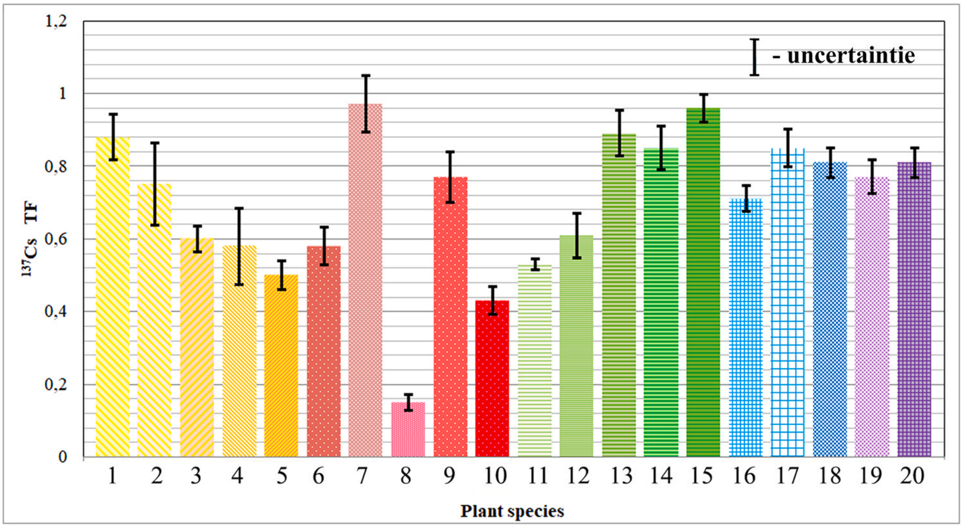

Fig. 6. The ^{137}Cs soil-to-plant transfer factors (TF) of the Dnieper river floodplain ecosystems plants: 1 – *Helichrysum arenarium*, 2 – *Calamagrostis epigejos*, 3 – *Thymus serpyllum*, 4 – *Oenothera biennis*, 5 – *Trifolium arvense*, 6 – *Artemisia absinthium*, 7 – *Berteroa incana*, 8 – *Cichorium intybus*, 9 – *Echium vulgare*, 10 – *Verbascum lychnitis*, 11 – *Achillea millefolium*, 12 – *Fragaria vesca*, 13 – *Hypericum perforatum*, 14 – *Poa pratensis*, 15 – *Vicia cracca*, 16 – *Alisma plantago-aquatica*, 17 – *Cicuta virosa*, 18 – *Glyceria maxima*, 19 – *Sium latifolium*, 20 – *Stachys palustris*.

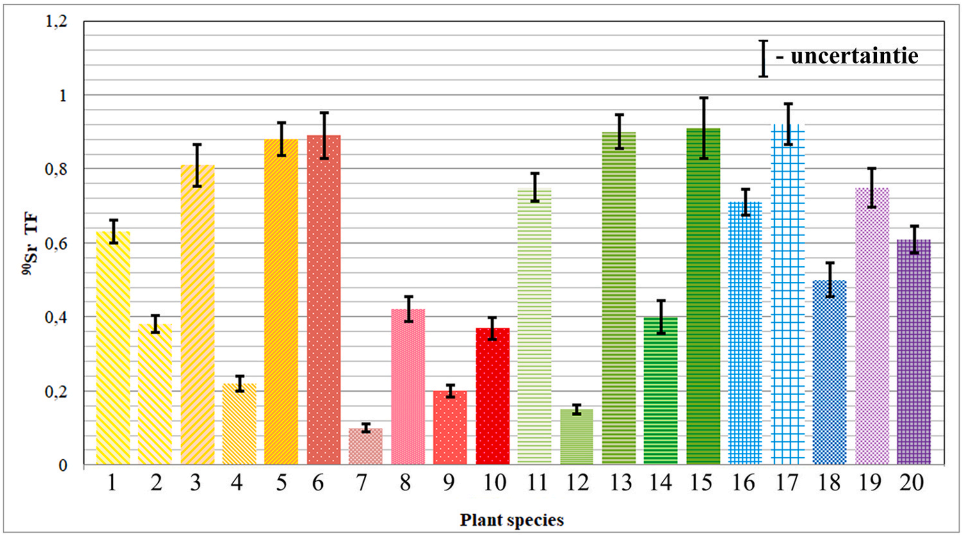

Fig. 7. The ^{90}Sr soil-to-plant transfer factors (TF) of the Dnieper river floodplain ecosystems plants (see Fig. 6).

the plant species. The variance analyses and linear regression coefficients (the beta index and its standard deviation) were calculated on these data. In this MANOVA analysis, statistically significant values of these parameters will be provided, compared based on the relative magnitudes of their values, as some of them may have negative values in the distribution.

The first step in our analysis was to analyse the variation in relation to the variables of ^{90}Sr and ^{137}Cs in the ecosystems, which can be considered as independent variables influencing other variables such as ecosystem types, vegetation types or plant species. The MANOVA analysis was used to assess whether there are statistically significant differences in the ^{90}Sr and ^{137}Cs concentrations among different ecosystem types (e.g., psamophyte, ruderal, meadow and marsh) and whether there are differences in these concentrations by the biomorph type or plant species. The MANOVA analysis allowed us to simultaneously examine these features to understand the complex interactions between them in the Dnieper ecosystems. The data analysis of $F_{19,180} = 195.95$ ($p = 0.000$) for ^{137}Cs and ^{90}Sr $F_{19,180} = 255.03$ ($p = 0.000$) was shown in the plants. For the ^{137}Cs and ^{90}Sr activity concentration in soil these dependencies were formed in the regression analysis as follows: for the soil ^{90}Sr the value of $\beta = -0.615 \pm 0.13$ ($p = 0.000$). The dependent variable regression summary analysis for the soil ^{137}Cs showed the $\beta = 1.338 \pm 0.13$ ($p = 0.000$) coefficient and the coefficient of correlation dependencies as $R = 0.786$, as well as the coefficient of determination $R^2 = 0.618$ and $R^2_{adj} = 0.614$ accordingly.

Thus, the MANOVA analysis revealed statistically significant differences in the content of the ^{137}Cs and Sr radionuclides levels both in plants and soil across the Dnieper river ecosystems. For plants, the significant dependencies were observed between ecosystem type and the content of both radionuclides, suggesting that different ecosystem types may be exposed to varying levels of contamination. In the regression analysis for soil radionuclide content, it was shown that there were statistically significant dependencies between the Sr content in soil and Sr content in plants, indicating the processes of migration and accumulation of this element within the ecosystem. Furthermore, the high correlation coefficient and determination coefficients for the ^{137}Cs content in soil suggest a strong relationship between the ^{137}Cs content in soil and its content in plants, pointing to transfer mechanisms of this radionuclide through the food chain and showed the dynamics of the spread and accumulation of radionuclides in ecosystems.

The summary of the dependent variable regression for the ^{137}Cs concentration in our MANOVA analysis, used for the examined using the β-coefficient in relation to the ecosystem type, biomorph type, soil ^{137}Cs and ^{90}Sr content, and species type, obtaining the following values (both positive and negative). Namely, for ^{137}Cs the dependences and biomorph factor was as $\beta = 0.267 \pm 0.056$ ($p = 0.000$), for soil ^{137}Cs it was the biggest and shown as $\beta = 2.047 \pm 0.179$ ($p = 0.000$) and for the soil Sr it was the following: $\beta = -0.939 \pm 0.138$ ($p = 0.000$). For the ^{137}Cs concentration the summary of the dependent variable regression was shown as the following: $R = 0.818$, the coefficients of determination are $R^2 = 0.669$ and $R^2_{adj} = 0.661$ and $F_{5,\ 194} = 78.73$ ($p = 0.000$).

The summary of the dependent variable regression for the ^{90}Sr concentration in different ecosystems was shown as the following: for ecosystem types the value of $\beta = -0.613 \pm 0.211$ ($p = 0.004$), for the soil ^{90}Sr $\beta = 0.452 \pm 0.155$ ($p = 0.004$), for the soil ^{137}Cs $\beta = 0.472 \pm 0.200$ ($p = 0.019$) and the biomorpha data $\beta = -0.303 \pm 0.060$ ($p = 0.000$). For the ^{90}Sr concentration the summary of the dependent variable regression was shown as the following: $R = 0.764$, the coefficients of determination are $R^2 = 0.583$ and $R^2_{adj} = 0.572$, and $F_{5,\ 194} = 54.29$ ($p = 0.000$).

Thus, the summary of the dependent variable regression for the ^{137}Cs concentration indicates a strong correlation and a high coefficient of determination, suggesting that the model accounts for a substantial portion of the variance in the ^{137}Cs concentrations. Similarly, the summary of the dependent variable regression for the ^{90}Sr concentration shows a strong correlation and a high coefficient of determination, indicating a good fit of the model for predicting the ^{90}Sr concentrations.

In our MANOVA analysis, we present the parameter estimates of the main factors that significantly influenced the distribution of the caesium and strontium radionuclides in the ecosystems, along with their respective β-coefficients, in Table 4.

From these data, it is evident that the distribution of caesium varied significantly depending on the ecosystem type, with the maximum distribution observed in the ruderal ecosystems and the minimum in the psamophytic ecosystems; both β-coefficient values were negative. Additionally, the maximum biomorph value relative to caesium was observed for Pc, also displaying a negative value. Regarding specific plant species, the statistical analysis revealed the maximum caesium distribution for *Achillea millefolium, Helichrysum arenarium*, and *Fragaria vesca*, and the minimum distribution for species such as *Alisma plantago-aquatica, Hypericum perforatum,* and *Glyceria maxima.*

Conversely, the effects of strontium relative to psamophytic and ruderal ecosystems exhibited high negative values compared to the meadow ecosystems, and the β-coefficient values for the Pc biomorph were significantly higher than for Mm. The maximum coefficient values were observed in the statistical analysis for the effects of strontium on

Table 4
The β-coefficient for the main effects impact (ecosystems type, biomorpha and plant species) dependently on the type of the ^{137}Cs and ^{90}Sr radionuclides content.

Effects	Type	^{137}Cs β ± SE	^{90}Sr β ± SE
Ecosystem type	psamophytic	−0.418 ± 0.069	−0.579 ± 0.062
	ruderal	−1.413 ± 0.037	−0.653 ± 0.032
	meadow	0.961 ± 0.051	0.323 ± 0.045
Biomorpha	Pc	−0.534 ± 0.038	0.120 ± 0.033
	Mm	−0.021 ± 0.037	0.036 ± 0.032
Plant species	*Helichrysum arenarium*	0.441 ± 0.037	0.281 ± 0.032
	Calamagrostis epigejos	0.291 ± 0.037	0.048 ± 0.037
	Thymus serpyllum	0.116 ± 0.042	0.442 ± 0.028
	Oenothera biennis	−0.147 ± 0.042	−0.068 ± 0.028
	Trifolium arvense	−0.240 ± 0.032	0.546 ± 0.028
	Artemisia absinthium	0.372 ± 0.022	0.298 ± 0.028
	Berteroa incana	0.176 ± 0.022	−0.066 ± 0.028
	Achillea millefolium	−0.538 ± 0.030	−0.125 ± 0.024
	Fragaria vesca	−0.428 ± 0.030	−0.593 ± 0.027
	Hypericum perforatum	−0.084 ± 0.012	−0.004 ± 0.021
	Poa pratensis	−0.130 ± 0.030	−0.402 ± 0.022
	Alisma plantago-aquatica	−0.038 ± 0.031	−0.058 ± 0.024
	Cicuta virosa	0.108 ± 0.042	0.211 ± 0.026
	Glyceria maxima	0.048 ± 0.022	−0.330 ± 0.023

plant species such as *Trifolium arvense, Fragaria vesca*, and *Thymus serpyllumb*, while the lowest values were found for *Hypericum perforatum* and *Oenothera biennis*, which also displayed negative influence effects.

Thus, the significant differences in the caesium and strontium distribution were observed across the ecosystems, likely influenced by the soil characteristics, vegetation types, and biomorphs. Our data suggests that the ecosystem type played a significant role, with caesium most prevalent in the ruderal ecosystems and least in the psamophytic ecosystems, while strontium effects were notably high in the ruderal and psamophytic ecosystems compared to meadows. We demonstrated the biomorph types showed distinct effects, with the Pc biomorphs having higher impacts on the radionuclide distribution compared to Mm, and the specific plant species exhibited varying radionuclide distribution, suggesting species-specific responses to contamination.

4. Discussion

This study was focused on the analysis of the caesium and strontium isotopes concentrations in the herbaceous phytocenoses within the Dnieper River floodplain ecosystems of northern Ukraine, using the multifactorial analysis of variance to explore the role of various environmental factors, including soil, in shaping the accumulation of these radioisotopes in plant species. This comprehensive analysis unveiled the intricate interactions between the environmental variables and radioisotope uptake, offering critical insights that are essential for the effective environmental management and risk assessment in the region. These findings contribute significantly to understanding the long-term effects of the radionuclide contamination and inform future strategies for addressing environmental challenges in the contaminated ecosystems.

This issue is of global importance and remains highly relevant in the field of the environmental research. The continuing problems associated with the radionuclide contamination, particularly in sensitive ecosystems, highlight the need for continued investigation. Understanding the impact of this contamination, both locally and internationally, is essential for the development of the effective management and remediation strategies. A number of studies have been undertaken in relation to the movement and impact of anthropogenic radionuclides on the environment, with particular reference to the marine and coastal ecosystems. The works of a number of the researchers [1,12,21,37,42] provide significant insights into the movement and impact of the anthropogenic radionuclides in the environment, specifically in the marine and coastal ecosystems. Aarkrog's work (2003) investigates the input of the anthropogenic radionuclides into the world ocean, which is essential for understanding the global contamination patterns. Dovhyi et al. [12] focus on the distribution of ^{137}Cs in the surface layer of the Black Sea in 2017, shedding light on the regional variations of contamination. Gulin et al. [21] assess the secondary radioactive contamination of the Black Sea after the Chernobyl accident, providing the data on recent levels, pathways, and trends of contamination. Kremenchutskii et al. [37] investigate the role of suspended matter in controlling beryllium-7 in the Black Sea, which is important for understanding how various particles influence the displacement of radionuclides.

The studies highlight the diverse applications and implications of the radioisotope research, ranging from soil science to environmental remediation following nuclear events. McLaren's [46] study highlights the versatility of radioactive isotopes as indispensable tools in soil science, demonstrating their ability to unravel complex processes such as nutrient cycling and isotope exchange kinetics. These insights are critical for addressing global challenges such as food security and climate change, and demonstrate the broad applicability of isotopic techniques beyond their traditional uses. In contrast, the studies of Larionova et al. [39] focus on the environmental impact of the radionuclide contamination in the regions affected by nuclear events, providing a detailed understanding of radionuclide behaviour under different geographical and environmental conditions. Larionova et al. [39] highlight the high transfer factors for ^{90}Sr in vegetation such as sagebrush at the Semipalatinsk Test Site (STS) as a result of the local soil and ecological characteristics. These contrasting scenarios highlight the important role of the local environmental factors such as vegetation type, soil properties and water circulation in determining radionuclide behaviour and persistence. The implications of these findings are profound, particularly for the environmental management and forecasting. The results of Larionova et al. [39] contribute to the development of the site-specific remediation strategies for the contaminated regions, addressing the unique local challenges such as radionuclide transfer from soil to plants.

Gulin et al. [21] and Dovhyi et al. [12] reveal that the semi-enclosed seas like the Black Sea experience the prolonged radionuclide retention due to the limited water exchange and interactions with suspended matter. The studies emphasise the importance of radionuclide monitoring for the environmental safety and provide predictive insights essential for managing future nuclear incidents. By advancing understanding of the radionuclide displacement and persistence, these works offer a robust foundation for improving the marine contamination assessments and mitigation strategies. Together, these studies deepen our understanding of the radioactive isotopes in different contexts and highlight their critical role in advancing both environmental science and practical remediation efforts. Their findings not only enhance our ability to manage the contamination, but also contribute to broader scientific and environmental goals, underscoring the importance of the continued research in this field [12,21].

Our findings highlight the complex interplay between various factors, including ecosystem types, soil characteristics, and biomorph types, in determining the ^{137}Cs and ^{90}Sr concentrations in the ecosystems. Understanding these relationships is crucial for the effective management and mitigation strategies in areas affected by the radionuclide contamination.

Firstly, as it is known, the radionuclide transferring to plants depends on many factors that are responsible for their considerable variations observed under field conditions. The dynamics of the decrease of the ^{137}Cs availability in the soil-plant system is considerably influenced by the soil properties [15]. Among the radioactive variants of ^{137}Cs, the anthropogenic ^{137}Cs ($t_{½}$ = 30.16 years) radioisotope is of a significant environmental concern [27], due to its rapid incorporation into biological systems and its emission of the β and γ radiation during the decaying process [68]. However, in contrast to ^{137}Cs, the availability of soil-derived ^{90}Sr to plants exhibits a minimal decline over time [62], indicating that the ageing effect is more pronounced for ^{137}Cs than for ^{90}Sr.

Zarubina et al. [82] demonstrated the presence of a ^{137}Cs retention mechanism in fungi, which contributes to prolonged contamination of their woody plant symbionts. This finding underscores the pivotal role of fungal associations in amplifying the longevity of radionuclides within forest ecosystems. Furthermore, the outer bark of *Pinus sylvestris* was identified as a long-term source of ^{137}Cs, continuously releasing the radionuclide into the forest litter. In contrast, the moss *Dicranum polysetum* did not exhibit seasonal variation in ^{137}Cs accumulation, which may be attributed to its specific physiological characteristics that enable stable radionuclide uptake and retention. These findings underscore the importance of accounting for seasonal dynamics in the distribution of ^{137}Cs when conducting environmental monitoring and risk assessments in contaminated forested areas. The combined effect of seasonal variability and species-specific retention mechanisms can significantly influence radionuclide cycling and bioavailability across trophic levels. Furthermore, recent studies in birch–Scots pine forest ecosystems have demonstrated that strontium-90 (^{90} Sr) tends to accumulate to a greater extent than ^{137}Cs [41], suggesting radionuclide-specific behaviours that must be considered in ecological impact assessments.

The basic mechanism of the ^{90}Sr absorption by soil is the ion exchange [22]. The strontium uptake by plants, in general, is the greatest of soils of a low calcium content and, in many cases, of a high organic matter content [6,59]. The strontium content can differ by more than a factor of 100, depending on the soil properties and biological features of plants. A decrease in the exchangable strontium in soil does occur, but only very slowly [62].

Secondly, our study of the soil and plant ecosystems in northern Ukraine, specifically within the Dnieper floodplain, revealed the significant findings regarding the radionuclide absorption. Our findings indicated that the rate of the radionuclide absorption is primarily influenced by the biological characteristics of the individual plant species concerned. Additionally, we observed the influence of soil type and other abiotic factors when comparing the radionuclide concentrations present in the soils and plant samples from various floodplain ecosystems. This underscores the complex interplay between the biological and environmental factors in shaping a radionuclide uptake. By assessing the levels of radioisotopes in the plants of this region, our study provides the essential data to improve our understanding of how these environmental changes affect ecological quality. This information is important for assessing the long-term effects of the contamination and for developing the strategies to address the challenges posed by such environmental changes [66].

The soil-to-plant transfer coefficient (TF) which varies with the type of a plant, soil characteristics, agricultural fertilizer management, manure application, climate, and the physical and chemical properties of the radionuclides [54], is considered as one of the important parameters used for the environmental safety assessment.

In Figs. 6, 7 one can see the difference in the TFs mean values, which are 0.15–0.97 for ^{137}Cs and 0.10–0.92 for ^{90}Sr. The comparison of the ^{137}Cs and ^{90}Sr TFs for the same plant species testified that for 7 plant species (*Thymus serpyllum*, *Trifolium arvense*, *Artemisia absinthium*, *Cichorium intybus*, *Achillea millefolium*, *Alisma plantago-aquatica*, *Cicuta virosa*) the ^{90}Sr TF exceeds this indicator for ^{137}Cs, for 4 plant species (*Verbascum lychnitis*, *Hypericum perforatum*, *Vicia cracca*, *Sium latifolium*) the values of the ^{137}Cs and ^{90}Sr transfer factors are very close, and for 9 plant species (*Helichrysum arenarium*, *Calamagrostis epigejos*, *Oenothera biennis*, *Berteroa incana*, *Echium vulgare*, *Fragaria vesca*, *Poa pratensis*, *Glyceria maxima*, *Stachys palustris*) the ^{137}Cs TF exceeds the ^{90}Sr TF.

The study results of the ^{137}Cs and ^{90}Sr transfer from soil to annual cereals and vegetable crops testified that the TF of ^{90}Sr were higher than those of ^{137}Cs [18,2,26,35,56,74]. Therefore ^{90}Sr rather than ^{137}Cs might be the limiting radionuclide concerning the use of the contaminated land for agricultural crops production [18]. It is worth emphasizing that such a difference in the soil-to-plant transfer factors of ^{137}Cs and ^{90}Sr was discovered during exploring the agroecosystems.

In addition to our data on higher values of the ^{137}Cs TF than the ^{90}Sr TF for the same plant species from one sample, there are the research results that prove a significant discriminatory effect of the potassium ions on the absorption of ^{137}Cs by grass: the TF values for ^{137}Cs are two times higher than the ^{90}Sr TF for most cases [69]. The mean values of the ^{137}Cs and ^{90}Sr TFs from soil to grass were determined in the grass samples taken at 10 points in the meadows of the Bug river floodplain.

Many parameters influence the processes of the radionuclide transfer from soil to plants. These parameters are related to the plant, soil, radionuclide, climate and time [5,19]. Guillén et al. [20] point out that there are many factors that can affect the radiocaesium transfer to plants, such as the considered plant species, its habitat, climatic conditions, type of soil (clay content, physico-chemical characteristics, organic matter, use of amendments, etc.). At the same time Nisbet and Woodman [53] statistically proved that the TF for radiocesium could not generally be predicted as a function of the climatic region, type of experiment, age of contamination, or soil characteristics. Besides in a semi-natural ecosystem of the alpine pasture a statistically significant correlation between the soil and plant concentration of ^{90}Sr was not detectable [64].

The study of Sarap et al. [63] concluded that the soil-to-plant transfer factors for ^{90}Sr and ^{137}Cs vary depending on the type of the plant and soil characteristics, as observed. It was further demonstrated that different plants exhibit varying abilities to accumulate these radionuclides, with specific plants showing higher transfer factors for certain isotopes. The necessity of taking into account plant species and soil properties in assessing the radionuclide mobility, and the potential impact on the environment, is thus emphasized.

In our opinion, to explain the difference in the transfer factors of ^{137}Cs and ^{90}Sr it is very important to understand that the processes in the rhizosphere differ from the processes in the bulk of the soil, which is associated with the presence of plant roots and the activity of soil microorganisms [5]. This is also one of the important factors affecting the transfer of radionuclides from soil to plants. The absorption of radionuclides by plants is also influenced by their structural and functional properties [5], as well as their biochemical peculiarities and ontogenetic state. Therefore, determining the peculiarities of the transfer of the radionuclides from soil to plants depending on their species-specific characteristics requires further research.

It was confirmed via the TF that the mean values (especially for ^{137}Cs) differ within the same ecosystem (except for ^{137}Cs in the marsh ecosystem) and close values for the plants in different ecosystems. For example, the group of plants with high TF values (in the range of 0.85–0.97) includes: *Helichrysum arenarium* (the psamophytic phytocenose), *Berteroa incana* (the ruderal phytocenose), *Hypericum perforatum*, *Poa pratensis*, *Vicia cracca* (the meadow phytocenose), *Cicuta virosa* (the marsh phytocenose). This emphasized once again that the rate of absorption of the radionuclides primarily depends on the biological characteristics of a particular plant species. The influence of the soil type and other abiotic factors is clearly observed when comparing the values of the radionuclide content in soils (as shown in Table 1) and plant samples of various floodplain ecosystems (Table 2, 3). The researchers, namely Yu and Mao [80], Vilic et al. [78], Gembal et al. [16], and Machraoui et al. [43], engage in a discourse on the regulatory framework governing the permissible levels of radioisotopes in the environment and their repercussions on public health. They underscore the significance of systematic monitoring and management of risks associated with the radioactive contamination.

Thirdly, our analysis of the data reveals several significant findings regarding the dependencies between variables, particularly in relation to the ^{137}Cs and ^{90}Sr concentrations in different ecosystems. The largest influence the ^{137}Cs activity concentration is observed in soil, with the β-coefficient as $\beta = 2.047 \pm 0.179$ ($p = 0.000$), emphasizing the significant role of soil characteristics in determining the ^{137}Cs levels. Conversely, for the soil ^{90}Sr concentrations, the β-coefficient is negative at β= -0.939 ± 0.138 ($p = 0.000$), implying an inverse relationship between the soil Sr content and other variables.

The significant differences in the distribution of the caesium and strontium radionuclides across various ecosystems were observed, suggesting variability potentially stemming from soil characteristics, vegetation types, and biomorphs. The type of the ecosystem appeared to have a substantial influence on the radionuclide distribution, with caesium being most prevalent in the ruderal ecosystems and least in pthe samophytic ecosystems, while for the strontium effects relative to the psamophytic and ruderal ecosystems exhibited notably high negative values compared to the meadow ecosystems. Depending on the absolute content of the ^{137}Cs radioisotope (as its content increases in plants and soil), the following series can be constructed for the Dnieper river floodplain: the ruderal ecosystem – the psamophytic ecosystem – the meadow ecosystem – the marsh ecosystem. For radiostrontium, the ruderal and marsh ecosystems hold their positions in a similar series.

Fourthly, our data consistent with the explanations for the reasons of different radionuclide contents in plants of different ecosystems of the floodplain depending on their proximity to the river bed: the differences in the radionuclide migration in the floodplain soils and their input into plants are determined by the relationship between the processes of their immobilization and migration with soil water [51]. Molchanova et al. [51] testified that the radionuclide distribution across the floodplain and along the river flow is determined by the formation of a barrier to their migration near the river channel, at which less mobile ^{137}Cs accumulates. The soil and plant cover of the central part of the Dnieper river floodplain, in particular psamophytic and marsh ecosystems (Figs. 3, 4), is enriched with ^{90}Sr.

The differences in the radionuclide fixation capacity of floodplain soils are reflected in the radionuclide uptake by plants [51]. As it has been already noted, in the Dnieper river floodplain, the studied meadow phytocenosis was formed on the site with meadow gleyed sandy soils enriched with nutrients. The meadow ecosystems together with the marsh ecosystems take the lead by the radiocaesium accumulation in soil and plants. In terms of the radiostrontium accumulation, they are inferior to the psamophytic ecosystems. The research conducted in the Shatsk National Natural Park indicates that the radionuclides contamination of the sod-less podzolic sand soil and the sod loamy sandy gleyed loamy sand soil are similar: the ^{137}Cs content slowly increases down to a depth of 0.12–0.13 m, and then an almost exponential decrease is observed at larger depths [25]. The analysis of the ^{137}Cs activity concentration of plants of large-sedimented, turf, coarse-grained and fine-grained meadow types shows that the greatest activity concentration of plant samples over the 5 years of observation was noticed in the meadow type with large leaves, which is 4 times more than in a fine-grained meadow. The decrease in the radioactive contamination of plants occurred with a simultaneous decrease in the density of the radioactive contamination of the soil [10].

The study of the pasture plants in northern Germany indicated that the ^{137}Cs and ^{90}Sr root uptake were controlled by their concentrations in soil water which were reported to increase at the reduced soil moistures [31]. The researchers [71] of the "the radiocaesium contamination of meadow vegetation – time – variability and influence of soil characteristics at meadow sites" problem in Austria, generalizing the results of the previous researchers, note that after the accident at the Chernobyl nuclear power plant, it became obvious that compared to arable land, the movement of soil-plant on meadows was higher, and the ecological half-life of radiocaesium in meadow ecosystems was greater than in the intensively used agroecosystems. The reasons for these differences are seen in the nutrient cycling in perennial meadow plants and environmental conditions characterized by lower pH, higher topsoil organic matter, and lower plant nutrient availability [13]. In the Dnieper river floodplain the ruderal ecosystems were until recently used for agricultural purposes.

The samples of the soil and plants collected from the marsh ecosystem in the Dnieper river floodplain are characterized by high levels of both ^{137}Cs and ^{90}Sr (Table 1–3). The study of the natural radionuclides transferring from soils to plants in a marsh showed that high concentration levels in plants are coincident with a high concentration in soils as well [44]. The soil-to-plant transfer of plants in the marsh ecosystems factor meaning has high values in a narrow range: for ^{137}Cs – from 0.77 to 0.85, for ^{90}Sr – from 0.5 to 0.92 (Figs. 6, 7).

Furthermore, significant differences in the radionuclide distribution were noted based on the biomorph types, with higher β-coefficient values observed for the polycarpic biomorph compared to monocyclic monocarpic, indicating potentially greater impact on the radionuclide distribution. Specific plant species also exhibited markedly different levels of radionuclide distribution, with certain species showing the maximum β-coefficient values for radiocaesium or radiostrontium, while others displayed minimum values, often accompanied by the negative influence effects.

Fifthly, our data for the ^{137}Cs dependencies, the β-coefficient indicates a positive connection with the biomorph factor, with a value of 0.267 ± 0.056 ($p = 0.000$), suggesting that changes in the biomorph types lead to corresponding changes in the ^{137}Cs concentrations. When comparing the levels of the plants radionuclide contamination and transfer factors of different biomorphs (polycarpic, dicyclic monocarpic, monocyclic monocarpic), it should be noted that within the same ecosystem, monocarpics in comparison with polycarpics have a definitely lower content of radionuclides. The exception is the content of radiostrontium in *Trifolium arvense* (516.20 ± 24.60 Bq/kg). The research of Srikhumsuk et al. [70] testifies that the representatives of the *Trifolium* genus efficiently accumulate strontium compared to the representatives of the *Poaceae* family (in particular the *Festuca* genus). In the Dnieper river floodplain ecosystem, all representatives of the *Poaceae* family have a low ^{90}Sr content: *Calamagrostis epigejos* (222.50 ± 13.11 Bq/kg), *Poa pratensis* (193.00 ± 20.91 Bq/kg), *Glyceria maxima* (404.60 ± 38.60 Bq/kg).

The strengths of our study are that the preliminary results of this study underscore its importance in improving our understanding of the radionuclide distribution and transfer in ecosystems, providing a sound basis for the future research aimed at improving environmental monitoring and phytoremediation strategies. This research highlights the critical need for ongoing monitoring of the radioisotope concentrations in ecosystems, especially in light of historical use of nuclear technology and potential incidents. Our results provide essential baseline data on the radionuclide transfer to rice plants in the Dnieper river floodplain, which is crucial for assessing the environmental health and identifying the contamination risks. Our study provides valuable insights into the potential for phytoremediation of the radionuclide contaminated soils. Our results suggest that plant species with high transfer factors could be used to sequester radionuclides from the soil. This approach could facilitate the removal of the contaminants from the environment or reduce their concentrations to safer levels, thereby contributing to the effective soil and environmental management strategies. Importantly, that radioactive isotopes such as caesium and strontium can pose significant health risks if they accumulate in the food chain [16]. Understanding their levels in plants, which may be consumed directly or indirectly by humans and animals, is essential for safeguarding public health. Another important aspect concerns with the riparian ecosystems that play vital roles in supporting biodiversity, regulating water quality, and providing ecosystem services [24]. Therefore, monitoring the radioisotope concentrations in plants within these ecosystems helps evaluate their ecological health and informs about conservation and management strategies.

The study has several limitations that should be addressed, despite the valuable insights it provides. A major limitation is the limited range of the ecosystems sampled, which may not fully represent the broader environmental variability in the region. In addition, the focus of the study on specific radionuclides and plant species may not capture the full range of the potential contaminants or ecological interactions. The lack of the long-term monitoring data also limits our ability to assess the temporal dynamics of the radionuclide accumulation and its long-term environmental impact.

The further research should broaden the scope of including a wider range of ecosystems and radionuclides to provide a more comprehensive view of the environmental contamination. Long-term studies are essential to track changes over time and to assess the effectiveness of the remediation strategies. In addition, the study of interactions between different contaminants and plant species will provide a deeper understanding of ecological responses and improve the strategies for the environmental management and protection. The incorporation of the advanced analytical techniques and wider geographical coverage will strengthen the robustness of the further studies in this critical area.

5. Conclusions

The activity concentration in grass stand depends on the floodplain ecosystems type and decrease in the following order: the marsh ecosystem > the meadow ecosystem > the psamophytic ecosystem > the ruderal ecosystem (for ^{137}Cs) and the marsh ecosystem > the psamophytic ecosystem > the meadow ecosystem > the ruderal ecosystem (for ^{90}Sr). According to the soil-to-plant transfer factors values it was confirmed that the rate of absorption of radionuclides depends on the biological characteristics of a particular plant species. Within the same ecosystem, dicyclic and monocyclic monocarpics in comparison with polycarpics have a definitely lower content of radionuclides and the transfer factor value.

The MANOVA analysis revealed statistically significant differences in the levels of the ^{137}Cs and ^{90}Sr radionuclides in both plants and soil across the Dnieper river ecosystems. This analysis highlighted that different ecosystem types had different levels of the contamination, with significant dependencies observed between the ecosystem type and radionuclide content in plants. These results suggested that the radionuclide exposure varies between the ecosystems, possibly due to the differences in the environmental conditions and contamination sources. Furthermore, the regression analysis testified significant correlations between the content of ^{90}Sr in soil and its concentration in plants, indicating the active migration and accumulation processes within the ecosystem. The strong correlation coefficients and coefficients of determination for the ^{137}Cs content further underline a robust relationship between the soil and plant concentrations of this radionuclide. This suggests the effective transfer mechanisms of ^{137}Cs through the food chain, providing insights into the dynamics of the radionuclide distribution and accumulation in ecosystems. These results do not only highlight the complex interactions between the radionuclides and environmental matrices, but also contribute to understanding of how these processes affect the ecosystem health and radionuclide management.

Our analysis identified the significant differences in the distribution of ^{137}Cs and ^{90}Sr in different ecosystems, revealing a complex interconnection between soil characteristics, vegetation types and biomorphs. The study highlighted that the ecosystem type has a significant effect on radionuclide levels, with the caesium concentrations being the highest in the ruderal ecosystems and the lowest in the psamophytic ecosystems. This variation suggests that the ruderal environments, often characterized by the disturbed or altered conditions, may be more conducive to the caesium accumulation. Conversely, the strontium levels were elevated in both ruderal and psamophytic ecosystems compared to meadows, suggesting that these ecosystems may experience different contamination dynamics or have different strontium retention capacities.

Furthermore, the analysis of the biomorph types showed that different biomorphs had different effects on the radionuclide distribution. The polycarpics biomorphs had a greater impact on the radionuclide levels than the monocarpics biomorphs, suggesting that certain biomorphs may play a more significant role in the radionuclide accumulation and distribution. In addition, the study revealed that specific plant species respond differently to the contamination, with different radionuclide distribution patterns observed between species. This species-specific variability highlights the need for targeted approaches to the assessment and management of the radionuclide contamination, as different plant species may have a unique capacity to uptake and retain radionuclides. Overall, these results highlight the importance of considering the ecosystem type, biomorphic characteristics and plant species when understanding and managing the radionuclide distribution and contamination in different environmental contexts.

The differences in the values of the ^{137}Cs and ^{90}Sr transfer factors are due to the landscape and ecological conditions of the environment, soil properties, as well as biomorphological, biochemical, physiological and ontogenetic peculiarities of plants.

The obtained results have provided valuable insights into the patterns of the radionuclide distribution and concentration in the flora of the region, which have informed the future environmental management strategies and risk assessment frameworks, contributing to a better understanding of the long-term environmental impact of the radioactive contamination in northern Ukraine.This study helps to ensure the compliance with these regulations by providing the valuable data that can inform policy makers and researchers about the current levels of radioisotopes. This information is essential for implementing the effective risk mitigation strategies and making informed decisions to manage and reduce the potential environmental and health risks associated with the radioisotope contamination.

Environmental implications

The study area was the most contaminated in the north of Ukraine after the Chernobyl accident. The study plots differed in varying degrees of radiation contamination. During the sample collection and analysis, precautions were taken, in particular: the selection of soil samples was performed with special sampling devices; the selection of plant samples was carried out in protective gloves; the selected samples were placed in a double polyethylene bag; careful labeling and documentation of the selected samples were carried out; decontamination of packaging with samples and their transportation to laboratories; containers free from contamination were always used in laboratory conditions.

CRediT authorship contribution statement

Yakovenko Oleksandr: Visualization, Investigation, Formal analysis, Data curation. **Lukash Oleksandr:** Writing – original draft, Investigation, Data curation, Conceptualization. **Strilets Svitlana:** Supervision, Data curation. **Szikura Anita:** Formal analysis, Data curation. **Tkaczenko Halina:** Software, Methodology. **Miroshnyk Iryna:** Validation, Formal analysis, Data curation. **Kurhaluk Natalia:** Writing – original draft, Project administration, Investigation, Conceptualization.

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The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.jhazmat.2025.138406.

Data Availability

Data will be made available on request.

Accumulation by dominants and co-dominants of the ruderal, psammophytic, marsh and meadow plant communities in the Dnieper River floodplain ecosystem (the Chernihiv Region, northern Ukraine) (Dataverse)

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