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Accumulation of ^{137}Cs and ^{90}Sr radionuclides by dominants and co-dominants of birch-pine forest communities in Northern Ukraine

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Investigation of the post-Chernobyl accumulation of radionuclides in forest communities not only sheds light on the specific ecological aftermath of the disaster but also holds broader significance for enhancing our knowledge of radioactive contamination in natural environments and informing strategies for mitigating its impacts. The study was carried out in an area with soil contamination exceeding the pre-accident level for the isotopes cesium (^{137}Cs, 5.0-15.0 Ci km^{-2}) and strontium (^{90}Sr, 0.15-3.0 Ci km^{-2}) in the Semenivka State Forestry (Chernihiv Region, Northern Ukraine). Four experimental plots with an area of 400 m^2 each were established in a birch-Scots pine forest, where dominant trees, herb and shrub layers, and mosses were analyzed for radionuclide bioaccumulation. Our results indicate a larger accumulation of ^{137}Cs compared to ^{90}Sr in the forest ecosystem. The highest ^{137}Cs and ^{90}Sr accumulation was detected in the fern *Pteridium aquilinum*, and the lowest in *Pinus sylvestris*. Based on our results, we hypothesized that the processes of accumulation and dispersion of ^{137}Cs among the different vegetation layers are more complex compared to ^{90}Sr. MANOVA regression analysis revealed significant differences in the accumulation of radionuclides between different layer levels, plant species and plant parts in the studied forest areas. According β coefficient analysis, both ^{137}Cs and ^{90}Sr are influenced by the site (area type) but in different ways. For ^{90}Sr, the negative β coefficient implies that certain area types are associated with lower Sr accumulation, while for ^{137}Cs the effect of area type may be more complex or context-dependent. These contrasting results suggest that Cs accumulation is more sensitive to changes in layer level compared to Sr. This could be due to differences in the environmental behaviour of these radionuclides, their chemical properties or differences in soil-plant transfer mechanisms. The significant effect of plant species on ^{137}Cs/^{90}Sr accumulation highlights that species-specific characteristics may play a role in radionuclide uptake. Moreover, we found significant differences in ^{137}Cs/^{90}Sr accumulation between different plant parts. Further research on the mechanisms of accumulation and distribution of these radionuclides are essential for better understanding their impact on human health and the environment.

Keywords: Forest Vegetation, *Peucedano-Pinetum*, Polesie, Radioactive Contamination, Radiocesium (^{137}Cs), Radiostrontium (^{90}Sr)

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Introduction

Research on the accumulation of radiocesium (^{137}Cs) and radiostrontium (^{90}Sr) in forest communities has particular significance in the context of the Chernobyl disaster in Ukraine. The Chernobyl nuclear power plant disaster in 1986 resulted in the release of large quantities of radioactive materials into the environment, including ^{137}Cs and ^{90}Sr, which persisted in the ecosystems for decades. Nowadays, the ecological situation in the Ukrainian Polesie forests is complicated by the contamination of a vast area with radionuclides resulting from a mixture of products of nuclear decay and neutron activation (Chernihiv Regional State Administration 2023).

Forests captured more than 80 percent of the Chernobyl-derived radionuclides, the most long-lived being ^{137}Cs, ^{239}Pu, ^{240}Pu, ^{241}Pu, and ^{90}Sr. Forest ecosystems incorporate the radioactive material into their biological processes, moving within woody plants/forest litter and soil/woody plant systems in stable annual cycles (Ipatyev 2001). Most of the radiocesium was initially trapped in the leaves and branches and then transferred to the forest floor through litterfall and rain in the first few years. A small percentage of the total amount of radiocesium in the forest is absorbed from soil by trees and eventually returns to the ground surface as litterfall; in other words, it is cycling in the forest. At present, most of the radiocesium has been transferred to mineral soil, and its circulation in the forest is slow (Hashimoto et al. 2022).

The bioaccumulation of radionuclides by plants may occur by two modes: foliar absorption by plant leaves and shoots, or root uptake from the soil. ^{90}Sr and ^{137}Cs are readily absorbed by leaves, but ^{137}Cs is translocated more into fruits and seeds than ^{90}Sr, as the latter tends to remain in the plant part where it was initially absorbed (Koranda & Robison 1978). Studies have been conducted on the accumulation and distribution of radionuclides in *Pinus sylvestris* (Ohashi et al. 2017, Holiaka et al. 2017, 2020, 2021, Soukhova et al. 2023). The main distribution patterns of radionuclides in the trunk do not significantly change with time (Holiaka et al. 2020). The distribution of ^{137}Cs in *Betula pendula* wood shows a stronger dependence on site characteristics and the longevity of trees compared to *Pinus sylvestris* (Soukhova et al. 2023).

In the Chernihiv region, land contamination is mainly due to the long-lasting radionuclides ^{137}Cs and ^{90}Sr resulting from the Chernobyl disaster. The total area contaminated by ^{137}Cs (above 1 Ci km^{-2}) is 174.72 thousand ha, including forests (102.70 thousand ha) and agricultural land (72.02 thousand ha), while 97% of the area is contaminated by ^{90}Sr above the threshold of 0.02 Ci km^{-2}. More than 19% of state forests are radioactively contaminated, and 11 state forestry farms are contaminated with ^{137}Cs above 1 Ci km^{-2}. All forestry farms are contaminated with ^{90}Sr above 1 Ci km^{-2} (Chernihiv Regional State Administration 2023).

Studying the accumulation of these radionuclides in the forest communities surrounding the Chernobyl Exclusion Zone provides valuable insights into the long-term ecological consequences of nuclear accidents. Forest ecosystems play a crucial role in the retention and redistribution of radionuclides, affecting their transfer to soil, vegetation, wildlife, and ultimately humans through food chains. Therefore, understanding the dynamics of post-Chernobyl radionuclide accumulation in forest ecosystems is essential for assessing the ongoing environmental risks and developing effective management strategies.

This investigation aims to provide knowledge and tools to guide decisions on monitoring and remediation of contaminated areas, as well as to inform land use policies to reduce human radiation exposure. Moreover, studying the accumulation of ^{137}Cs and ^{90}Sr in forest communities provides a better understanding of the mechanisms driving the persistence and mobility of radioactive contaminants in terrestrial environments. This knowledge is crucial for predicting the long-term behavior of radionuclides in similar forest ecosystems affected by nuclear accidents worldwide, contributing to global efforts in nuclear safety and environmental protection.

The mobility and bioavailability of radionuclides of accidental origin in the terrestrial and aquatic environment are affected by both their chemical forms in the fallout and site-specific environmental characteristics, which determine the rate of leaching, fixation-remobilization, and absorption-desorption of the mobile fraction (Beresford et al. 2016).

Pine and birch-pine forests of the *Peucedano-Pinetum* W. Mat. (1962) 1973 association are the most widespread in the Ukrainian Polesie, primarily established on sandy deposits (Lukash et al. 2020). In Scots pine (*Pinus sylvestris* L.) forests, large fractions of total radionuclide depositions can be found in the aboveground biomass and litter (Holiaka et al. 2020). The possibility of economic utilization of forest products in radioactively contaminated areas depends on the compliance of radionuclide activity concentrations in plant tissues with the norms or national standards established by governments or regulators (Holiaka et al. 2020). This highlight the need of considering the different forest stand components (stems, leaves, shoots, roots, fruits, etc.) as repositories of biologically mobile radionuclides such as ^{90}Sr and ^{137}Cs.

The role of plants in monitoring radionuclides serves two purposes: to indicate recent atmospheric releases of radionuclides and to reflect the long-term behavior of aged radionuclide deposits in the soil. (Koranda & Robison 1978). Data on the accumulation of radionuclides in plants of different ecological and taxonomic groups are crucial for understanding the long-term dynamics of radionuclides in the entire forest ecosystem. Special attention should be paid to the radionuclide content in plants with the largest biomass (dominant and co-dominant species).

This study aimed at the analysis of radiocesium and radiostrontium accumulation in forest ecosystems by investigating the differences in the accumulation of radionuclides among different layer levels, plant species, and plant parts within specific forest areas and also evaluate the main effects of the area type, layer level, plant species (dominants and co-dominants of birch-pine forest communities), and plant part on radionuclide accumulation using a modeling approach.

Material and methods

Field research

A preliminary study was carried out in 2015 in areas of soil contamination exceeding the pre-accident level of two radioisotopes: cesium (^{137}Cs, from 5.0 to 15.0 Ci km^{-2}), and strontium (^{90}Sr, from 0.15 to 3.0 Ci km^{-2} – Supreme Rada of Ukraine 1991). The study area is located in the Bleshnya and Orlykivka forestry of the Semenivka State Forestry (Chernihiv Region, Northern Ukraine), which is known to be the most contaminated region in northern Ukraine following the Chernobyl accident.

Four experimental plots (~400 m^2) were selected and georeferenced using a Garmin

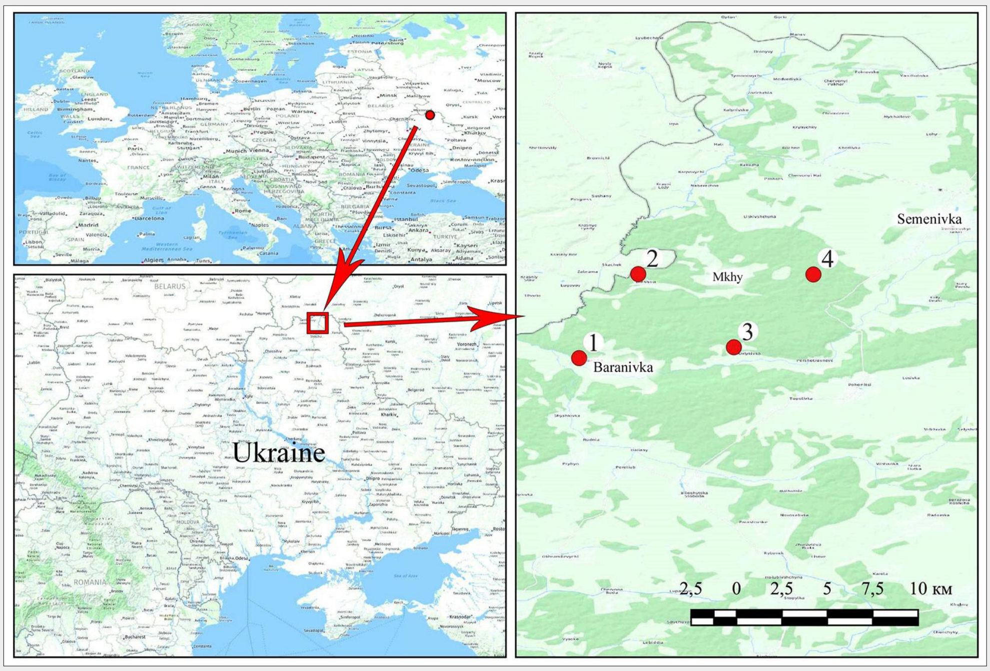

Fig. 1 - Location of experimental plots. (1): Baranivka; (2): Bleshnya; (3): Orlykivka; (4): Mohy.

eTrex™ 10 GPS receiver (Garmin Ltd., Olathe, KS, USA). Soil samples were collected according with the sampling methods for radiation control (Ministry of Agrarian Policy of Ukraine 2006). Soil samples (each about 1 kg) were taken from 10 randomly chosen points in each plot (n=10), combined to obtain one cumulative sample per plot, and then measured for contamination.

All plots were established in birch-pine forests belonging to the *Peucedano-Pinetum* W. Matuszkiewicz (1962) 1973 association of the *Dicrano-Pinion sylvestris* (Libbert 1933) W. Matuszkiewicz 1962 alliance of the *Pinetalia sylvestris* Oberd. 1957 order of the *Vaccinio-Piceetea* Br.-Bl. in Br.-Bl. et al. 1939 class. In all areas, the birch-pine forests were formed on sandy soils. The four experimental plots were homogeneous in terms of age (50-70 years), floristic composition, and structure of phytocoenoses but differed in the levels of soil radiation contamination.

Plot 1 (Baranivka) is located 1.4 km north of Baranivka village on the right-bank pine terrace of the Revna River (52.0689° N, 32.2931° E, 136 m a.s.l. – Fig. 1). Based on the measurements of the radionuclide activity in the collected soil samples, the soil depositions were estimated at 328 ± 21.56 Bq kg^{-1} of ^{37}Cs and 2011 ± 241.47 Bq kg^{-1} of ^{90}Sr.

Plot 2 (Bleshnya) is located 1.0 km north of Bleshnya village on the left-bank pine terrace of the Snov River (52.1361° N, 32.3403° E, 130 m a.s.l. – Fig. 1). The radionuclide activity of the soil samples was 354 ± 26.33 Bq kg^{-1} of ^{37}Cs and 2326 ± 284.28 Bq kg^{-1} of ^{90}Sr.

Plot 3 (Orlykivka) is located 1.2 km north of Orlykivka village on the right-bank pine terrace of the Revna River (52.0776° N, 32.4167° E, 145 m a.s.l. – Fig. 1). The radioactive contamination of the soil samples from this experimental plot is 387 ± 27.82 Bq kg^{-1} of ^{37}Cs and 927 ± 178.23 Bq kg^{-1} of ^{90}Sr.

Plot 4 (Mohy) is located 2.8 km east of Mohy village on the right-bank pine terrace of the Revna River (52.0776° N, 32.4167° E, 145 m a.s.l. – Fig. 1). The contamination in the soil was 380 ± 25.12 Bq kg^{-1} of ^{37}Cs. The ^{90}Sr activity in the soil was 1003 ± 221.16 Bq kg^{-1} of ^{90}Sr.

Vegetation sampling

The vegetation relevés were taken during the optimum vegetation period (Jun-Aug 2015). The forest layers and the projective coverage of trees and understory species in each plant community was determined according to Yakubenko et al. (2018). Syntaxa were identified according to Matuszkiewicz (2023).

Plant material for radiological analysis was collected from each plot. The tree layer was primarily dominated by *Betula pendula* Roth and *Pinus sylvestris* L., covering 40%-60% of the area. In the shrub layer, *Frangula alnus* Mill. was the dominant species, making up 30%-40% of the coverage, while *Pteridium aquilinum* (L.) Kuhn was a co-dominant species, accounting for 15%-20% of the cover in the herb layer. In the dwarf shrub layer, *Vaccinium myrtillus* L. was dominant (covering 40-60%) and *Calluna vulgaris* (L.) Hill co-dominant (15-20%). The plant community was also characterized by a moss layer with a projective cover of 50-75%. In this layer, *Pleurozium schreberi* (Willd. ex Brid.) Mitt. was the dominant species covering 40-65%, while *Ptilium crista-castrensis* (Hedw.) De Not. was co-dominant, accounting for 10-15%. All dominant and co-dominant species were selected for further analyses (Fig. 2).

In each experimental plot, samples of vegetative plant organs were collected in 10 replicates for each component within a species. Ten samples were taken from each compartment, and one sample was obtained from each individual plant (Ukrainian Scientific Research Institute of Agricultural Radiology 1997). The ^{137}Cs content determination in the plant samples and soil was performed using a Gamma plus U spectrometer (Expert Center, Russia), whereas the ^{90}Sr content determination was carried out with a radiometric ending at α-β detector CANBERRA-2400® (Mirion Technologies Inc., Atlanta, GA, USA).

Statistical analysis

The Statistica v. 13.3 package (TIBCO Software, Palo Alto, CA, USA) was used for statistical analysis and the results were expressed as means ± standard deviation. Significant differences between the means were determined using a multiple-range test, with p-values < 0.05 considered significant. The data were tested for homogeneity of variance using Levene's test, and normality was checked with the Kolmogorov-Smirnov test.

Differences in the accumulation of radionuclides (in terms of ^{137}Cs/^{133}Cs ratios) among different layer levels, plant species (including *Betula pendula* Roth, *Pinus sylvestris, Frangula alnus, Pteridium aquilinum, Vaccinium myrtillus. Calluna vulgaris, Pleurozium schreberi*, and *Ptilium crista-castrensis*), and plant parts in the four plots were analyzed using four-way ANOVA and Tukey's *post-hoc* test. The application of multivariate significance tests for the main effects (plot type, layer level, plant species, and plant part) on radionuclide accumulation enabled to estimate the mean value of the dependent variable, the main effect, and the experimental random error using the F-test. We have also used the concept of the maximum permissible specific activity (MPSA, 100%) as a point of reference for our comparisons. The multiple correlation coefficient (R), the coefficient of determination (R^2), and its corrected form reduced by random errors (R^2 adjusted) were obtained from MANOVA analysis. For each predictor variable (area, layer level, plant species, and plant part), the beta coefficient (β) of a regression model was used to indicate the magnitude and direction of its effect on the dependent variables (accumulation of ^{137}Cs and ^{90}Sr radionuclides).

Results

The ^{137}Cs and ^{90}Sr specific activity in the plant samples and its dependence on the layer level, plant species (*Betula pendula, Pinus sylvestris, Frangula alnus, Pteridium aquilinum, Vaccinium myrtillus, Calluna vulgaris, Pleurozium schreberi*, n=10), and plant part in the experimental plots Baranivka (1), Bleshnya (2), Orlykivka (3), and Mohy (4) are presented in Tab. 1, Tab. 2, Tab. 3 and Tab. 4, respectively.

The comparative analysis showed that

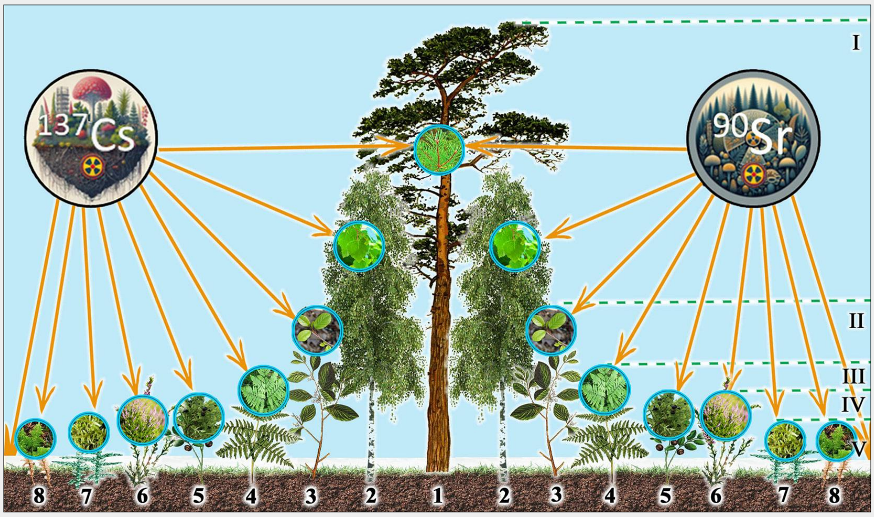

Fig. 2 - Plant species included in the study and their allocation by layers. Plant species: 1 - *Pinus sylvestris*, 2 - *Betula pendula*, 3 - *Frangula alnus*, 4 - *Pteridium aquilinum*, 5 - *Vaccinium myrtillus*, 6 - *Calluna vulgaris*, 7 - *Pleurozium schreberi*, 8 -*Ptilium crista-castrensis*. Phytocenosis layers: I - tree layer , II - shrub layer , III - herb layer, IV - dwarf shrub layer, V - mosses layer. The circles show parts of plants that were selected for radiological analysis.

the highest ^{137}Cs specific activity was recorded in the *Frangula alnus* plant samples in plot 3, with a mean value of 352.00 ± 40.07 Bq kg^{-1} (Tab. 3). This value exceeds the maximum permissible specific activity (MPSA) by 76% (Fig. 3). It should be noted that the ^{137}Cs MPSA for vegetable raw materials is 200 Bq kg^{-1} (Supreme Rada of Ukraine 2008).

Radiostrontium (^{90}Sr) exhibited a higher bioaccumulation in plant tissues than ^{137}Cs. This confirms the findings obtained by previous studies showing that pharmaceutical tree and shrub plants exhibited much stronger accumulation of strontium than cesium (Solecki et al. 2003). The comparative analysis showed the highest value of ^{90}Sr accumulation in the vegetative organs of *Pteridium aquilinum* and mosses in the experimental plots 1 and 2 (Tab. 1, Tab. 2). The highest ^{90}Sr specific activity was recorded in the *Pteridium aquilinum* plant samples in plot 2 (2860.00 ± 378.49 Bq kg^{-1} – Tab. 2). The ^{90}Sr MPSA threshold for vegetable raw materials is 500 Bq kg^{-1} (Supreme Rada of Ukraine 2008). The highest excess of the ^{90}Sr MPSA was observed in *Pteridium aquilinum* from plot 2, equalling 372% of the threshold (Fig. 4). In the herb layer, the excess of ^{137}Cs MPSA in the leaves of the co-dominant fern *Pteridium aquilinum* was estimated to be between 7.5% and 21.5% across samples from all plots.

The lowest ^{90}Sr specific activity (212.00 ± 26.15 Bq kg^{-1}) was recorded in the *Frangula alnus* branches with leaves in plot 3 (Tab. 3). It should be noted that ^{90}Sr specific activity of 39.4 Bq kg^{-1} was observed in *Frangula alnus* cortex from the Lublin (Poland) region (Solecki et al. 2003). For comparison, this is more than 10 times less than the ^{90}Sr specific activity in *Viola tricolor* L. flowers collected in this region. The high bioaccumulation of radionuclides detected for *Frangula alnus* might be a species-specific characteristic, but further studies are needed to confirm this result.

The tree layer dominants (*Pinus sylvestris* and *Betula pendula*) were minimally contaminated with radiostrontium. A slight excess (2%) of the ^{90}Sr MPSA was found in plot 2 in the *Pinus sylvestris* branches with needles. The deviation (62%-73.4%) from the ^{90}Sr MPSA (Fig. 4) is smaller in the *Vaccinium myrtillus* shoots compared to the *Calluna vulgaris* shoots. Schmidt et al. (2023) carried out a study on the radionuclide accumulation in Bryophytes in the Chernobyl Exclusion Zone, showing that the ^{90}Sr uptake behaviour in mosses is counterintuitive and not affected by the presence or lack of vascular tissue. In this study, we obtained similar values of ^{90}Sr specific activity in both moss species (*Pleurozium schreberi* and *Ptilium crista-castrensis*) within the same experimental plot for all the plots. In Bryophytes, an excess of the ^{90}Sr MPSA in the range of 56%-328% was observed in all the plots (Fig. 4).

Both ^{90}Sr and ^{137}Cs are readily absorbed by plant leaves. However, ^{137}Cs is more likely translocated into fruits and seeds compared to ^{90}Sr, which tends to remain in the plant part where it was initially absorbed. The uptake of these radionuclides from soil to root is conditioned by soil chemical and physical factors, which may selectively retain a radionuclide, such as ^{137}Cs. The presence of organic matter, inorganic colloids (clay), and competing elements can strongly affect the uptake of radiostrontium and radiocesium by plants from the soil.

MANOVA analysis

The results of MANOVA showed significant differences in the $^{137}Cs/^{90}Sr$ ratio among the different layer levels, plant species, and plant parts among the specified forest areas.

In the case of the ^{137}Cs bioaccumulation, the MANOVA yielded a significant F-ratio ($F_{[4, 315]}$ = 172.64, p<0.001), indicating that the relationship between the dependent variable (^{137}Cs accumulation) and the predictors (area type, layer level, plant species, and plant part) is highly significant. Moreover, the MANOVA results revealed a high multiple correlation coefficient (R = 0.829), which indicates that approximately 82.87% of the variance in the dependent variable can be explained by the combination of the predictor variables. The coeffi-

Tab. 1 – The accumulation of ^{137}Cs and ^{90}Sr radionuclides (in Bq kg^{-1}) in plot 1 according to layer, species and plant part in Bleshnya and Orlykivka forests of the Semenivka State Forestry (Chernihiv Region, Northern Ukraine). The mean ± standard error (SE) are presented (n = 10). Significant differences (p<0.05) of each mean with other plant species groups after *post-hoc* Tuckey test are indicated by numbers in superscript. Plant species groups: [1] *Betula pendula* and *Pinus sylvestris;* [2] *B. pendula* and *Frangula alnus;* [3] *B. pendula* and *Pteridium aquilinum;* [4] *B. pendula* and *Vaccinium myrtillus;* [5] *B. pendula* and *Calluna vulgaris;* [6] *B. pendula* and *Pleurozium schreberi;* [7] *B. pendula* and *Ptilium crista-castrensis;* [8] *Pinus sylvestris* and *F. alnus;* [9] *P. sylvestris* and *P. aquilinum;* [10] *P. sylvestris* and *V. myrtillus;* [11] *P. sylvestris* and *C. vulgaris;* [12] *P. sylvestris* and *P. schreberi;* [13] *P. sylvestris* and *P. crista-castrensis;* [14] *F. alnus* and *P. aquilinum;* [15] *F. alnus* and *V. myrtillus;* [16] *F. alnus* and *C. vulgaris;* [17] *F. alnus* and *P. schreberi;* [18] *F. alnus* and *P. crista-castrensis;* [19] *P. aquilinum* and *V. myrtillus;* [20] *P. aquilinum* and *C. vulgaris;* [21] *P. aquilinum* and *P. schreberi;* [22] *P. aquilinum* and *P. crista-castrensis;* [23] *V. myrtillus* and *C. vulgaris;* [24] *V. myrtillus* and *P. schreberi;* [25] *V. myrtillus* and *P. crista-castrensis;* [26] *C. vulgaris* and *P. schreberi;* [27] *C. vulgaris* and *P. crista-castrensis;* [28] *P. schreberi* and *P. crista-castrensis.*

Radio nucl.	Layer	Plant species	Plant part	Mean ± SE	Min	Max	Variance	Skewness
^{137}Cs	Tree	-	branches with leaves	135.00 ± 13.47	112	154	181.56	-0.32
	Tree	*Pinus sylvestris*	branches with needles	95.00 ± 12.99 [1]	81	123	168.67	1.30
	Shrub	*Frangula alnus*	branches with leaves	296.00 ± 27.05 [2,8]	251	329	731.78	-0.54
	Herb	*Pteridium aquilinum*	leaves	215.00 ± 22.52 [3,9,14]	184	252	507.11	0.23
	Dwarf shrub	*Vaccinium myrtillus*	shoots	210.00 ± 23.66 [4,10,15]	180	252	559.78	0.50
	Dwarf shrub	*Calluna vulgaris*	shoots	223.00 ± 25.95 [5,11,16]	186	264	673.56	0.32
	Mosses	*Pleurozium schreberi*	caulidia with philidia	223.00 ± 30.70 [6,12,17]	187	277	942.22	0.68
	Mosses	*Ptilium crista-castrensis*	caulidia with philidia	132.00 ± 15.48 [13,28]	113	158	239.56	0.47
^{90}Sr	Tree	*Betula pendula*	branches with leaves	1050.00 ± 94.72	920	1220	8972.22	0.64
	Tree	*Pinus sylvestris*	branches with needles	450.00 ± 51.69 [1]	365	535	2672.22	0.27
	Shrub	*Frangula alnus*	branches with leaves	670.00 ± 84.75 [2,8]	545	805	7183.33	-0.01
	Herb	*Pteridium aquilinum*	leaves	2364.00 ± 341.20 [3,9,14]	1864	2765	116417.67	-0.39
	Dwarf shrub	*Vaccinium myrtillus*	shoots	1210.00 ± 213.25 [4,10,15,19]	896	1470	45477.11	-0.53
	Dwarf shrub	*Calluna vulgaris*	shoots	1520.00 ± 217.96 [5,11,16,20,23]	1194	1875	47505.56	0.24
	Mosses	*Pleurozium schreberi*	caulidia with philidia	2005.00 ± 256.20 [6,12,17,24,26]	1647	2520	65639.78	0.81
	Mosses	*Ptilium crista-castrensis*	caulidia with philidia	1884.00 ± 230.25 [7,13,18,25,27]	1574	2225	53016.89	0.19

Tab. 2 – The accumulation of ^{137}Cs and ^{90}Sr radionuclides (in Bq kg^{-1}) in plot 2 according to layer, species, and plant part in Bleshnya and Orlykivka forests of the Semenivka State Forestry (Chernihiv Region, Northern Ukraine). The mean ± standard error (SE) are presented (n = 10). Significant differences (p<0.05) of each mean with other plant species groups after *post-hoc* Tuckey test are indicated by numbers in superscript. For plant species groups, see Tab. 1.

Radio nucl.	Layer	Plant species	Plant part	Mean ± SE	Min	Max	Variance	Skewness
^{137}Cs	Tree	*Betula pendula*	branches with leaves	160.00 ± 15.55	127	180	241.88	-1.15
	Tree	*Pinus sylvestris*	branches with needles	125.00 ± 11.15[1]	108	143	124.22	0.24
	Shrub	*Frangula alnus*	branches with leaves	320.00 ± 28.21[2,8]	289	374	795.78	0.70
	Herb	*Pteridium aquilinum*	leaves	236.00 ± 30.32[3,9,14]	194	284	919.56	0.23
	Dwarf shrub	*Vaccinium myrtillus*	shoots	179.00 ± 16.48[4,10,15,19]	147	201	271.56	-0.62
	Dwarf shrub	*Calluna vulgaris*	shoots	165.00 ± 14.79[5,11,16,20,23]	132	182	218.89	-1.22
	Mosses	*Pleurozium schreberi*	caulidia with philidia	142.00 ± 24.70[6,17,21,26]	115	178	610.22	0.44
	Mosses	*Ptilium crista-castrensis*	caulidia with philidia	144.00 ± 16.70[7,13,18,22,28]	114	172	278.89	-0.33
^{90}Sr	Tree	*Betula pendula*	branches with leaves	1200.00 ± 296.64	830	1600	87993.56	-0.19
	Tree	*Pinus sylvestris*	branches with needles	510.00 ± 76.16[1,]	385	738	4307.45	0.36
	Shrub	*Frangula alnus*	branches with leaves	684.00 ± 80.04[2,8]	564	819	6406.44	0.52
	Herb	*Pteridium aquilinum*	leaves	2860.00 ± 378.49[3,9,14]	2380	3393	143256.00	0.37
	Dwarf shrub	*Vaccinium myrtillus*	shoots	1367.00 ± 222.37[4,10,15,19]	1006	1715	49448.89	0.16
	Dwarf shrub	*Calluna vulgaris*	shoots	1734.00 ± 223.66[5,11,16,20,23]	1394	2074	50026.00	0.15
	Mosses	*Pleurozium schreberi*	caulidia with philidia	2141.00 ± 317.84[6,12,17,21,24,26]	1702	2563	101022.90	-0.18
	Mosses	*Ptilium crista-castrensis*	caulidia with philidia	1985.00 ± 370.23[7,13,18,22,25,27,28]	1390	2610	137068.90	0.05

cient of determination R^2 was approximately 68.67%; however, after correction of the degrees of freedom for the number of predictors and sample size, the adjusted R^2 value was 0.683, *i.e.*, 68.28% of the total variance was explained by the combination of predictor variables.

Regarding ^{90}Sr bioaccumulation, the results yielded a significant F-ratio ($F_{[4, 315]}$ = 30.607, p<0.001), indicating a significant relationship between the predictors and the dependent variable. The multiple correlation coefficient (R) was 0.529, while the coefficient of determination R^2 was 0.279 and the adjusted R^2 was 0.271, suggesting that approximately 27.1% of the variance in the dependent variable can be explained by the combination of predictors.

The beta coefficients of the regression analysis indicated the magnitude and direction of the effect of the different predictor variables (area type, layer level, plant species, and plant part) on radionuclide accumulation. In the case of ^{137}Cs, the layer level (β = 2.601 ± 0.159, p < 0.001), the plant species (β = -0.429 ± 0.151, p = 0.005) and the plant part (β = -2.456 ± 0.101, p < 0.001) showed a significant impact on the accumulation of radiocesium in the studied forest biocoenoses. Regarding the ^{90}Sr bioaccumulation, the only significant coefficient was found for the area type (β = -0.425 ± 0.048, p < 0.001).

Tab. 3 – The accumulation of ^{137}Cs and ^{90}Sr radionuclides (in Bq kg^{-1}) in plot 3 according to layer, species, and plant part in Bleshnya and Orlykivka forests of the Semenivka State Forestry (Chernihiv Region, Northern Ukraine). The mean ± standard error (SE) are presented (n = 10). Significant differences (p<0.05) of each mean with other plant species groups after *post-hoc* Tuckey test are indicated by numbers in superscript. For plant species groups, see Tab. 1.

Radio nucl.	Layer	Plant species	Plant part	Mean ± SE	Min	Max	Variance	Skewness
^{137}Cs	Tree	*Betula pendula*	branches with leaves	204.00 ± 22.66	169	244	513.56	0.13
	Tree	*Pinus sylvestris*	branches with needles	73.00 ± 8.25[1]	610	860	68.00	0.16
	Shrub	*Frangula alnus*	branches with leaves	352.00 ± 40.07[2,8]	286	412	1605.78	-0.35
	Herb	*Pteridium aquilinum*	leaves	243.00 ± 28.42[3,9,14]	205	297	807.78	0.29
	Dwarf shrub	*Vaccinium myrtillus*	shoots	198.00 ± 21.65[10,15]	156	232	468.89	-0.36
	Dwarf shrub	*Calluna vulgaris*	shoots	154.00 ± 21.21[5,11,16,20,23]	118	179	450.00	-0.61
	Mosses	*Pleurozium schreberi*	caulidia with philidia	135.00 ± 19.69[6,12,17,21,24]	109	171	387.78	0.50
	Mosses	*Ptilium crista-castrensis*	caulidia with philidia	138.00 ± 19.68[7,13,18,22,25,28]	113	169	387.11	0.28
^{90}Sr	Tree	*Betula pendula*	branches with leaves	402.00 ± 51.94	315	482	2697.78	-0.28
	Tree	*Pinus sylvestris*	branches with needles	461.00 ± 58.20[1]	345	532	3387.56	-0.64
	Shrub	*Frangula alnus*	branches with leaves	212.00 ± 26.15[2,8]	180	255	683.78	0.43
	Herb	*Pteridium aquilinum*	leaves	728.00 ± 105.22[3,9, 4]	562	865	11071.11	-0.61
	Dwarf shrub	*Vaccinium myrtillus*	shoots	415.00 ± 60.50[4,10,15,19]	325	510	3660.44	-0.01
	Dwarf shrub	*Calluna vulgaris*	shoots	578.00 ± 77.85[5,11,16,23]	452	701	6060.89	-0.13
	Mosses	*Pleurozium schreberi*	caulidia with philidia	790.00 ± 82.50[6,12,17,21,24,26,]	650	945	6805.56	0.21
	Mosses	*Ptilium crista-castrensis*	caulidia with philidia	780.00 ± 67.33[7,13,18,22,25,27,28]	632	848	4534.00	-0.59

Tab. 4 - The accumulation of ^{137}Cs and ^{90}Sr radionuclides (in Bq kg^{-1}) in plot 4 according to layer, species, and plant part in Bleshnya and Orlykivka forests of the Semenivka State Forestry (Chernihiv Region, Northern Ukraine). The mean ± standard error (SE) are presented (n = 10). Significant differences (p<0.05) of each mean with other plant species groups after *post-hoc* Tuckey test are indicated by numbers in superscript. For plant species groups, see Tab. 1.

Radio nucl.	Layer	Plant species	Plant part	Mean ± SE	Min	Max	Variance	Skew-ness
^{137}Cs	Tree	*Betula pendula*	branches with leaves	212.00 ± 23.99	187	268	575.33	1.48
	Tree	*Pinus sylvestris*	branches with needles	146.00 ± 15.25 [1]	123	165	232.44	-0.19
	Shrub	*Frangula alnus*	branches with leaves	348.00 ± 34.18 [2, 8]	286	409	1168.44	-0.13
	Herb	*Pteridium aquilinum*	leaves	228.00 ± 31.04 [3, 9, 14]	186	274	963.56	0.27
	Dwarf shrub	*Vaccinium myrtillus*	shoots	206.00 ± 27.38 [4, 10, 15, 19]	168	243	749.56	-0.07
	Dwarf shrub	*Calluna vulgaris*	shoots	177.00 ± 23.36 [11, 16, 20]	138	213	545.78	-0.11
	Mosses	*Pleurozium schreberi*	caulidia with philidia	133.00 ± 13.16 [6, 17, 21, 24, 26]	114	151	173.11	0.10
	Mosses	*Ptilium crista-castrensis*	caulidia with philidia	141.00 ± 18.32 [7, 13, 18, 22, 25, 28]	112	173	335.56	0.06
^{90}Sr	Tree	*Betula pendula*	branches with leaves	456.00 ± 54.11	380	528	2927.78	-0.60
	Tree	*Pinus sylvestris*	branches with needles	492.00 ± 52.16 [1]	390	576	2720.22	-0.46
	Shrub	*Frangula alnus*	branches with leaves	238.00 ± 31.30 [2, 8]	188	292	979.78	-0.07
	Herb	*Pteridium aquilinum*	leaves	794.00 ± 83.50 [3, 9, 14,]	665	942	6972.89	0.14
	Dwarf shrub	*Vaccinium myrtillus*	shoots	487.00 ± 75.75 [4, 10, 15, 19]	378	592	5739.33	-0.02
	Dwarf shrub	*Calluna vulgaris*	shoots	589.00 ± 88.26 [5, 11, 16, 23]	467	751	7789.56	0.41
	Mosses	*Pleurozium schreberi*	caulidia with philidia	814.00 ± 69.38 [6, 12, 17, 21, 24, 26]	730	970	4814.00	0.71
	Mosses	*Ptilium crista-castrensis*	caulidia with philidia	822.00 ± 92.10 [7, 13, 18, 22, 25, 27, 28]	675	964	8481.78	-0.38

Both ^{137}Cs and ^{90}Sr are influenced by plot type, but in a different way. For ^{90}Sr, the negative beta coefficient implies that lower ^{90}Sr accumulation are associated to certain area types (=sites). While significant, the effect of area type for ^{137}Cs suggests that plot characteristics may affect ^{137}Cs bioaccumulation in a more complex way. These contrasting results also suggest that ^{137}Cs accumulation is more sensitive to changes in the stratum level compared to ^{90}Sr. This could be due to differences in the environmental migration of these radionuclides, their chemical properties, differences in soil-plant transfer mechanisms or how each radionuclide interacts with different forest layers. The significant effect of plant species on $^{137}Cs/^{90}Sr$ accumulation highlights the role of plant-specific characteristics in influencing radionuclide uptake. The significant variation in $^{137}Cs/^{90}Sr$ accumulation between different plant parts suggests that certain plant parts accumulate more ^{137}Cs than others.

The results of MANOVA indicate a higher accumulation of ^{137}Cs compared to ^{90}Sr. The R^2 values and the F-tests indicate a significant and strong relationship between the independent and dependent variables. Hence, it can be hypothesized that the processes of accumulation and dispersion of ^{137}Cs are more complex in the studied areas and among plant layers than those of ^{90}Sr. Further research on the mechanisms of accumulation and distribution of these radionuclides may be essential for a better understanding of their impact on the environment and human health.

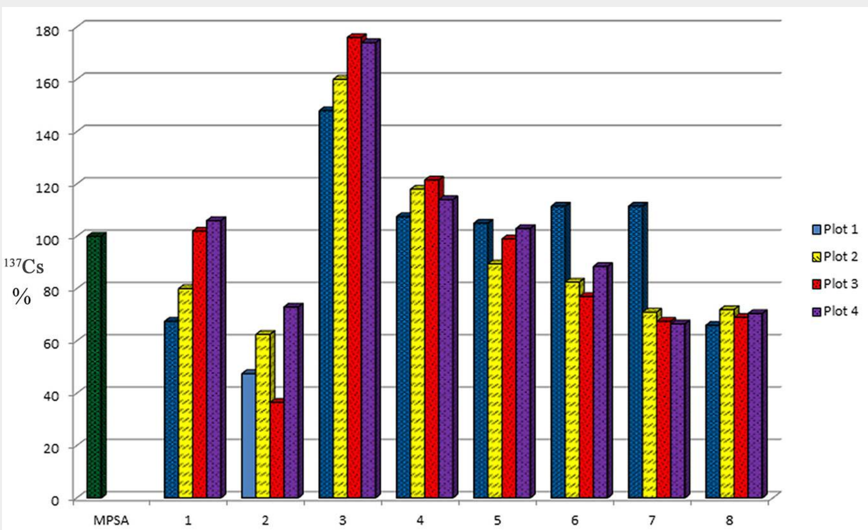

Fig. 3 - The mean values of ^{137}Cs relative specific activity (%) in plant samples compared to maximum permissible specific activity (MPSA); 1 - *Betula pendula*, 2 - *Pinus sylvestris*, 3 - *Frangula alnus*, 4 - *Pteridium aquilinum*, 5 - *Vaccinium myrtillus*, 6 - *Calluna vulgaris*, 7 - *Pleurozium schreberi*, 8 -*Ptilium crista-castrensis*.

Discussion

Our study examines the differences in the accumulation of specific radionuclides and their ratios across various soil layers, plant species, and plant parts within birch-pine forest communities near the Chernobyl Exclusion Zone, specifically the Bleshnya and Orlykivka forests of the Semenivka State Forestry in the Chernihiv Region of Northern Ukraine. This study explores the dynamics of radionuclide accumulation in forest ecosystems following the Chernobyl disaster, which is crucial for assessing current environmental risks and developing effective management strategies. Additionally, our research enhances the understanding of radionuclide dynamics in these ecosystems, providing valuable insights into ecological responses to radioactive contamination and guiding future research and environmental management efforts. Ultimately, our results contribute to a better understanding of the patterns of ^{137}Cs and ^{90}Sr radionuclide accumulation in the birch-pine forest communities of the Chernihiv region in Ukraine.

We found the lowest ^{137}Cs specific activity in the *Pinus sylvestris* plant samples in plot 3 with a mean value of 73.00 ± 8.25 Bq kg^{-1} (Tab. 3). The *Pinus sylvestris* branches with needles from all the plots did not exceed the radiocesium MPSA threshold. The *Betula pendula* branches with leaves from the third and fourth plots had a slight 2% and 6% MPSA excess, respectively (Fig. 4). These results are in good agreement with findings from Eastern Poland (Strzalek et al. 2021), which indicate that higher levels of ^{137}Cs accumulate in birch (*Betula pendula*) than in pine (*Pinus sylvestris*). This is also confirmed by the transfer coefficients of the ^{137}Cs isotope, which were higher in birch wood than in pine wood, especially in older stands. Indeed, as the age of the stand increases, the accumulation of ^{137}Cs in wood has been also found to increase (Strzalek et al. 2021).

As for the herb layer, in the leaves of the co-dominant fern *Pteridium aquilinum*, the ^{137}Cs excess was estimated to be 7.5%-21.5% higher than MPSA level in the samples from all the plots. The significant accumulation of ^{137}Cs in ferns has been previously reported in the scientific literature. Calmon et al. (2009) found that the aggregated transfer factors for vascular plants growing in forests on mineral soils were generally lower than in a peat-land forest or in plants growing on a thick organic soil layer. Both perennial and annual plants differed in the uptake of ^{137}Cs. The highest values were found for the fern *Dryopteris carthusiana* (Vill.) H.P.Fuchs (Calmon et al. 2009) in an ecosystem similar to the forest ecosystems considered in this study.

Notably, isolated cases of MPSA excess for ^{137}Cs were found in the moss and dwarf shrub layers. For example, the dominant species *Calluna vulgaris* and *Pleurozium schreberi* exhibited an excess of the radiocesium only in the samples from plot 1 (11.5% higher than the MPSA threshold). It is known that mosses accumulate pollutants from precipitation and, to a lesser extent, from the substrate (Stanojković et al. 2023). The vegetative organs of *Vaccinium myrtillus* had a moderate degree of ^{137}Cs accumulation. Following the Chernobyl accident, the ^{137}Cs content in all plant organs across various berry species demonstrated a clear decreasing trend. Long-term monitoring data after the Chernobyl accident (Calmon et al. 2009) indicated a relatively rapid decline in the ^{137}Cs specific activity in both the aboveground biomass and in the berries of the main berry species in the initial period following deposition (1986-1995). However, this decrease slowed significantly in the years following 1995.

It is well-established that mosses absorb radioisotopes from the environment differently than higher plants due to their unique structural features. This difference occurs both in the quantity and quality of uptake. Moreover, mosses are likely to display a wide range of uptake patterns influenced by their anatomy, the availability of radioisotopes on the surface layer of their substrate – such as soil, rock, or tree bark – as well as from unusual substrates like animal corpses or hairballs. Dust deposition may also play a role in determining these patterns (Schmidt et al. 2023). A study on ^{137}Cs in Bryophytes found pronounced differences between samples but no conclusive evidence for differences between taxa (Cevik & Celik 2009). Our research confirms the above evidence for Bryophytes in plots 2 and 3 (Tab. 2, Tab. 3). In plot 1, both the lowest and the higher average values of the radiocesium-specific activity (32.00 ± 15.48 and 223.00 ± 30.70 Bq kg^{-1} in *Ptilium crista-castrensis* and *Pleurozium schreberi*, respectively) were recorded in Bryophytes.

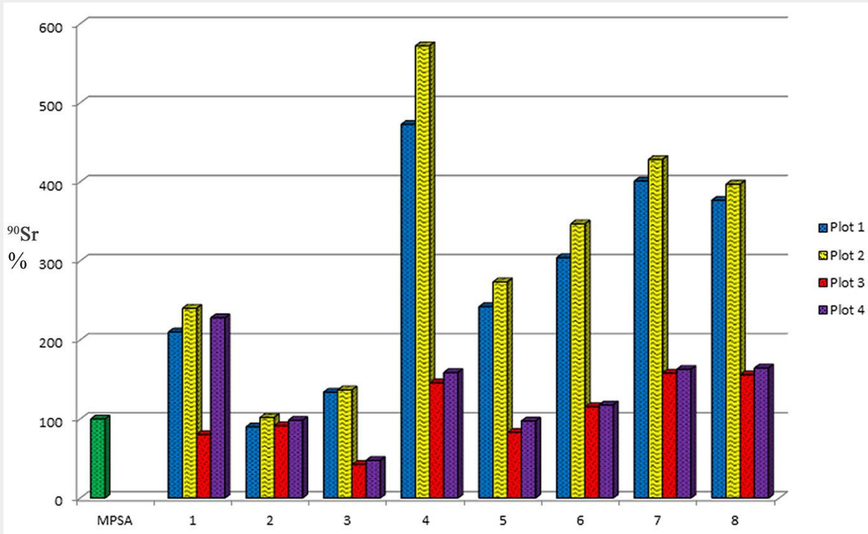

Fig. 4 - The mean values of ^{90}Sr relative specific activity (%) in plant samples compared to maximum permissible specific activity (MPSA, in green); 1 - *Betula pendula*, 2 - *Pinus sylvestris*, 3 - *Frangula alnus*, 4 - *Pteridium aquilinum*, 5 - *Vaccinium myrtillus*, 6 - *Calluna vulgaris*, 7 - *Pleurozium schreberi*, 8 -*Ptilium crista-castrensis*.

This study combined field research methods with laboratory analysis techniques, including gamma spectrometry and radiochemical methods. This methodological approach represents an advancement in assessing radionuclide accumulation in plant samples as it considers plants to be effective indicators for monitoring the environmental conditions. Plants can absorb radionuclides through their leaves and shoots from the air or from the soil *via* their roots. The epidermal characteristics of plant foliage may affect particle retention on leaves and the subsequent uptake of radionuclides from the surface. The transport of radionuclides through the cuticle and epidermis of leaves is affected by leaf anatomy and physiological factors, which can largely differ across different species. Moreover, evidence of long-term deposit of radionuclides in the soil has been reported.

Our results indicated that different species respond uniquely to radionuclide uptake. For example, the fern *Pteridium aquilinum* exhibited an outstanding level of bioaccumulation in this study. This highlights the need to consider species-specific responses when dealing with radioactive contamination. Understanding these differences is crucial for creating targeted mitigation strategies and evaluating ecological risks.

In our study, we observed variations in the accumulation of the radionuclides ^{137}Cs and ^{90}Sr among different plant species. These differences can be attributed to several factors, including variations in root morphology and depth, differences in uptake mechanisms, variations in metabolic processes, or species-specific affinity for these radionuclides. Environmental factors, such as soil composition, pH levels, and the availability of nutrients, also play a significant role in influencing how plants uptake and accumulate radionuclides. Understanding the complex interplay of these factors is essential for a comprehensive understanding of the variations in radionuclide accumulation among different plant species.

The accumulation of ^{137}Cs and ^{90}Sr in various forests of Ukraine following the Chernobyl disaster differs significantly. These differences can be attributed to several factors, including differences in soil composition, vegetation types, and environmental conditions across the affected regions. Additionally, the intensity of radioactive fallout and subsequent remediation efforts may vary from one forest to another, leading to differences in radionuclide accumulation levels. Understanding these variations is crucial for assessing the long-term environmental impact of the nuclear disasters and implementing targeted management strategies to mitigate further contamination.

In this study, we showed that ^{90}Sr had greater accumulation than ^{137}Cs in birch-Scots pine forest ecosystems. These findings offer important insights into the dynamics of radionuclide bioavailability, which is essential for predicting their fate and transport in terrestrial environments.

Understanding the mechanisms driving the retention, translocation, and bioaccumulation of radioactive contaminants, can help develop targeted approaches for monitoring and remediating contaminated areas, thereby mitigating potential threats to both human health and the environment (Krasnov et al. 2021, Oughton & Strand 2022, Bezhenar et al. 2023, Zarubina 2023, Schmidt et al. 2023).

The insights gained from studying the Chernobyl-affected forests should serve as a benchmark for similar environments worldwide, informing global efforts in nuclear safety, environmental protection, and sustainable land management practices.

Conclusions

Our study helps understand how ^{137}Cs is absorbed by plants and how its presence affects the birch-Scots pine forest ecosystems in Ukraine. We found variations in the accumulation of the ^{137}Cs and ^{90}Sr radionuclides among different plant species. The MANOVA regression analysis revealed significant relationships in radionuclide accumulation across different layer levels, plant species, and plant parts in the studied forest areas. The analysis showed that ^{90}Sr accumulation is lower in certain area types, while the effect of area type on ^{137}Cs is more variable. ^{137}Cs accumulation is more sensitive to layer-level changes compared to ^{90}Sr, probably due to differences in environmental behavior, chemical properties, or soil-plant transfer mechanisms. Plant species significantly differed in $^{137}Cs/^{90}Sr$ ratio, and several parts of plants showed more ^{137}Cs bioaccumulation than others. These differences may be attributed to various factors, such as root structure, uptake mechanisms, or specific physiological characteristics of each plant species.

Further research is needed to elucidate the underlying mechanisms driving these variations and their implications for ecosystem dynamics and environmental management. Continued research in this field is essential for better understanding the long-term effects of radioactive contamination.

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