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Short Communication

Accumulation Radiocesium (^{137}cs) By Plants of the Dnipro River's Floodplain Ecosystems after Chernobyl Contamination

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Abstract

The analysis of radiocesium (^{137}Cs) accumulation by plants of forest, marsh, meadow, psamophytic, and ruderal communities in the Dnipro River floodplain (Ukraine) was carried out. The species specificity of radiocesium accumulation by plants of specific biotopes and the direct dependence of the plant accumulation coefficient on the density of biotope contamination with radionuclides were confirmed. Differences in different radiocesium accumulation by plants of different ecosystems are probably related to the fact that the bioavailability of radiocesium strongly depends on soil properties. In the analyzed statistical model, the processes of accumulation and dissipation of ^{137}Cs are significant.

Introduction

Radionuclide contamination is a concerning threat due to unexpected nuclear disasters and authorized discharge of radioactive elements, both in the past and in present times. The use of atomic power for energy generation is associated with unresolved issues concerning the storage of residues and contaminants. For example, the nuclear accident in Chernobyl in 1986 resulted in the considerable deposition of cesium (Cs) in soil, along with other radionuclides. Among Cs radioactive variants, the anthropogenic radioisotope ^{137}Cs ($t_{1/2}$ = 30.16 years) is of serious environmental concern, owing to its rapid incorporation into biological systems and emission of β and γ radiation during the decaying process [1]. Transfer factors of radionuclide from soil/water to plant ([Radionuclide] plant / [Radionuclide] soil) vary widely in different plants. Rhizosphere, rhizobacteria, and varied metal transporters like NRAMP, ZIP families CDF, ATPases (HMAs) family like P1B-ATPases, are involved in the radio-phytoremediation processes [2].

After the accident at the Chernobyl NPP in 1986, the ecological situation in the floodplain ecosystems of Ukrainian Polesia was contaminated by radionuclides. The result of the accident was radioactive contamination of the territory with a mixture of products of nuclear decay and neutron activation.

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The radiation state of the territories is formed mainly under the influence of the long-existing radionuclides ^{137}Cs and ^{90}Sr. The total area of the Polesia territories classified as zones of radiation contamination due to the Chernobyl disaster by ^{137}Cs above 1 Ci/km^2 is 174.715 thousand ha, including agricultural land – 72.015 thousand ha, forests – 102.7 thousand ha and 107 settlements [3-5].

The publications pay special attention to radionuclides of Chernobyl origin (of which the longest-lived are ^{137}Cs, ^{239,240,241}Pu and ^{90}Sr), which migrate in forest ecosystems [6]. Forests have the ability to retain radiocesium. Researchers of radiocaesium contamination of meadow vegetation and its influence on soil characteristics 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 is higher, and the ecological half-life of radiocesium in meadow ecosystems is greater than in intensively used agroecosystems [7]. At present, most of the radiocesium has transferred to the mineral soil, and the circulation of radiocesium in the forest is slow [8]. Studies of different types of ecosystems on the territory of Polesia were carried out within Gomel Polesia (Belarus), Zhytomyr, and Kyiv Polesia (Ukraine) [9-11].

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 different ecosystems. So the purpose of our work was to compare the ^{137}Cs accumulation by plants of forest, marsh, meadow, psamophytic, and ruderal communities (Figure 1.) in the Dnipro River floodplain (the Chernihiv Polesia, Ukraine) after radioactive contamination of the river floodplain as a result of the Chernobyl disaster.

The objectives of the research are the analysis of the ^{137}Cs accumulation in the River floodplain ecosystems during the post-Chernobyl period and understanding the movement of radionuclides as a basis for developing effective monitoring and risk assessment strategies in areas affected by radioactive contamination.

Materials and methods

The selection of experimental plant material samples was carried out in the Dnipro River floodplain (the Chernihiv Region, Northern Ukraine) in the summer of 2021 to the north of the Zadekriivka village (Chernihiv region, Ukraine) on 5 test plots: forest (N51.9193°, E30.8616°), marsh (N51.9231°, E30.8460°), meadow (N N51.9231°, E30.8373°), psamophytic (N51.9248°, E30.8315°), and ruderal (N51.9251°, E30.8266°). The area of each plot is 25 m^2. These sites are located in the area that was the most contaminated in the northwest of the Chernihiv Region after the Chernobyl accident. However, these plots differed in varying degrees of soil 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.

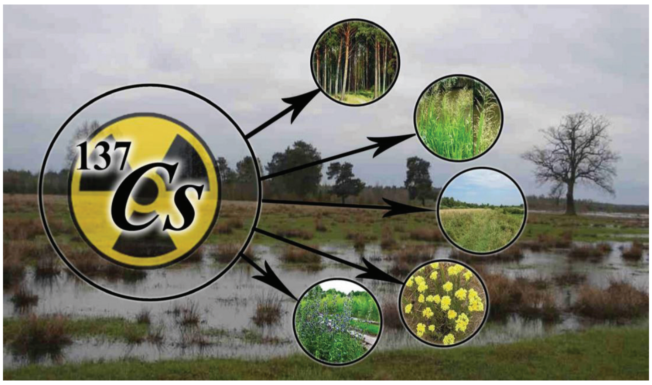

Figure 1: Ecosystems of the Dnipro River's floodplain, the plants of which were investigated to study radiocesium accumulation. The author of the collage is O. Yakovenko, photo by O. Lukash, Y. Karpenko.

Determination of plant communities was carried out according to W. Matuszkiewicz [12]. The collection of point samples in each of the plots was carried out following soil sampling methods for radiation control [4,5]. At each experimental site, samples of plant organs were taken in 10 replicates for each component within a plant species: 10 individuals for each species were considered and 1 sample for each plant compartment was sampled. The ^{137}Cs content determination in plant samples and soil was performed using a Gamma plus U spectrometer (Expert Center, Russia).

The Statistica 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. By employing analysis of variance (ANOVA), we simultaneously evaluated the impact of factors on radionuclide accumulation

Results and discussion

Plant communities in the ecosystems under study have the following syntaxonomic affiliation: plot 1 (forest ecosystem) – the *Peucedano-Pinetum* W.Matuszkiewicz (1962) 1973 association of the *Vaccinio-Piceetea* Br.-Bl. 1939 class, plot 2 (marsh ecosystem) – the *Glycerietum maximae* Hueck 1931 association of the *Phragmito-Magnocaricetea* Klika in Klika et Novak 1941 class, plot 3 (meadow ecosystem) – the *Agrostio vinealis-Calamagrostietum epigeous* Shelyag-Sosonko et all. 1985 association of the *Molinio-Arrhenatheretea* R.Tx. 1937 class, plot 4 (spermophytic ecosystem) – the *Corynephoro-Silenetum tataricae* Libbert 1931 association of the *Sedo-Scleranthetea* Br.-Bl. 1955 class, plot 5 (ruderal ecosystem) – the *Melilotetum albo-officinalis Sissingh* 1950 (1942) 1943 association of the *Artemisietea vulgaris* Lohmeyer, Preising et R.Tx. in R.Tx. 1950 class. The results of the ^{137}Cs-specific activity in plant samples measuring are presented in Table 1.

As can be seen from Table 1, the soil in plot 2 was the most polluted (504.0 Bq/kg), and the soil in plot 5 was the least polluted (40.5 Bq/kg).

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Table 1: The absolute specific activity of ^{137}Cs (Bq/kg) in soil and plant samples.

Plot	Soil	Plant species	Mean ± SE	Skewness
1	388.5	*Quercus robur* L.	403.8 ± 35.7	0.81
1	388.5	*Robinia pseudoacacia* L.	321.4 ± 45.9	-0.35
1	388.5	*Rubus idaeus* L.	417.7 ± 54.3	-0.54
1	388.5	*Chelidonium majus* L.	421.9 ± 37.8	-0.58
1	388.5	*Convallaria majalis* L.	496.8 ± 22.9	0.61
1	388.5	*Calluna vulgaris* (L.) Hill.	563.0 ± 136.8	0.70
1	388.5	*Pleurozium schreberi* (Willd. ex Brid.) Mitt.	668.3 ± 104.3	0.31
2	504.0	*Glyceria maxima* (Hartm.) Holmb.	296.8 ± 32.9	0.61
2	504.0	*Alisma plantago-aquatica* L.	336.3 ± 41.4	0.34
2	504.0	*Galium palustre* L.	352.0 ± 46.2	0.87
2	504.0	Stachys *palustris* L.	307.0 ± 50.1	0.46
2	504.0	*Lycopus europaeus* L.	244.6 ± 34.2	0.03
3	426.4	*Hypericum perforatum* L.	298 ± 53.0	-0.56
3	426.4	*Achillea millefolium* L.	300 ± 51.0	0.32
3	426.4	*Agrostis vinealis* Schreb.	338.9 ± 41.3	0.58
3	426.4	*Bromus inermis* Leyss.	303.4 ± 60.7	0.43
3	426.4	*Calamagrostis epigejos* (L.) Roth	292.2 ± 35.0	-0.46
4	407.2	*Berteroa incana* (L.) DC.	334.0 ± 45.7	-0.07
4	407.2	*Thymus serpyllum* L.	280.9 ± 11.0	0.06
4	407.2	*Helichrysum arenarium* (L.) Moench	245.6 ± 41.5	0.98
4	407.2	*Oenothera biennis* L.	140.4 ± 16.8	0.56
4	407.2	*Verbascum lychnitis* L.	130.9 ± 19.9	0.96
5	40.5	*Tanacetum vulgare* L.	74.8 ± 11.8	0.59
5	40.5	*Artemisia absinthium* L.	56.0 ± 9.5	0.30
5	40.5	*Melilotus albus* Medik.	16.2 ± 9.2	-0.08
5	40.5	*Cichorium intybus* L.	55.5 ± 12.6	0.37
5	40.5	*Echium vulgare* L.	83.9 ± 15.8	0.52

In the case of the ^{137}Cs bioaccumulation, the ANOVA results indicate a strong relationship among the predictor variables, with a multiple correlation coefficient R = 0.769, which suggests that approximately 76.91% of the variance in the dependent variables can be explained by the combination of the predictor variables. The coefficient of determination R^2 supports this conception, showing that approximately 61.37% of the variance in the dependent variables is accounted for by the predictor variables. However, after correction for the number of predictors and sample size, the adjusted R^2 value is 0.584, which implies that around 58.48% of the variance in the dependent variables is explained by the predictor variables, taking into account the degrees of freedom. The ANOVA also yielded a statistically significant F-ratio $F_{4, 315}$ = 164.12, indicating that the relationship between the predictor variables and the dependent variables is significant (*p* = 0.000).

ANOVA results indicate the influence of ecosystem type on the accumulation of ^{137}Cs by plants. The R^2 values and F test indicate a significant and strong relationship between the independent and dependent variables. Thus, in the analyzed statistical model, the processes of accumulation and dissipation of ^{137}Cs are significant.

It is known that radiocesium uptake by plants was evaluated by ratios of the radiocesium concentration in plants to that in soil [13]. It was established that plants of saprophytic and ruderal habitats are characterized by insignificant ^{137}Cs pollution (from 334 to 16.2 Bq/kg) and a low radionuclide accumulation coefficient (from 0.4 to 0.82). This primarily concerns such species as *Berteroa incana* (L.) DC., *Calamagrostis epigejos* (L.) Roth, *Tanacetum vulgare* L., *Echium vulgare* L., *Oenothera biennis* L., *Artemisia absinthium* L., *Verbascum lychnitis* L., *Melilotus albus* Medik., *Helichrysum arenarium* (L.) Moench, *Cichorium intybus* L., *Achillea millefolium* L., *Hypericum perforatum* L., and *Thymus serpyllum* L. (Table 1). It is known that plants of the genus *Artemisia* are characterized by higher parameters of both intra-tissue and surface accumulation of radionuclides [14]. As we can see, the activity of ^{137}Cs in the plants of the ruderal ecosystem was the lowest and amounted to 16.2 – 83.9 Bq/kg (accumulation coefficient 0.4 – 2.1).

In the plant samples taken from the meadow and the swamp ecosystems, the ^{137}Cs content did not exceed the permissible level (370 Bq/kg). Exceeding the normative indicator for ^{137}Cs was detected in the forest ecosystem plant samples. Among such economically valuable plant species are *Chelidonium majus* L., *Convallaria majalis* L., *Quercus robur* L., *Rubus idaeus* L., and *Calluna vulgaris* (L.) Hill. In addition, the ^{137}Cs accumulation coefficient of certain perennial species of mossy, herbaceous, and dwarf shrub layers (*Pleurozium schreberi* (Willd. ex Brid.) Mitt., *Convallaria majalis*, and *Calluna vulgaris*) exceeds this value for the woody plant species [15]. For this group of plants with a high accumulation coefficient r radionuclides undergo radioactive decay releasing ionizing radiation like gamma ray(s) and/or alpha or beta particles that can displace electrons in the living matter (like in DNA) and disturb its function. Radionuclides are highly hazardous pollutants of considerable impact on the environment, food chain, and human health [2].

For comparison, we present the results obtained from studying the accumulation of plant radiocesium in different types of Polesia ecosystems. Analysis of the specific activity of ^{137}Cs plant samples that were collected in the floodplain of the Sozh River demonstrated that the greatest excess of the maximum permissible of ^{137}Cs content was observed in plant species of aquatic plant communities. For example: rooting euhydrophyte *Ranunculus circinatus* Sibth exceeded the permissible level by 1.27 times; for the non-rooting, free-floating pleistohydrophyte *Lemna trisulca* L. – 3.16 times, for the tall aero hydrophyte *Typha latifolia* L. – 1.61 times [9]. Studies conducted in forest phytocenoses in the exclusion zone of the Chernobyl NPP (Kyiv Polesia) plant suggested that the constant circulation of ^{137} Cs in the soil-plant system can cause seasonal changes in the content of ^{137}Cs in the living organs of woody plants (phanerophytes), in particular pine. In the cycle of 137-radiocesium in forest ecosystems, mycorrhizal fungi can play an important role [11]. Investigation results of oligotrophic and mesotrophic bogs, which are common ecosystems of Zhytomyr Polesia, testify about intensive ^{137}Cs migration on sphagnum bogs of Polesia of Ukraine. Results of the investigation conducted 34 years after the Chernobyl

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accident showed low values of ^{137}Cs specific activity in cranberry (*Vaccinium oxycoccus* L.) on all stationary experimental plots [10].

It is known to use *Robinia pseudoacacia* L. and other woody plant species for reference inventory of ^{137}Cs on eight undisturbed, non-eroded, uncultivated terraces [16]. In our studies, this species showed an insignificant degree (Table 1) of radiocesium accumulation.

Our research confirms the previous fact that biological features of plants affect the accumulation of radionuclides in plants, and the morphology of plants to the level of surface contamination [14].

Conclusion

The intensity of radionuclide uptake by plants is determined both by the biological characteristics of the species and by the soil and the cenotic habitat conditions. The species specificity of radiocesium accumulation by plants of specific biotopes and the direct dependence of the plant accumulation coefficient on the density of biotope contamination with radionuclides were confirmed. The conducted studies illustrated not only interspecies differences in the intensity of ^{137}Cs accumulation in one type of local habitat but also variations in the accumulation of radionuclides in different systematic groups and life forms. The highest intensity of radiocesium accumulation was observed in forest plants and the lowest – in plants of the ruderal ecosystem. Such differences in different accumulation of radiocesium by plants of different ecosystems are probably related to the fact that the bioavailability of radiocesium strongly depends on soil properties, in particular, such as potassium status and clay content.

It assessed the effects of the phytochromes type using the ANOVA on radionuclide accumulation in a model approach. This research is important to a comprehensive understanding of the ^{137}Cs radionuclide dynamics for environmental health and human well-being to contribute to the development of effective monitoring and risk assessment strategies in areas affected by radioactive contamination.

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Author contributions

Conceptualization, O.L. and N.K.; methodology, O.L.; validation, H.T.; formal analysis, O.L., and N.K.; investigation, O.L., and A.S.; resources, O.L., H.T., and N.K.; data curation, O.L., A.S., Y.K., O.Y., O.S., A.S., S.K., V.P., and S.P.; writing—original draft preparation, O.L., and A.S.; writing—review and editing, O.L., H.T. and N.K.; visualization, O.L.; supervision, N.K.; project administration, N.K.; funding acquisition, A.S. and H.T. All authors have read and agreed to the published version of the manuscript.

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