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Radioactive contamination in the Belarusian sector of the Chernobyl Exclusion Zone

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Abstract. This article summarises some key activities undertaken as part of a NATO-funded project to map and improve our understanding of the behaviour and fate of radionuclides in the Belarusian Sector of the Chernobyl Exclusion zone. Data are presented concerning activity concentrations of ^{137}Cs, ^{90}Sr and selected actinides and how these data have been used to produce contour maps of contamination densities. Factors affecting the transfer of radionuclides to plants and animals at selected study sites are considered and the geochemical phase association of radionulcides in soils and implications for actinide mobility commented upon. A final important subject for elaboration has been the transboundary transport of contamination by natural phenomena. The influence of forest fires on remobilisation of radionuclides, for example, has been addressed through the application of a bespoke probabilistic model.

1. INTRODUCTION

The most severe accident in the history of the global nuclear industry occurred at the Chernobyl nuclear power plant in April 1986 and resulted in the wide scale contamination of large areas within Europe but in particular within the territories of Belarus, Ukraine and the western Russian Federation. In parts of the southern part of Belarus the deposition exceeded 1500 kBq/m^2 ^{137}Cs [1], a level which is approximately 3 orders of magnitude higher than the level associated with atmospheric nuclear weapons testing alone. 115 000 people were evacuated from the territories of Belarus, Ukraine and the Russian Federation in the spring and summer of 1986 from the area surrounding the Chernobyl plant [2]. This area was designated as the Chernobyl exclusion zone and extends with a radius of 30 km around the accident site. The Polessie State Radiation Ecological Reserve (PSRER), Figure 1, covers the Belarusian part of the exclusion zone and the scientists working at the reserve are responsible, amongst other duties, for monitoring the levels of radioactivity in the local environment and providing recommendations to the Department for Mitigation of Consequences of the Catastrophe at the Chernobyl NPP of the Ministry of Emergency Situations (DMCCC) in relation to management options within the reserve.

Although numerous radioecological studies had been conducted within the Chernobyl exclusion zone in the years following the Chernobyl accident (e.g. [3, 4]) there were significant uncertainties

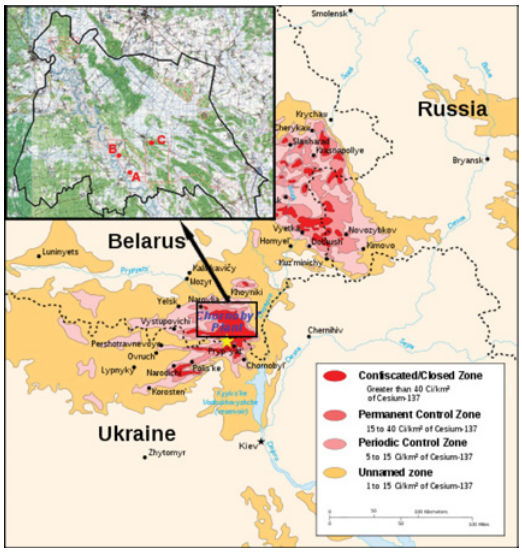

Figure 1. The Polessie State Radiation Ecological Reserve.

associated with maps of radionuclide distributions within the territory of PSRER and simulating the dynamics of radionuclide migration within the territory and in relation to trans-boundary transport to other regions.

This inadequate scientific basis meant that there were difficulties in forecasting the future radiation situation on the territory of Belarus and assessing the dynamics of secondary contamination by Chernobyl-derived radionuclides from natural phenomena and human activities. The requirement to improve this situation was therefore identified and a project planned to confront some of the more pressing scientific issues. Plans were made to improve substantially current contamination maps and it was considered necessary to adapt existing and develop new models for simulating consequences under selected scenarios pertaining to the redistribution of radionuclides within and across the boundaries of the contaminated zone. Such information was required for the planning of scientific, experimental, economical and social activity in the PSRER and to allow radiological assessments to be performed appropriately.

1.1 Project objectives

The overall goal of the proposed project was to obtain comprehensive information about the radioactive contamination of the territory of Polessie State Radiation-Ecological Reserve (PSRER), with the following objectives:

1. Develop uniform procedures and methods for sampling and the determination of radionuclides
2. Collate archived information on radionuclide levels
3. Determine the contamination densities of with ^{137}Cs, ^{90}Sr, plutonium isotopes, ^{241}Am through in the PSRER and estimate transboundary transfer of radionuclides via water transport.
4. Identify physico-chemical forms for different radionuclides in soil and sediments.
5. Examine the mechanisms of radionuclide inclusion in natural food-chains through the collation of data on accumulation in plants and animals.
6. Create a database and build digitized maps of radioactive contamination, and combine sampling and mapping data with similar results on the Ukrainian side;

Table 1. Results of measurements of soil samples, taken from the different sites of PSRER in 2009.

Point of sampling	^{137}Cs, kBq/m^2	^{90}Sr, kBq/m^2	Pu, kBq/m^2	Point of sampling	^{137}Cs, kBq/m^2	^{90}Sr, kBq/m^2	^{238,239,240}Pu, kBq/m^2
FS Orevichy				FS Krasnoselje			
1	966	61	0.85	1	1797	494	10.36
2	1168			2	2053		14.80
3	1258	490	0.33	3	2134		31.82
4	1242			4	2202		3.18
5	1393			5	2247		27.01
6	1950	382	0.81	6	1887	382	11.84
7	604			7	3124		8.88
8	1999			8	3976		20.72
9	1265	141	1.26	9	2911		2.63
10	1725			10	4515		28.86
11	2067	1079		11	5695	607	26.27
12	1910						
FS Borschevka							
1	317	373	12.95	6	1573	162	11.84
2	645	121		7		121	
3	600	51		8		314	
4	1388	523	44.40	9		8	0.70
5	3864	106					

7. Improve models for ^{137}Cs and ^{90}Sr migration in terrestrial landscapes (soils) of the exclusion zone and its vicinity.
8. Compile data on extreme natural phenomena and other factors affecting the transport of radionuclides, and simulate their flows from the contaminated zone within Belarus as well as transboundary transport to the Ukraine during unfavorable natural and man-caused conditions.

2. KEY RESULTS

The full compliment of results is too extensive to report in this paper so highlights from the work have been selected for the sake of presentation. For more details concerning the project activities the reader is directed to the project website (www.polessie.net).

2.1 Determination of radionuclide contamination levels and mapping

Numerous field studies have been conducted within the project framework and surface soils analysed by gamma and alpha spectrometry.

By way of example, selected radionuclide contamination density data from the analyses of soil samples measured at various former settlements (FS) by the Republican Center of Radiation Control and Environment Monitoring within the activities of the project are presented in Table 1. The highest ^{137}Cs contamination determined was in excess of 5 MBq m^{-2} and the variability observed in the contamination densities for ^{239,240}Pu and ^{90}Sr appear to exceed the variability associated with radiocaesium. Geostatistical methods have been applied in the analyses of geospatial datasets on activity concentration of radionuclides in sampled surface soils. Variograms have been applied to explore the spatial dependence of soil contamination with ^{137}Cs in contamination 'traces' from the accident. Isoline step values have been defined and contamination maps created for sectors within the exclusion zone

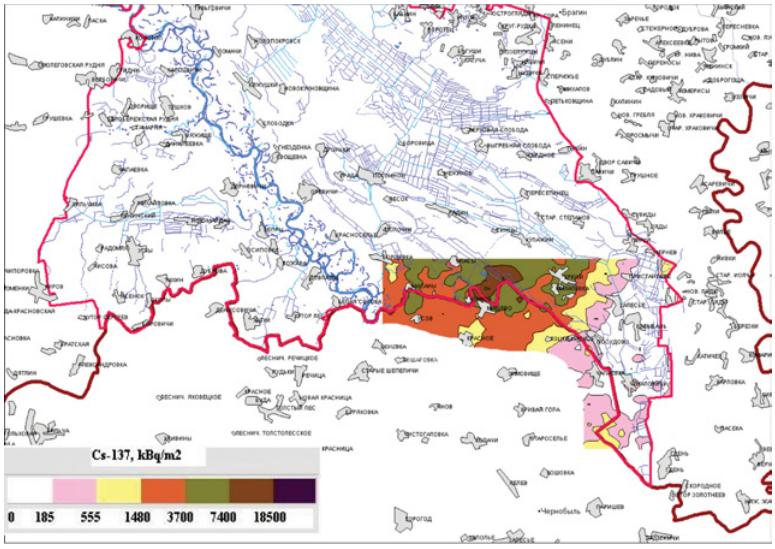

Figure 2. Cs-137 Contamination Density in soil at site No 1 and Ukraine.

(Figure 2). The Inverse distances method was used for interpolation and data processing performed using the software 'Mapinfo'.

2.2 Radioecology – activity concentration in and transfer to plants and animals

Numerous plant and animal samples have been collected and measured for their radionuclide content allowing a robust set of transfer factors to be derived for plants in relation to particular environments within the Chernobyl exclusion zone. By way of example, ^{239,240}Pu aggregated transfer factors for selected plants growing over various soil types are presented in Table 2.

The aggregated transfer factors for the plant species analysed varies from 7×10^{-5} to $1.2 \times 10^{-3} \mathrm{m}^2 \cdot \mathrm{kg}^{-1}$, values that are somewhat lower than determinations for these types of plants based on measurements from Scandinavia following inputs from weapons testing global fallout (see e.g. [5]). The influence of soil type on the value of transfer factor is illustrated taking an example of *Carex acuta* (Slender Tufted-sedge). The transfer factor for this species appears to increase in the order of soils: peaty-gley, peaty-gleish – alluvial soddy loamy sand, alluvial soddy-podzolic sand – peaty-sand. However, the limited number of samples renders it impossible to establish whether these differences are statistically significant.

2.3 Geochemical phase association

Within the framework of the project, Ovsiannikova et al. [6] employed a method of sequential selective extraction to analyse physicochemical forms of radionuclides in PSRER soils. Activity concentrations of ^{238}Pu, ^{239,240}Pu and ^{241}Am in the samples were determined via radiochemical analysis with alpha-spectrometric identification of radionuclides. The inventories of mobile and biologically available forms of plutonium and americium, expressed as a percentage of the total radionuclide content in soil, lie in the ranges of 1.1–9.4 and 2.7–29% respectively. Greater proportions of mobile and biologically available forms of radionuclides appear to be associated with mineral soil as compared to organic soil. In both mineral and organic soils, although the portion of mobile americium is similar to plutonium in the

Table 2. Transfer of ^{239,240}Pu in the soil–plant system.

Plant species	$\mathbf{A_P}$, **Bq** $\cdot$ **kg**$^{-1}$	**Soil type (plot)**	$\mathbf{A_S}$, **Bq** $\cdot$ **m**$^{-2}$	$\mathbf{T_f}$, **m**^{2} $\cdot$ **kg**$^{-1}$
Eletregia repens	1.8 ± 0.2	Soddy-podzolic loamy sand (SP1)	$26\,000 \pm 2\,000$	$(7 \pm 1) \cdot 10^{-5}$
Cladina arbureula	1.3 ± 0.1	Soddy-podzolic sand (SP5)	5100 ± 300	$(2.5 \pm 0.4) \cdot 10^{-4}$
Corynephorus canesecus	1.1 ± 0.1	Soddy-podzolic sand (SP5)	$5\,100 \pm 300$	$(2.2 \pm 0.3) \cdot 10^{-4}$
Daktulis glomerata	1.7 ± 0.2	Alluvial soddy loamy sand (S4)	$4\,800 \pm 400$	$(3.5 \pm 0.6) \cdot 10^{-4}$
Carex acuta	$0,8 \pm 0.1$	Alluvial soddy loamy sand (S4)	$4\,800 \pm 400$	$(1.7 \pm 0.4) \cdot 10^{-4}$
Carex acuta	0.34 ± 0.05	Alluvial soddy-podzolic sand (S2)	$1\,500 \pm 150$	$(2.3 \pm 0.6) \cdot 10^{-4}$
Carex acuta	1.0 ± 0.1	Peaty-gley (P1)	$8\,800 \pm 800$	$(1.1 \pm 0.2) \cdot 10^{-4}$
Carex acuta	0.21 ± 0.04	Peaty-gleish (P3)	$1\,500 \pm 100$	$(1.4 \pm 0.4) \cdot 10^{-4}$
Carex acuta	0.9 ± 0.1	Peaty-sand (P4)	900 ± 100	$(1.0 \pm 0.2) \cdot 10^{-3}$
Circium arvense	1.1 ± 0.1	Peaty-gley (P1)	$8\,800 \pm 800$	$(1.3 \pm 0.2) \cdot 10^{-4}$
Circium arvense	0.9 ± 0.1	Peaty-sand (P4)	900 ± 90	$(1.0 \pm 0.2) \cdot 10^{-3}$
Conium	0.62 ± 0.07	Peaty-gley (P1)	$8\,800 \pm 800$	$(7 \pm 1) \cdot 10^{-5}$
Festuca pratensis	0.50 ± 0.08	Peat gleish (P3)	$1\,500 \pm 100$	$(3.3 \pm 0.7) \cdot 10^{-4}$
Festuca ovina	1.1 ± 0.1	Peaty-sand (P4)	900 ± 100	$(1.2 \pm 0.2) \cdot 10^{-3}$

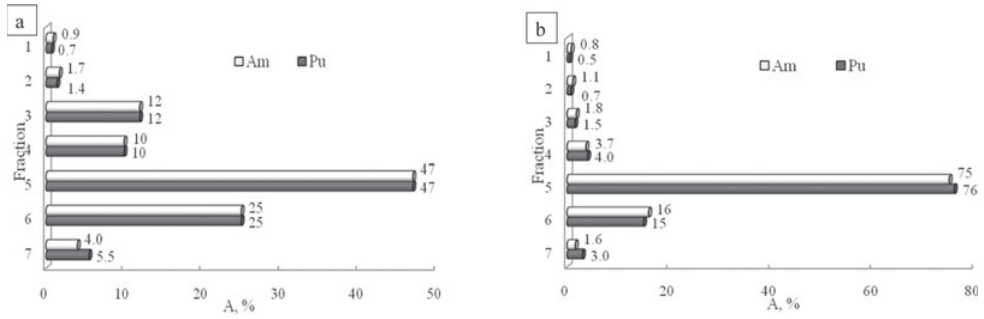

Figure 3. The relative content of ^{239,240}Pu and ^{241}Am in the fractions separated from 0–5 cm layers in a) alluvial soddy-podzolic sandy soil samples; b) Peaty soil. The numbers of fractions correspond to 1 = Water-soluble, 2 = Reversibly bound; 3 = Reversibly bound with soil components; 4 = Associated with easily reduced components e.g. oxides of iron and manganese ; 5 = Associated with oxidisable components e.g. organic material and/or uranium oxide particles; 6 = Acid-soluble; 7 = Soil residue. Reproduced from Ovsiannikova et al. (2010).

surface (0-5cm) soil (Figure 3), a larger fraction of americium is associated with soluble/reversibly bound phases for deeper soil increments.

2.4 Modelling of radionuclide dispersion with forest fires

Models have been developed [7] to predict parameters of radionuclide resuspension, transport and deposition during forest and grassland fires. The prognostic power of the models was furthermore tested through comparison with experimental data of controlled burning of prepared experimental plots in the Chernobyl exclusion zone [8]. Using this work as a paragon, a probability model based on the principles of probability distributions according to the maximum entropy principle (Maxent) has been developed

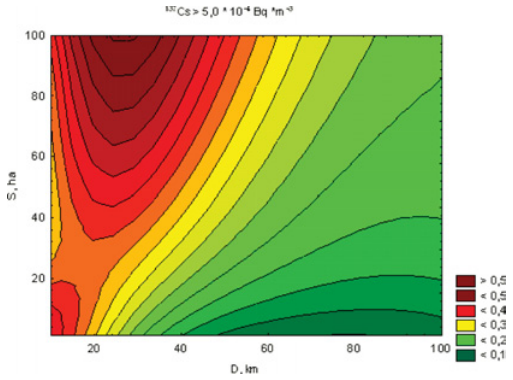

Figure 4. Probability of excess level 0.5 mBq/m^3 by average monthly specific activity of ^{137}Cs in near ground air in the period of first month after a forest fire according to the distance from forest fire and its area.

in order to estimate the possibility of transboundary transfer of radionuclides that are entrained into the atmosphere by forest fires. This method has a rather low sensitivity to random errors in data and to the influence of non-essential factors. Furthermore, the method requires relatively few data for model parameterisation. Maxent has no limitation concerning *a priori* ideas about mechanisms of the system construction and therefore it provides a more exact description of behavior on the basis of existing data set. Data on long-term monitoring of radionuclides in the bottom layers of the atmosphere in the PSRER and vicinity and data concerning forest fires in the period from 2000 until 2008 were used for model parameterisation. This model allows the prediction of the probability of excess of some level of monthly average activity of ^{137}Cs and ^{239,240}Pu in the air layer near the ground level in relation to power of forest fire, activity of radionuclides in the top layer of soil and distance. For model testing, the calculated probability of excess of the levels 2.5×10^{-4} and 5.0×10^{-4} Bq/m^3 (Figure 4) of ^{137}Cs specific activity in the near ground air were selected.

Model runs were also made for plutonium. By comparison, Caesium entrained into the atmosphere by forest fires travelled further than plutonium, and the probability of elevated levels in bottom layers of the atmosphere decreases more gradually with increased distance. In the case of a relatively extensive forest fire, there is a fairly high probability to expect rising cesium-137 activity concentrations in the atmosphere even at distances of 50 km. It appears that, atmospheric transfer of caesium-137 and plutonium isotopes from forest fires obey rather different patterns with caesium137 exhibiting a higher risk of transfer to relatively greater distances than those expected for plutonium isotopes.

3. CONCLUSIONS

The collaborative work between scientists from Belarus, Ukraine and Norway within the framework of this project has added considerably to our understanding of the distribution, behaviour and fate of radionuclides in the Belarusian sector of the Chernobyl exclusion zone. In particular the geostatistical methods applied to contamination data, information concerning the speciation of radionuclides in soils of the PSRER and models that allow trans-boundary migration of radionuclides to be simulated and predicted provide invaluable analytical tools with regards to this endeavour.

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