Comparative analysis of ^{137}Cs bioavailability in forest ecosystems of different type

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Abstract. A quantitative analysis of ^{137}Cs bioavailability in forest soils in the long term after the Chernobyl NPP accident based on a 3 years (1996-1998) investigation is presented. Five sites with different trees composition and properties of soil were studied to identify factors determining radiocaesium transfer to trees and different under story species. The following parameters were investigated: ^{137}Cs activity concentrations and its speciation in various horizons of forest soil, accumulation of this radionuclide by different species of under story vegetation and distribution of their root biomass in the soil profile. It has been shown that one decade after the deposition maximum ^{137}Cs activity in soil of the experimental sites considered is located in different soil layers dependent on moisture regime, characteristics of litter and soil properties. High level of heterogeneity of ^{137}Cs specific activity in different parts of tree, which is related to physiological peculiarities of their functions, has been shown. The data obtained have demonstrated a non-uniform character for ^{137}Cs distribution along trunks, which can be explained by radionuclide fixation by walls of xylem vessels and by changes in geometry along the tree trunk. It has been found that the radial distribution of ^{137}Cs in the tree trunk is dependent on the availability of ^{137}Cs in soil, which governs the transfer of this radionuclide via xylem sap, and on the properties of the xylem. The accumulation of ^{137}Cs by both trees and under story species was influenced by ^{137}Cs vertical distribution and availability in soil as well as by the root (mycelia) biomass distribution in different soil horizons. A "bioavailability factor", which takes into account the above factors, is proposed for comparative analyses of ^{137}Cs transfer from soil to plants in different types of forest ecosystems.

1. INTRODUCTION

After the nuclear reactor accident at Chernobyl vast forested areas were contaminated with radioactive fallout. In the first few years after the accident the interest of the scientific community was mainly directed towards agricultural ecosystems. In recent years, the level of radioactive contamination in forested areas and contamination of main forest products like wood, mushrooms and berries is receiving more and more attention.

Depending on hydrological regime of forest soils the radiocaesium T_{ag} for trees, mushrooms, berries and shrubs can vary over a range of more than three orders of magnitude ([2, 1, 3, 7]). Several another factors that can cause the observed variation in T_{ag} have been identified. Among these the following are most notable: the radiocaesium distribution in the soil profile; the radiocaesium physico-chemical form in the soil; the distribution of root systems (mycelia) in the soil profile and the capacity of different plants for radiocaesium accumulation. The influence of these factors has, however, not yet been quantified or fully understood.

The objectives of the present study were to compare the availability of ^{137}Cs for transfer from soil to the under story vegetation in different forest ecosystems and, to identify and characterise the main factors determining differences in the radiocaesium accumulation by different under story species.

2. MATERIALS AND METHODS

The study was carried out between 1996-1998 in forests of the Bryansk region of Russia that were heavily contaminated by deposition after the Chernobyl accident. The experimental plots of the size 100 to 100 m^2 were situated in forests with different types of trees (coniferous and deciduous) and soils (automorphic, semi-hydromorphic and hydromorphic) The study comprised field sampling and measurements, and was aimed at obtaining data on the following features and processes: the vertical distribution of radiocaesium in the soil; soil properties; radiocaesium speciation in different soil layers; distribution of root biomass in the soil profile; radiocaesium concentrations in mosses, under story plants and mushrooms.

3. RESULTS

3.1. Vertical distribution of radiocaesium in the soil

The vertical distribution of ^{137}Cs in soils of the experimental sites observed in 1996 is shown in Figure 1 (normalised to a ^{137}Cs activity density of 1 kBq m^{-2}).

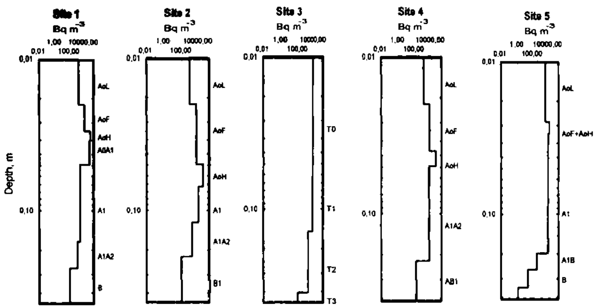

Figure 1. Vertical distribution of ^{137}Cs in soils of the experimental sites normalised to a ^{137}Cs deposition density of 1 kBq m^{-2}.

The radiocaesium vertical distributions in soils observed in the studied sites were quite different. A nearly uniform distribution of ^{137}Cs was observed in the upper horizons of the hydromorphic soil (Site 3). This can be explained by the high level of humidity in this soil, which, as shown elsewhere ([6]), results in increased diffusion rates of ions in the soil. In the case of automorphic and semi-hydromorphic soils the highest ^{137}Cs activity concentrations were observed between 3 and 7 cm from the soil surface. For coniferous and mixed (with prevalence of pine trees) forests on automorphic and semi-hydromorphic soils (Sites 1 and 2) the most contaminated layer was the A_oH litter horizon. In deciduous forest on automorphic soil the highest concentrations of ^{137}Cs were observed in the upper (transient) layer of horizon A_1.

3.2. ^{137}Cs speciation in different soil horizons

For all automorphic sites the highest percentage of available (exchangeable and mobile) ^{137}Cs fractions (from 27.3% in Site 5 to 48.9% in Site 1) was observed for mineral horizons. The lowest percentage of these fractions (from 1.7 % in Site 5 to 4.2% in Site 1) was found for humid soil horizons located directly under the litter layer. The fractions of exchangeable and mobile radiocaesium were 3-5 times higher in the litter horizons A_0F and A_0H than in the humid soil horizons, but 6-8 times lower than in the mineral soil horizons. The same trend, though less pronounced, was observed in the site with semi-hydromorphic soil (Site 2).

This suggests that in forest soils there is a geochemical barrier, which results in increased accumulation of radionuclides in certain soil layers. The location and importance of this barrier depends on those features that govern the litter and humid soil horizons development such as age and type of forest, soil humidity, mechanical composition and acidity of underlying soil, etc. Simultaneously, the observed heterogeneity in soil properties results in a need for a special consideration of certain litter-soil horizons when comparing differences in ^{137}Cs availability between experimental sites.

3.3. Distribution of root systems of plants in soil

For most plants studied the main portion of roots was found within the most ^{137}Cs contaminated soil layers (see Figure 1). The roots of all plant species growing on mineral soils (except for *Fragaria vesca* on site 2) were found mainly (from 52.2% to 83.9% of the total biomass) in the upper layer of the humid horizon. No roots of these species were found in the litter A_0L horizon and only a few roots were found in A_0F, A_0H and mineral soil horizons. Bushes showed deeper root systems than dwarf shrubs and grasses. Accordingly, the ^{137}Cs activity in litter layers (A_oF+A_oH) is less important for species of bushes such as *Rubus idaeus*, than for species with superficial root systems like *Vaccinium myrtillus* and *Fragaria vesca*.

3.4. ^{137}Cs uptake by dwarf shrubs, shrubs and mosses

The highest T_{ag} values were found for site 3 with a high level of humidity content. The lowest T_{ag} values were observed for deciduous forests on automorphic soils. It should be noted that the contrasting environmental conditions prevailing in the studied sites have resulted in a different species composition in these sites. This poses some difficulties for comparison of T_{ag} obtained for different sites. Nevertheless, the data for similar grass species allow the conclusion that T_{ag} values for hydromorphic are about three times higher than for semi-hydromorphic soils and about 10 times higher than for automorphic soils. The T_{ag} values for different moss species varied in wide ranges: from 8.7 to 62.9 10^{-3} m^2/kg for automorphic soils and from 78 to 200 10^{-3} m^2/kg for semi-hydromorphic and hydromorphic soils. The ^{137}Cs T_{ag} to mosses growing on hydromorphic soils were from 3 to 20 times higher than those for mosses growing on automorphic soils.

3.5. ^{137}Cs uptake by berries and mushrooms

Berries are especially sensitive to the environmental conditions, which explains the large intersite variation in species composition. *Vaccinium myrtillus* was found only in sites with semi-hydromorphic and hydromorphic soils (Site 2 and 3), while *Rubus idaeus* and *Fragaria vesca* were found only in the sites with automorphic soil (Site 1) and semi-hydromorphic soil (Site 2) respectively.

The highest T_{ag} values were found for *Vaccinium myrtillus* on hydromorphic soil. For semi-hydromorphic soil observed T_{ag} values were by a factor of 3.6 lower. The ratios between T_{ag} for soils considered in the study are close to similar ratios calculated for grasses and dwarf-shrubs and seem to reflect differences in availability of radiocaesium in these soils.

Ratios of the T_{ag} values observed in different sites were calculated separately for each growth period and mushroom species. The geometric mean and confidence intervals of these ratios were subsequently calculated to get an overall ratio of T_{ag} between different sites. The obtained values indicate that the T_{ag} for mushrooms growing in Site 2 are higher by a factor of 4.4 (confidence intervals are 1.6-7.1) than for mushrooms growing on Site 5 and by a factor 2.9 (confidence intervals are 2.8-4.0) than for mushrooms growing on Site 1.

The lowest levels of ^{137}Cs transfer to similar species of mushrooms were observed for deciduous forests on automorphic soil. The observed values in coniferous forest on automorphic soils were 2.6 times higher. The highest values were observed for forest on semi-hydromorphic soil. The geometric means of T_{ag} observed for individual species of mushrooms can be ranked as follows: *Chantharellus cibarius* < *Boletus edulis* ≈ *Leccinum scabrum* ≈ *Russula sp.* < *Lactarius deliciosus* < *Paxillus involutus*.

Another observed regularity was that the contamination of mushrooms sampled in autumn was from 2.5 to 7.1 times higher than of those sampled in July. Seasonal variability in the weather conditions and humidity of the forest soil may be one of the reasons for these differences. Another possible explanation is that radiocaesium is transferred from roots to fruit bodies of mushrooms via mycorrhizae. This would occur mainly in autumn when potassium, and accordingly caesium, is transferred from leaves and needles to roots ([4]).

3.6. Correlation between exchangeable and available fractions of radiocaesium and the T_{ag}

To allow for a comparative analysis of the ^{137}Cs availability in soil, the actual amounts of exchangeable and available fractions of radiocaesium in different soil layers (Figure 2) were calculated for a radiocaesium activity density of 1 kBq m^{-2}. The data presented in Figures 1 and 2 show that there are differences between the distributions of total and available fractions of ^{137}Cs in the soil profile. This is probably due to differences in the capacity of different soil-litter horizons for ^{137}Cs fixation. So, for site 1 the maximal ^{137}Cs activity concentration was observed in A_0H, A_0A_1 horizons. The activity concentrations of this radionuclide in underlying layers are much less (Figure 1). However, because of the low ^{137}Cs availability in the A_0A_1 horizon of Site 1 and its high availability in the deeper layers, concentrations of exchangeable and mobile fractions of this radionuclide are rather similar for horizons A_0A_1, A_1 and A_1A_2 (Figure 2). This effect, albeit less pronounced, is also observed for the other sites.

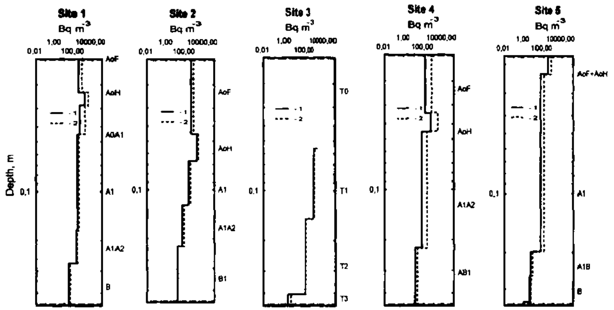

Figure 2. Vertical distribution of exchangeable (1) and available (2) fractions of radiocaesium in soil profile of experimental sites normalised to a ^{137}Cs deposition density of 1 kBq m^{-2}.

These data show that the accumulation of ^{137}Cs by plants in site 1 depends mainly on the radionuclide content in the humus soil horizon. Site 2 is characterised by a thicker litter layer and therefore ^{137}Cs activity in this horizon for this site is more important. Hence, for species of grasses and dwarf shrubs, which have superficial roots, higher T_{ag} values should be expected in Site 2 than in Site 1. In the contrast, for bushes, which have deeper root systems similar T_{ag} values should be expected for both sites.

The rankings of sites in terms of average T_{ag} values and amounts of exchangeable (available) radiocaesium were similar, which suggests that there is correlation between these two parameters. At the same time, there are differences in the available fractions of ^{137}Cs in different litter-soil horizons. This indicates that the root biomass distribution between these horizons also has to be taken into account. Therefore, the total fraction of exchangeable and available radiocaesium in the soil-litter system that can be transferred to under story species (bioavailability factor BF^J, dimensionless) can be given by:

$$BF^J(t) = \sum_i^N \delta_i(t) * q_i(t) * k_i^J$$

Where, q_i is the fraction of the total ^{137}Cs activity in the soil profile that is in the *i-th* horizon; δ_i is the fraction of exchangeable (or available) radiocaesium in the *i-th* horizon; k_i^j is the fraction of roots biomass of *j*-th species of under story in the *i-th* horizon; *N* is the number of genetic litter-soil horizons with different properties.

The data on distribution of total activity, exchangeable and available radiocaesium fractions in different genetic horizons of the soils as well as the distributions of root biomass in soil profiles observed for different groups of under story were used to compare T_{ag} and the BF^J calculated for the study sites. No experimental data was available for direct estimation of the mycelia distribution in the soil profiles. However, taking into account that all sampled mushrooms species are of mycorrhizal type it was assumed that their mycelia are located in A_0H horizon. This is in accordance with data reported by [5]. It is known that mosses are characterised by air type of nutrition, however some nutrients such as potassium and calcium are also transferred to mosses via rizosphere from litter. Therefore, in the calculations it was assumed that litter is the source of moss contamination.

The relationship between the geometric means of T_{ag} calculated for each group of under story and the bioavailability factors (based on radiocaesium exchangeable and available fractions in soil) are shown in Figure 3.

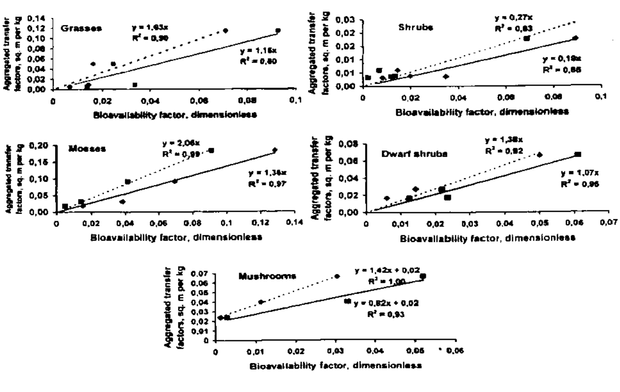

Figure 3. Relationship between aggregated transfer factors to different groups of under story and the bioavailability factors. Rhombuses represent the dependence calculated on the basis of exchangeable fractions and squares - available ones. Doted and solid lines show the appropriate linear fits.

The relationship between the T_{ag} and the bioavailability factors for all studied groups of under story, except for mushrooms, passes through zero, i.e. the T_{ag} equals zero when the BF^i is nil. In the case of mushrooms when the BF^i is zero the T_{ag} equals 0.02 m^2/kg. This may be explained by the fact that an exchange of radiocaesium between roots and mycorrhizae takes place, which can be an additional source of ^{137}Cs to mushrooms. This additional source of radiocaesium may be independent or have a more complex relationship with litter and soil properties. Another possible explanation is that part of the total ^{137}Cs bound to mycorrhizae is not extractable by the reagents used.

4. CONCLUSION

The results of the study allow the conclusion that vertical distribution of ^{137}Cs activity, the percentage of exchangeable radiocaesium in the litter and soil horizons and distribution of root systems (mycelia) in the soil profile are key factors governing the observed variations of radiocaesium availability for uptake by under story components.

References

1. Horina J. and Randa Z., Uptake of radiocaesium and alkali metals by mushrooms. J Radioanal Nucl Chem. Letters 1988; 127/2:107-120.
2. Kammerer L, Hiersche L, Wirth E. Uptake of radiocaesium by different species of mushrooms. J. Environ Radioact 1994; 23:135-150.
3. Mascanzoni D. Uptake of Sr-90 and Cs-137 by mushrooms following the Chernobyl accident. In: Desmet G, Nassimbeni P, Belli M, editors. Transfer of radionuclides in natural and semi-natural environments. London: Elsevier, 1990:459-467.
4. Rochon P, Paré D, Messier C. Development of an improved model estimating the nutrient content of the bole for four boreal tree species. Can J Forest Res 1998; 28:37-43.
5. Rühm W, Kammerer L, Hiersche L, Wirth E. The $^{137}Cs/^{134}Cs$ ratio in fungi as an indicator of the major mycelium location in forest soil. J. Environ. Radioact 1997;35(2):129-148.
6. Prokhorov VM. Migration of radioactive contaminants in soil. Physico-chemical mechanism and modelling. Moscow: Energoizdat, 1981: 98. (In Russian with English abstract)
7. Yoshida S, Muramatsu Y, Ogawa M. Radiocesium concentrations in mushrooms collected in Japan. J Environ Radioact 1994; 22:141-154.