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Radiation Dose From Chernobyl Forests: Assessment Using The FORESTPATH Model

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Abstract. Contaminated forests can contribute significantly to human radiation dose for a few decades after initial contamination. Exposure occurs through harvesting the trees, manufacture and use of forest products for construction materials and paper production, and the consumption of food harvested from forests. Certain groups of the population, such as wild animal hunters and harvesters of berries, herbs and mushrooms, can have particularly large intakes of radionuclides from natural food products. Forestry workers have been found to receive radiation doses several times higher than other groups in the same area. The generic radionuclide cycling model FORESTPATH is being applied to evaluate the human radiation dose and risks to population groups resulting from living and working near the contaminated forests. The model enables calculations to be made to predict the internal and external radiation doses at specific times following the accident. The model can be easily adjusted for dose calculations from other contamination scenarios (such as radionuclide deposition at a low and constant rate as well as complex deposition patterns). Experimental data collected in the forests of Southern Belarus are presented. These data, together with the results of epidemiological studies, are used for model calibration and validation.

1. Introduction

The Republic of Belarus is one of the areas most significantly affected by radionuclides from the Chernobyl NPP accident. After the accident, immediate attention was given to the prevention of human external irradiation due to the gamma shine from the radionuclide cloud and to the clean-up of agricultural areas contaminated by radionuclide deposition. Natural and semi-natural ecosystems, especially forests, initially were not a high priority but subsequently have been found to be efficient reservoirs for deposited radionuclides. The residence times of stable elements and long-lived radionuclides can approach several thousand years. Radionuclides and nutrient elements incorporated into forest biota, harvested as construction materials and consumed as foodstuff can contribute significantly to human radiation dose. This contribution was found to be as high as 37% of the total radiation dose due to consumption of forest-related foods by several populations in Belarus [1].

Several pathways exist whereby people are exposed to radionuclides from contaminated forest ecosystems. In general, external and internal components of the total radiation dose can be distinguished. The external dose results from direct irradiation due to the radionuclides present in the local environment, while ingested and inhaled radionuclides contribute to the internal dose. In the case of contaminated forest ecosystems, the external dose can be received by the general public via direct gamma shine while walking in the forest or through irradiation from radionuclides incorporated into construction materials and paper. The occupational exposure can be received by working in the contaminated environment and by irradiation from by-product materials and from timber cut for forest industries. The internal dose arises from the ingestion of forest products (berries, mushrooms, birds, game, etc.) and from inhalation of resuspended radionuclides from soil and plants; in addition, radiation dose is received from ash caused by forest fires and from wood burned for heating purposes. These exposure routes can affect populations far removed from the contaminated zones.

Actual doses received by members of the public and forest workers vary widely, depending on the individual characteristics, workplace and living habits as well as on the environmental level of contamination. General dose assessment guidelines are required to set standards for radiation protection. Radiation doses can be measured using individual dosimeters, whole-body counting, hematological tests, etc., but these techniques are expensive and provide only individual-specific data. Modeling can provide not only estimates of the doses but also can predict future trends of dose accumulation.

We have developed a generic model, FORESTPATH [2], which describes the major kinetic processes and pathways of radionuclide movement in forests and natural ecosystems and which can be used to predict future radionuclide concentrations. The FORESTPATH model was successfully applied in a general evaluation of remedial policies for contaminated forests [3] and used to direct a sampling program in the Chernobyl Exclusion Zone [4]. In this paper, the FORESTPATH model is used to evaluate internal radiation doses resulting from the consumption of forest berries and mushrooms as well as external dose due to working in highly contaminated forests. Results of model simulations show that forests can contribute significantly to the human radiation dose and thus need to be considered for the purpose of radiation protection.

2. Exposure Assessment

We consider a rural population such as that inhabiting an area near the Exclusion Zone of Belarus contaminated by 5 Ci/km^2 of ^{137}Cs. The average annual consumption of forest products for this population is about 10 kg of fresh mushrooms and 20 kg berries collected from a pine forest near a village which has 5 Ci/km^2. The biomasses of tree, understory and organic layer are chosen to be 14, 0.2 and 6 kg/m^2 respectively, which is typical of the 30-year-old pine plantations in Belarus [1]. Large segments of this population are involved in forestry and agriculture activities. Work in forests implies an annual occupational exposure of about 1,000 hours in areas characterized by a surface deposition of 20 Ci/km^2.

The two major routes of exposure for this population are external, due to gamma emission from soil, and internal, due to radionuclide ingestion from forest berries and mushrooms (hunting is not considered to be popular for this population). The resulting average external dose for the i-th year following the deposition can be calculated using:

$$E_i = R_i * O * DR, \quad \text{where} \qquad (1)$$

E is the annual average external dose (Sv/yr),
R is the activity which remains in forests at i-th year following the deposition (Bq/m^2),
DR is the dose rate factor (1.1 nSv/h per Bq/m^2 for ^{137}Cs [5])

The average internal dose can be calculated using

$$I_i = (OL_i * M + U_i * B) * DC * F_r, \quad \text{where} \qquad (2)$$

I is the annual average internal dose (Sv/yr),
OL is the radionuclide concentration in mushrooms (Bq/kg fresh weight),
U is the radionuclide concentration in berries (Bq/kg fresh weight),
M is the ingestion rate for mushrooms (kg/yr),
B is the ingestion rate for berries (kg/yr),

DC	is the ingestion dose coefficient ($1.4 * 10^{-8}$Sv/Bq for ^{137}Cs [6]), and
F_r	is the food processing retention factor (0.7 for berries and 0.2 for mushrooms [7]).

Additional irradiation dose can arise from radionuclide resuspension by soil or ash (if timber is used for heating purposes), use of contaminated construction materials and paper, forest fires, etc. The resulting dose from these and other processes is a subject for future investigation and are not considered in this paper.

3. Model Description

The FORESTPATH model calculates a time series of inventories for a specific radionuclide distributed within the following six compartments: Understory, Tree, Organic Layer, Labile Soil, Fixed Soil and Deep Soil. Six coupled ordinary differential equations describe the transfer of a radionuclide between the forest compartments. The residence times are the major parameters governing the transfer. The initial data for a given radionuclide is the radioactivity to be distributed within the forest compartments. A complete description of the FORESTPATH model can be found in reference [2].

Berries are assumed to be a part of the Understory compartment and have similar contamination density. Fungi can be important media for radiocesium migration in forests. According to estimates and experimental data [8], they can be responsible for holding up to 40% of the radiocesium present in the Organic Layer. As a first approximation, mushrooms are, therefore, assumed to be a part of the Organic Layer and thus have the same contamination density. A more advance model for the mushroom contamination is currently being developed [9].

4. Results

Figure 1 presents a 50-year FORESTPATH simulation for ^{137}Cs concentrations in mushrooms and berries found in coniferous forests. An initial contamination density of 5 Ci/km^2 and generic FORESTPATH parameters [2] were used, as well as the forest characteristics presented above. We assume that mushrooms and berries are parts of the Organic Layer and Understory compartments and thus have the same contamination density. The current radioactivity of mushrooms is significantly higher because they take up nutrients, such as K, and, therefore, absorb radionuclides from the Organic Layer. On the other hand, the activity in berries, which have a deeper root zone and extract their nutrients from the Labile Soil, is shown to increase with time reaching a maximum at about 10 years following the accident [2]. Our model simulations represent well the concentrations and time trends which have been measured in different species of mushrooms and berries in Belarus [1].

Figure 2 presents the external radiation dose resulting from living in an area with contamination density of 5 Ci/km^2 as well as the additional radiation doses due to occupational exposure in the forest and by the forest product food consumption. Work in a contaminated forest of 20 Ci/km^2 leads to an annual external dose of 4.2 mSv (sum of public and forest worker) for the fifth year following the accident. This is more than twice the average external dose received by the non-forest-worker population in this area. Dose rate measurements for forest workers were conducted at several Belarussian sites [1]. The occupational exposure was found to be 1.75 to 2.9 times higher than the external dose of the public living in the same area, which is in agreement with the model predictions. According to the model, the human radiation dose is slowly decreasing with a half-time of about 30 years due to the physical decay of ^{137}Cs.

5. Conclusions

The complex problem of radionuclide contamination in forest ecosystems requires the use of a model to synthesize and analyze the properties of the entire ecosystem as well as to evaluate the radiation dose resulting from forest usage. The generic forest model developed and used here provides a beginning point for evaluating internal and external radiation doses over long time periods. The model uses dynamics consistent with biological processes and

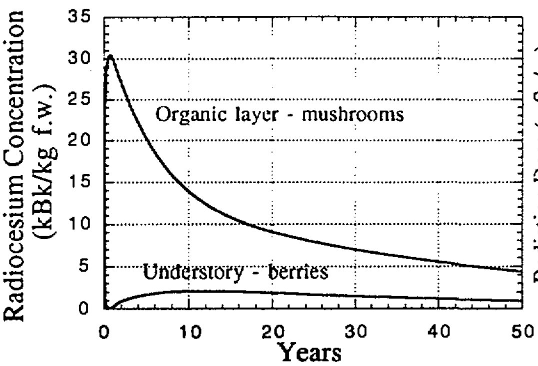

Figure 1. ^{137}Cs concentration in compartments of a coniferous forest following an acute deposition.

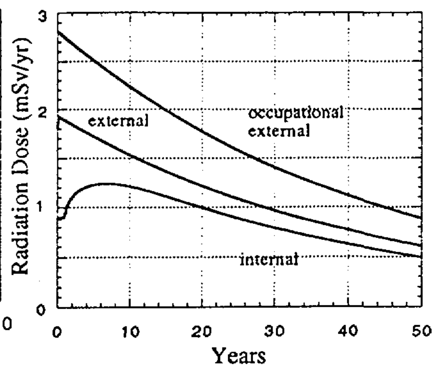

Figure 2. Radiation doses received by different populations.

calculates the resulting human radiation doses which would be received over some 50 years. While not yet validated, the initial results on mushroom and berry consumption do provide dose estimates that can be compared with experimental measurements. Contaminated forests constitute a significant hazard to the public over long periods of time depending primarily on the forest food intake. Occupational exposure can be several times greater than that for the general public. The use of a dynamic model can facilitate the decision-making process and help in the design of efficient abatement, remedial and social policies.

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