HUMAN RADIATION DOSE RESULTING FROM FORESTS CONTAMINATED BY RADIONUCLIDES: GENERIC MODEL AND APPLICATIONS TO THE CHERNOBYL ECOSYSTEMS

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ABSTRACT

Forest ecosystems have been found to contribute significantly to the human radiation dose in the intermediate and long terms following radionuclide releases. Evaluation of the internal and external radiation dose for these critical population groups requires knowledge of radionuclide transport processes in forest ecosystems, as well as the extent of forest utilization by these populations. The high complexity of the problem requires the use of models to define and analyze the properties of the forest as well as to evaluate the ecosystem response to possible human intervention. A generic FORESTPATH model is used to calculate the internal and external radiation doses for different critical groups of consumers at different times following radionuclide release. The model is tested using the information available for contaminated forests in Belarus. Uncertainty of the model predictions are estimated by means of Monte-Carlo simulations.

EXPOSURE ASSESSMENT

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 the direct gamma shine while walking in the forest or through irradiation from radionuclides incorporated into construction materials and paper. 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 and for fuel. 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.

A scenario is considered for a rural population inhabiting an area near the Exclusion Zone of Belarus contaminated by 5 Ci/km^2 of ^{137}Cs. This population consumes forest products collected from a pine forest near the village which has 5 Ci/km^2. Large segments of this population are involved in forestry and agriculture activities. Work in the forests implies an annual occupational exposure of about 1,000 hours in areas characterized by a surface deposition of 20 Ci/km^2. Table 1 presents probability distributions for the average annual consumption of forest products, exposure time for occupational forest use, forest characteristics which are typical of the 30-year-old pine plantations in Belarus and conversion factors.

Table 1. Parameters used for probabilistic modeling of risk associated with contaminated forest ecosystems

Parameter	Notation	Unit	Distribution			Reference
			shape	mean	range	
residence area contamination	RAC	kBq/m^2	constant	185		site-specific
forest contamination	FOC	kBq/m^2	constant	740		site-specific
Organic Layer accumulation	OL	% initial inventory	triangular	55	15 - 75	1
Organic Layer biomass	OLB	kg/m^2	triangular	3.1	2.4 - 4.5	2
Understory biomass	UN	% initial inventory	triangular	0.2	0 - 2.2	1
Understory biomass	UNB	kg/m^2	triangular	0.5	0.01 - 1	estimates
mushroom consumption	MUC	kg/yr	triangular	10	5 - 15	3
mushroom processing retention	MPR	fraction	triangular	0.2	0.1 - 0.4	4
berry consumption	BEC	kg/yr	triangular	6	5 - 20	3
berry processing retention	BPR	fraction	triangular	0.6	0.7 - 0.8	4
external dose rate factor	DRE	(nSv/yr)/(Bq/m^2)	triangular	24.5	22 - 30	3
internal commited dose rate	DRI	nSv/Bq	triangular	13	10 - 22	3,5
occupational time spent in forest	FOO	hr/yr	triangular	1000	500 - 2000	estimates
dose-fatal cancer risk conversion factor	DRC	Sv^{-1}	uniform	0	0.08	6, estimates

Two major routes of exposure for this population are the external irradiation due to gamma emission from the forests and the internal exposure due to radionuclide ingestion from forest berries and mushrooms. The resulting average external dose for the i-th year following the deposition can be calculated using:

$$EP_i = (RAC_i + FOC_i * FOO) * DRE \quad (1)$$

where EP_i is the annual average external dose (mSv/yr).

The average internal dose can be calculated using:

$$IP_i = ((OL_i/OLB) * MUC * MPR + (UN_i/UNB) * BEC * BPR) * DRI \quad (2)$$

where IP_i is the annual average internal dose (mSv/yr),
OL_i is the radionuclide concentration in the Organic Layer (% of initial inventory),
UN_i is the radionuclide concentration in the Understory (% of initial inventory),

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

The risks of low-dose-rate external exposure to radiation have been obtained by extrapolation from high-dose-rate data (5). Recent compilation of the available data for different exposed population (7) provides reasonable doubt that low-level radiation is harmful. Thus, a uniform distribution from zero to twice the value recommended in (5) was used for dose-risk conversion factor in risk calculations:

$$R_i = (EP_i + IP_i)) * DRC \quad (3)$$

RADIATION DOSE AND RISK

The FORESTPATH model (1, 8) is used to establish the radionuclide distribution among forest compartments. In this paper, coniferous forest ecosystems which are typical for the Chernobyl Exclusion Zone are considered. An initial contamination density of 5 Ci/km^2 and generic FORESTPATH parameters (1, 8) were used, as well as the forest characteristics presented above. The current radioactivity of mushrooms is significantly higher than that found in berries because mushrooms take up nutrients and, therefore, absorb radionuclides from the Organic Layer (1, 8). 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 (1, 8).

Figure 1a 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 to 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 exposures) for the fifth year following the accident. This is about 2.5 times greater than 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 (2). Their occupational exposure was found to be 1.75 to 2.9 times higher than the external dose to the general public living in the same area, which is in agreement with the model predictions. After eight years, the human radiation dose is slowly decreasing with a half-time of about 30 years due to the physical decay of ^{137}Cs.

Monte-Carlo simulations were conducted to address the influence of the uncertainty in input parameters (Table 1) to the internal radiation dose (Figure 1b). Each Monte-Carlo simulation produced 300 estimates of the internal dose resulting from the berry and mushroom consumption seven years following the contaminating event. Parameter values were selected using the random Latin Hypercube method. Cumulative distribution functions for internal dose reveal a wide range of variation depending on consumption of the forest products and site contamination.

The cumulative distribution function for the risk of developing a fatal cancer for the general public is presented in Figure 2a. The high range of variation results from the uncertainty in input parameters (Table 1). To find the most important parameters for the model performance, a sensitivity analysis was conducted using the technique of partial rank correlation (Figure 2b). The uncertainty in the DRC (dose-risk conversion factor) dominates the range of model outputs. Unfortunately, current literature does not allow any better estimation of this parameter. All other parameters are significantly less important. Among the other parameters, the organic layer contamination (OL) and internal commited dose rate (DRI) are relatively important.

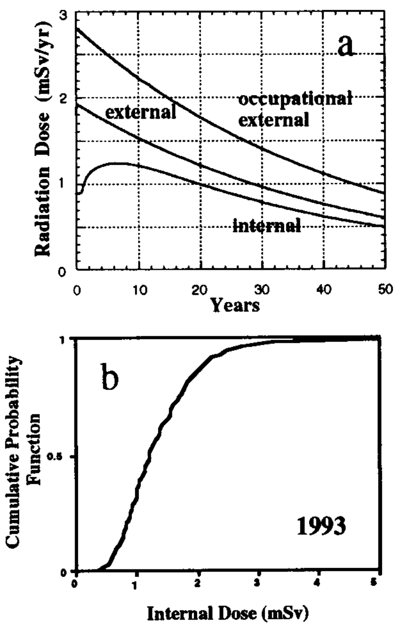

Figure 1. Excess radiation doses received by different populations (a) and cumulative probability function for internal dose received in 1993 (b).

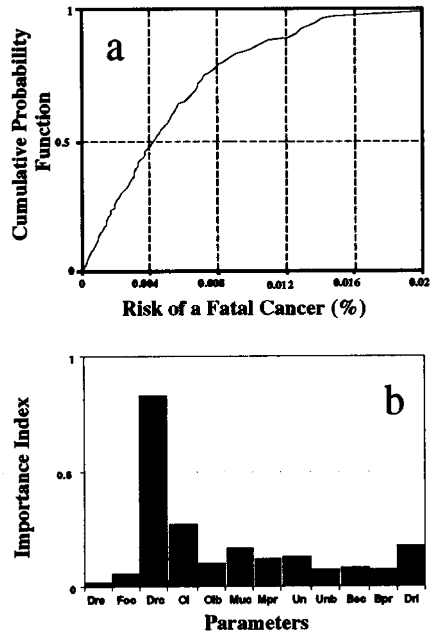

Figure 2. Cumulative probability function for risk of a fatal cancer due to consumption of forest product by a critical population group (a) and importance index for model parameters (b).

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. Modeling can provide not only estimates of the radiation dose but also can predict future trends of dose accumulation. The generic forest model developed and used here provides a starting point for evaluating internal and external radiation doses and risks over long time periods. Contaminated forests constitute a significant hazard to the public over long periods of time depending, in a major part, 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 helping to design efficient abatement, and remedial and social policies in radionuclide contaminated regions.

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