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FINAL REPORT

CHERNOBYL FOREST ECOSYSTEM MODELING

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2. Schell, W.R., Linkov, I. Belinkaia, et al.. (1996). Radiation Dose From Chernobyl Forests: Assessment Us The FORESTPATH Model. Proceedings Of The First International Conference On The Consequences Of The Chernobyl Accident, IOP, Amsterdam; p. 217.
3. Schell, W.R., Linkov, I., Belinkaia, E., Morel, B. (1996) Application of a dynamic model for evaluating radionuclide concentration in fungi. In: Proc. of 1996 International Congress on Radiation Protection. Vienna; p.2752.
4. Linkov, I., Kandlikar, M., Morel, B., Belinkaia, E., Schell, W.R. (in preparation) "Application of the generic model FORESTPATH for radionuclide migration in Chernobyl forests".
5. Linkov, I., Belinkaia, E.,et al. (submitted) "Fate and transport of radionuclides in Chernobyl forests: dynamic modeling for risk assessment and remedial policy evaluation" Society for Risk Analysis, 1996 Annual Meeting.

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RESEARCH RESULTS

Project: **Chernobyl Forest Ecosystem Modeling**

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Principal Investigator: W.R. Schell

Analysts: W.R. Schell and Elena Belinkaia

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Abstract

This report and the accompayning documents demonstrate the use of a model to better understand complex forest ecosystem processes. Key advances in our understanding have been made this year by using Monte Carlo methods in uncertainty analysis of model predictions. These findings, with collaboration of Elena Belinkaia, show that the computer simulations are consistent with the experimental variations found from actual sample measurements in Chernobyl N.P.P. contaminated forest.

The several papers published at the three international meetings noting the 10th Anniversary of Chernobyl N.P.P. Accident disaster, illustrate the current development and importance of the research. The application of the model to radiation dosimetry, site remediation, risk assessment and remedial policy evaluation are highlight of the past year's work (see Appendix)

Introduction

The complex problem of radionuclide contamination in forest ecosystems requires the use of a model to organize the available information and to analyze the biogeochemical processes for the entire ecosystem; in addition, a model can be used to evaluate and to predict the radiation dose to man resulting from forest use. The dynamics of these processes are poorly understood and no generic model is available to describe the radionuclide pathways in forests from deposition to repository. Nevertheless, a number of the principal mechanisms governing the behavior of radionuclides in natural ecosystems have now been elucidated and can be used in the development of a generic model.

Generic Model Development

A generic model, FORESTPATH, has been developed to describe the radionuclide pathways and dynamics in forest ecosystems based on the current understanding of the physical, chemical and biological processes involved. Due to the different nature of biological transformations in deciduous and coniferous forests, at least two generic forest models must be considered. Due to mechanisms responsible for radionuclide fixation in forest soil, labile and fixed compartments must be distinguished to obtain an appropriate description of the radionuclide migration. The model is designed to be flexible and simple in order to incorporate different types of radionuclides and contamination (atmospheric deposition, waste disposal, etc.) as well as to further evaluate human dosimetry and remedial policies.

The results of simulations carried out using the FORESTPATH model show that forests are efficient sinks for radionuclides. Understory, Tree and Organic Layer are the major sinks for radionuclides in the short and medium terms. A variability analysis technique was developed to determine the extent of possible variations in radionuclide distributions. Tree and understory uptake half-times as well as organic layer removal half-times were found to be the key parameters for the model. When FORESTPATH was run with a representative set of values for these parameters, totally different radionuclide cycling patterns were found. Careful selection of parameters is thus important for FORESTPATH applications.

Results and Discussion

The generic FORESTPATH model structure can be easily adjusted for different site-specific applications. For a given site, FORESTPATH can incorporate particular radionuclide pathways by adding or changing compartments. In such situations, the input parameters can be represented by probability distributions and uncertainty analysis using the Monte-Carlo method have been conducted to estimate the uncertainty of the model predictions. The FORESTPATH model was applied to Chernobyl forests. Modeling results reproduce the existing experimental data well. Uncertainty ranges predicted by the probabilistic model using Monte-Carlo simulations are consistent with the experimental variation found in the Chernobyl forests.

Reported measurements from the global fallout of atmospheric nuclear tests, as well as radionuclide deposition after Chernobyl and Kyshtym accidents, were used for the model validation studies. Both generic and site-specific model applications to the Chernobyl forests are in good agreement with the available experimental data.

The FORESTPATH model can be developed further for evaluation of the human radiation dose and the effectiveness of remedial policies. Dosimetric application requires determination of site-specific parameters for the forest, as well as for the consumption of forest products by critical

population groups. A detailed description of remedial policy is being evaluated using FORESTPATH. As an example, the effects of removing the organic layer from contaminated forests was considered and this intervention was found to be very efficient for the acute deposition scenario. The FORESTPATH calculations suggest similar magnitude and optimal timing for the organic layer removal policy. The proposed methodology can be used in an evaluation of the ecosystem's evolution after the contamination and of the applied interventions.

A sampling methodology was developed based on a model-directed approach and was conducted in the Chernobyl Exclusion Zone. The FORESTPATH model was used to guide the development of this experimental program and to assist in the analysis of results. The implications of this program led to a broad scale international collaboration, which is engaged permanently in data collection, analyses and evaluation using standardized protocols and procedures as well as quality assurance.

Conclusions and Recommendations

It is evident that a dynamic model can be used to improve the knowledge and understanding of processes and mechanisms involved in radionuclide transport in natural ecosystems, and facilitate the decision-making process in the design of efficient remedial policies. The existing database on useful parameters for modeling contaminated forests still remains incomplete and further sampling and measurements are required. FORESTPATH can be used to guide the development of possible experimental programs. Special attention should be given to root uptake studies. The usual approach to root uptake processes is the use of transfer factors for plants. This approach to forest dynamic modeling can lead to significant difficulties in deciding which values to use because of the layered forest soil structure, chemical speciation and the long radionuclide lifetime of trees. The use of uptake half-times provides parameters which best describe the kinetic processes for modeling.

Radionuclide resuspension is an important processes which has not been addressed by the modeling. Geographical Information Systems (GIS) appears to be a suitable environment where this can be accomplished. Important factors to be taken into account are site topography, soil properties and hydrology. This subject has been part of the course of study and research undertaken by Elena Belinkaia at Carnegie Mellon University.

The future development of a model-based decision-support system on forest remediation requires: 1) human radiation dose evaluation, and 2) cost-benefit analysis of possible remedial policies. Social environment and consequences should be incorporated into the analysis. Advanced decision science methodologies could be used to facilitate this task.

A list of conferences and presentations to which the grant recipient, Elena Belinkaia, contributed are shown in Table 1. Papers and abstracts are attached in the Appendix.

Table 1. List of publications written and/or presented at international Meetings during the term of Grant.

#	Date	Title of publication	Location
1	October 1995	FORESTPATH Model for Radionuclide Migration	University of Pittsburgh, USA
2	March 1996	Radiation Dose From Chernobyl Forests: Assessment Using The FORESTPATH Model	EU, CIS, Minsk, Belarus
3	April, 1996	Application of a dynamic model for evaluating radionuclide concentration in fungi	IAEA, Vienna
4	July 1996	Fate and transport of Pu in forest ecosystems: Assessment using FORESTPATH model	NATO, Crete, Greece
5	July 1996	Risk assessment and Remedial policy Evaluation using predictive modeling	HPS, Seattle
6	December 1996	Fate and transport of radionuclides in Chernobyl forests: dynamic modeling for risk assessment and remedial policy evaluation	SRA, New Orleans

APPENDIX

The papers prepared under the CAST 95 program are shown in the Appendix.

Paper #1 applies FORESTPATH model for Plutonium migration in forests. The recipient of the Grant, Elena Belinkaia, conducted comprehensive literature review for existing models for plutonium migration to determine appropriate modeling parameters and modified the model accordingly.

Paper #2 introduces probabilistic analysis of risks resulting from using of contaminated forests by population. She contributed to the development of methodology for probabilistic modeling as well as to uncertainty and variability analyses.

Paper #3 models specifically radionuclide accumulation by mushrooms. Her research assisted in addressing the most important mushroom species used by population in NIS. A model was designed specifically to incorporate variations in mushroom morphology and uptake mechanisms.

Paper #4 , Abstract #5 and Paper #6 introduce current research on Bayesian updating of the model predictions using information collected at Chernobyl forests. Elena contributed to software development and analyses.

"*Actinides and the Environments*", P.A. Sterne, A. Gonis and A.A. Borovoi, eds.
Kluwer, Netherlands 1996.

FATE AND TRANSPORT OF PLUTONIUM IN FOREST ECOSYSTEMS: ASSESSMENT USING THE FORESTPATH MODEL

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Abstract

This paper illustrates the application of a dynamic model, FORESTPATH [1-2], to evaluate dynamic processes in forest ecosystems resulting from accidental releases or continuous deposition of plutonium. Only a few studies have been made to model the fate and transport of plutonium in natural ecosystems. These studies generally are limited to soil transport and do not address soil-to-plant uptake. The FORESTPATH model uses residence half-times for radionuclides in the several compartments to describe this kinetic process. Experimental measurements of fallout from nuclear weapon tests and from the Chernobyl accident have been used to test the predictions made using the FORESTPATH model.

1. Introduction

Long-lived radionuclides from nuclear weapons tests and reactor accidents can accumulate significantly in natural ecosystems as their effective residence times are often relatively long. If incorporated into natural products such as firewood, construction materials, or consumed in foodstuffs, these radionuclides can contribute significantly to the human dose for intermediate and long time periods following the contaminating event [3-4]. Often, the response of the ecosystem and the fate and transport of the radionuclides can only be evaluated using models which should be tested and validated in order to help formulate public policy concerning abatement and remediation of contaminants.

The Chernobyl accident provided valuable information for calibrating and validating radionuclide transport models. Unfortunatelly, most of the information gathered has been limited to Cs-137 and Sr-90. Very little is known about the mechanisms involved in actinide transport in terrestrial ecosystems. Studies have shown that trees can effectively accumulate actinides deposited from atmospheric fallout as well as from waste disposal [5-8]. Mechanisms responsible for plant uptake of actinides as

well as the effects of chemical speciation in the environment are subjects of active investigations.

In this paper, the generic model FORESTPATH has been used to describe the fate and transport of Pu in forest ecosystems. The FORESTPATH model has been validated on ecosystems contaminated by Cs-137 resulting from global fallout and/or from the Chernobyl accident [2]. To model Pu transport, the generic FORESTPATH parameters as well as the few available data for Pu are used as an initial approach.

2. Modeling of Pu Transport in Forest Ecosystems

The FORESTPATH model [1-4] 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. In this paper, the model was developed further to incorporate details of radionuclide migration in the Organic Layer. The Organic Layer is represented by three horizons: Ol (litter), Of and Oh (Figure 1). The few residence time values reported for Pu in these horizons, along with generic values for the other FORESTPATH parameters for coniferous forests, were used in model simulations and are presented in Table 1.

TABLE 1. FORESTPATH model coefficients used as Pu input in generic coniferous forest

Parameter	Generic value	Range	Reference	Comments
absorption half-time (yrs) desorption half-time (yrs)	0 0			No information has been found on the rate of Pu absorption and/or desorption No adsorption/desorption assumed
leaching half-time (yrs)	1000	247-4100	[9-12]	Pu removal from root zone to deep soil
removal half-time from OL horizons (yrs):			[13]	Total Pu inventory is considered
Ol		0.3-1		
Of		0.4-3		
Oh		0.2-0.6		
understory uptake half-time tree uptake half-time (yrs)	150 500	70-2000 200-6000	[5], [8]	Calculated value based on proportion of Pu removed by plants (Table 2.5 in [8]) Biomass adjustment was made
tree removal half-time			[2]	Valus for Cs-137 based on extensive literature review
short (< 1 weeks)	3.6 d	1.4-5 d		
intermediate (< 1yr)	80 d	21-175 d		
long (> 1yr)	3 yr	1-10 yr		
understory removal half-time (d)			[2]	Valus for Cs-137 based on extensive literature review
short (< 1 weeks)	12	9-19		
intermediate (< 1yr)	32	8-64		
long (> 1yr)	84	38-130		

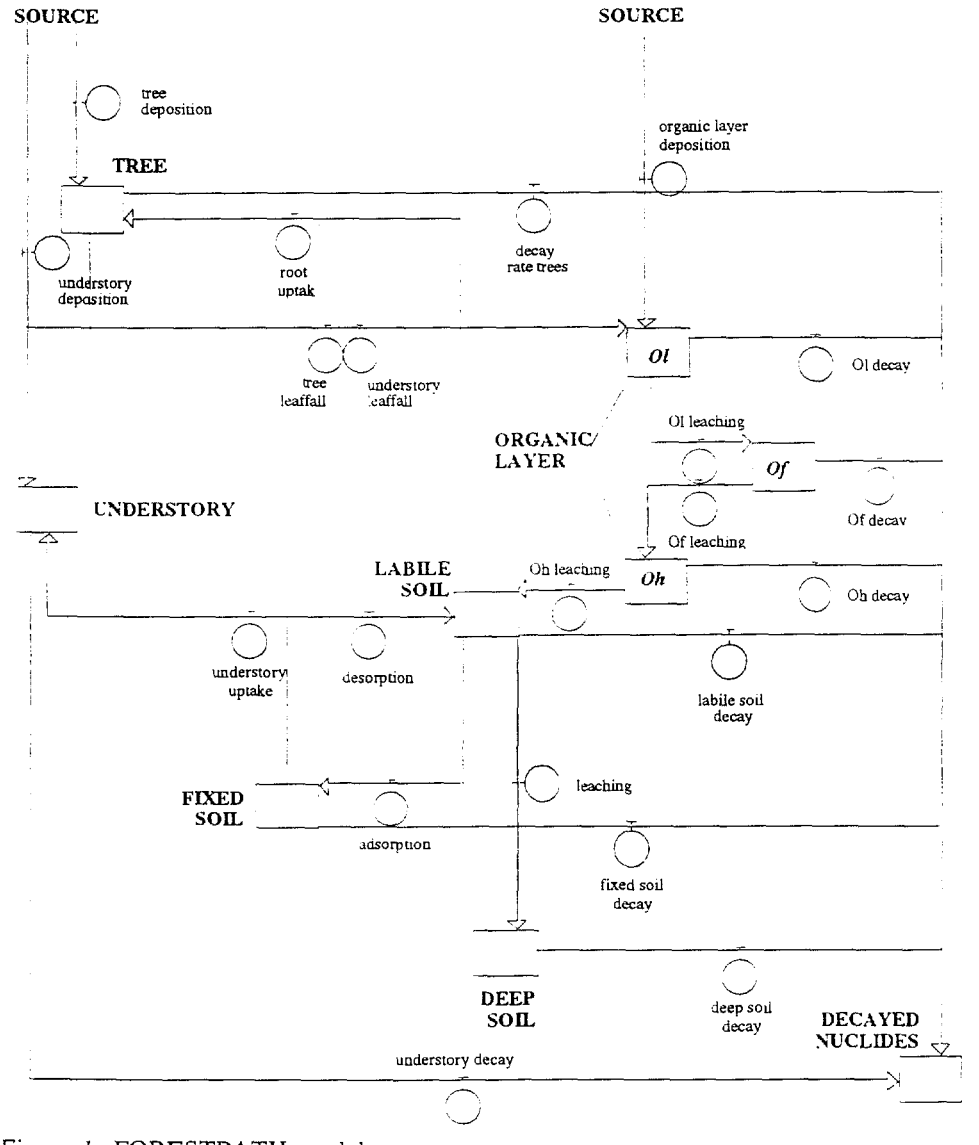

Figure 1. FORESTPATH model

Plutonium, like most radionuclides, can be efficiently sorbed by various soil components (organic matter, clay minerals, etc.). Although this issue is discussed in numerous papers [14,15], no quantitative parameters on the rate of Pu absorption and desorption have been reported. Similarly, mechanisms of Pu uptake by roots are still not understood [16,17]. The crucial information required is on the labile fraction of Pu in soil, not its total content. In order to be taken by plants, plutonium must be in the form of organic complexes of humic and fulvic acids or their smaller sized degraded molecular

compounds. These smaller sized organic molecules formed by microbial induced decomposition are consequently more mobile then the original complexes. An indication of this process is shown by McGarry [18]. The vertical profiles of both plutonium and cesium in the same samples collected in high rainfall zones in Ireland after the Chernobyl accident were analyzed. The plutonium appeared to migrate at almost the same rate as cesium according to measurements made in peat bog cores.

Transfer factors (TF) have been widely used to model Pu uptake by plants. Recent studies shows that TF are of strictly limited value, providing only a site-specific statistical measure of radionuclide uptake [19-21]. Better results may be obtained if TF are calculated using soil solution concentration [20-21], though this adjustment still will not make TF into suitable parameters for dynamic modeling since they are derived by assuming equilibrium in the ecosystem.

Some of the dynamic parameters required for the FORESTPATH model can be evaluated using reported values for radionuclide migration rates. Residence half-times for the organic layer and soil compartments are shown in Table 1 with ranges of variability and references. These half-times were obtained for the total Pu inventory. Similarly, the estimated proportion of Pu removed from the total Pu soil inventory by plants can be used to derive plant uptake half-times [8]. However, the available parameters reported do not allow consideration of Pu fixation in soil and plant uptake from the labile fraction, although they do consistently deal with the total Pu inventory.

Plutonium interception and removal from Tree and Understory in this first test case is assumed to be similar to that of Cs; generic FORESTPATH values are used [2], even though the chemical properties of the two elements are very different. The migration of the organo-complex species of plutonium in terrestrial ecosystems, however, may not be very different from cesium, as indicated by McGarry [18] and Bunzl [13].

3. Results

Figure 2a shows the results of a simulation for radionuclide accumulation over time by the Organic Layer and Soil compartments in a coniferous forest. Organic Layer compartments exhibit complex time dynamics. The litter compartment is significantly contaminated immediately after the deposition, but loses most of its activity during the first year due to wash-off and leaching towards deeper layers. Of and Oh horizons show accumulation peaks at about two and three years respectively following the initial deposition. Most of the radioactivity is accumulated in the Soil compartment. leaching to Deep Soil is slow, while Tree and Understory accumulate only about 1% of the activity available (Figure 2b). The Pu concentration in Tree and Understory does not change much after the initial decrease due to root uptake.

Figure 3 shows simulations assuming a constant annual rate of Pu deposition on coniferous forests. Such a situation would be typical of continuous low level emissions from a nuclear power plant, nuclear waste disposal sites or redistribution by fires and dust. The radioactivity in all compartments increases with time and is much higher than the annually deposited inventory (Tree contains about three times the annual radionuclide deposition), predicting that forests accumulate radionuclides. Moreover, significant Pu

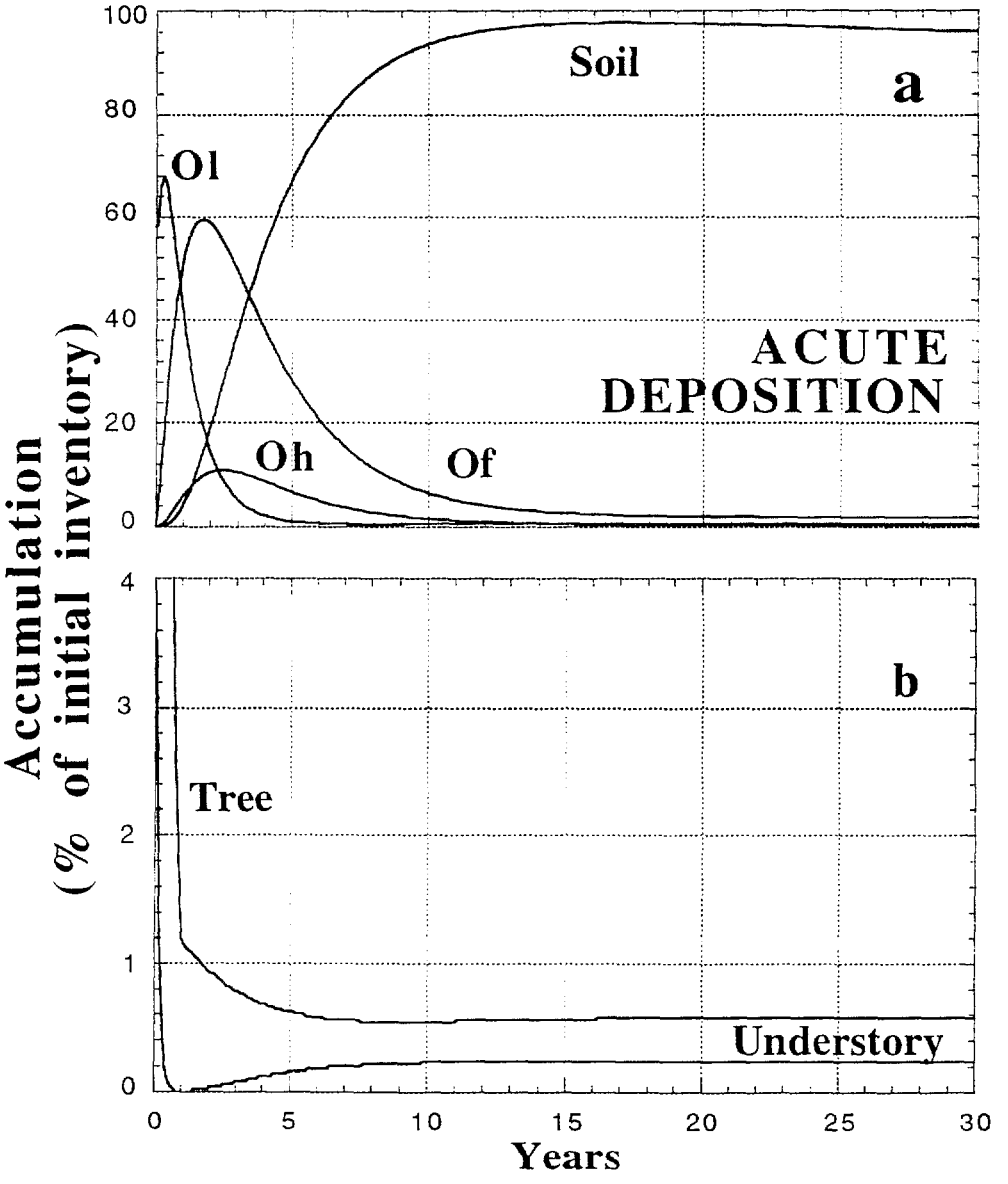

Figure 2. Plutonium accumulated in compartments of generic coniferous forest over 50 years from an initial acute deposition (percent of initial inventory): a) Soil (Labile and Fixed) and Organic Layer (Ol, Of and Oh); b) Tree and Understory. Leaching to Deep Soil is negligible (not shown).

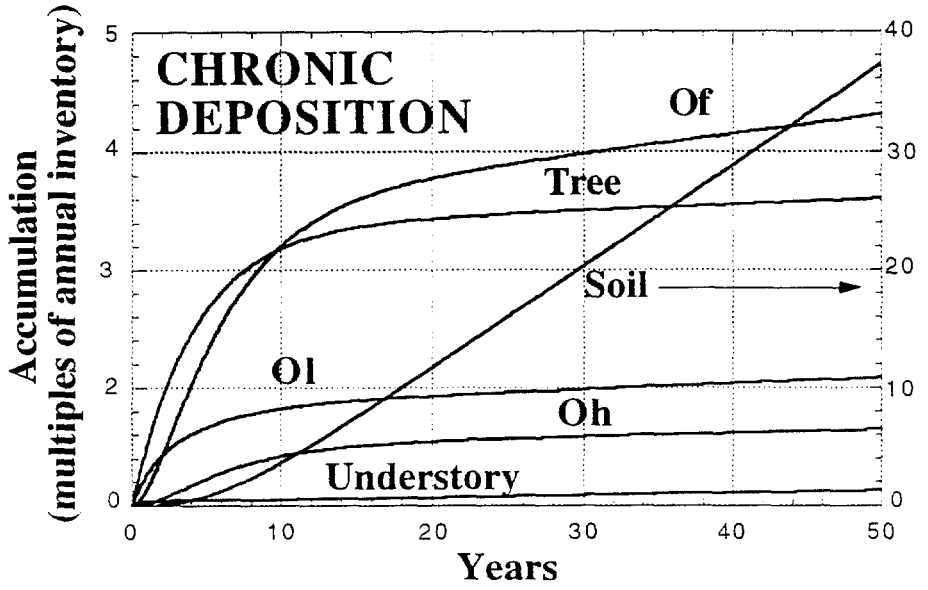

Figure 3. Plutonium accumulated in generic coniferous forest compartments over 50 years for a deposition with a constant rate in multiples of annual inventory (i.e., deposition, leaching from waste disposal sites, etc)

accumulation occurs in the Understory, Tree and Organic Layer compartments. Only a negligible fraction of the Pu reaches the Deep Soil compartment.

Model validation can be achieved by compiling original literature values that describe a time-based series of radionuclide measurements in forest compartments after fallout deposition. Given the high uncertainty and variability associated with residence times, only a qualitative comparison for cesium is made at this stage of the FORESTPATH model development. Limited experimental data on Pu migration in natural ecosystems is currently being evaluated. Published experimental data are in good agreement with FORESTPATH predictions. For example, tree was found to uptake efficiently actinides from old burial ground six meters deep at the Savannah River Site [22]. Near Hiroshima, Japan, the 1965±3 tree rings showed significant accummulation of plutonium originating froom the atomic bomb explosion in 1945, i.e., 20 years after coontamination [23]. This accumulation pattern is again consistent with model prediction (Figure 2).

4. Conclusions

An attempt has been made to evaluate the processes which redistribute transuranic radionuclides in natural terrestrial (forest) ecosystems. Because of the limited number of systematic measurements for plutonium, a comparison has been made with radioactive cesium where extensive data are now available from the Chernobyl NPP accident. Even

recognizing the very different chemical properties of plutonium and cesium, many of the mechanisms which are responsible for their transport are related to the organo-metal complexes of these two elements; these complexes may, in fact, be redistributed similarly. By using a simple model, the parameters which are most important can be identified and a sensitivity study initiated. The appropriate field sampling and analysis can thus be defined [24]. Biological uptake of both of these elements occurs through their transfer across the root membrane of plants; ionic balance is controlled by the presence of the potassium and cesium cations. However, the cesium cation is strongly fixed by certain clays in soil and is unavailable for uptake. It is the labile fraction component in soil, not the total concentration, that is important for both plutonium and cesium transfer to plants. We recommended that future work be focused on the mechanisms of plant uptake of radionuclides and on the presence of the "exchangeable" or labile fraction in natural ecosystems in order to provide the essential data for predictive models.

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The radiological consequences of the Chernobyl accident

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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 radionuclide from the Chernobyl NPP accident. After the accident, immediate attention was given to th prevention of human external irradiation due to the gamma shine from the radionuclide clou and to the clean-up of agricultural areas contaminated by radionuclide deposition. Natural an semi-natural ecosystems, especially forests, initially were not a high priority but subsequentl have been found to be efficient reservoirs for deposited radionuclides. The residence times c stable elements and long-lived radionuclides can approach several thousand years Radionuclides and nutrient elements incorporated into forest biota, harvested as constructio 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 t consumption of forest-related foods by several populations in Belarus [1].

Several pathways exist whereby people are exposed to radionuclides from contaminate forest ecosystems. In general, external and internal components of the total radiation dose ca be distinguished. The external dose results from direct irradiation due to the radionuclide present in the local environment, while ingested and inhaled radionuclides contribute to th internal dose. In the case of contaminated forest ecosystems, the external dose can be receive by the general public via direct gamma shine while walking in the forest or through irradiatio

exposure can be received by working in the contaminated environment and by [illegible] 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),

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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].

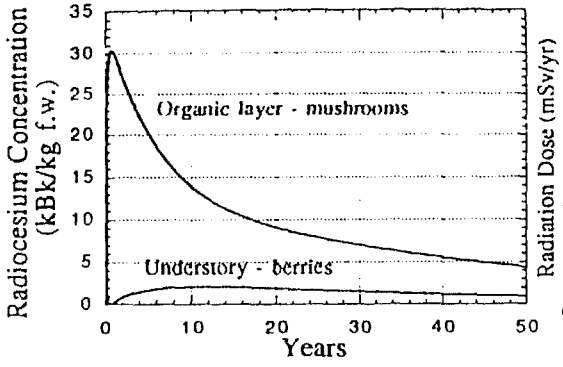
4. Results

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 dose over long time periods. The model uses dynamics consistent with biological processes and



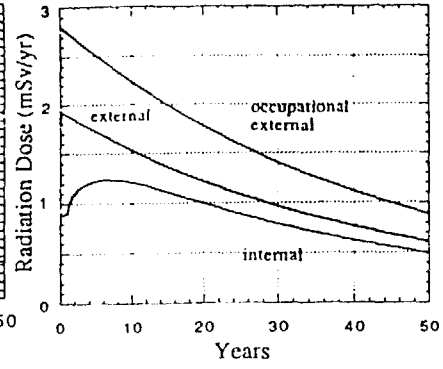


Figure 1. ^{137}Cs concentration in compartments of a coniferous forest following an acute deposition.

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.

Acknowledgments

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APPLICATION OF A DYNAMIC MODEL FOR EVALUATING RADIONUCLIDE CONCENTRATION IN FUNGI

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ABSTRACT

Global fallout from nuclear weapon tests in the 1960s revealed the potential of fungi as an enh accumulator of radioactivity. Data derived from Chernobyl fallout sampling has shown fungi to be a accumulator of radiocesium and an important food-chain contributor to the human radiation dose. Fung significantly affect the radionuclide cycling in forests. According to experimental data and estimations, microflora, particularly fungi mycelia, could retain up to 40% of radiocesium. This paper illustrates the applic of the dynamic model FORESTPATH to evaluate the contamination dynamics in fungi and the relative impor of fungal species for forest cycling. Only a few studies have been made to model fungi contaminate radionuclides and these utilize Transfer Factors to describe soil-to-fungi uptake of radionuclides. Such an app has serious limitations, since equilibrium conditions and specified soil sampling depths must be assumed. FORESTPATH model uses rate of uptake and residence half-times for radionuclides to describe this process. model was applied to describe radionuclide dynamics in fungi for the case of chronic deposition and for the accic release of radionuclides. Experimental measurements of fallout from nuclear weapon tests and from the Cherr accident were used to test the FORESTPATH predictions.

INTRODUCTION

Data derived from sampling of the areas contaminated by the Chernobyl fallout have implicated the Org Layer as being a major accumulator of radiocesium (1, 2). Fungi are the highest living biomass in the decompo organic layer and are the primary sources of the enzymes necessary to degrade the litter and, thus, are very impo for radionuclide migration in forests. Fungi mycelia and fruit bodies are mainly located in the upper part of organic layer. Although above-ground mushrooms are a minor contributor to the total fungal biomass (accordir Olsen (3), this contribution may be as low as 1%, leaving 99% in the below-ground biomass) they can contri significantly to the human radiation dose being consumed as a food.

Very little is known about the mechanisms involved in the radionuclide uptake and retention by fu Fungi can play a significant role in radionuclide retention by the organic layer. Olsen et al. (4) estimated that s 32% of the total Chernobyl-derived radiocesium present in a forest soil in Norway is contained in fungi. estimate was confirmed by experimental data (5). Their experiments with artificial washout of humus samples s that forest microflora (particularly fungi mycelia) could retain up to 40% of radiocesium. The absorptior nutrients (and thus radionuclides) by fungi from the ground occurs in aqueous solution usually from the solution. Fungi use enzymes to break down macromolecular complexes in solution for digestion. Once bro down, most substances are thought to move into the *hyphae*, being bound to specific carrier molecules. The rat this uptake by both saprophytic and symbiotic fungi depends on concentration of the ion, moisture content of soil, the growth rate of the plant and, in the case of symbiotic fungi, the transpiration rate of the host plant.

Several studies have examined the differences in the ability of saprophytic and symbiotic fungi accumulate radiocesium. Results of several studies (5, 6) indicated that the symbiotic fungi accumulated, on avera statistically higher concentrations of radiocesium although both types of fungi collect radiocesium quite effective These observations can be explained by the differences in mycelium location in the soil profile as well as migration of Chernobyl-derived radiocesium through forest soil. Other hypotheses include differential retention radionuclides by fungi (5).

The life cycle of soil fungi may have an impact on the time of immobilization of radionuclides mycelium. Differences exist between the life time of different species of fungi. According to Olsen et al. (4), lifetime of mycorrhizal fruit bodies (mushrooms) is normally between 10 and 17 days. The life of fungal biomass

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soil is not as well understood and is suggested to be on the order of two years. After death, the release of nutrients proceeds primarily by leaching. As water comes in contact with the cell wall of the fungi, nutrients such as K^+ diffuse across their concentration gradient and into solution. Another less important release pathway is due to animal consumption.

Quantitative evaluation of the relative fungi contamination is a challenging task. The traditional approach is to evaluate the Transfer Factor (TF) for soil-to-fungi transfer. TF can be defined as the ratio between the activity in plant (Bq/kg dw) divided by the activity in soil (Bq/kg dw) or by the deposition per unit area (Bq/m^2). Large variability in the TF values has been reported. TF across different species varies over several orders of magnitude (7).

The TF approach has serious fundamental limitations because it is applicable only to equilibrium situations, which can only be achieved in natural ecosystems a long time after the contamination event (10-20 years for the case of forest ecosystems (1,8)). Multi-layered soil structure with variable depth of soil horizons of the natural environment and inhomogeneity of the radionuclide deposition and its soil migration requires definition of conditions for sampling depth and volume. By including an estimate of the depth to which the radiocesium has migrated (i.e., Cs-134/Cs-137), Guillitte et al. (5) were able to obtain a more accurate estimate of the ability of a particular fungi species to take up radiocesium. Thus, it is problematic in defining the soil volume where nutrient uptake occurs. The dynamics of fungal biomass growth and decay are not well understood and questions remain regarding the nutrient requirements of this plant over time.

MODELING OF ORGANIC LAYER AND MUSHROOM CONTAMINATION

The FORESTPATH model (1, 8) 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. In this paper, the model was developed further to incorporate details of radionuclide migration in the Organic Layer and fungi. The Organic Layer is represented by three horizons: Ol (litter), Of and Oh. Reported residence time for Cs in these horizons (see (1) for review) along with values for other FORESTPATH parameters for Chernobyl forests (1, 8) were used for model simulations. Figure 1 shows radionuclide accumulation by the Organic Layer as well as by the Labile and Fixed Soil compartments, in a coniferous forest in Chernobyl described in (1, 9) (an initial deposition of 5 Ci/km^2 was assumed in the calculations). Organic Layer compartments exhibit complex time dynamics. The litter compartment is significantly contaminated immediately after the deposition, but looses all its activity during the first year due to wash-off and leaching towards deeper layers. Of and Oh horizons show accumulation peaks at about two and four years respectively following the initial deposition.

Mushroom mycelia exist in different soil horizons. Given the complexity of the nutrient uptake by mushrooms and lack of theoretical description of this process, it could be assumed that mushrooms have the same contamination density as the layer in which their mycelia are located. Using this methodology, calculations have been made for contamination of two types of mushrooms in coniferous forests. The first type has mycelium developed in the Of horizon, while the second type has mycelium located in the Oh-upper layer of mineral soil. A representative edible mushroom species of the first type is *Boletus badius* (or *Xerocomus badius*) (10), while *Boletus edulis* is representative of the second type (5). Based on the FORESTPATH model, *Boletus badius* would be expected to have the same dynamic of contamination as the Of horizon (i.e., have maximum accumulation during the second year following the accident (Figure 1). *Boletus edulis* which takes nutrients from the labile soil, would be expected to increase its contamination during the first decade following the accident.

MODEL VALIDATION

Model predictions are validated based on: 1) compilation of the reported ^{137}Cs concentrations in these two mushroom species in Central Europe (generic model), and 2) concentrations reported for contaminated forests in the Exclusion Zone (site-specific model). Figure 2 shows compilation of the existing literature values for mushroom contamination (see (1) for compilation tables). It is clear that *Boletus badius* exhibits an accumulation peak around 1988, while *Boletus edulis* concentration still increases (at least until 1991). Significant variability in the reported data can be explained by different contamination levels, climatic conditions, soil structure and types, etc. In the Chernobyl forests, *Boletus badius* and *Boletus edulis* exhibit the time dynamics expected for plants with roots developed in Of and Oh-Mineral Soil compartments (Figure 3). Predicted values from the FORESTPATH are about two times larger than the values measured by the Forest Research Institute, Belarus. Due to the fact that the experimental data were obtained based on reported values for the TF, the differences of a factor of two can be explained by the large uncertainty incorporated in the TF determination.

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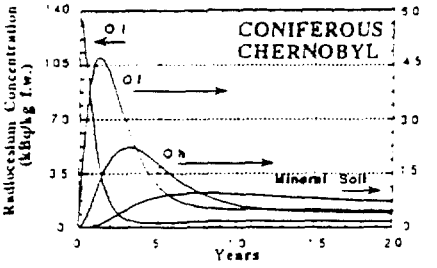

Figure 1. ^{137}Cs concentration in soil compartments of a coniferous forest in Chernobyl over 20 years from an initial acute deposition (kBq/kg f.w.). The scale of the ordinate is 140 kBq/kg for the Ol horizon and 60 kBq/kg for all other compartments.

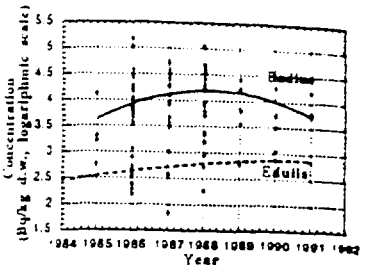

Figure 2. ^{137}Cs concentration in *Boletus badius* and *Boletus edulis* collected in European countries.

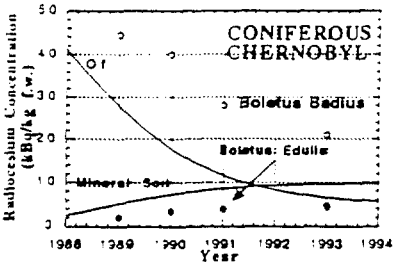

Figure 3.
Cs-137 concentration in Boletus badius and Boletus edulis collected in Chernobyl forests (circles, after Ipatyev (11)) compared to those predicted by FORESTPATH for species having mycelia in Of and Mineral Soil horizon (solid lines).

CONCLUSIONS AND RECOMMENDATIONS

FORESTPATH can be applied for detailed evaluation of the radionuclide accumulation in a specific compartment. The model predicted an enhanced accumulation by fungi with shallow mycelia during the first after an acute deposition, while the accumulation peak for deep-rooted species is delayed. These predictions been validated based on the experimental data collected in Europe (generic approach) and in the Chernobyl Exc Zone (site-specific application).

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APPLICATION OF THE GENERIC MODEL FORESTPATH FOR RADIONUCLIDE MIGRATION IN CHERNOBYL FORESTS

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ABSTRACT

The generic model FORESTPATH was applied to simulate radionuclide transport in coniferous forest ecosystem within the Chernobyl Exclusion Zone. Deterministic model analysis reproduces well observed radionuclide distribution among forest compartments. The model predicts future radionuclide distributions and can be used to facilitate policy decisions. A series of sensitivity analyses with Monte-Carlo sampling designs was conducted. The dominant parameters affecting concentration of radionuclides in forest compartments were the tree and understory uptake half-times and the organic layer residence time. The results indicate which parameters are crucial for FORESTPATH calculations and help prioritize future research.

1. INTRODUCTION

Radionuclides from nuclear weapons tests and reactor accidents can accumulate in natural ecosystems. If incorporated into products, construction materials, or consumed as food radionuclides cause significant exposure in human dose for intermediate and long time periods following the contamination event. The response of the ecosystem and the fate and transport of the radionuclides should be evaluated using validated models to help in formulating remediation measures.

Ecological modeling is a powerful tool which can be used to synthesize information on the dynamic processes which occur in the ecosystems (1). Generic models can be designed to generalize radionuclide cycling in a variety of similar ecosystem types. We have developed generic model, FORESTPATH (2), which provides pattern for radionuclide distribution in forest compartments at different time following the initial release of radioactivity in a temperate forest. The FORESTPATH input coefficients are based on the existing data on radionuclide transport in forests and the values used correspond to averages over time, space and species. Generic model can provide only partial information about specific ecosystem. Because of high variability among

forests, the range of values a parameter can take can be large. "Variability Analysis" (2) which analyzes consequences of the difference in values of input parameters across several ecosystems, should be viewed as a crude estimate of a general trend. The Variability analysis provides variation for model outputs across the range of input parameters that correspond to different ecosystems.

The application of FORESTPATH at a specific site requires the use of local input parameters. Available experimental data often are unreliable due to the limited number of experimental measurements. As a result, parameters are uncertain even when estimated at a specific location. "Uncertainty Analysis" is an appropriate tool to study the role of uncertainty in the input parameters within a specific ecosystem. For such applications, it is not possible to assign precise values to the parameters characterizing the ecosystem but many parameters can be described by a probabilistic distribution of values. Model outputs are described by the probability distribution functions (PDF). Monte-Carlo methods are very powerful tool to perform the uncertainty analysis.

2. MODEL DESCRIPTION

FORESTPATH model (2) calculates time series of inventories for a specific radionuclide distributed within six representative compartments: Understory, Tree, Organic Layer, Labile Soil, Fixed Soil and Deep Soil. Six coupled ordinary differential equations describe the transfer of the radionuclide between the forest compartments. The initial data for a given radionuclide is the radioactivity to be distributed within the forest compartments. The values are converted to percentage of the total radionuclide inventory and can be further converted into concentration units for the purpose of assessing their impact on humans. The FORESTPATH formulation has the flexibility of including source terms from different processes (atmospheric deposition, disposal in soil, discharge to ground water, etc.) A complete description of the FORESTPATH model can be found elswhere [2].

The generic FORESTPATH model can be adjusted for site-specific applications. For a given site, FORESTPATH can incorporate particular radionuclide pathways by adding to or changing compartments of the model. In these situations, the input parameters can be represented by probability distributions and their ranges of variation should be narrowed for better model predictions at the specific site. If available information on specific parameters or pathways is not sufficient, the generic values can be used.

Distributions were constructed for the FORESTPATH input parameters (Table 1). Existing literature was reviewed to evaluate of the residence half-times for radionuclides in coniferous forest ecosystems which are typical for the Chernobyl Exclusion Zone (Linkov, 1995; Schell et al., 1996). The data relevant to many of the parameters are sparse or non-existent. Thus, expert judgement was necessary to construct probability distributions for some of the parameters. The

choice of parameter distributions below attempt to represent an average coniferous forest in the Chernobyl Exclusion Zone and was based on a combination of literature review, expert judgements and FORESTPATH simulations.

Table 1. FORESTPATH model coefficients used as ^{137}Cs input for coniferous forest in the Exclusion Zone

Parameter	Notation	Distribution	Parameters		Reliability
			mean	a - b[a]	
absorption half-time (years)	t_{ab}	triangle	0.6	0.2 - 1	poor
tree biomass (%)	B_t	triangle	0.8	0.7 - 0.9	good
understory biomass (%)	B_u	triangle	0.1	0.1 - 0.3	good
desorption half-time (years)	t_{ds}	triangle	1.1	0.5 - 10	poor
interception fraction (%)	f	triangle	0.7	0.6 - 0.9	good
leaching half-time (years)	t_{lc}	triangle	800	350 - 3000	moderate
organic layer removal half-time (years)	t_{or}	triangle	8	1 - 60	poor
radiation half-time (years)	$t_{1/2}$	constant	30.14	na	good
tree uptake half-time (years)	t_{tu}	uniform	10	1 - 100	poor
tree removal half-time long (> 1yr)	t_{tr}	triangle	3	1 - 10	poor
understory removal half-time long (> 1yr)	t_{ur}	triangle	0.2	0.1 - 2.8	moderate
understory uptake half-time (years)	t_{uu}	uniform	8	1 - 100	poor

[a]a is the minimum value and b is the maximum value for triangular and uniform distributions

The uptake half-times have the highest degree of uncertainty (Schell et al., 1996) and, thus, they are represented by the uniform distributions. Literature values allow median, high and low estimates to be made for other parameters (Linkov, 1995). These can be represented by triangular distributions, in which the parameter is sampled between low and high values with higher probabilities for the median region.

3. RESULTS

The results of FORESTPATH modeling are grouped into three sections. The first section describes deterministic model simulations, when calculations were done using mean values for the parameters. The second section involves the propagation of all parameter uncertainties through the model to obtain probability distributions for model outputs, conditional on input values. The third section analyzes the relationship between model outcomes and inputs to find their relative importance for the model predictions.

3.1 Deterministic Analysis

The Chernobyl source term was modeled by assuming that all deposition took place during the first week after the accident. A 50-year FORESTPATH simulation for ^{137}Cs cycling in coniferous forests in the Chernobyl Exclusion Zone is presented in Figure 1 (mean values for parameters from Table 5.1 were used). The results are qualitatively similar to those obtained for the generic coniferous forest (Schell et al, 1996). During the first fifty years after deposition, radioactive decay removes about 70% of radiocesium from active cycling in the forest ecosystem. The Deep Soil, which is the geophysical sink in the model, accumulates only a small fraction of the radionuclides deposited initially. The Organic Layer compartment holds the highest concentration of radiocesium (25%-85% of the initial radionuclide inventory over the 50-year period). Lesser amounts are associated with the Labile Soil and Fixed Soil compartments. Approximately 10% of the radionuclides are incorporated in both Tree and Understory compartments, the main sources of human radiation dose. Thus, forests are efficient reservoirs for radionuclides.

It is clear from the model that the time at which the predicted maximum ^{137}Cs accumulation occurs is different for different compartments within the forest. The amount of radionuclides in the Understory and Tree compartments increases immediately after deposition but decreases sharply during the first year, due to precipitation removal and leaf fall. A second broad peak is observed in the Tree compartment about six years after deposition and is related to root uptake. Fixed Soil and Labile Soil reach maximum contamination levels some four years after deposition, while the Deep Soil accumulates radionuclides continuously as a sink. Due to radionuclide fixation on clays, only a negligible part of ^{137}Cs reaches the Deep Soil.

3.2 Probabilistic Monte-Carlo Simulations

The Monte Carlo approach was used to perform propagation of parametric uncertainties. The inputs to the model are treated as uncertain, and a representative sample is generated from a suitably chosen uncertainty distribution (Table 1). A pseudo random number generator was used to approximate a uniform distribution. The specific values for each input variable are selected by inverting uniform samples over the appropriate cumulative distribution function. The model is then run iteratively for each of sampled inputs for the deposition scenario described above. Each Monte-Carlo simulation produced 100 estimates of the radionuclide concentration in each forest compartment for 50 years following the contamination event.

Figure 2 presents the cumulative distribution functions for radionuclides in forest compartments 50 years after the initial radionuclide deposition. A range of variation in radionuclide accumulation is shown. Accumulation in the Tree compartment can vary from 0.5 to 3%, while Organic Layer can accumulate from 1 to 18% of the initial inventory (values for 95% percentile are given). Although these ranges are wide, they are limited compared to the results of

the Variability Analysis for the generic model (Schell et al., 1996). As expected, the site-specific application of FORESTPATH provides better predictions than the generic applications.

Figure 3 compares the results of the probabilistic analysis and experimental data obtained for coniferous forests in the Exclusion Zone in the 1993 sampling program (Dvornik, 1995, Ipatyev, 1994). Ranges of the uncertainty predicted by the model are consistent with experimental variation in the organic layer accumulation.

3.3 Sensitivity Analysis and Importance Ranking

There are many commonly used formal and informal techniques for performing importance ranking or sensitivity analysis of model inputs. In a review of the literature Helton (1993) describes several approaches for performing sensitivity analysis. These include 1) Informal ranking schemes 2) Taylor's series expansions & Differential Sensitivity approaches 3) Fourier Amplitude Sensitivity Test and 4) Monte Carlo based Input-Output Correlation approaches. It is widely accepted that the Monte Carlo based approach provides the most robust overall approach for sensitivity analysis and below we provide a brief description (Morgan and Henrion 1990; Helton 1993) .

Importance ranking using Monte Carlo simulations is possible through the use of regression based techniques. The simplest approach is to perform a multiple linear regression analysis between the input samples and the model output. The standardized regression coefficients (SRC) associated with the individual input variables provide a measure of the relative importance of each model input when the model output response is linear in nature. If inputs are correlated then it is possible to evaluate the effect of each input variable on the model output using partial correlation coefficients (Iman and Conover 1982) which account for correlations among input variables by removing the effect of all other inputs on the model output. Partial correlation coefficients (PCC) measure the contribution of each input to the model output as long as the model has linear behavior in the range of model inputs. If the model response is non linear but monotonic, then partial correlations on rank transformations of model inputs and output provide a reliable measure for importance ranking (Iman et al., 1995). Partial rank correlation coefficient (PRCC) is the most frequently used measure for importance ranking because it is simple to use and implement and it breaks the linearity requirement of the other measures. A list of model input parameters ranked using PRCC in the order of their importance to the model outcome of choice — in this case the concentration in tree compartment — is presented in Table 2.

Table 2. Model parameters ranked in the order of their importance to the radionuclide accumulation in forest compartments

Parameter	Notation	Rank		
		Tree	Understory	Organic Layer
absorption half-time (years)				
tree biomass (%)				
understory biomass (%)				
desorption half-time (years)				
interception fraction (%)				
leaching half-time (years)				
organic layer removal half-time (years)				
radiation half-time (years)				
tree uptake half-time (years)				
tree removal half-time long (> 1yr)				
understory removal half-time long (> 1yr)				
understory uptake half-time (years)				

3. CONCLUSIONS AND RECOMMENDATIONS

The generic FORESTPATH model can be easily adapted for different site-specific applications. For a given site, FORESTPATH can incorporate its particular radionuclide pathways by adding or changing compartments. In these situations, the input parameters can be represented by probability distributions and uncertainty analysis using Monte-Carlo methodology should be conducted to estimate the uncertainty in the model predictions. FORESTPATH application for the Chernobyl forests shows that the model predict broad distribution for radionuclide accumulation in forest compartments. The ranges of the uncertainty for model predictions are consistent with experimental variations observed in the Chernobyl forests.

References

Figure 1. ^{137}Cs accumulated in Chernobyl forest compartments over 50 years from an initial acute deposition (percent of initial inventory). Leaching to Deep Soil is negligible (not shown). The scale of the ordinate is 100% for the Organic Layer and 50% for all other compartments.

Figure 2. Cumulative distribution functions for radionuclides in Chernobyl forest compartments 50 years after the initial radionuclide deposition

Figure 3. Cumulative distribution functions for radionuclides in the Organic Layer of Chernobyl 1993 in comparison with the experimental distribution obtained by Dvornik, 1995 and Ipatyev, 1994 during 1993 sampling program

FATE AND TRANSPORT OF RADIONUCLIDES IN CHERNOBYL FORESTS: DYNAMIC MODELIN FOR RISK ASSESSMENT AND REMEDIAL POLICY EVALUATION

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We use the generic model FORESTPATH to simulate radionuclide transport in coniferous forest ecosyste within the Chernobyl Exclusion Zone. The model predicts future radionuclide distributions among for compartments and can be used to facilitate policy decisions. In previous work we found that determinis model simulations compared well with the observed radiouclide distributions. In this work we extend t analysis to account for uncertainties in model parameters and measurements. A Monte-Carlo simulation w used to propagate parametric uncertainties through the model. Probabilistic estimates for radionucli concentrations were obtained for the forest compartments. The results of the Monte-Carlo simulation we also used to study key parametric uncertainties. The analysis shows that uncertainties in tree and understo uptake half-times and the organic layer residence time contribute most to uncertainties in future radionucli concentrations. Bayesian updating of the input parameter distributions was conducted using experimen information collected in the Chernobyl Exclusion Zone. The results allow for the calculation of indicators t estimate the value of gathering new information.

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