REVIEW OF FOREST MODELS DEVELOPED AFTER THE CHERNOBYL NPP ACCIDENT

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1. Introduction

The investigation of transfer processes and the description of radionuclide circulation in forest ecosystems by appropriate models is a difficult and challenging task. The Chernobyl accident showed the importance of understanding such fluxes in these complex ecosystems. Due to the long ecological half-lives of released radionuclides it became necessary to develop models for dose and risk assessment which also could be used to assess the effect of countermeasures and to develop strategies to remediate such forests. The necessity of having such models is underlined by national and international organisations such as the IUR with a subgroup for forest ecosystems, the IAEA with a Forest Working Group within the BIOMASS program (BIOspheric Modelling and ASSessment) and the EC with the SEMINAT [1] and LANDSCAPE [2] projects.

The aims of the present review are:

- to compile a list of forest models,
- to compare the models developed after the Chernobyl accident in relation to the compartments they include, the transfer processes they describe and the conditions which they have been developed for and
- to look at the endpoint predictions of the models.

2. Models considered and their general features

Myttenaere *et al.* [3], Schell *et al.* [4] and Avila *et al.* [5] have previously published reviews of forest models. In this review emphasis is put on models developed after the Chernobyl accident. Not included are forest models developed before the Chernobyl

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accident (TABLE 1), models describing radionuclide dynamics in fruit trees or models describing only processes in selected parts of a forest ecosystem. Also not included in this review are models which have been presented the first time during this NATO workshop.

TABLE 1. Overview of forest models developed before 1986 (adapted from Schell *et al.* [4])

References	Forest	Source	Compartments used
Olson [6]	Liriodendron trees	caesium inoculation	source, leaves, bark, roots, undercover, littermat, soil
Prohorov and Ginzburg [7]	generic forest	radionuclide enter via leaves, twigs and litter	litter, soil, roots, trunk, twigs, leaves
Aleksakhin *et al.* [8]	deciduous, coniferous	Sr-90 enter via leaves, twigs and litter	litter, soil, branches, wood, bark, herbs, needles/leaves
Mednik *et al.* [9]	deciduous (birch), coniferous (pine)	Sr-90 enter via leaves, twigs and litter	litter+soil, branches, wood, bark, leaves/needles
Jordan *et al.* [10], Jordan and Kline [11]	Tropical rain forest	strontium and manganese from atmospheric weapon testing	canopy, litter, soil, wood
Garten et al. [12]	deciduous (oak)	plutonium and fission products	consumer, ground vegetation, soil, litter, soil fauna, leaves, wood, roots
Croom and Ragsdale [13]	deciduous (oak)	caesium injection from atmospheric bomb testing into the litter	tree, litter, lower soil, upper soil; available for uptake, upper soil

TABLE 2. Overview of forest models developed after 1986 in chronological order

Acronym/reference	*	Nuclide	Forest type	Soil type	No. of sites	
RADFORET [14]	A	Cs	decidous	loamy clay, sandy	2	USA
Prohorov and Ginzburg [7], applied by Alexakhin *et al.* [15]	B	Sr	birch pine	chernozem soddy podzol	2	RUS
FORESTPATH [1] [4]	D	Cs, Pu	decidous coniferous	generic	na	USA, BEL
FOA [2, 5]	C	Cs	boreal, coniferous	not specified	1	SWE
RIFE 1 [16]	E	Cs	different types	not specified	2 2	RUS, UKR IRL, GER
FORESTLIFE [1] [16, 17]	F	Cs	pine	not specified	13	BEL
FORM [18]	G	Cs	generic	generic	na	
ECORAD [19]	H	Cs, ^{14}C, ^{129}I	generic	soddy podzol	4/4	RUS/UKR
RIFE2 [1] [20]	I	Cs	pine	not specified	5	Europe
LOGNAT [2] [2, 5]	K	Cs	needle, deciduous	not specified	1	ITA
FORESTLAND [1] [21]	This model was presented during the NATO-ARW					
Seymour [1] [22]	This model was presented during the NATO-ARW					

* internal reference (cf *Figures 1* and *2*, TABLE 3)
[1] model described in this volume
[2] model under development
na not applicable

From TABLE 2 which shows 10 post-Chernobyl models it can be seen that

- the majority of the models describe caesium fluxes.
- the majority of the models have been calibrated for one forest type with the exception of RIFE 1 and 2 [1, 16] which offer the possibility to select between different types of sites. Generic models are designed to be applicable for several sites and are calibrated using a wide range of available experimental data.
- the models were parameterized with site specific experimental data (between 1 and 13 sites).

3. Model structure

The migration of radionuclides in forest ecosystems involves multiple components and interactions. As the different models have been designed for special purposes and selected sites a comparison is only partly valid. However, there are three major predictive compartments which can be reasonably well compared: the tree, the understorey and the soil compartment.

TABLE 3 gives an overview of the compartments included in the 10 studied models. Considering transfer processes in trees, the whole range of differentiation can be found. FORESTPATH [4] and the FOA model [2, 5] which are focused on generic applications on an ecosystem and landscape level have one compartment for the whole tree or the perennial vegetation, respectively. In contrast, Prohorov and Ginzburg's model [7, 15] and ECORAD [19] have a needle, branch, bark and wood compartment. The most common to all models is an additional model-specific compartment.

Considering transfer processes in soil, it is found that all models have a litter and a more or less differentiated soil compartment. In the original version of FORESTPATH [4] the organic soil compartment includes litter. Some models including a further developed version of FORESTPATH [23] additionally distinguish between litter and one or two organic horizons. In FORESTPATH [4], FORM [18], ECORAD [19] and RIFE 2 [20] mineral soil is further divided in several compartments. In RADFORET [14] and FORESTLIFE [16] corrections of transfer rates are made to allow a description of vertical migration and sorption processes in soil. So far FORESTPATH [4] is the only model which distinguishes between a labile/available soil compartment and a fixed/unavailable compartment permitting a better description of sorption-desorption processes in soil. ECORAD [19] considers three layers of surface organic horizons and divides mineral and mineral organic layers into 1-cm layers down to 15 cm. Such a detailed description creates difficulties in applying this model to other sites. RIFE 2 [20] offers 6 soil layers which can be defined to suit the need of the corresponding modeler.

All models have varying descriptions of an understorey compartment except LOGNAT [2, 5]. Another specific compartment is the fungi/mushroom compartment which is included in 4 models. The FOA model [2, 5] appears to be the only model at present that identifies retention of radionuclides in a moss or lichen carpet, potentially constituting a significant secondary source to radioactive caesium transferred into circulation. The only other model considering animals is *FORM* [18], which has a game and roe deer compartment. Another endpoint in this model is the ingestion dose from forest products calculated from activity assessments in mushrooms, berries, honey and milk.

TABLE 3. Overview of compartments considered in 10 post-Chernobyl forest models and their assignment (X) to single models

compartment	Model*									
	A [14]	B [15]	C [2,5]	D [4,23]	E [16]	F [16]	G [18]	H [19]	I [20]	K [2,5]
leaf/needle	X	X					X	X		X
leaf internal									X	
leaf external									X	
tree external				X	X					
tree internal					X					
external bark								X		
internal bark										
bark		X					X			
branches	X	X						X		
living tree						X				X
bole	X									
wood		X				X	X	X	X	X
xylem										
perenn. veg.			X							
fresh litter						X				
Litter/Ol	X	X	X	X	X	X	X	X	X	X
Of				X	X		X	X	X	X
Oh				X				X	X	
soil 1	X	X	X	labile	X	X	X	X	X	X
soil 2				fixed			X	X	X	
soil 3				deep			X	X	X	
roots	X					X		X		
understorey	X	herbs		X	herbs	X	X		X	
perenn. veg.			X							
ground veg.										
soil fauna										
mushrooms					(X)		X		X	
game							X			
forest product							X			
mammals										
distributive pool								roots, fungi		
moss/lichen			X	(X)						
competitors			X							

* letters from TABLE 2.

From TABLE 3 it can be concluded that all long-term models have at least 5 compartments:

1. a needle or leaf compartment, which is reasonable considering the important role played by leaf fall in caesium recycling within the system.
2. a wood compartment which is more or less differentiated
3. a litter or organic soil compartment
4. a mineral soil compartment
5. an understorey compartment

4. Transfer processes in forest ecosystems

A summary of the migration of radionuclides described in the 10 forest models is shown in a matrix diagram (*Figure 1*) which is described more detailed elsewhere [24]. In this case the matrix is only used to visualise the various transfer processes and their inclusion frequency in the 10 models. The leading diagonal elements display the main compartments of radionuclide cycling as identified before. The off-diagonal elements correspond to the transfer processes between these compartments. The diagram is read clockwise. The shading of the single boxes corresponds to the frequency the process is included in the 10 models. The diagram does not indicate the importance of the process in relation to the whole ecosystem. However, the frequency numbers give an indication about the availability of data, about the state of the understanding of a process and about the consensus among modelers to include the process in their model. This may be illustrated by the example of litterfall. Litterfall is relatively easy to measure and is described in nearly all the models. It is a necessity to include this pathway which returns radionuclides from trees and understorey vegetation to the ground in a research model. However, the importance given to this pathway by modelers does not necessarily correspond to the importance of it when the whole forest ecosystem is considered. The soil compartment is represented by a single box in this matrix although it was shown that most models have several soil compartments. To describe the processes occurring in soil a second matrix was drawn (*Figure* 2). Taking into account that soil can contribute to external radiation in a dose assessment model and following the tendency to work with aggregated transfer factors, e.g., in the RESTORE project of the EC, the representation of soil by one box seems justified. The example of the soil-plant transfer also demonstrates, how differently this pathway is modelled in contrast to the previously mentioned litterfall.

leaf needle	1	3		8		1			
2	branch			3		1			
4	3	Tree (bole, bark)		2		2			
			under-storey	5		2			
		1	1	litter A_f, A_h	1	7			1
1	1	[illegible]		1	Roots	1			
2	1	6	5	2	3	soil	1	1	3
							game		
								berries and others	
									fungi

process considered in 1-2 models
process considered in 3-5 models
process considered in > 5 models

Figure 1. Matrix description of caesium fluxes in a forest ecosystem and frequency of the transfer processes applied in 10 forest models (cf TABLE 2)

5. Endpoints from a radiation protection perspective

Ultimate endpoints in forest models can be concentrations in forest components, or from a radiation protection point of view, doses due to external radiation or internal radiation caused by contaminated forestry products for human consumption. Other possible endpoints are external radiation from forest products of industrial use or radiation effects from the forest itself. According to Table 2 the soil and wood compartment could be used as a basis for the corresponding dose calculations in all models. However, the food pathway is only included in the FORM model [18]. With few exceptions the connection of the models under consideration with existing food-chain models is not yet realised. Dose calculations are not addressed, probably because methods for calculating doses from activity concentrations already exist. What is missing at the moment therefore is an extension of present forest models to dose assessments or the connection with dose assessment models as it is done between FORESTLIFE [16] and FORESTDOSE [25]. Also FORESTPATH has been applied for dose and risk assessment [26].

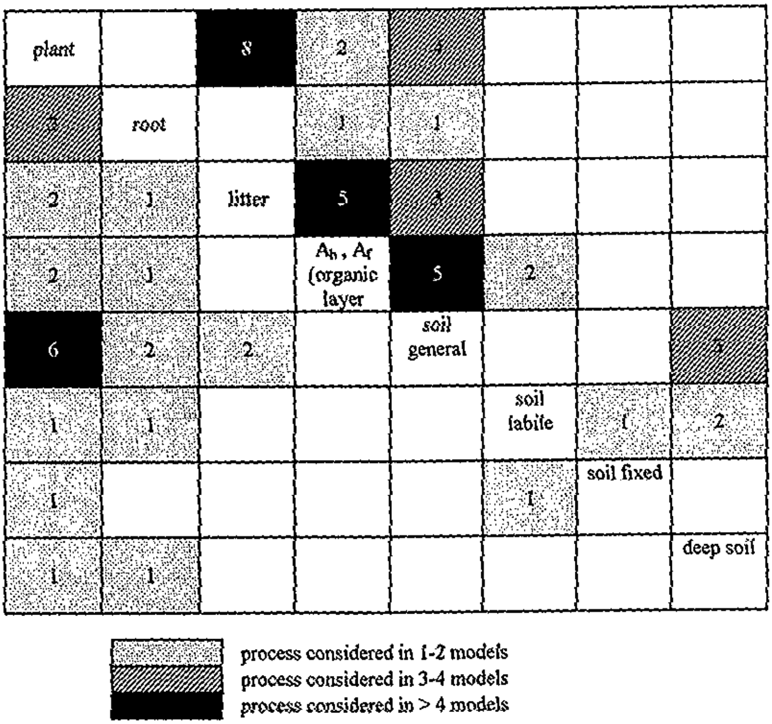

Figure 2. Matrix description of caesium fluxes in the soil compartment and frequency of the transfer processes applied in 10 forest models (cf TABLE 2)

6. Factors influencing caesium migration

Table 4 shows how the factors which influence caesium migration are considered in the 10 models. A factor is considered in the model if it is possible to use the model for evaluating the degree of influence of this factor on caesium migration. A model considers a factor if the following two conditions are fulfilled:
(i) it describes the transfer processes that are significantly influenced by the "factor" and (ii) it provides relationships between transfer rates and some qualitative and quantitative measure of the "factor". The factors influencing caesium migration are in general poorly considered by the models and most models include only a few or none of the parameters listed in TABLE 4.

TABLE 4. Factors influencing caesium migration considered by 10 models (cf Table 2).

Factor	Model
Type of deposition [1]	
Season of the deposition	
Type of forest (deciduous, coniferous)	FORESTPATH, FORM, Prohorov and Ginzburg
Biomass growth	RADFORET, FORESTLIFE
Age of the trees	RADFORET, FORESTLIFE, FORM
Soil characteristics	RADFORET

[1] dry, wet, chronic, pulse deposition

7. Conclusions

- Most of the transfer processes in the reviewed models are described with rate constants. These are often highly variable and include several processes.
- The models can hardly be applied for explaining and predicting differences in the behaviour and distribution of radionuclides in different forest types. All models except FORESTPATH [4] and FORM [18] are site specific and the characteristics of forests used for calibrations are usually not provided, which basically makes it difficult to apply them for other sites. The parameters in FORESTPATH and FORM are given for generic forest ecosystems but some of them vary within two orders of magnitude.
- The improvement of models is constrained by the availability of experimental data and by lack of sufficient knowledge of migration mechanisms. Future effort should be put into describing some important transfer rates at a process level.

It seems impossible to have one model describing all relevant processes and types of forest ecosystems. Generic models can be used to show general trends. A simple basic model describing the main processes with attached sub-models for complex compartments, e.g., a soil compartment, and selected forest types is a possible format for assessing radionuclide distribution in different forest environments.

8. References

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