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Modelling of radionuclide migration in forest ecosystems. A literature review

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SAMMANFATTNING: Kärnkraftsolyckan i Tjernobyl har på ett tydligt sätt visat på de långsiktiga effekterna i skogsekosystemet av ett radioaktivt nedfall. I denna litteraturstudie ges en översikt av modeller som beskriver migrationen av radioaktiva ämnen, radioaktivt cesium i synnerhet, i skogsekosystemet. Rapporten beskriver några speciella egenheter hos skogsekosystemet, det radioaktiva nedfallets omfördelning i tiden, överföringsprocesser mellan olika delar av ekosystemet samt faktorer som påverkar cesiums migration. Utifrån denna beskrivning diskuteras olika angreppssätt för att modellera cesiums migration. En av slutsatserna är att existerande dynamiska modeller innehåller de mest relevanta processerna såväl för perioden närmast efter ett nedfall som i det långa tidsperspektivet. Men modellerna är vanligen platsspecifika och de beaktar inte faktorer som påverkar radionuklidernas uppträdande och fördelning i olika skogstyper. Förbättringar av modellerna begränsas av tillgången på experimentella data och av bristen på förståelse av vissa mekanismer som styr cesiums migration. I rapporten lämnas några förslag till förbätttringar. Rapporten är en del av LANDSCAPE projektet som syftar till att ge en sammanvägd bild av de flöden av radionuklider i skogsekosystemet som leder till att människan exponeras för joniserande strålning från skogsprodukter.

ABSTRACT: The Chernobyl accident has clearly shown the long-term effects of a radioactive contamination of forest ecosystems. This report is based on a literature review of models which describe the migration of radionuclides, radioactive caesium in particular, in forest ecosystems. The report describes the particularities of the forest ecosystem, the time dynamics of the contamination, the transfer processes and factors influencing caesium migration. This provides a basis for a discussion of different approaches for modelling caesium migration in the forest. It is concluded that the studied dynamic models include the most relevant transfer processes both for the acute and the long-term phase after a radioactive deposition. However, most models are site specific and do not consider some of the factors responsible for the differences in radionuclide behaviour and distribution in different types of forests. Although model improvements are constrained by the availability of experimental data and by the lack of knowledge of the migration mechanisms some possible improvements are discussed. This report is part of the LANDSCAPE project - An integrated approach to radionuclide flow in the semi-natural ecosystems underlying exposure pathways to man.

NYCKELORD (valda av författaren): Modellering, cesium, migration, skog, ekosystem

KEY WORDS (chosen by the author): Modelling, radionuclide, caesium, migration, forest

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Modelling of radionuclide migration in forest ecosystems

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1. Introduction

The Chernobyl accident has shown the importance of understanding the behaviour of radioactive contamination of the forest ecosystem. Due to the long ecological half-lives of radionuclides in plants and animals in forest ecosystems, the radiological effects will remain for tens of years.

One task of the project LANDSCAPE[1] is to study variations of radionuclide flows, Cs-137 in particular, in different types of forests using mathematical models. A final step in dealing with this task is to develop an ecosystem model or models that can also be used in connection with GIS for this purpose. The GIS model will be used to explain and predict large-scale horizontal patterns of the radioactive contamination of forested areas. The aim of the present report is to provide a basis for this task by reviewing existing ecosystem models describing the migration of radionuclides in forest ecosystems.

Myttenaere et al. (1993) and Schell (1996) have published reviews of forest ecosystem models. We have used these publications as a starting point for the present review, but have focused on the analysis of the latest models.

The present report starts with a brief review of features of Cs-137 migration in forest ecosystems (chapter 2). This provides a basis for the discussion on existing approaches for modelling caesium migration presented in chapter 3. Possible improvements of forest models are also discussed. The aims of the suggested improvements are twofold: i) to allow for a better consideration of factors influencing caesium migration, and ii) to increase the possibilities for estimation of transfer rates for different sites and conditions. More detailed descriptions of the models selected from the literature are given in the Appendices.

2. Features of Cs-137 behaviour in forest ecosystems

Some of the main features of Cs-137 behaviour in forest ecosystems are presented in this chapter. More detailed descriptions of the behaviour of caesium in forest ecosystems can be found in several of the referenced papers, especially in the review papers (Fraiture, 1992; Myttenaere *et al.* 1993; Thiry and Myttenaere, 1993; Tikhomirov and Scheglov, 1994; Nimis, 1996).

2.1 PARTICULARITIES OF FOREST ECOSYSTEMS

Before 1986 most studies of terrestrial radioecology dealt with agricultural ecosystems. As a result there is a rather good knowledge of the migration of radionuclides in this type of ecosystems. When extrapolating this knowledge to forest ecosystems the particularities of the latter should be carefully considered. Forest ecosystems differ from agroecosystems in several important ways, the main ones being the heterogeneity of the soil profile, the plant biodiversity, the extent of mycorrhization and the animal diversity.

HETEROGENEITY OF THE SOIL PROFILE

In agroecosystems soils are periodically ploughed and fertilised, while in forest ecosystems they exhibit a more or less clear subdivision into an upper, mainly organic horizon and a lower mineral horizon, differing in characteristics such as density, pH, clay content, moisture, nutrient

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[1] LANDSCAPE – An integrated approach to radionuclides flow in semi-natural ecosystems underlying exposure pathways to man. EU Contract F14P – CT 96- 0039, 1997-1999.

status, biological activity, etc. (Frissel *et al.* 1990). Forest soils usually have a low clay content and a poor nutrient status, which enhance the uptake of caesium by plants.

PLANT BIODIVERSITY

The agroecosystems are often monocultures, while forests are generally species rich. Forests have a much more complicated structure than agroecosystems, and a much wider range of ecological conditions. One of the main components of forest ecosystems, the tree, is a perennial plant. As a consequence, the migration of radionuclides in forests is a polycyclic process. Long-term cycles are composed of many annual cycles. Annual cycles involve the removal of radionuclides from the soil compartment during growth and the subsequent return of a portion of them through litter-fall, dead wood, etc.

MYCORRHIZATION

In forest ecosystems the extent of mycorrhization is much higher than in agricultural ecosystems as most plants are in symbiosis with mycorrhizal fungi. This fact complicates the interpretation of uptake and transfer mechanisms from soil to plants via roots.

ANIMAL DIVERSITY (HERBIVORES)

In agricultural ecosystems the animals usually live in conditions controlled by man, whereas forest animals have a free-ranging habitat. Wild forest animals often move over large distances within a short time span. This makes it difficult to measure their feed composition and to characterise the habitat conditions and accordingly estimate activity concentrations in individual animals. (The LANDSCAPE project includes a large scale study of feed intake and composition of free ranging moose).

2.2 TIME DYNAMICS OF THE CONTAMINATION

After a radioactive contamination of the forest ecosystem, the process of radionuclide migration and redistribution between the components of forest ecosystems can be divided into two stages (Tikhomirov and Shcheglov, 1994). In the first stage (the acute phase), contamination of plants mainly results from primary aerosol precipitation of radionuclides on their surface. The deposited nuclides can be incorporated into assimilating organs and further transported to other structural parts of the plants. The processes of radionuclide transfer from the phytomass into the forest litter (decontamination) dominate the redistribution at this stage leading to a decrease in contamination levels of structural parts of trees. The second stage (the long-term phase), follows the transfer of nuclides into the root-inhabited soil layers, and is characterised by a predominance of root uptake. During this stage an enhancement of radionuclide content in the phytomass can be observed, until some quasi-steady equilibrium is achieved. In these conditions, the annual transfer of radionuclides from soil exceeds its return with litter fall only by the radionuclide content in the added phytomass during the year. In the forest studied by Tikhomirov and Scheglov (1994) the period of time for achieving such equilibrium is around 10-15 years. Shell *et al.* (1996) estimated that it could take several decades for radionuclides fluxes to reach equilibrium in forest ecosystems.

2.3 TRANSFER PROCESSES IN FOREST ECOSYSTEMS

The migration of radionuclides in forest ecosystems involves multiple components and interactions. The transfer processes are essentially the same as in agricultural ecosystems. However, due to the particularities of forest ecosystems, there are many more factors that can significantly influence the transfer processes compared to the agricultural ecosystems. This leads to a higher degree of variability of transfer rates in forest ecosystems.

Figure 1 provides a matrix description of the migration of radionuclides in a forest ecosystem. The diagonal elements display the main components of the system, while the off-diagonal elements correspond to transfer processes between these components. All transfer processes take place in both the acute and long-term phases of the contamination, but they usually have a different relevance in these phases. In Fig.1 the most relevant processes in the acute and long-term phases are shaded with blue and yellow colours respectively. (For more detailed information of the matrix representation of the migration in forest ecosystems see Avila and Moberg (1997)).

2.4 FACTORS INFLUENCING CAESIUM MIGRATION

There are many factors that influence the migration of caesium in forest ecosystems. Some of them are discussed in this section. Special emphasis is put on factors responsible for horizontal patterns of the contamination after an aerial deposition of radionuclides.

TYPE AND SEASON OF THE DEPOSITION

The type of deposition, the weather and the season, as well as the type of vegetation, are important factors for the initial horizontal distribution of deposited radionuclides after an aerial contamination. The type of deposition (wet or dry) influences the amount of radioactivity initially intercepted by the vegetation. Fraiture (1992) for example reported that the interception by tree canopies is much larger for dry than for wet deposition. In the case of wet deposition the amount of precipitation and the type of rainfall strongly affect the horizontal patterns of the contamination (Nimis 1996).

The season when the fallout occurs is also important due to differences in the active surface exposed to fallout (Tobler *et al.* 1988). A smaller interception fraction is observed in winter, especially in deciduous forests. Snow cover and run-off also affect the horizontal distribution of the deposited radionuclides and these are subject to seasonal variations.

TYPE OF FORESTS (DECIDUOUS AND CONIFEROUS)

Deciduous and coniferous trees differ concerning the capability to intercept radionuclides. As mentioned the interception fraction depends on the surface exposed to fallout. Given this, we should find higher interception fractions in conifers than in broad-leaf trees (Nelin and Nylen, 1994). The influence of the season of deposition on the interception fraction is more pronounced for deciduous than for coniferous forests, due to more intensive foliage fall in deciduous forests.

The dynamics of litter fall in coniferous and deciduous forests lead to an enrichment with radionuclides of the respective litter layers. In conifers weathering is an important removal mechanism during the first weeks after deposition. The amount remaining in the needles is deposited gradually as they fall, thus spreading the initial residual deposit over several years. The average life of needles of Scots pine and Norway spruce is 3-6 years and thus there will be a differential input of radiocaesium to the ground via needle fall, with a maximum value corresponding to the fall of needles that were exposed to direct contamination (Guillitte *et al.* 1990). The contamination of deciduous leaves is high only in the first year after deposition (assuming leaves were on the tree during deposition) and is almost totally deposited on the litter layer during this year.

The rate of litter decomposition is also an important difference between these types of forests. The decomposition of coniferous needles is rather slow and it is quicker for deciduous leaves (Henrich *et al.* 1990). Thus, the input period into the root-inhabited soil layer is more prolonged in coniferous forests than in deciduous.

1.1 Atmosphere (Air)	1.2 Interception	1.3 Interception	1.4 Interception	1.4	1.5	1.6 Interception	1.7 Interception	1.8 Interception
2.1	2.2 Tree leaves	2.3 Translocation	2.4 Leaves fall Weathering	2.5	2.6	2.7 Weathering Interception	2.8 Weathering Interception	2.9 Ingestion
3.1	3.2 Translocation	3.3 Tree other	3.4 Weathering Interception	3.5 Fertilisation	3.6 Fertilisation	3.7	3.8 Weathering Interception	3.9 Ingestion
4.1 Resuspension	4.2	4.3 Rain splash	4.4 Litter	4.5 Litter Decomposition, Percolation	4.6 Percolation	4.7 Root uptake	4.8 Rain splash	4.9 Ingestion
5.1	5.2	5.3 Root uptake	5.4	5.5 Soil organic Adsorption/ desorption	5.6 Percolation, Diffusion/ Advection	5.7 Root uptake	5.8 Root uptake	5.9
6.1	6.2	6.3 Root uptake	6.4	6.5	6.6 Soil mineral Adsorption/ desorption	6.7 Root uptake	6.8 Root uptake	6.9
7.1	7.2	7.3 Root uptake (Mycorrhizae)	7.4 Fertilisation	7.5 Fertilisation	7.6 Fertilisation	7.7 Fungi	7.8 Root uptake (Mycorrhizae)	7.9 Ingestion
8.1	8.2	8.3	8.4 Leave fall, Weathering Interception	8.5 Fertilisation	8.6 Fertilisation	8.7	8.8 Understorey	8.9 Ingestion
9.1	9.2	9.3	9.4 Fertilisation	9.5	9.6	9.7 Consumption	9.8 Consumption	9.9 Wild animals

Fig. 1 Matrix description of the migration of Cs-137 in a forest ecosystem.

Relevant transfer processes: acute phase ▨ long-term phase

BIOMASS GROWTH

The intercepted radionuclides are distributed among forest plants approximately in proportion to the biomass of each plant (Van Voris, 1990; Fraiture, 1992; Schell *et al.* 1996). The biomass of trees is the highest in the forest ecosystems; thus trees will intercept an important part of the deposition. The structure of the forest canopy is important in determining the type of interception phenomena. The more dense the canopy, the higher will be the quantity of radionuclides retained by tree crowns. In some forests, especially in forests of rainy areas, bryophytes (lichens, mosses) are an important element of the total biomass. The thick carpets of bryophytes covering large parts of the forest floor can intercept a great quantity of the total deposition, slowing down the transfer to soil.

Radiocaesium accumulates in the trees and forest understorey from the soil in proportion to the biomass of the various tree components or understorey. Van Voris *et al.* (1990) pointed out that the total activity in forest understorey is very small in comparison to that in the tree canopy, as reflected in the comparative biomass of each. According to Anderson (1973) the main factor limiting the supply of potassium (and hence, probably, also of caesium) to the growing plant shoot is not concentration, but some intrinsic factor connected with plant growth. Thus, correlation between root uptake rates and biomass growth is to be expected.

Due to dilution by growth there is a progressive lowering of radiocaesium in plants. The mass concentration of any material associated with the vegetation will decrease at about the same rate as the rate of the plant growth. However, it should be stressed that dilution phenomena are of importance mainly when plants are contaminated by direct deposition, without significant root uptake. In a growing plant "dilution" phenomena may to some extent be counterbalanced by an input of new radiocaesium from the roots, influenced by growth itself.

AGE OF THE TREES

The biomass growth of trees is more intensive in young trees than in mature trees. Thus, root uptake rates are expected to be higher for young trees than for mature trees. Studies in Belorussian pine forests (Shaw *et al.* 1996), for example, showed that young trees (10-20 years old) can accumulate up to 6 times more radiocaesium than older trees (70-80 years). Mamikhin *et al.* (1997) observed that needles, wood and branches of young trees were 2.5-3.5 times more contaminated with Cs-137 than mature trees. These authors explained this difference by a higher content of meristematic tissues in the phytomass of the young trees. Similar observations were made in Sweden (Hubbard et al. 1997).

SOIL CHARACTERISTICS

Soil characteristics influence strongly the root uptake of radionuclides by plants. The main factors influencing root uptake are pH, clay and organic matter content, type of clay, concentration of other ions, moisture and degree of mycorrhization. A good review of these factors can be found in Nimis (1996). Most of these factors influence the caesium availability for root uptake by affecting the processes of adsorption-desorption, fixation and demobilisation of the radionuclides in the soil.

3. Description and analysis of existing models

This chapter provides a description and analysis of a number of mathematical models of migration of radionuclides in forest ecosystems. The aim of the analysis is to evaluate the applicability of these models for explanation and prediction of differences in the behaviour and distribution of radionuclides, primarily Cs-137, in different types of forests. The chapter is divided into two sections dealing with static and dynamic models respectively.

3.1 STATIC MODELS

Static (equilibrium) models assume a static situation in the system and therefore simple algebraic equations can be applied. The advantages of using static models are that an analytical solution might be provided. In most cases fewer data are needed, a parameterisation is easier and the computations are carried out more easily. A static model can of course not be used in a transient dynamic state like the acute phase, but it can be used to describe the situation a long time after deposition of radionuclides, i.e., in the quasi-equilibrium phase.

3.1.1. TRANSFER FACTORS

Static models have been widely used for migration studies in different ecosystems. One example is the use of transfer factors, TF, for evaluating radionuclide uptake by plants. In this case the TF is defined as the ratio of radioisotope concentration in the plant (Bq kg $^{-1}$ dry or wet weight) to that in soil at a defined depth (Bq kg $^{-1}$ dry or wet weight). This is the approach recommended by the IAEA to use in agricultural modelling (Howard *et al.* 1993; IAEA, 1994). Transfer factors have also been widely used in modelling radionuclide uptake by forest plants. Unfortunately, the available soil-to-plant transfer factors are difficult to interpret and to extrapolate to other geographical areas for the following reasons.

i) High variability of the TF.

A review by Lembrechts (1993) shows that the TF for agricultural plants vary by a factor of up to 25 even for plants grown at the same site. Different types of soils lead to a TF variation by a factor of 50. The values of TF recommended by the International Union of Radioecology (Frissel, 1992) lie within the confidence limits of about two orders of magnitude. A higher variability of the soil-to-plant TF in forest ecosystems can be explained by the extreme conditions (see 2.1) in forest ecosystems (Frissel *et al.* 1990).

ii) Non- equilibrium conditions.

The TF can only be applied to describe equilibrium conditions (Ward and Johnson, 1985). As mentioned in section 2.2, it can take decades for radionuclide fluxes to reach equilibrium in forest ecosystems. In practice the TFs have often been measured in non-equilibrium conditions in the system, without taking into account the dynamics of the migration processes. Another problem to account for is that the overall radionuclide concentration in a plant may be subjected to changes during its growth phase, specially if the data are expressed in dry weight (Nimis, 1996). A clear protocol for the experimental determination of the TF is needed.

iii) Speciation and bioavailability are not considered.

The use of TF presumes that there is linearity between the activity concentration in the plant and the total concentration of the radionuclide in soil. At the same time, several studies (Horrill et al. 1990; Desmet et al. 1991 and Myttenaere et al. 1993) have suggested that the bioavailability in soil of a given nuclide, not its concentration, is important for plant uptake. Only a small fraction of the total content of the radionuclide is available for uptake and it is strongly dependent on soil properties.

iv) Variation of soil density with depth is not considered.

Thiry and Myttenaere (1993) highlighted the potential for misinterpretation of radioactivity measurements in forest soils when the values are based on weight (the different layers having different densities). The conditions of the soil profile vary strongly from place to place. Thus, it is difficult to extrapolate TF calculated from this type of data.

The TF have also been applied for evaluating radionuclide accumulation by domestic animals. In this case the TF is defined as the ratio of the radioisotope concentration in meat or milk (Bq kg^{-1} or Bq l^{-1}) to that in the animal feeds (Bq kg^{-1} dry wet) or to the daily intake of the radioisotope by the animal (Bq d^{-1}). The application of this type of TF to free ranging forest animals is more difficult because the diet composition of wild animals is hard to measure in most situations.

3.1.2. AGGREGATED TRANSFER FACTORS

The limitations for application of the transfer factor in forest ecosystems have lead to the use of Aggregated Transfer Factors (TF_{ag}) instead. The TF_{ag} is defined as the ratio of the radioisotope concentration in a certain component of the ecosystem (Bq kg^{-1} dry or wet weight) to the total deposition density in the soil (Bq m^{-2}). The TF_{ag} can easily be measured and can be applied to any component of the ecosystem, including animals. The TF_{ag} is free of the problem arising from differences in densities of different soil layers. However, other limitations of TF are also inherent to TF_{ag}.

Despite the limitations inherent to TF and TF_{ag}, they can be very useful for radiation protection assessments. Often the use of TF or TF_{ag} is the only available alternative for evaluating radionuclide accumulation. In radioecology they can be applied for systemisation of the experimental data and for studies on natural variability of the intensity of transfer processes.

3.2 DYNAMIC MODELS

The earliest mathematical models of the migration of radionuclides in forest ecosystems were developed from data obtained in experiments with caesium inoculation (Olson's model and Croom's model) and from studies of migration of stable isotopes (Jordan's model). Other models are based on knowledge from studies in forests contaminated by global fallout from tests of nuclear weapons (Croom's model), by the Kyshtym (Prokhorov's model and Alexakhin's models) and Chernobyl (Bergman's model, FORESTPATH, ECORAD, FORESTLIFE, RIFE.I, FORM) accidents and by releases during the Manhattan project (RADFORET, Garten's model).

Table 1 summarises some characteristics of dynamic models, while more detailed and systematic model descriptions are given for ten models in Appendix A. The diagrams of the conceptual models are given in Appendix B. In Table 1 the column "compartments" contains the components (state variables) of the models, column "parameterisation" indicates the method and source of information used to obtain parameter values and the column "forest" indicates the types of forests used for calibrating the models. The methods of parameterisation are divided into two categories:

Category A	Methods consisting of determining transfer rates of single processes, i.e. transfer between two compartments (components) by conducting independent experiments or literature reviews.
Category B	Methods consisting of fitting the model with site-specific experimental data.

The most common dynamic models of radionuclide migration in the environment are the so-called linear compartment models. In a linear compartment model, a set of coupled linear differential equations describes the net accumulation of radionuclides in compartments over time. The classic compartment models describe the transfer between compartments as the product of a rate constant and the radionuclide content in the source compartment. All studied models belong to this last type, but in some models a number of transfer processes have been described in a different way. In ECORAD and FORESTLIFE the vertical transfer of Cs-137 in soil is described by diffusion-advection equations. In RIFE.I and FORM the activity of forest products is calculated with an equilibrium model. RADFORET and the Bergman's model are coupled to a model of forest growth, which is used to describe some of the transfer rates. In FORESTLIFE the root uptake by trees and the accumulation in wood is described by a product of integral empirical functions.

3.2.1. CONCEPTUAL MODELS

The main conceptual differences between the generic[2] models of caesium migration in forest ecosystems are which compartments are included in the models and how different transfer processes are described. The selection of a conceptual model depends on the purpose of the model, the phase of migration dynamics addressed and the time scale. In practice it is also influenced by the state of knowledge about the migration processes and the availability of data for calibration of the model. The way transfer processes have been described by different models will be addressed in section 3.2. Diagrams of the different conceptual models can be found in Appendix B.

TIME SCALE OF THE MODELS

All models, except FORESTPATH and RIFE. I, are designed for long-term assessments[3]. The starting point for calculations with long-term models is a user defined initial distribution of the radionuclide in the model compartments at a specified time after the deposition. The calculations are usually made on a yearly basis using yearly averages of transfer rates, which are considered as constants. In RADFORET, FORESTLIFE and Bergman's model some transfer rates depend on biomass growth and are therefore time-dependent. FORESTPATH and RIFE.I are designed for assessments in both acute and long-term phases. These models use time-dependent transfer rates to represent the migration of Cs-137 during the first period after an aerial contamination. The differential equations are solved by numerical methods, which make it easy to have time-dependent parameters.

SELECTION OF COMPARTMENTS

LITTER

Litter is described in all models as a separate compartment, where mosses and lichens are often included. Bergman's model describes mosses and lichens in a separate compartment. This model therefore permits a better resolution of the processes of litter decomposition and retention of radionuclides by mosses and lichens.

SOIL

The models developed in the sixties and seventies describe soil with only one compartment. The lack of experimental data for calibration of more sophisticated models was probably the reason for this simplification. In RADFORET and FORESTLIFE the same method is adopted, but corrections of transfer rates are made to allow a description of vertical migration and sorption processes in soil. Other models describe vertical migration by dividing the soil into upper and lower layers. FORESTPATH, ECORAD and Croom's model divide further the upper layer into labile and fixed components permitting a better description of sorption-desorption processes in soil. ECORAD considers three layers of surface organic horizons and divides mineral and mineral organic layers into 1-cm layers down to 15 cm. Such detailed description would probably rise difficulties for applying this model to other sites.

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[2] Generic model in this context includes the conceptual and mathematical models, but not the parameter values, which can be different for different sites and situations. This means that there can be two or more different site-specific models based on the same generic model.

[3] These models (i.e. all but FORESTPATH and RIFE.I) will be called *long-term models* in this work

Table 1 Characteristics of studied models

Model Reference	**Compartments**	**Parameterisation**	**Forest**	**Comments**
Olson, (1965)	Leaves, bark, roots, undercover, littermate, soil	A (experiments with caesium inoculation)	Liriodendron trees in Oak Ridge	
Jordan et al. (1973)	Canopy, litter, soil, wood	B (One site in Puerto Rico)	Tropical rain	Parameterised for Sr and Mn using data of concentration and fluxes of stable isotopes.
Prohorov and Ginzburg, (1973)	Litter, soil, roots, trunk, twigs, leaves		Deciduous and coniferous	Parameterised for Sr with data from areas contaminated by the Kyshtym accident.
Alexakhin et al. (1976)	Litter, soil, branches, wood, bark, leaves, herbs	B (One site in Russia)	Deciduous and coniferous	
Garten et al. (1978)	Soil, litter, ground vegetation, leaves, root , wood, consumer, soil fauna	A+B (One site near Oak Ridge)	Deciduous	The model was parameterised for Pu using data obtained in areas contaminated by releases during the Manhattan project.
Croom and Ragsdale, (1980)	Tree, litter, lower soil, upper soil available for uptake, upper soil unavailable for uptake	A (experiments with caesium inoculation)	Deciduous (oak trees)	Validated with fallout data form one site in South Carolina.
RADFORET Van Voris et al. (1990)	Soil, roots, bole, branch, leaf, litter, understorey	B (two sites in south-eastern USA)	Deciduous	Cs availability in soil is related to the clay content. Coupling to a tree growth model.
Bergman et al. (1993)	Throughfall, needles, perennial vegetation, competitors, moss and lichen, litter, soil	B (experimental plots in the northern part of Sweden)	Coniferous	Competition of biomass for the available Cs is a central concept of this model.

Model Reference	Compartments	Parameterisation	Forest	Comments
Alexakhin et al. (1994)	Litter upper, litter lower, soil, branches, wood, bark, leaves, and herbs.	B (One site in East Ural)	Deciduous (birch) and coniferous (pine)	Parameterised for Sr with data from areas contaminated by the Kyshtym accident.
FORESTPATH Schell et al. (1996)	Tree, understorey, organic layer, labile soil, fixed soil, deep soil.	A (literature review)	Generic, deciduous and coniferous	
FORESTLIFE Shaw et al. (1996)	Bark, branches, needle 1, needle 2, understorey, fresh litter, litter, soil.	B (13 monitoring plots in Belarus)	Pine	Includes a model of vertical migration in soil.
RIFE.I Shaw et al. (1996)	Tree external, tree internal, litter layer, Soil - organic horizon, soil – mineral horizon, fungi, herbs.	B (experimental sites in Ukraine, Belarus, Germany and Ireland)	Different types of forests	The activities in fungi and herbs are calculated with an equilibrium model.
FORM IAEA (1995)	Bark, leaves, litter, organic matter (soil), soil mineral, forest products: wood, fruits, herbs and berries, mushrooms, roe deer, other game, domestic animals meat, domestic animals milk, honey.	A (literature review of temperate and boreal forests)	Generic coniferous and deciduous	The activities in forest products are calculated with an equilibrium model.

TREE

Most long-term models describe the tree divided into several compartments, each compartment corresponding to a real part of the tree (roots, bark, wood, branches, leaves or needles, etc.). The selection of compartments has been influenced by the availability of experimental data and often it does not reflect the physiological processes occurring in the tree. An interesting way to describe the tree was applied by Antopoulus-Domis (1990, 1996) in a model for fruit trees. This model divides the tree in unavailable and available parts. This approach allows a better representation of translocation and root uptake. All long-term models have considered leaves (needles) as a separate compartment, which is sound, considering the important role played by leaf fall on caesium recycling in the system.

FORESTPATH represents the tree as one compartment and RIFE.I divides it into external and internal tree parts. Neither approach seem to be optimal for consideration of factors affecting interception and weathering.

UNDERSTOREY

The understorey vegetation and fungi are considered by RADFORET, Bergman's model, Alexakhin's model, FORESTPATH, FORESTLIFE, RIFE.I and FORM. Some of these models (Garten's model, RADFORET, Alexakhin's model and FORESTLIFE) include all species in one compartment, while others consider some species (berries, fungi, etc.) separately. None of these models divide understorey vegetation (fungi) in parts (roots, leaves, etc.).

ANIMALS

FORM is the only model that includes forest animals in the conceptual formulation. In FORM the accumulation of Cs-137 by animals is described with an equilibrium model. The reasons why animals are not considered in other models are probably the lack of experimental data, and the poor state of knowledge of dietary habits and habitat of wild animals.

3.2.2. TRANSFER PROCESSES

Table 2 presents an overview of how the transfer processes outlined in chapter 2 are addressed by a selected group of models[4]. The selected models are the latest developed and described in the literature. They permit a more complete accounting of transfer processes than earlier models and have benefited from the knowledge obtained during investigations in areas contaminated by the Chernobyl accident.

Table 2 Transfer processes used in the models

TRANSFER PROCESS	MODELS	TRANSFER PROCESS	MODELS
Interception by trees	2,5	Translocation	1,3,4,7
Interception by understorey	2	Vertical migration	2,3,4,5,6,7
Weathering (trees)	2,3,4,5,6	Soil leaching	1,4,6
Weathering (understorey)	2,3,4	Adsorp./desorp. (soil)	1,2,3,4
Foliar adsorption	5	Litter decomposition	1,2,3,4,5,6,7
Leaves fall (tree)	1,2,3,4,5,6,7	Root uptake	1,2,3,4,5,6,7
Senescence (understorey)	7	Fertilisation (trees)	3

1- RADFORET, 2- FORESTPATH, 3- ECORAD, 4- FORESTLIFE, 5- RIFE. I, 6- FORM, 7- Alexakhin's model

No model addresses all transfer processes, which is understandable since not all transfer processes are relevant for a particular model or site. Less important processes like resuspension, rainsplash, percolation, and fertilisation of the root zone are not described by any model. Only FORM includes

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[4] Only the models indicated below this table were included in the analysis of transfer processes

game; thus fertilisation and consumption of vegetation by game are not described. These processes, however, can be important for some forests.

All models include the most relevant processes of the long-term phase: (litter fall, litter decomposition and root uptake). Among them, the ones that describe the most transfer processes are FORESTPATH and FORESTLIFE. The models for the acute phase (FORESTPATH and RIFE.I) address the relevant transfer processes for this phase (interception and weathering).

APPROACHES FOR DESCRIPTION OF TRANSFER PROCESSES

The transfer rates between compartments are, in most cases, described with rate constants (time^{-1}). The advantage of this method is its simplicity. The disadvantage lies in the difficulty to extrapolate the values of the rate constants to other geographical areas. The rate constants are usually highly variable. They often include several physical processes and are therefore hard to interpret. A possible alternative is to express the transfer rates as a function of the involved physical processes. In this way all model parameters could have a well-defined physical meaning. This could facilitate their experimental determination and estimation by expert judgement. Examples of the last approach in the studied models are discussed below.

INTERCEPTION

This process is relevant for the acute phase and therefore has only been addressed by FORESTPATH and RIFE.I. In RIFE.I the fraction of total deposition intercepted by the tree canopy is user defined. It is assumed that the rest of the activity falls on the ground litter surface. FORESTPATH describes the process in the same way, but it assumes that the intercepted fraction is distributed between tree and understorey in proportion to the biomass of these compartments. However, in this model the whole tree is considered as one compartment. The total tree biomass does not change during a year. Given this, also the total intercepted fraction by the trees will not change substantially during the year. Several experimental observations have indicated that the season of fallout strongly influences the interception fraction (Melin and Wallberg, 1991; Feige *et al.* 1988). This is due to seasonal changes of the surface area of the tree exposed to the fallout in connection to foliage fall.

VERTICAL MIGRATION IN SOIL

ECORAD and FORESTLIFE describe the vertical migration of radionuclides in soil using an advection-diffusion approach. ECORAD describes the processes of advection and diffusion with a series of first order differential equations. Each layer of the soil comprises two compartments, representing mobile and fixed forms of the radionuclide. The vertical transfer between soil layers within the mobile compartments is described by a first order advection rate while vertical movement between fixed compartments occurs by diffusion, the rate of diffusion being determined by the diffusion coefficient and the gradient of radionuclide concentration between compartments. An additional compartment within the model is a so-called "distributive pool" (Mamikhin, 1994), which represents the biological components in the soil of higher and lower plants (i.e. roots and fungal hyphae). ECORAD therefore considers the role of biological transport processes in redistributing radionuclides vertically within the soil.

FORESTLIFE uses two alternative approaches to describe the vertical migration of caesium in soil. The first approach is a quasi-diffusion model and the following equation is applied:

$$\frac{dq}{dt} = D \cdot \frac{d^2 q}{dx^2} \qquad (1)$$

Where q is the activity of the radionuclide and D is the diffusion coefficient of the radionuclide in the soil under consideration. In order to describe observed distributions of radionuclides in soils, "fast" and "slow" diffusion coefficients are applied. The analytical solution of equation (1) is obtained assuming a homogeneous soil profile subjected to both fast and slow diffusion.

The second approach involves the use of the advection-diffusion equation:

$$\frac{dq}{dt} = D \cdot \frac{d^2q}{dx^2} - V \cdot \frac{dq}{dx} \qquad (2)$$

Both approaches have several conceptual problems: 1) they assume a homogeneous soil profile, which is not a good approximation in the forest, 2) they do not consider retardation due to adsorption/desorption processes, 3) they do not consider the influence of root uptake and biological immobilization. Konshin (1992) showed that the model described with equation (2) has two fundamental limitations: it systematically underestimates the concentrations of radionuclides at great depths and it reduces the values of V and D as the observation period increases. Another problem is the ambiguity of the parameters V and D when they are fitted independently. Different combinations of V and D will produce identical results. Konshin (1992) demonstrated that the only way of obtaining good agreement with experimental data using this model is to introduce $V(x,t)$ and $D(x,t)$, which makes the situation much more complex and introduce uncertainty in the predictive capacity of the model. These limitations are also inherent to the model described with equation (1).

ADSORPTION AND DESORPTION IN SOILS

Caesium availability is assumed to be inversely related to the strength of the sorption of caesium to the soil particles in RADFORET. It is also assumed that sorption of caesium to soil is controlled by the amount of clay in the soil. A K_d value of approximately 1,000*clay (%)[5] is used to estimate the fraction of caesium in the soil that is available for uptake by trees and understorey. The model, however, does not consider other factors that influence on adsorption- desorption, such as cationic status of the soil (K^+, NH_4^+), the type of clay minerals present in the soil, etc. Neither are biological mechanisms of fixation of caesium considered.

A function for the vertical distribution of the bio-available forms of radionuclides in the soil is used for calculation of the root uptake of radionuclides over time in FORESTLIFE (see below). This function is derived from field measurements and is expressed as an empirical equation. Unfortunately the experimental determination of the bio-available caesium in soil is difficult from the methodological point of view.

ROOT UPTAKE

RADFORET and Bergman's model consider root uptake by trees and understorey as a function of biomass growth. Forest growth in RADFORET was estimated by using FORET- a model for simulation of growth and fate of individual trees. The effect of competition for the available caesium is considered in Bergman's model.

FORESTLIFE applies a time-dependent coefficient, FTF(t) for evaluating radionuclide accumulation in wood via root uptake. The FTF(t) is defined as the product of three functions:

$$FTF\ (t) = FK\ (t) \cdot FAC\ (t) \cdot FD\ (t)$$

FD(t) describes the radioactive decay. FAC(t) describes the accumulation of radionuclides by wood expressed as the product of three empirical functions corresponding to biological characteristics of the tree: FAD (t) - age dependence, FRD (t) - radial distribution in growing tissues and FIB (t) - increase in biomass. FK(t) describes the root uptake of radionuclides expressed as the product of three empirical functions: FR (x) - vertical distribution of absorbing roots, FA (x) - vertical distribution of bio-available forms of radionuclides and FM (t, x) – vertical migration of the total radionuclide inventory within the soil profile.

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[5] For soils with clay content ranging from 15 % to 90 %.

This approach has the advantage that it allows the important factors influencing accumulation of nuclides via root uptake to be addressed. However, describing the transfer processes with empirical functions limits the applicability of the model to other areas and types of forests.

3.2.3. PARAMETERISATION OF THE MODELS

In all models, except FORESTPATH and FORM, the parameters were estimated using experimental data measured at specific sites for one specific case of contamination (see table 1). These models are therefore site and case specific. Nevertheless, they can be applied to other forests with characteristics similar to the specific site of parameterisation. Moreover, some of these models, for example RIFE.I, ECORAD and FORESTLIFE are calibrated for several sites. This increases the possibility of their direct application to other sites. Unfortunately, in most cases the characteristics of the forests used for model calibration are not provided. At the same time, the generic model of a site-specific model can be recalibrated for any other site. The only condition is that the assumptions made for the conceptual model remain valid.

In FORESTPATH and FORM the model parameters were estimated from a literature review and by expert judgement. Both models provide a best estimate and interval of variation for the rate constants or transfer factors. However some of these parameters, like root uptake rate in FORESTPATH and soil-to-plant TFs in FORM, fluctuate within two or more orders of magnitude.

3.2.4. CONSIDERATION OF FACTORS INFLUENCING CAESIUM MIGRATION BY THE MODELS

The following presents an analysis of how the factors influencing caesium migration, outlined in section 2.3, are considered in the models (see Table 3). It is understood that 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 conditions are fulfilled: 1) it describes the transfer processes that are significantly influenced by the "factor", 2) it provides relationships between transfer rates and some quantitative or qualitative measure of the "factor".

Table 3 Factors influencing caesium migration considered by the models

FACTORS	MODELS
Type of deposition	
Season of the deposition	
Type of forest (deciduous, coniferous)	2,4,5
Biomass growth	1,3
Age of the trees	1,3,4
Soil characteristics	1

1- RADFORET, 2- FORESTPATH, 3-FORESTLIFE, 4- FORM,
5- Alexakhin's model

The factors influencing caesium migration are in general poorly considered by the models. No model considers all the factors and most of them consider only a few or none.

TYPE AND SEASON OF THE DEPOSITION

No model allows study of the influence of the factors associated with the type and season of deposition. FORESTPATH and RIFE.I could however be easily adapted for this purpose. A simple implementation would be to include a separated compartment for leaves (needles) linked to a model that allows prediction of seasonal variations of leaf (needle) biomass and the density of the tree canopy.

TYPE OF FOREST (DECIDUOUS, CONIFEROUS)

FORESTPATH and Alexakhin's model consider this factor by having different parameter values for leaf (needle) fall and for litter decomposition. FORM uses the same approach, but differentiation on parameter values is made only for the rate of leaf (needle) fall.

BIOMASS GROWTH

RADFORET and FORESTLIFE consider the influence of biomass growth by assuming that root uptake rates are proportional to the increase in biomass. Dilution effects due to biomass growth are also described in these models. The biomass growth model used in RADFORET is quite complicated and can only be applied to a coniferous forest. FORESTLIFE only considers biomass growth for accumulation of radionuclides by wood.

An interesting way to consider the influence of biomass growth on root uptake is used in the dynamic models for agricultural crops PATHWAY (Whicker and Kirchner, 1987) and COMIDA (Abbott and Rood, 1994). These models express root uptake rates to edible parts of plants as a function of plant growth rates and soil-to-plant TFs. Radioactivity uptake into plants is, therefore, a time variable depending upon the seasonal plant growth rate. This approach could be applied to forest ecosystems, but some modifications are needed, mainly to account for the non-homogenous soil profile.

AGE OF TREES

FORESTLIFE and FORM have explicitly considered this factor. Both models use functions of tree age that modify time-dependent TFs. FORESTLIFE uses an empirical function (see epigraph 3.3.2.2), while FORM applies the following expression:

$$TF_t = TF_e * t/(t + A_c)$$

Where TF_t is the TF factor “t” years after the contamination, TF_e is the transfer factor at equilibrium and A_c is the age of the tree at the moment of the contamination.

Plant growth rates are age dependent. Thus, considering the influence of biomass growth on root uptake rates is an indirect way of considering the influence of tree age on caesium uptake (RADFORET).

SOIL CHARACTERISTICS

RADFORET provides a relationship between root uptake and soil characteristics. However, clay content is the only soil characteristic considered by this model. FORESTPATH, ECORAD and FORESTLIFE could be adapted for consideration of this factor. The reason is that only these models describe adsorption and desorption processes in the soil. (These two processes are those that are most influenced by soil characteristics).

4. Implementation of the spatial dimension in modelling forest ecosystems: GIS, Geographical Information Systems.

This report covers the state-of-the art of existing ecosystem models describing the radioecology of forests. These models incorporate dynamics in the time dimension, at one point in space. A model system which describes radioactive concentrations in the different forest compartments as a function of both time and space has the added ability to predict the dose received by a population over a wide geographical area. This is exactly the development that is currently proceeding in the field of radioecology. The tool for implementing the spatial dimension is a large collection of different software packages collectively called Geographical Information Systems, or GIS. The GIS environment encompasses digitised maps containing a variety of different parameters geographically distributed, plus the ability to manipulate the maps statistically and mathematically, both in the spatial and temporal domains. It also includes the ability to display the maps in a variety of different forms (digitised cartography).

There are two main areas of development in the GIS modelling effort. The first is the development of the most efficient technique to incorporate an ecosystem model into the GIS environment. This involves choosing the most relevant ecosystem model which is also easy to implement, i.e., minimising the number of parameters while optimising the information obtained in the output, and choosing the technique for implementing the ecosystem model within the GIS software.

The second area of development involves collecting maps that contain, geographically distributed as a function of the physical environment, all the relevant parameters that are needed in the ecosystem model. This is a large task which involves collecting maps of the parameters which already exist in digitised form for a given region, and creating the maps of those parameters which do not currently exist. The number of parameters depends on the choice of ecosystem model. It is therefore important to optimise the choice of the ecosystem model. This review presents the state-of-the art in non-spatial modelling of forest ecosystems and is one part of the process of choosing the optimum ecosystem model for use in the GIS environment.

There are currently ongoing efforts at SSI and elsewhere to implement modelling of forest radioecology into a GIS environment, with the ultimate goal of providing radionuclide distribution and dose calculations on a regional basis.

5. Conclusions

1. Static models have a limited applicability in forest ecosystems. This is primarily because the migration of radionuclides in forests is a non-equilibrium process. Many years (decades) after a deposition, however, a quasi-equilibrium state can be reached concerning the uptake of radionuclides by forest plants. At this stage transfer factors can be applied with a better confidence. A combination of transfer factors with dynamic models, as implemented in FORM, FORESTLIFE and RIFE.I, provides one way of using the available data on aggregated transfer factors.
2. The dynamic models include the most relevant transfer processes, both for the acute and the long-term phases of the contaminated forest. Most of the transfer processes are, however, described with rate constants. These are often highly variable and include several processes, which make the interpretation, measurement and estimation difficult.
3. The models can hardly be applied for explaining and predicting differences in the behaviour and distribution of radionuclides in different types of forests. First, all models, except FORESTPATH and FORM, are site specific and the characteristics of the forests used for calibrations are usually not provided, which basically makes it difficult to apply them for other sites. The parameters in FORM and FORESTPATH are given for generic forest ecosystems, but some of them vary within two or more orders of magnitude. Second, the models, with few exceptions, do not allow considering the factors (studied in this work) responsible for differences in radionuclide behaviour and distribution in different types of forests.
4. The improvement of models is constrained by the availability of experimental data and by lack of knowledge on migration mechanisms. Some improvements are, nevertheless, possible; for instance by combining existing modelling approaches. The main efforts, in our opinion, should be put on describing some important transfer rates at a process level (instead of using rate constants). Such an approach will allow considering the factors influencing the radionuclide transfer. Examples of possible applications of this approach are: description of the interception fraction by trees with a function of the leaf biomass or projected area of the tree canopy; description of the translocation inside the tree using compartments for living and non-living wood, description of root uptake as a function of biomass growth and concentration ratio of radionuclides in soil,

description of adsorption- desorption and vertical migration in the soil as a function of the soil characteristics.

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8. Appendices

8.1 APPENDIX A. MODEL CHARACTERISTICS

Model: Olson's model
Reference: Olson, J.S. 1965 Equations of Caesium transfer in Liriodendron forest. Health Phys. 11: 1385-1392

State variables:

Leaves, bark, roots, undercover, littermate, soil

Parameterisation:

The values of the model parameters were obtained from experiments consisting of introducing Cs-137 (as carrier-free chloride) into the trunks of the dominant trees. Some transfer rates were estimated by sampling actual transfer and expressing these as daily fractions of the quantity in the source compartment. Other fractional rates were assumed tentatively to find a combination of parameters which would create approximately the right pattern of cumulative change through time.

Characteristics of the forests used for the calibration:

The experiments were carried out on a forest plot on the Oak Ridge Reservation

Type of forest: Liriodendron forest (the dominant trees are yellow poplar or tulip poplar, *Liriodendron tulifera*)

Type of soil: Not indicated

Time scale: The model parameters were obtained for the firsts months after innoculation of caesium.

Transfer processes:

Interception (tree)	☐	Leaves fall (tree)	☐	Percolation	☒	Root uptake	☒
Interception (und)	☒	Leaves fall (und)	☐	Vert. migr. (soil)	☐	Fertilis.(tree)	☒
Weathering (tree)	☒	Translocation	☒	Soil leaching	☐	Fertilis.(und)	☐
Weathering (und)	☒	Resuspension	☐	Ads./desorp (soil)	☐	Fertilis.(game)	☐
Foliar absorption	☐	Rainsplash	☐	Litter decompos.	☐	Veg. cons. (game)	☐

Factors influencing radionuclide migration:

Type of deposition	☐
Moment of the deposition	☐
Type of forest (coniferous, deciduous)	☐
Biomass growth	☐
Age of the trees	☐
Soil characteristics	☐

Model: Garten's model
Reference: Garten, C.T., Gardner, R.H., Dahlman, R.C. 1978. A compartment model of plutonium dynamics in a deciduous forest ecosystem. Health Physics, 34:611-619

State variables:

Soil, litter, ground vegetation, leaves, roots, wood, consumers, soil fauna.

Parameterisation:

The model was parameterised for plutonium. A majority of the transfer coefficients in the model were calculated on the basis of biomass flux from the donor compartment. Biomass fluxes were first derived, independently of the model performance. Some parameter adjustment was later necessary to calibrate the predicted amount of Pu in forest components with the calculated inventory based on field data.

Characteristics of the forests used for the calibration:

The parameters were derived from data collected for eastern deciduos forests in the Oak Ridge area. The adjustment of the parameters was made for a mixed deciduous forest dominated by white ash (*Fraxinus americana*) -8 trees per hectare and sycamore (*Platanus occidentalis*) - 3 trees per hectare.

Type of forest: Deciduos
Type of soil: Not indicated

Time scale: Long term behaviour of plutonium in forest ecosystems (up to 500 years).

Transfer processes:

Interception (tree) ☐
Interception (und) ☐
Weathering (tree) ☐
Weathering (und) ☐
Foliar absorption ☐
Leaves fall (tree) ☒
Leaves fall (und) ☒
Translocation ☒
Resuspension ☒
Rainsplash ☐
Percolation ☐
Vert. migr. (soil) ☐
Soil leaching ☐
Ads./desorp (soil) ☐
Litter decompos. ☒
Root uptake ☒
Fertilis.(tree) ☒
Fertilis.(und) ☐
Fertilis.(game) ☒
Veg. cons. (game) ☒

Factors influencing radionuclide migration:

Type of deposition ☐
Moment of the deposition ☐
Type of forest (coniferous, deciduous) ☐
Biomass growth ☐
Age of the trees ☐
Soil characteristics ☐

Model: RADFORET
Reference: Van Voris, P., Cowan, C.E., Cataldo, D.A., Wildung, R.E., Shugart, H.H. 1990. Chernobyl case Study: *Modelling* the dynamics of long-term cycling and storage of Cs-137 in forested ecosystems. In Desmet, P. Nassimbeni and M. Belli (Eds), Transfer of radionuclides in Natural and Semi-natural Environments. Elsevier Applied Science, Barking, UK, pp. 61-73.

State variables:

Soil, roots, bole, branch, leaf, litter, understorey

Parameterisation:

The parameter values were calculated by calibrating the model to the data reported for two sites in south-eastern USA: Oak Ridge, Tennessee, and Savannah River, Georgia.

Characteristics of the forests used for the calibration:

Site in Tennessee: floodplain low-land forest dominated by sycamore, white ash and tulip poplar. The forest follows a typical climax forest growth pattern. (All simulations of forest growth are made for this type of forest).

Site in Georgia: the overstorey of the flood plain forests is dominated by shrubby growth such as turkey oak and tends to be controlled by growth and burn cycles rather than by a climax forest dynamics.

Type of forest: Deciduous
Type of soil: Loamy clay with a clay content of 24 %

Time scale: Applicable for long-term predictions (after the acute phase)

Transfer processes:

Interception (tree) ☐
Interception (und) ☐
Weathering (tree) ☒
Weathering (und) ☒
Foliar absorption ☐
Leaves fall (tree) ☒
Leaves fall (und) ☐
Translocation ☒
Resuspension ☐
Rainsplash ☐
Percolation ☐
Vert. migr. (soil) ☐
Soil leaching ☐
Ads./desorp (soil) ☒
Litter decompos. ☐
Root uptake ☒
Fertilis.(tree) ☐
Fertilis.(und) ☐
Fertilis.(game) ☐
Veg. cons. (game) ☐

Factors influencing radionuclide migration:

Type of deposition ☐
Moment of the deposition ☐
Type of forest (coniferous, deciduous) ☐
Biomass growth ☒
Age of the trees ☐
Soil characteristics ☒

Model: FORESTPATH
Reference: Schell, W.R., Linkov, I., Myttenaere, C., Morel, B. 1996. A dynamic model for evaluating radionuclide distribution in forest from nuclear accidents. Health Physics: 70 (3): 318-335

State variables:

Tree, understorey, organic layer, labile soil, fixed soil, deep soil

Parameterisation:

Literature review of residence half lives

Characteristics of the forests used for the calibration:

Generic forest

Type of forest: Deciduous and coniferous
Type of soil: Generic

Time scale: Applicable for the acute phase and for long-term predictions

Transfer processes:

Interception (tree) ☒
Interception (und) ☒
Weathering (tree) ☒
Weathering (und) ☒
Foliar absorption ☐
Leaves fall (tree) ☒
Leaves fall (und) ☐
Translocation ☐
Resuspension ☐
Rainsplash ☐
Percolation ☐
Vert. migr. (soil) ☐
Soil leaching ☒
Ads./desorp (soil) ☒
Litter decompos. ☒
Root uptake ☒
Fertilis.(tree) ☐
Fertilis.(und) ☐
Fertilis.(game) ☐
Veg. cons. (game) ☐

Factors influencing radionuclide migration:

Type of deposition ☐
Moment of the deposition ☐
Type of forest (coniferous, deciduous) ☒
Biomass growth ☐
Age of the trees ☐
Soil characteristics ☒

Model: ECORAD
Reference: Shaw, G., Mamikhin, S., Dvornik, A., Zhuchenko, T. Forest model descriptions. II Behaviour of radionuclides in natural and semi-natural environments. Experimental collaboration project No 5. Final report, European Commission EUR 16531, 1996, pp. 26-31

State variables:

Needles/leaves, wood, external bark, internal bark, branches, roots, distributive pool, six soil layers.

Parameterisation:

Fitting the model predictions to experimental data of transfer coefficients

Characteristics of the forests used for the calibration:

Eight sites representing different types of forests in areas contamianted by the Chernobyl accident. Four of the sites are situated in the Briansk and Kaluga regions, Russia and the rest in Ukraine (within the 30 km exclusion zone).

Type of forest: Generic
Type of soil: Soddy podzolic

Time scale: Applicable for long-term predicitons (after the acute phase)

Transfer processes:

Interception (tree)	☐	Leaves fall (tree)	☒	Percolation	☐	Root uptake	☒
Interception (und)	☐	Leaves fall (und)	☐	Vert. migr. (soil)	☒	Fertilis.(tree)	☒
Weathering (tree)	☒	Translocation	☐	Soil leaching	☐	Fertilis.(und)	☐
Weathering (und)	☐	Resuspension	☐	Ads./desorp (soil)	☒	Fertilis.(game)	☐
Foliar absorption	☐	Rainsplash	☐	Litter decompos.	☒	Veg. cons. (game)	☐

Factors influencing radionuclide migration:

Type of deposition	☐
Moment of the deposition	☐
Type of forest (coniferous, deciduous)	☐
Biomass growth	☐
Age of the trees	☐
Soil characteristics	☒

Model: FORESTLIFE
Reference: Shaw, G., Mamikhin, S., Dvornik, A., Zhuchenko, T. Forest model descriptions. II Behaviour of radionuclides in natural and semi-natural environments. Experimental collaboration project No 5. Final report, European Commission EUR 16531, 1996

State variables:

Bark, branches, needle 1, needle 2, understorey, fresh litter, litter, soil.

Parameterisation:

Fitting the model predictions to experimental data of transfer coefficients. The model includes several empirical functions to represent the root uptake.

Characteristics of the forests used for the calibration:

Pine forests in the highly contaminated by Chernobyl in the south eastern corner of Belarus.

Type of forest: Pine forests
Type of soil: Not indicated

Time scale: Applicable for long term predictions (after the acute phase)

Transfer processes:

Interception (tree)	☐	Leaves fall (tree)	☒	Percolation	☐	Root uptake	☒
Interception (und)	☐	Leaves fall (und)	☐	Vert. migr. (soil)	☒	Fertilis.(tree)	☐
Weathering (tree)	☒	Translocation	☒	Soil leaching	☐	Fertilis.(und)	☐
Weathering (und)	☒	Resuspension	☐	Ads./desorp (soil)	☒	Fertilis.(game)	☐
Foliar absorption	☐	Rainsplash	☐	Litter decompos.	☒	Veg. cons. (game)	☐

Factors influencing radionuclide migration:

Type of deposition	☐
Moment of the deposition	☐
Type of forest (coniferous, deciduous)	☐
Biomass growth	☒
Age of the trees	☒
Soil characteristics	☒

Model: RIFE.I
Reference: Shaw, G., Mamikhin, S., Dvornik, A., Zhuchenko, T. Forest model descriptions. II Behaviour of radionuclides in natural and semi-natural environments. Experimental collaboration project No 5. Final report, European Commission EUR 16531, 1996, pp. 26-31

State variables:

Tree external, tree internal, litter layer, soil organic horizon, soil mineral horizon, fungi, herbs.

Parameterisation:

Fitting the model predicitons to experimental data of tarnsfer coefficients.

Characteristics of the forests used for the calibration:

Forests in contaminated area of Ukraine (within the Chernobyl 30 km zone), Belarus (within 200 km of the ChNPP), Gemany and Ireland.

Type of forest: Not specified
Type of soil: Not specified

Time scale: Applicable for the acute phase and for long term predicitons (up to 50 years). The outputs are given at 200 user defined time steps.

Transfer processes:

Interception (tree) ☒
Interception (und) ☐
Weathering (tree) ☒
Weathering (und) ☐
Foliar absorption ☒
Leaves fall (tree) ☒
Leaves fall (und) ☐
Translocation ☐
Resuspension ☐
Rainsplash ☐
Percolation ☐
Vert. migr. (soil) ☒
Soil leaching ☐
Ads./desorp (soil) ☐
Litter decompos. ☒
Root uptake ☒
Fertilis.(tree) ☐
Fertilis.(und) ☐
Fertilis.(game) ☐
Veg. cons. (game) ☐

Factors influencing radionuclide migration:

Type of deposition ☐
Moment of the deposition ☐
Type of forest (coniferous, deciduous) ☐
Biomass growth ☐
Age of the trees ☐
Soil characteristics ☐

Model: FORM
Reference: IAEA working document

State variables:

Bark, leaves, litter, organic matter (soil), soil mineral, forest products: wood, fruits, herbs and berries, mushrooms, roe deer, other game, domestic animals meat, domestic animals milk, honey

Parameterisation:

Literature review

Characteristics of the forests used for the calibration:

The literature review was concentrated on boreal and temperate forests

Type of forest: Deciduous and coniferous
Type of soil: Generic

Time scale: Applicable for long term predictions (after the acute phase). The time step for the calculations is one year.

Transfer processes:

Interception (tree) ☐
Interception (und) ☐
Weathering (tree) ☒
Weathering (und) ☐
Foliar absorption ☐

Leaves fall (tree) ☒
Leaves fall (und) ☐
Translocation ☐
Resuspension ☐
Rainsplash ☐

Percolation ☐
Vert. migr. (soil) ☒
Soil leaching ☒
Ads./desorp (soil) ☐
Litter decompos. ☒

Root uptake ☒
Fertilis.(tree) ☐
Fertilis.(und) ☐
Fertilis.(game) ☐
Veg. cons. (game) ☐

Factors influencing radionuclide migration:

Type of deposition ☐
Moment of the deposition ☐
Type of forest (coniferous, deciduous) ☒
Biomass growth ☐
Age of the trees ☐
Soil characteristics ☐

Model: Alexakhin's model
Reference: Alexakhin, R.M., Ginsburg, L.R., Mednik, I.G., Prokhorov, V. M. 1994. Model of Sr-90 cycling in a forest biogeocenosis. The Science of the Total Environment 157: 83-91

State variables:

Litter A_{01}, Litter A_{02}, soil, branches, wood, bark, leaves, herbs.

Parameterisation:

Fitting the model predictions to experimental data obtained in areas contaminated by the Kysthym accident in the South Urals and by global fallout.

Characteristics of the forests used for the calibration:

The experimental plots were established in a birch forest and in a pine forest.

Type of forest: Birch (50 years old) Pine (60 years old)
Type of soil: leached chernozem soddy podzolic

Time scale: Applicable for long term predictions (after the acute phase). The calculations are made on a yearly basis.

Transfer processes:

Interception (tree)	☐	Leaves fall (tree)	☒	Percolation	☐	Root uptake	☒
Interception (und)	☐	Leaves fall (und)	☒	Vert. migr. (soil)	☒	Fertilis.(tree)	☐
Weathering (tree)	☐	Translocation	☒	Soil leaching	☐	Fertilis.(und)	☐
Weathering (und)	☐	Resuspension	☐	Ads./desorp (soil)	☐	Fertilis.(game)	☐
Foliar absorption	☐	Rainsplash	☐	Litter decompos.	☒	Veg. cons. (game)	☐

Factors influencing radionuclide migration:

Type of deposition	☐
Moment of the deposition	☐
Type of forest (coniferous, deciduous)	☒
Biomass growth	☐
Age of the trees	☐
Soil characteristics	☐

Model: Bergman's model
Reference: Bergman, R., Nylén, T., Nelin, P., Palo, T. 1993. Caesium-137 in a boreal forest ecosystem- Aspects of the long term behaviour. FOA report C 40284-4.3.

State variables:

Throughfall, needles, perennial vegetation, competitors, moss and lichen, litter, soil.

Parameterisation:

The parameter values were obtained by fitting the model to the data obtained in forests located at Vindeln, 60 km NW of Umeå, Sweden.

Characteristics of the forests used for the calibration:

Boreal forests.

Type of forest: Pine forest
Type of soil: Podsolic

Time scale: The model is applicable for long-term assessments.

Transfer processes:

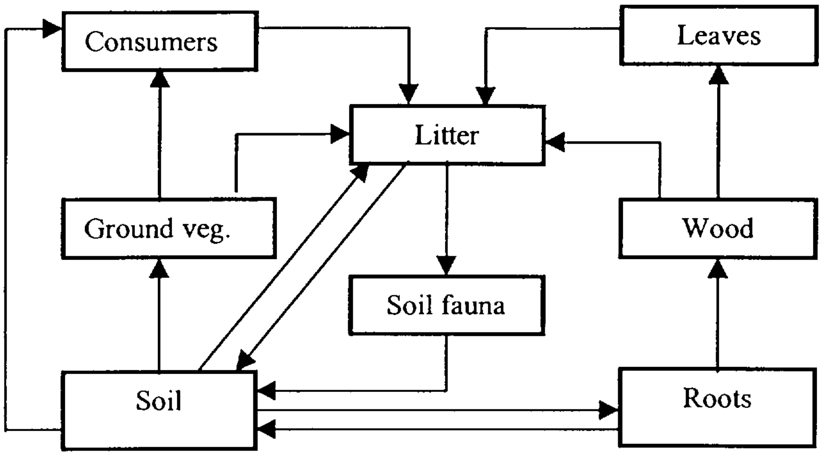
Interception (tree)	☐	Leaves fall (tree)	☒	Percolation	☐	Root uptake	☒
Interception (und)	☒	Leaves fall (und)	☐	Vert. migr. (soil)	☐	Fertilis.(tree)	☐
Weathering (tree)	☒	Translocation	☐	Soil leaching	☐	Fertilis.(und)	☐
Weathering (und)	☒	Resuspension	☐	Ads./desorp (soil)	☐	Fertilis.(game)	☐
Foliar absorption	☐	Rainsplash	☐	Litter decompos.	☒	Veg. cons. (game)	☐

Factors influencing radionuclide migration:

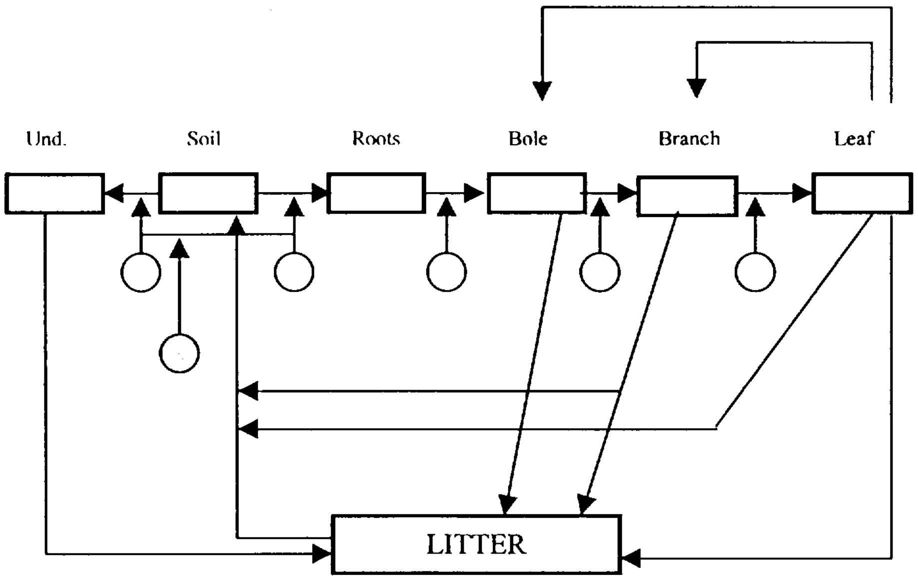
Type of deposition	☐
Moment of the deposition	☐
Type of forest (coniferous, deciduous)	☐
Biomass growth	☒
Age of the trees	☒
Soil characteristics	☐

8.2 APPENDIX B . DIAGRAMS OF THE CONCEPTUAL MODELS

Garten's model



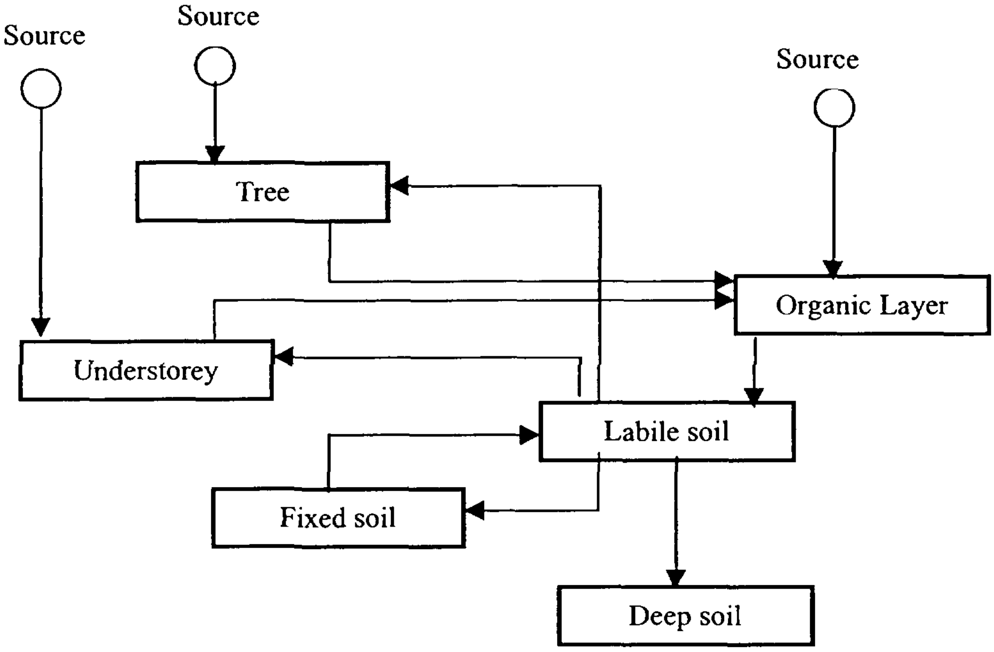
RADFORET



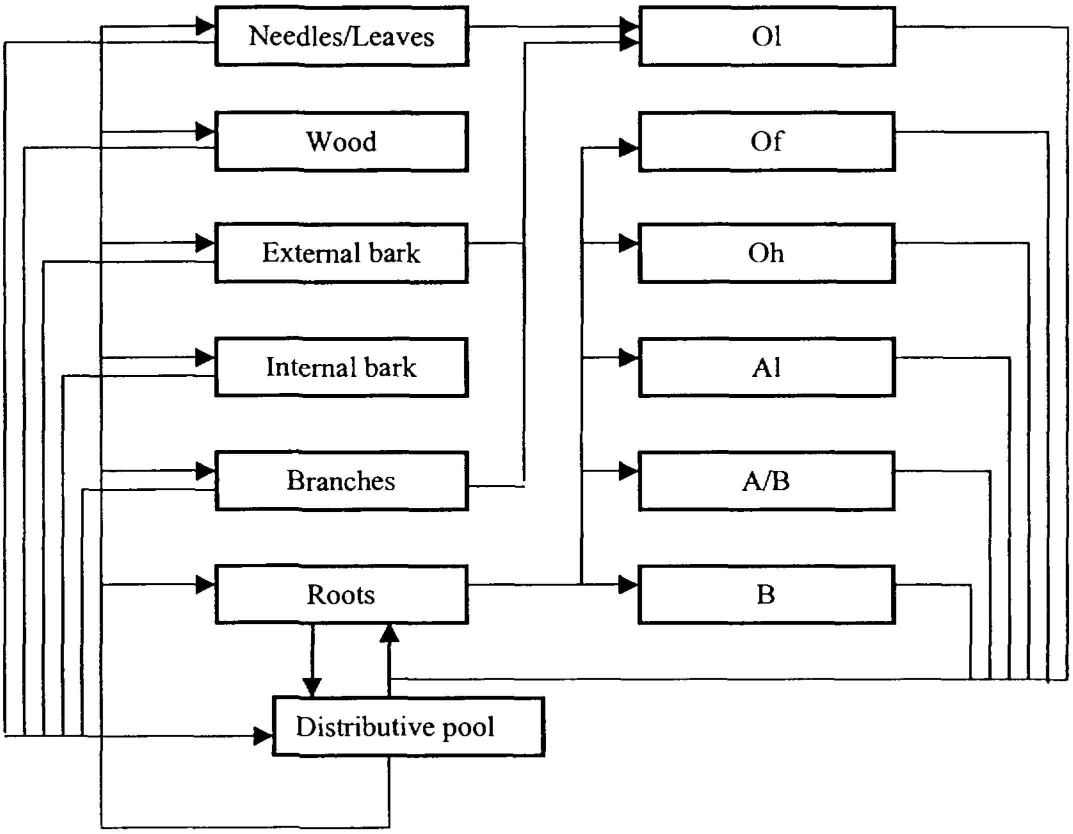
○ Biomass of the compartment-receptor

○ Clay content of the soil

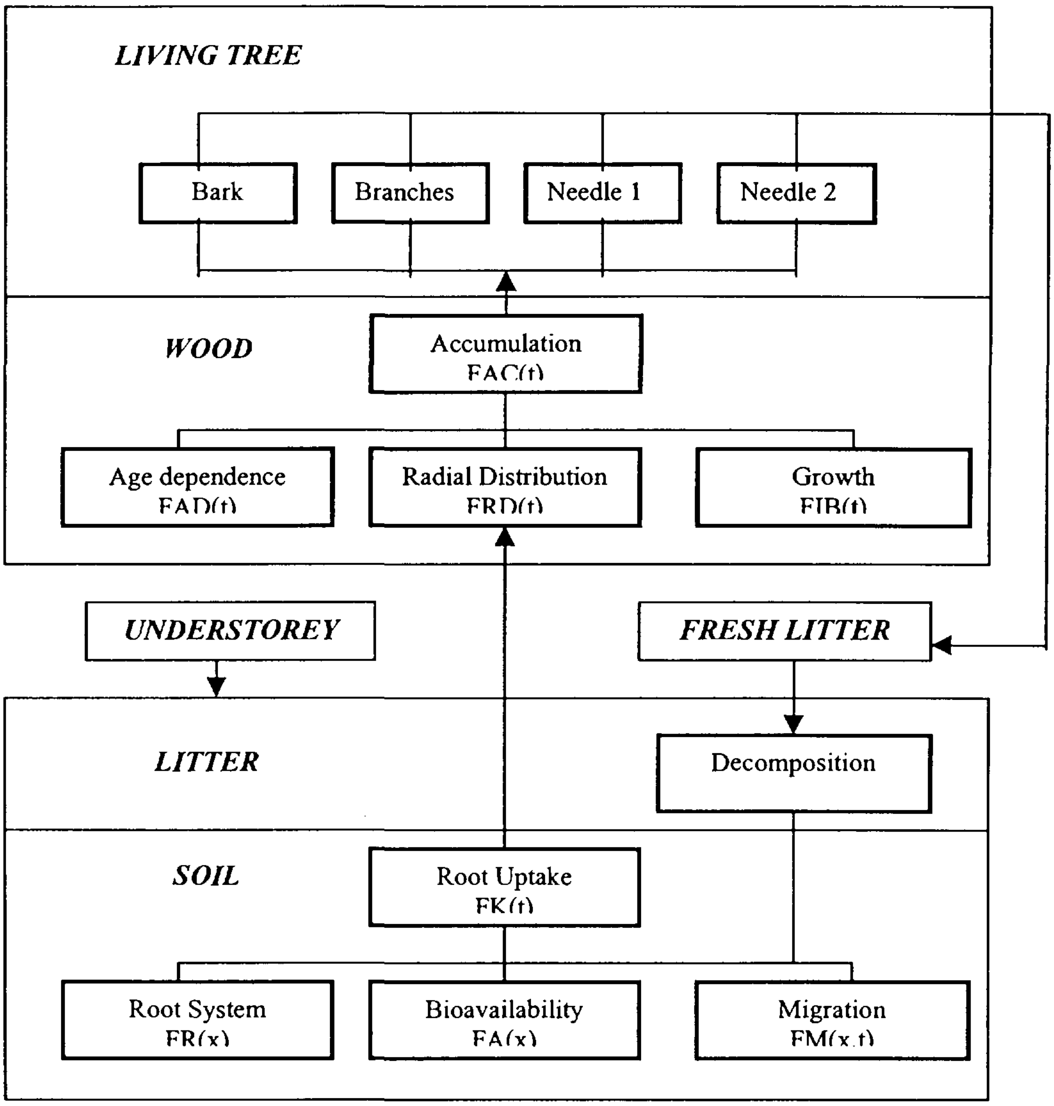
FORESTPATH



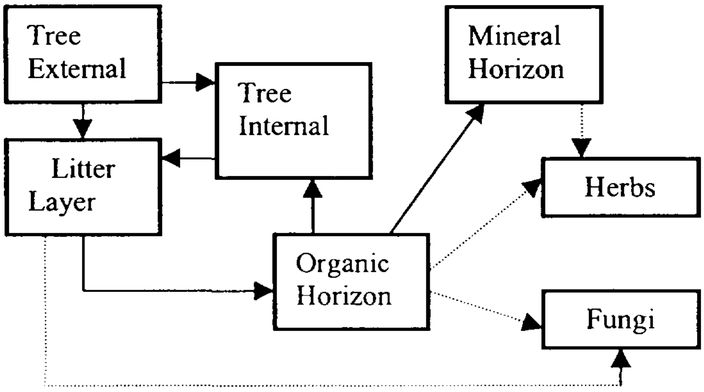
ECORAD



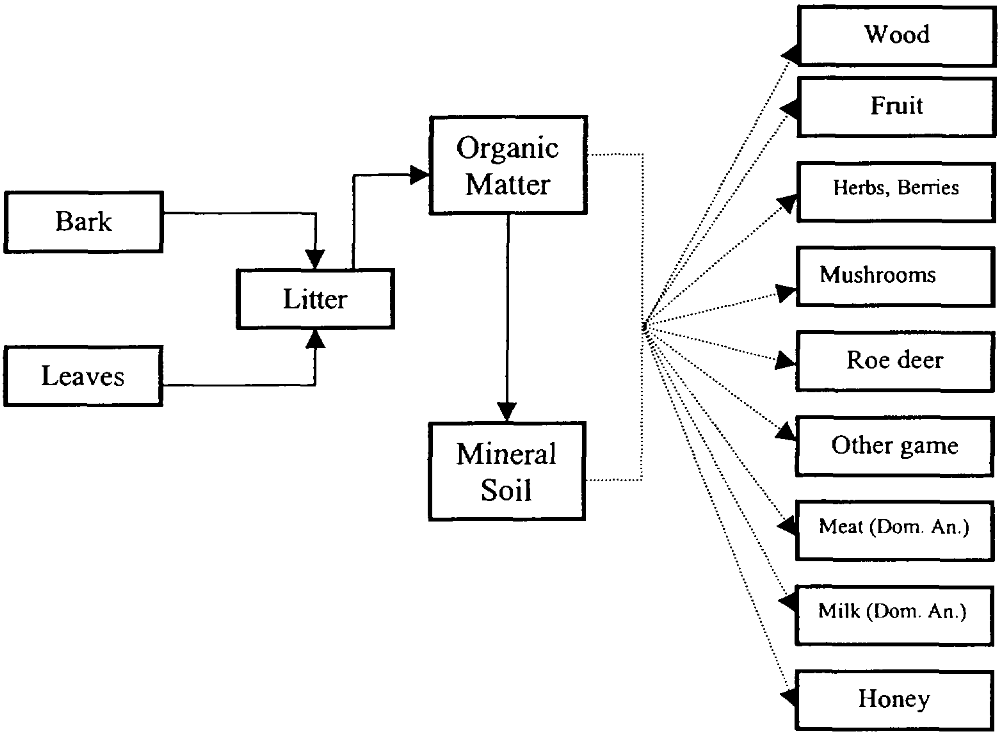
FORESTLIFE



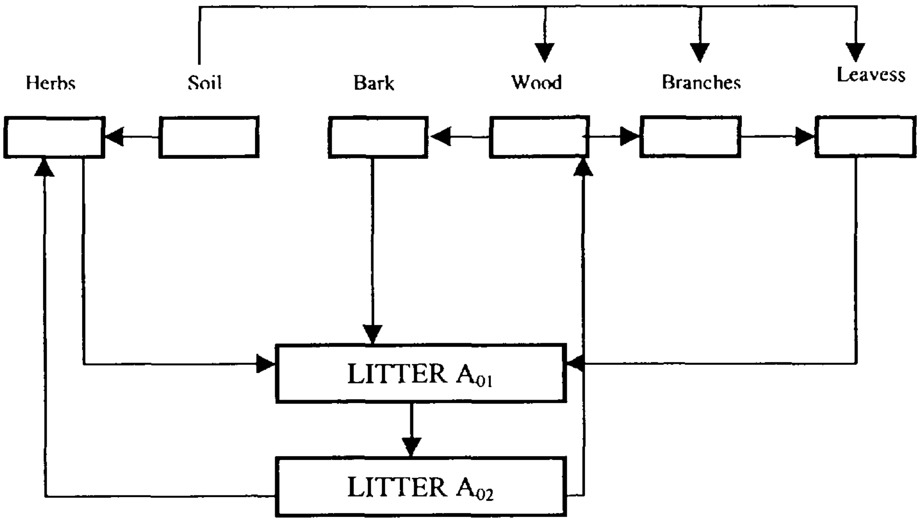
RIFE.I



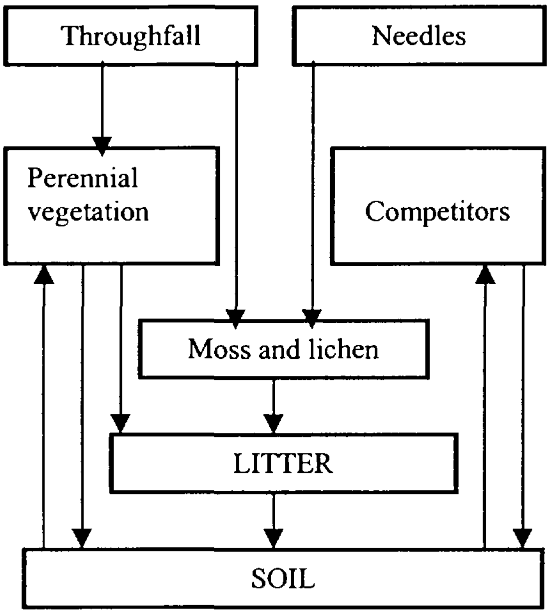
FORM



Alexakhin's Model



Bergman's model



SSI-rapporter 1998
SSI reports 1998

98:01 Publikationer 1997
Statens strålskyddsinstitut

98:02 The Systemic Roles of SKI and SSI in the Swedish Nuclear Waste Management System
Syncho's Report for Project RISCOM
Raul Espejo, Anthony Gill

98:03 Review/Decide and Inquiry/Decide Two Approaches to Decision Making
editor: Kjell Andersson

98:04 Building Channels for Transparent Risk Assessment, Final Report RISCOM Pilot Project
Kjell Andersson, Raul Espejo, Clas-Otto Wene

98:05 Test Case For A Near-Surface Repository;
Test Case for IAEA's First Regional Workshop on Safety of Near-Surface Disposal Facilities, Stockholm, Sweden, September 9-19, 1997
Kemakta Konsult AB: Elert, M.; Jones, C. ; Nilsson, L.B.; Skagius, K.; Wiborgh, M.

98:06 Säkerhets- och strålskyddsläget vid de svenska kärnkraftverken 1997 (SKI 98:10)

98:07 Modelling of radionuclide migration in forest ecosystems. A literature review
Department of Waste Management & Environmental Protection ; Department of Environmental Monitoring and and Dosimetry
Rodolfo Avila, Leif Moberg, Lynn Hubbard

SSI Rapport

SSI Rapport

STATENS STRÅLSKYDDSINSTITUT, SSI, är en central tillsynsmyndighet med uppgift att skydda människor, djur och miljö mot skadlig verkan av strålning. SSI arbetar för en god avvägning mellan risk och nytta med strålning, och för att öka kunskaperna om strålning, så att individens risk begränsas.

SSI sätter gränser för stråldoser till allmänheten och till dem som arbetar med strålning, utfärdar föreskrifter och kontrollerar att de efterlevs, bland annat genom inspektioner. Myndigheten informerar, utbildar och ger råd för att öka kunskaperna om strålning. SSI bedriver också egen forskning och stöder forskning vid universitet och högskolor.

Myndigheten medverkar i det internationella strålskyddssamarbetet. Genom projekt Strålskydd Öst bidrar SSI till förbättringar av strålskyddet i främst Baltikum och Ryssland. SSI håller beredskap dygnet runt mot olyckor med strålning. En tidig varning om olyckor fås genom svenska och utländska mätstationer och genom internationella varnings- och informationssystem.

SSI har idag ca 125 anställda och är beläget i Stockholm.

THE SWEDISH RADIATION PROTECTION INSTITUTE (SSI) is a government authority with the task of protecting people and the environment from the harmful effects of radiation. SSI ensures that the risks and benefits inherent to radiation and its use are compared and evaluated. SSI also develops competence on radiation to minimise the risk involved for the individual.

SSI decides the dose limits for the general public and for workers exposed to radiation and also issues regulations which, through inspections, it ensures are being followed. SSI provides information, education, advice, carries out research and also administers external research projects.

SSI participates on a national and international level in the field of radiation protection. A special SSI project called Radiation Protection East is contributing towards improvements in radiation protection standards in the former Soviet states.

SSI is responsible for coordinating activities in Sweden should an accident occur involving radiation. Its resources can be called upon at any time of the day or night. In the event of an accident, a special emergency preparedness organisation comes into operation. Early notification of emergencies is obtained from automatic alarm monitoring stations in Sweden and abroad and through international and bilateral agreements on early warning and information.

SSI has 125 employees and is situated in Stockholm.

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