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Forest food chain and dose model (FDMF) for RODOS

Model description

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FOREWORD

This report describes the basic model assumptions of the Forest Food Chain and Dose Module (FDMF) of RODOS as it is integrated into the version PV 4.0 of RODOS, a real-time, on-line decision support system for off-site emergency management in Europe.

The model calculates the deposition and time-dependent distribution of radionuclides in forests, and also the radiation doses received externally and through ingestion after accidental radioactive contamination of forests. The report content corresponds to the document RODOS(WG3)-TN(99)-53 added by Discussion in Chapter 3.

For the forest model FDMF, the algorithms for external radiation and effective doses derived from kerma were developed by a group in the Institute of Radiation Hygiene, St. Petersburg, Russia. Their results are published in Golikov et al. (1999); also a report given under the subcontract with STUK (Balonov et al. 1998) is referred to in this report.

We thank most warmly Wolfgang Raskob, Heinz Müller and Florian Gering for advice, support and comments, Arnaud Berry for coding and describing the computer programme submodules for deposition and ingestion dose, Michael Ammann for finalising the code developed at STUK, Hannu Sihvonen for data analysis for modelling of wet deposition, and Kari Sinkko who coordinated the RODOS Customisation project (contract F14P-CT96-0053) under which this work was carried out.

Further information on the RODOS system will be available on RODOS Homepage: http://www.rodos.fzk.de

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Keywords Forest, wild foods, forest gifts, fallout, deposition, radionuclides, decision support, model, radiation doses, external exposure, kerma, ingestion dose

ABSTRACT

In the early phase of a large-scale fallout situation, both access to forests and the use of wild foods may need temporal restrictions. In a later phase wild foods and internal doses received through them may still need surveillance of radioactivity. After accidental fallout a major source of external radiation are the ground deposits, and in forests contaminated overstorey can also be a considerable source. For consideration of dose pathways related to forests during a nuclear emergency the Forest Food Chain and Dose Model (FDMF) was developed. It is an integral part of RODOS, a real-time, on-line decision support system for off-site emergency management in Europe.

The forest module FDMF receives radionuclide concentrations in air as input from the air dispersion model of RODOS, and calculates activities deposited on various parts of the forest. The model simulates the transfer of radionuclides in the forest ecosystem. It quantifies the dynamic changes for three types of forests, typical of a region. The model gives the contamination of forest products and dose rate for external radiation as a function of time. External and internal radiation doses for various population groups according to their stay in forests and their use of forest products can be assessed since the first year until the 50th year after the fallout event. Doses are calculated for children and adults representing the public, and ingestion doses also for pickers of berries and mushrooms, and hunters. Forest workers are a special group due to their

potentially enhanced external dose from outdoor working. The model results can be shown as spatial distributions on top of geographical maps.

Many parameters in the FDMF database are regional and have to be adjusted when the model is adapted for local conditions or new radioecological regions. Long-term predictions will be considerably improved when site-specific parameters are used.

STUK developed the forest module together with IPSN (Institut de Protection et de Sûrete Nucléaire), France, under the umbrella of the RODOS project of the 4th Framework Programme of the EC.

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Avainssanat Metsä, laskeuma, radionuklidit, metsäluonnosta saatavat elintarvikkeet, päätöksenteon tuki, malli, ulkoinen ja sisäinen säteilyannos, säteilyaltistus, kerma

TIIVISTELMÄ

Laaja-alaisen laskeumatilanteen varhaisvaiheessa voi olla tarve rajoittaa sekä pääsyä metsiin että metsistä hankittavien elintarvikkeiden käyttöä. Myöhemminkin metsäluonnosta peräisin olevat elintarvikkeet ja niistä aiheutuvat säteilyannokset voivat edellyttää radioaktiivisuuden seurantaa. Pääasiallinen ulkoisen säteilyn lähde laskeuman jälkeen ovat maahan kertyneet laskeuman radioaktiiviset aineet. Metsissä puustoon pidättynyt laskeuma voi myös olla merkittävä säteilylähde. Helpottamaan metsiin liittyvien säteilyn altistusteiden huomioonottamista ydinlaitosonnettomuuksien jälkeen kehitettiin säteilytilanteen annoslaskentamalli metsiä varten (FDMF). Se on integroitu osaksi eurooppalaista ydinonnettomuustilanteiden päätöksenteon tukijärjestelmää nimeltä RODOS.

Metsien annoslaskentamalli (FDMF) vastaanottaa ilman radioaktiivisuustiedot RODOS-järjestelmän leviämismallista ja laskee niistä metsikön eri osiin tulevan laskeuman radionuklideittain. Mallilla voidaan simuloida radionuklidien kulkeutumista metsäekosysteemissä sekä laskea dynaamiset muutokset kolmelle metsätyypille, jotka ovat luonteenomaisia maantieteelliselle laskenta-alueelle. Tuloksena saadaan metsäntuotteiden radionuklidipitoisuudet ja metsissä vallitsevat ulkoiset annosnopeudet ajan funktiona. Malli laskee eri väestöryhmien saamat säteilyannokset sekä metsissä oleskelusta että metsistä saatavien elintarvikkeiden käytöstä ensimmäisestä laskeuma-

vuodesta alkaen aina 50 vuoteen asti. Väestön saamat annokset arvioidaan lapsille ja aikuisille ja sisäinen annos lisäksi marjojen ja sienten poimijoille sekä metsästäjille. Yhtenä erityisryhmänä ovat metsätyöntekijät, joiden ulkoinen säteilyannos voi olla muuta väestöä suurempi ulkona työskentelyn takia. Laskentatulokset voidaan esittää alueellisina jakaumina karttojen avulla.

STUK kehitti metsien annoslaskentamallin yhdessä Ranskan säteilyturvallisuuslaitoksen IPSN:n (Institut de Protection et de Sûrete Nucléaire) kanssa. Työ oli osa RODOS-hanketta EU:n neljännessä puiteohjelmassa.

Lisätietoa RODOS-järjestelmästä löytyy hankkeen kotisivulta: http://www.rodos.fzk.de

CONTENTS

1 INTRODUCTION

The need to include a separate module to describe forest food chains in the RODOS system arose from the unique ecosystem structure of forests and, coupled to this, the dynamic behaviour of radionuclides in this environment. The long residence times of radionuclides in forest vegetation and surface soil result in increased internal and external human doses over decades. It was therefore necessary not only to clarify the significance of forests as sources of environmental radiation but also to device a tool to predict the impact of radiation. The Forest Food Chain and Dose Module (FDMF), which was developed to estimate human radiation doses after the accidental contamination of forested areas in Europe is a response to these needs.

Internal doses received through wild foodstuffs, and external exposure from radionuclides distributed in forests can be predicted for periods of between one day and 50 years after the day of deposition. Doses to the population and its subgroups by age or by the way in which it uses forests and forest products can be calculated.

The FDMF module was developed as an integral part of the RODOS system. The program uses the same database as the Terrestrial Food chain and Dose Module (FDMT). Some data files were extended and include forest specific sections.

FDMF receives data on time-integrated air concentrations and total wet deposition to the ground from the Atmospheric Dispersion Module (ADM). The initial distribution of the dry and wet deposition to forests is calculated from these data. The time-dependent transfer processes between trees, understorey vegetation and soil are modelled to provide input data for calculations of concentrations in foodstuffs and of external dose rates. Doses through ingestion and external exposure are also derived. Exposed subjects represent different age groups of the population, forest workers, hunters and berry and mushroom pickers. One of the endpoints of the FDMF module is input to the Dose Combination Module (DCM), which calculates total human doses through all the dose pathways in RODOS (Fig. 1). The graphical outputs of the FDMF are maps, pies and time plots showing the results for either individual nuclides or groups of nuclides by subgroups of population.

The two radioecological regions considered in the current version of FDMF are Northern and Central Europe. The area of interest is covered by a calculation grid, which can contain parts from several radioecological regions.

Climatic conditions in connection with time-dependent transfer processes influenced by ground frost are taken into account. Model parameters are given for the two radioecological regions with their forest vegetation zones and plant and game animal species. The model parameters further include data for estimating human exposure due to the consumption of wild food products or spending time in forests for either work or leisure activities.

Ingestion doses from isotopes of iodine, caesium, strontium and plutonium in wild berries, mushrooms and game meat are calculated. The seasons when these food products are available, radionuclide losses during cooking, and consumption rates are specified for each radioecological region.

External doses are derived through kerma rates caused by radiation sources in the crown layer, in trunks, in ground layer vegetation and in the soil. Nuclides emitting gamma radiation, and included in the ADM outputs, are used to calculate the kerma rate. In all, the contributions of some 50 nuclides to the external doses can be estimated with FDMF.

The model endpoints are calculated for a grid of 2520 locations defined for the geographical area of interest. All doses are given for three different forest types, which may differ from one radioecological region to another. The FDMF database considers forests on mineral soils, but the user can apply the module to an area with organic soils by changing the forest type and giving new values for parameters related to the soil either directly or indirectly. In the future, the four most im-portant European soil types will be defined through the RODOS data-base for each location.

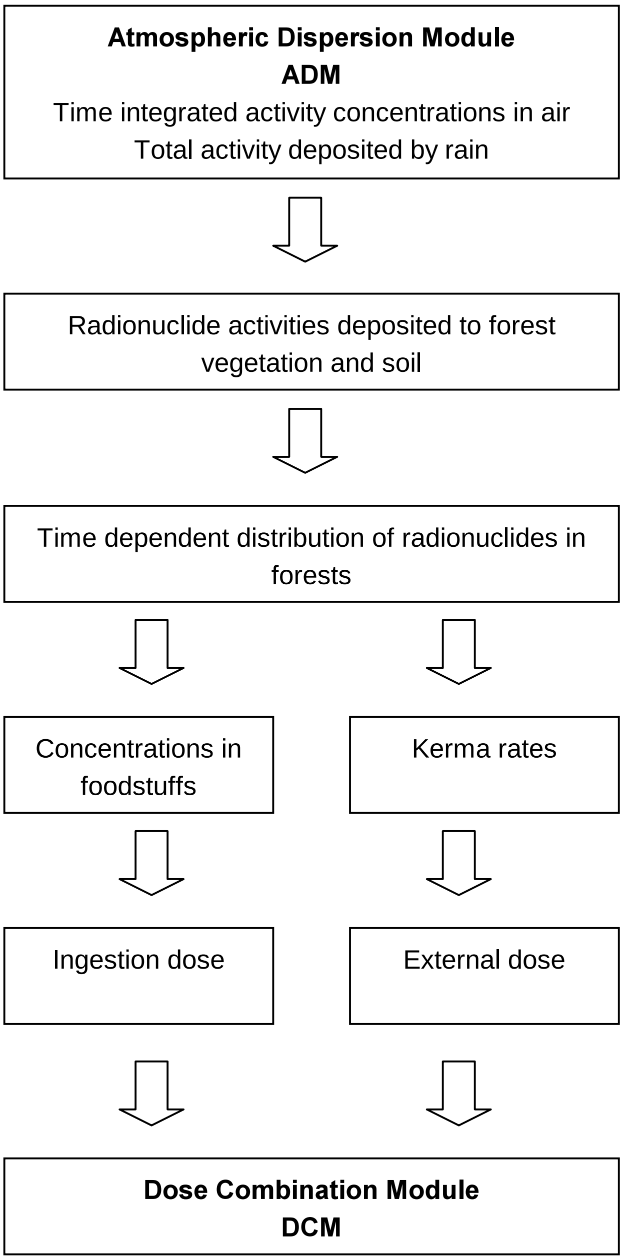

Figure 1. *Sequence of calculations in FDMF.*

2 MODEL CALCULATIONS

This chapter describes the calculation methods and endpoints of the FDMF module. The symbols used in the algorithms are listed in Appendix A and the values of the parameters for the two radioecological regions, Central and Northern Europe, can be found in Appendix B.

2.1 Deposition

The deposition submodule calculates dry deposition to the forest ecosystem from time-integrated radionuclide concentrations in the air received from ADM. Total wet deposition is calculated in ADM, and in FDMF is divided into the fractions intercepted by the vegetation and soil by the end of the deposition event.

2.1.1 Dry deposition

Dry deposition is estimated using deposition velocities for different surfaces and radionuclides, relative leaf area indices with respect to season and time integrated concentrations of radionuclides in air. All parameters except for nuclide dependent deposition velocities are regional, and leaf area indices are seasonal as well.

The dry deposition to forest is calculated from the time-integrated air concentration with deposition velocity:

$$A_{\text{d crowns}} = V_{\text{g crowns max}} \times LAI_{\text{crowns}}/LAI_{\text{crowns max}} \times C_a$$
$$A_{\text{d trunks}} = V_{\text{g trunks}} \times C_a$$
$$A_{\text{d understorey}} = V_{\text{g understorey max}} \times LAI_{\text{understorey}}/LAI_{\text{understorey max}} \times C_a$$
$$A_{\text{d soil}} = V_{\text{g soil}} \times C_a$$

where

$A_{d\ crowns}$ = dry deposition to tree crowns (Bq m^{-2})
$A_{d\ trunks}$ = dry deposition to tree trunks (Bq m^{-2})
$A_{d\ understorey}$ = dry deposition to understorey (Bq m^{-2})
$A_{d\ soil}$ = dry deposition to soil (Bq m^{-2})
$V_{g\ crowns\ max}$ = dry deposition velocity for tree crowns (m s^{-1})
$V_{g\ trunks}$ = dry deposition velocity for tree trunks (m s^{-1})
$V_{g\ understorey\ max}$ = dry deposition velocity for understorey (m s^{-1})
$V_{g\ soil}$ = dry deposition velocity for soil (m s^{-1})
$LAI_i / LAI_{i\ max}$ = ratio between the leaf area index of tree crowns or of understorey at time of deposition and the maximum leaf area index, respectively
C_a = time-integrated concentration of radionuclides in air (Bq s m^{-3})

The values for $V_{g,\ i}$ and LAI_i are given in Appendix B.

The depletion of the plume is calculated in the ADM using parameters chosen for a 'general' European mixed forest for the default, Central European data set.

For the plume depletion, dry deposition to a generic mixed forest composed of trees, understorey and soil, is calculated by

$$A_{d,\ forest} = [(V_{g\ crowns} \times LAI_{crowns} / LAI_{crowns\ max}) + (V_{g,\ understorey} \times LAI_{understorey} / LAI_{understorey\ max}) + V_{g\ trunks} + V_{g\ soil}] \times C_a$$

where $LAI_I / LAI_{i,\ max}$ is considered for trees and understorey of a mixed forest.

2.1.2 Wet deposition

The total wet deposition received by an area is distributed on the surfaces of the vegetation and soil. The fraction of the deposited radionuclides intercepted by the various vegetation components varies, depending on forest structure and weather conditions during the cloud passage. The method for wet deposition calculation is based on information on throughfall in forests (Päivänen 1966, Seppänen 1964) and on the approach described in FDMT which is the same as published originally in ECOSYS-87 (Müller & Pröhl 1993).

The interception of wet deposition (fw) is assumed to depend on the leaf area index (LAI), canopy cover fraction (c_f), retention coefficient of different radionuclides (S) and rainfall (R). The leaf area index for deciduous and mixed forests and for understorey vegetation depends on the season. For crowns, the leaf area index also varies by tree species and forest type. A corresponding surface area index, which depends on the stem volume ($m^3\ ha^{-1}$) of the forest and on the height of the crown limit, is applied to the trunk layer below crown limit. The canopy cover fraction defines the fraction of ground area covered by the crowns of trees and thus describes the density of the forest. The retention coefficients of radionuclides are related to the water storage capacity of the vegetation surfaces and to the properties of radionuclides retained by the vegetation. A correction factor (p_i) for the retention of crowns, trunks and understorey adjusts the interception fractions to better correspond to the values measured and the morphology of complete plants. The interception fractions are given by

$fw_{crowns} = LAI_{crowns} \times c_f \times S / R \times [1-\exp(-\ln 2 \times R / p_{crowns}S)]$
$fw_{trunks} = LAI_{trunks} \times S / R \times [1-\exp(-\ln 2 \times R / p_{trunks}S)]$
$fw_{understorey} = LAI_{understorey} \times S / R \times [1-\exp(-\ln 2 \times R / p_{understorey}S)]$

where

fw_i = interception fraction for crowns, trunks and understorey
LAI_i = leaf area index ($m^2\ m^{-2}$) of crowns, trunks and understorey at time of deposition. For trunks, only the area below the crown limit is considered.
c_f = canopy cover fraction
S = retention coefficient of different radionuclides (mm)
R = rainfall (mm)
p_i = correction factor for retention of crowns, trunks and understorey.

The values for LAI_i, c_f, S and p_i are given in Appendix B.

Trunk, understorey and soil interception is calculated taking into account only the amount of wet deposition that is not intercepted by the next higher layer. In detail, then, interception by the trunk layer is calculated using as input the total wet deposition minus the part intercepted by the crown layer, and interception by the understorey is calculated using as input the total wet deposition minus the parts intercepted by the crown layer and trunk layer. In the same way, the throughfall to soil corresponds to the total wet deposition minus the activity intercepted by the overhanging vegetation. The wet deposition to crowns, trunks, understorey and soil is given by

$$
\begin{aligned}
A_{w\ crowns} &= fw_{crowns} \times A_w \\
A_{w\ trunks} &= fw_{trunks} \times (1\text{-}fw_{crowns}) \times A_w \\
A_{w\ understorey} &= fw_{understorey} \times (1\text{-}fw_{trunks}) \cdot (1\text{-}fw_{crowns}) \times A_w \\
A_{w\ soil} &= (1\text{-}fw_{understorey}) \times (1\text{-}fw_{trunks}) \times (1\text{-}fw_{crowns}) \times A_w
\end{aligned}
$$

where

$A_{w,\,i}$ = wet deposition on crowns, trunks, understorey and soil (Bq m^{-2})

fw_i = interception fraction for crowns, trunks and understorey

A_w = total wet deposition (Bq m^{-2})

If fw_{crown} is >1, then the value 1 is taken.

2.1.3 Total deposition

The total deposition to vegetation compartments and soil is a sum of the activities resulting from dry and wet depositions and is given by

$$A_i = A_{d,\,i} + A_{w,\,i}$$

where

A_i = total deposition to tree crowns, trunks, understorey and soil (Bq m^{-2})

$A_{d,\,i}$ = dry deposition to tree crowns, trunks, understorey and soil (Bq m^{-2})

$A_{w,\,i}$ = wet deposition to tree crowns, trunks, understorey and soil (Bq m^{-2}).

2.2 Time-dependent radionuclide transfer in forests

This section describes the environmental transfer processes relevant to radionuclide dynamics in forests, as modelled in FDMF. It also explains how forests have been structured and quantified for the calculation of radionuclide contents in different parts of the forest. To calculate kerma rates for external dose estimation it was necessary to define the source geometry and the element composition of forests.

2.2.1 Forest compartments

Forest was divided into almost equal compartments for quantification of environmental transfer of radionuclides and for definition of sources of external radiation. Dynamic processes are described for soil, understorey, and trunks and crowns of trees (Fig. 2).

For calculation of kerma rates in air, the soil and understorey compartments were combined, and activities in ground layer refer to the sum of activities in understorey and soil. In connection of external radiation, the total (bioavailable plus fixed, non-available) activity in soil is used.

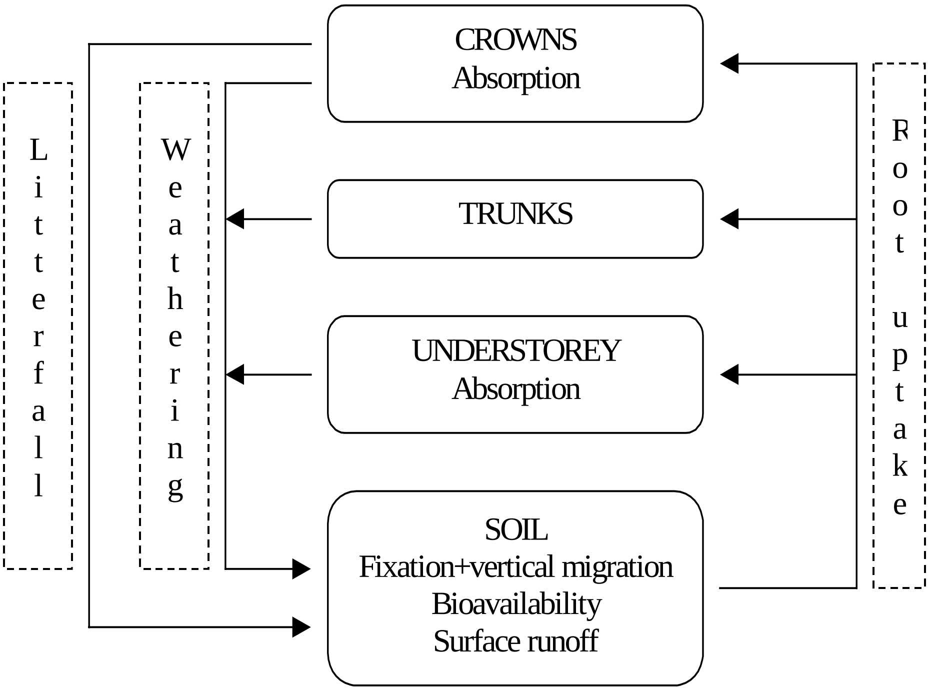

Figure 2. Compartments used and processes considered in dynamic submodule of the FDMF.

Trees were divided into crowns and trunks for their different radionuclide uptake rates, to achieve a realistic vertical distribution of overstorey activity. Crown comprises all parts of a standing tree above the crown limit: stem, branches, twigs and leaves or needles. The words "tree" and "overstorey" refer to combined trunk and crown compartment when used later in this report (e. g. in connection of graphical outputs) or in the database. The word "canopy" refers entirely to the crown of a tree. When "trunk" is used, the meaning is always the same: the part of the stem below the crown limit of a standing tree.

Forest biomass was assumed to consist of three homogeneous layers which are understorey, trunk and crown layer. The two layers of trees plus air comprise a "forest equivalent medium" (FEM) which interacts with photon radiation. These layers are assumed homogeneous, and horizontally infinite or semi-infinite. Most of the activities for forest compartments are given per surface area of the ground.

Stand characteristics

The dimensions and biomass of forests were defined on the basis of data on forest resources in Finland collected for the Eighth National Forest Inventory (e.g. Salminen 1993; the Finnish Forest Research Institute 1996). The mean height of trees, the mean height of the crown limit and the mean volume of stemwood per hectare for forests at different development stages in different regions were obtained from these data. Stem biomass was estimated from volume data using species-specific bulk densities for Scots pine, Norway spruce and birch (Hakkila 1979, 1989; Kauppi et al. 1995, 1997; Table I).

In the conversion of dry masses to fresh weight, moisture content was assumed to be 50% (Hakkila 1989). Branch and foliage biomass was estimated with conversion coefficients relating other woody biomass to stem biomass. The biomass of the trunk layer was estimated from the stem biomass using the ratio of crown limit to tree height. The biomass of the crown layer consists of foliage, branches and the part of the stem in the crown. The biomass densities (kg m^{-3}) were calculated separately for the two layers by dividing their masses (kg m^{-2}) by the heights of the layer (m).

Table I. *Mass of foliage and branches as a fraction (%) of stemwood (Kauppi et al. 1995).*

Species and development class	Percentage of stemwood mass Foliage	 Branches
Scots pine		
Seedling stands	20	27
Young thinning stands	10	20
Advanced thinning stands	5	15
Mature stands	5	15
Norway spruce		
Seedling stands	27	41
Young thinning stands	20	35
Advanced thinning stands	15	30
Mature stands	15	30
Birch and other deciduous species		
Seedling stands	6	15
Young thinning stands	5	15
Advanced thinning stands	4	15
Mature stands	3	15

The densities and heights of stands vary, depending on the age or stage of development of the stand and the fertility of the soil at the site. When algorithms for kerma rates from sources in forest were derived, five densities of the forest biomass, 0, 0.5, 1, 2, and 5 kg/m^3 were used. The densities of air and soil were ρ=1.2 kg/m^3 and ρ=10^3 kg/m^3, respectively. Air was added to the forest biomass, so that the density of FEM was 1.2, 1.7, 2.2, 3.2, and 6.2 kg/m^3. The values 0.05, 0.5, 1, 3, 10, 30, 50 m were used for the height of trees. Depths of a plane source in soil were: 0, 0.3, 1, 3, 10, 30, 50, 70 g cm^{-2}. Calculations were performed for 18 source energies from 20 keV to 3 MeV.

Information on the mineral concentration in the dry biomass of softwoods in Finland was used for the element composition of the crown and trunk layers (Hakkila & Kalaja 1983; Finér 1989), with the addition of water.

The element compositions for air and soil, given in Table II were used in the calculations.

***Table II**. Element composition of air (relative humidity 40%, P 760 mmHg, T 20° C,) and soil (moisture content 20%; Saito and Jakob 1995).*

Element	**Concentration mass (%)**	
	Air	**Soil**
N	75.5	
O	23.2	57.5
Ar	1.3	
Si		26.2
Al		8.5
Fe		5.6
H		2.2

2.2.2 Dynamic processes

After a deposition event, the initial distribution of different radionuclides in a forest will change continuously, and in a few days, the tree canopy will have lost a considerable fraction of the intercepted radioactive material. The chemical form and physical characteristics of the substances carrying the radionuclides and the chemical behaviour of the isotopes themselves will affect the rate at which the radionuclides are removed from the canopy to the undervegetation and soil. As to weathering, the weather type will have an influence on the fractions removed by wind and by the processes of throughfall and stemflow. Litterfall, especially of leaves and needles in autumn, transfers both external and internal contaminants from plants to the forest floor.

A fraction of the deposited material can be absorbed and metabolised through the foliar and twig surfaces of plants. The plants transport radioisotopes in their nutrient cycle, but only the isotopes of the nutrient elements can follow the corresponding nutrient pool completely. After the external contaminants have been removed from the tree crowns and undervegetation, the annual change in the radionuclide content of plants is controlled mainly by the root uptake of radionuclides from the soil.

The soil compartment receives radioactive material directly from the fallout and from all types of forest vegetation through weathering and litterfall. However, the availability of radioisotopes to plants is delayed due to the ground vegetation layers and dissolution of particle-bound isotopes.

Surface runoff from the catchment can be significant during snow melt and rainy seasons, especially in alpine regions. When the topography is flat, even the first-year runoff from forests on mineral soils is only a few per cent of the total deposited radioactivity (Nylén 1996). During and after the deposition, radioisotopes migrate downwards in the soil. Vertical activity distribution in soil varies by vegetation type, forest structure, soil type and rainfall. In forests, the migration of radioisotopes in soil differs from that in open areas due to processes of nutrient uptake by trees. In the long term, delayed downward migration due to efficient nutrient processes in the root zones is noticeable, especially in boreal forests.

Irreversible fixation of radiocaesium in agricultural soils is rather well known. In Europe, forest soil types vary and the clay minerals (known for an almost irreversible fixation of caesium) are found also in forests, although not often in root zones of boreal forests. Organic surface layers of soil are crucial to nutrient uptake, and also to radionuclide uptake by trees and understorey. Various soil processes mainly explain the time-dependent changes in radionuclide distribution in forest in the long term.

In arctic or subarctic regions, the snow cover on canopies slows down the weathering and foliar absorption of intercepted radioisotopes. Moreover, chemical and biological processes in soil are interrupted during ground frost. However, the growth of trees normally starts early in spring, and nutrients stored in the roots and aboveground parts of the trees are used then. The seasonal differences in transfer processes are considered in the model through monthly values of the related transfer rates.

2.2.3 Radionuclide activities in forest compartments

Owing to radioactive decay, a number of deposited short-lived radioisotopes are insignificant in the long term. Radioactive decay is included in activity calculations in FDMF and is not discussed here. Radionuclide activities in forest compartments are primarily calculated in becquerels per ground area (Bq m^{-2}). The term surface density was not used to avoid associations with various surfaces of vegetation.

The following notation (which differs from the symbols in the computer program) is used in this section:

$A_c(t)$	activity in crowns at time t (Bq m^{-2})
$A_t(t)$	activity in trunk layer at time t (Bq m^{-2})
$A_b(t)$	activity of outer bark at time t (Bq m^{-2})
$A_u(t)$	activity in understorey at time t (Bq m^{-2})
$A_{ac}(t)$	activity absorbed by crown from initially intercepted activity by the time t (Bq m^{-2})
$A_{wc}(\Delta t)$	activity removed from crown by weathering during time interval Δt
$A_{wt}(\Delta t)$	activity removed from trunk by weathering during time interval Δt
$A_{wu}(\Delta t)$	activity removed from understorey by weathering during time interval Δt
$A_{lc}(\Delta t)$	activity removed from crown by litter fall during time interval Δt.
$A_{rc}(\Delta t)$	activity uptake from soil to crowns during time interval Δt
$A_{rt}(\Delta t)$	activity uptake from soil to trunks during time interval Δt
$A_{ru}(\Delta t)$	activity uptake from soil to understorey during time interval Δt
$A_{runoff}(\Delta t)$	activity removed from soil through surface runoff during time interval Δt
$A_{s,dyn}(t)$	activity in soil at time t available to root uptake
$A_{s,ext}(t)$	activity in soil at time t causing external radiation
$A_{sf}(t)$	soil activity excluded from root uptake due to fixation and vertical migration by time t
lop	length of litter fall period (Julian days)

The transfer of radioisotopes between the model compartments (Fig. 2.1) is described by exponential functions, derived from first order differential equations. All the transfer rates used in calculations are denoted by λ_i (d^{-1}) with an appropriate index i indicating the process under consideration. Transfer processes other than root uptake are explained here for each vegetation compartment. Activity transferred from soil to plants by root uptake, $A_{r(i)}$ is explained in the section on soil.

Crown layer

Radioisotopes are transferred from crown layer to the soil by weathering and litterfall. Immediately after deposition, radionuclides are absorbed by the crown, and the absorbed fraction of activity is then no longer available to the weathering process. Absorption is described by an absorption rate, λ_a, which is applied during the first 15 days after the deposition event. Thus,

$$A_{ac}(t+\Delta t) = A_{ac}(t) + (A_c(t)-A_{ac}(t)) \times (1-\exp(-\lambda_a \times \Delta t))$$

Weathering is described by a weathering rate, λ_{wc}.

The activity removed by weathering, A_{wc}, is thus calculated as

$$A_{wc}(\Delta t) = (A_c(t) - A_{ac}(t+\Delta t)) \times (1-\exp(-\lambda_{wc} \times \Delta t))$$

The absorption rate, λ_a, is regarded as a nuclide specific, seasonal and forest type-specific parameter. The weathering rate, λ_{wc}, is nuclide independent, forest type specific, and decreases during the successive phases following deposition: early phase (first two months after deposition), medium phase (until the end of first year following deposition) and late phase (after the first year following deposition).

Litterfall. With the change of seasons, radionuclides are translocated between leaves/needles and branches, stem and roots: in autumn from leaves/needles to branches and vice versa in spring. The translocated fraction, f_{trans}, is not available to litterfall. For simplicity, this fraction was assumed to be a fixed fraction of the crown activity (f_{trans} =0.8).

For coniferous trees, the fraction of activity removed from the crown by litterfall is further reduced since only the needles of the oldest year class fall to earth. Therefore, age classes of leaves or needles of a tree are defined for various forest types as follows:

- 4 age classes of needles in pine dominant-forests
- 6 age classes of needles in spruce-dominant forests
- 1 age class of leaves in deciduous forests.

In mixed forest, the fractions of different species are taken into consideration. The default value is the age class of the default type of forest in each region. If "nof_yc" is the number of age classes, the fraction of activity removed, "f_{lit}", is calculated as

$$f_{lit} = (1- f_{trans})/nof\_yc$$

During the litter fall period, the corresponding activity is removed from the crown layer and added to the soil compartment. For the time interval Δt, the activity removal due to litterfall is then

$$A_{lc}(\Delta t) = A_c(t) \times (1\text{-}\exp(-\lambda_l \times \Delta t'))$$

where the litterfall rate λ_l = flit/lop, and Δt' is the part of Δt, which coincides with the litter fall period.

Thus, the crown layer activity at a time t+Δt is

$$A_c(t+\Delta t) = A_c(t) - A_{wc}(\Delta t)\text{-}A_{lc}(\Delta t) + A_{rc}(\Delta t)$$

Trunk layer

Radionuclides are transferred from trunk layer to the soil by weathering of the initially deposited activity from the outer bark. This activity A_b is calculated as trunk activity minus the fraction of activity gained by root uptake. For the time interval Δt, the removal due to weathering is

$$A_{wt}(\Delta t) = A_b(t) \times (1\text{-}\exp(-\lambda_{wt} \times \Delta t))$$

where λ_{wt} is the weathering rate for bark. The weathering rate λ_{wt} is nuclide independent, forest type specific, and decreases during successive stages following deposition: early phase (first two months after deposition), medium phase (until the end of first year following deposition) and late phase (after the first year following deposition).

The trunk layer activity at time t+Δt is thus calculated as

$$A_t(t+\Delta t) = A_t(t) - A_{wt}(\Delta t) + A_{rt}(\Delta t)$$

Understorey

Radionuclides are transferred from the understorey to the soil in the course of weathering. In the early phase after deposition, activity is absorbed by understorey vegetation. The absorbed fraction of activity is then no longer available to the weathering process. Absorption is described by an absorption rate λ_a, which is applied during the first fifteen days after the deposition event. Thus,

$$A_{au}(t+\Delta t) = A_{au}(t) + (A_u(t)-A_{au}(t)) \times (1-\exp(-\lambda_a \times \Delta t))$$

The absorption rate λ_a is regarded as a nuclide specific, seasonal and forest type specific parameter. It is the same parameter as that used for crowns.

Weathering is described by a weathering rate λ_{wu}. The weathering rate λ_{wc} is nuclide independent, forest type specific, and varies with the phases after deposition: early phase (first two months after deposition), medium phase (first year after deposition) and late phase (after the first year after deposition).

The activity removed by weathering is thus

$$A_{wu}(\Delta t)= (A_u(t) -A_{au}(t)) \times (1-\exp(- \lambda_{wu} \times \Delta t))$$

At the end of a time step, Δt, this leads to understorey activity

$$A_u(t+\Delta t) = A_u(t) - A_{wu}(\Delta t) + A_{ru}(\Delta t)$$

Understorey litterfall was not taken into consideration.

Soil

The soil compartment interacts with all other compartments. It receives activity from the crown layer via weathering and litter fall, and from trunks and the understorey by weathering.

Besides runoff, which usually only plays a minor role, especially after the first year, the crowns, trunks and understorey remove activity from the soil by root uptake. Immediately after deposition the radionuclides are not totally available to root uptake from the root zone of trees and the understorey. Therefore, transfer of deposited radionuclides into the root zone and becoming available to root uptake is taken into account by an availability rate λ_{avail}.

Due to further fixation and vertical migration, a fraction of the radionuclides becomes unavailable to root uptake over time. However, also this fraction of soil activity contributes to kerma rates from the soil. Therefore, two types of soil activity are calculated. The first one, $A_{s,ext}(t)$, includes the fraction of activity bound by fixation and the activity that has migrated downwards. $A_{s,ext}(t)$ is used in the external dose calculation. The second type, $A_{s,dyn}$ (t), excludes the fixed and migrated fraction of activity. It represents the radionuclides that are available for forest transfer processes. Soil activities are calculated as follows:

$A_{s,ext}(t+\Delta t) = A_{s,ext}(t) + A_{wc}(\Delta t) + A_{wt}(\Delta t) + A_{wu}(\Delta t) + A_{lc}(\Delta t) - A_{rc}(\Delta t) - A_{rt}(\Delta t) - A_{ru}(\Delta t) - A_{runoff}(\Delta t)$.

and

$A_{s,dyn}(t+\Delta t) = A_{s,dyn}(t) + (1-\exp(-\lambda_{avail} \times \Delta t)) \times (A_{wc}(\Delta t) + A_{wt}(\Delta t) + A_{wu}(\Delta t) + A_{lc}(\Delta t)) - A_{rc}(\Delta t) - A_{rt}(\Delta t) - A_{ru}(\Delta t) - A_{sf}(\Delta t)-A_{runoff}(\Delta t)$.

Root uptake is defined by constant, nuclide dependent, forest type specific root uptake rates, λ_{rc}, λ_{rt}, λ_{ru}, for crowns, trunks and understorey, respectively. With the nuclide-dependent and forest type-specific availability rate λ_{avail}, the increase in bioavailable activity added to the forest floor during a time interval Δt is calculated.

Activity transferred from the soil to vegetation is

$A_{ru}(\Delta t) = (A_{s,dyn}(t) \times (1-\exp(-\lambda_{ru} \Delta t))$ for the understorey,

$A_{rt}(\Delta t) = (A_{s,dyn}(t) - A_{ru}(\Delta t)) \times (1- \exp(-\lambda_{rt} \Delta t))$ for trunks, and

$A_{rc}(\Delta t) = (A_{s,dyn}(t)- A_{ru}(\Delta t)- A_{rt}(\Delta t)) \times (1-\exp(-\lambda_{rc} \Delta t))$ for crowns.

The fixed and vertically migrated fraction of activity, $A_{sf}(t)$, is described by the forest specific, nuclide dependent and seasonal removal rate λ_{rem} as

$A_{sf}(\Delta t) = A_{s,dyn}(t) \times (1-\exp(-\lambda_{rem} \times \Delta t))$

Up to the maximum fraction of activity, runoff is calculated using a nuclide-independent, seasonal runoff rate

$A_{runoff}(\Delta t) = A_{s,ext}(t)(1\text{-}\exp(-\lambda_{runoff} \times \Delta t))$.

2.3 Ingestion dose

Ingestion doses are calculated by food types that are mushrooms, wild berries, and game meat. Regional parameters consider the selection of species contributing most to the human dietary intake. Consumption rates refer to edible fractions of different food types by subgroups of population.

Consumption of wild food products is supposed to be constant over the year. However, during hunting season and berry or mushroom picking, radionuclide concentration is determined by calculation with transfer coefficients from soil to edible part of forest product. Outside these periods, radionuclide concentration is derived from the activity of wild food products at the end of these seasons, with the correction of radioactive decay. Changes in activity concentration during culinary preparation are considered, and default values for retention fractions of iodine, caesium, strontium and plutonium are given for different types of foodstuffs of wild origin.

Ingestion dose is calculated for members of population and for hunters and pickers of wild foodstuffs. For other subgroups of population, average consumption rates are used.

2.3.1 Activity concentrations in foodstuffs

Calculation of activity concentrations in foodstuffs (Bq kg^{-1}) receives time-dependent surface densities of activity (Bq m^{-2}) in understorey (A_u) and soil ($A_{soil,\ dyn}$) from the dynamic submodule. A_u (t) is used to calculate activity concentrations in berries and game until the end of the first growing season after deposition. From the beginning of the second growing season onwards $A_{soil,\ dyn}$ (t) is used for calculation of activity concentrations in all foodstuffs with transfer factors TC (m^2 kg^{-1}).

Transfer of radionuclides from soil to wild foodstuffs is calculated by product types as follows:

Mushrooms

During the first ten days after deposition, the activity concentration in mushrooms is related to deposition and translocation as follows:

$$C_{mushrooms}(\Delta t) = 1/Y_{mushrooms} \times c_m \times A_{soil}(t=0) \times \exp[-(\lambda_r + \lambda_{w,\,m})\Delta t]$$

where

$C_{mushrooms}(\Delta t)$ = activity concentration in mushrooms (Bq kg^{-1} fresh weight)
$Y_{mushrooms}$ = yield of mushrooms at time of harvest (kg m^{-2})
c_m = mushroom land cover ratio at time of deposition (m^2 m^{-2})
A_{soil} (t=0) = total deposition to soil (Bq m^{-2})
λ_r = radioactive decay rate of a radionuclide (d^{-1})
$\lambda_{w,\,m}$ = decrease rate by weathering (d^{-1}) for mushrooms
Δt = time span between deposition and time of collection of mushrooms until ten days after deposition (d)

The following default values for these parameters are used:

$Y_{mushrooms}$ = 0.05 kg m^{-2}. This value depends on the species of mushrooms and the radioecological region.
c_m = 0.001 for all types of mushrooms
$\lambda_{w,\,m}$ = 0.05 d^{-1}, that corresponds to a period of 14 days for caesium, iodine, strontium and plutonium. Since no value was available for mushrooms, this parameter is fixed to the same rate as for vegetation.

More than ten days after deposition, a transfer coefficient which gives the ratio of activity concentration in mushrooms (Bq kg^{-1} fresh weight) and soil (Bq m^{-2}) is applied:

$$C_{mushrooms}(t) = TC_{mushrooms} \times A_{soil,\,dyn}(t)$$

where

$C_{mushrooms}(t)$ = activity concentration in mushrooms at time of collection (Bq kg^{-1} fresh weight)

$TC_{mushrooms}$ = nuclide dependent transfer coefficient soil - mushrooms (m^2 kg^{-1} fresh weight)

$A_{soil, dyn}(t)$ = bioavailable activity concentration in soil (Bq m^{-2})

Values of $TC_{mushrooms}$ for radionuclides and the grouping of mushrooms according to transfer of ^{137}Cs are given in Appendix B.

Berries

During the first growing season after deposition, berries are contaminated by translocation of radionuclides via foliar absorption, as follows:

$$C_{berries}(\Delta t) = 1/Y_{understorey} \times T_{berries} \times A_u(\Delta t)$$

where

$C_{berries}(\Delta t)$ = activity concentration in berries at time of collection (Bq kg^{-1} fresh weight)

$Y_{understorey}$ = yield of understorey (kg m^{-2})

$T_{berries}$ = translocation factor for berries

Δt = time span between deposition and collection of berries (d)

A_u = activity in understorey, given per ground area (Bq m^{-2})

The following default values for these parameters are used:

$Y_{understorey}$ = 1.5 kg m^{-2}. This value depends on the radioecological region.

$T_{berries}$ = 0.1 for caesium and iodine, 0.02 for strontium and plutonium.

From the beginning of the second year after deposition, a transfer coefficient, which gives the ratio of activity concentration in berries (Bq kg^{-1} fresh weight) and soil (Bq m^{-2}) is applied:

$$C_{berries}(t) = TC_{berries} \times A_{soil, dyn}(t)$$

where

$C_{berries}(t)$ = activity concentration in berries at time of collection (Bq kg^{-1} fresh weight)

$TC_{berries}$ = nuclide dependent transfer coefficient soil - berries (m^2 kg^{-1} fresh weight)

Values of $TC_{berries}$ for radionuclides are given in Appendix B.

Game

Until the end of the first hunting season after deposition, game animals are contaminated by ingestion of understorey feed:

$$C_{game}(T) = (1/Y_{understorey}) \times I_{game} \times TF_{game} \times \lambda_g \times \int_0^T A_u(t) \times \exp[-(\lambda_g+\lambda_r)(T-t)]dt$$

where

$C_{game}(T)$ = activity concentration in game animals at time of hunting (Bq kg^{-1} fresh weight)
$A_u(t)$ = activity in understorey as a function of time (Bq m^{-2})
$Y_{understorey}$ = yield of understorey (kg m^{-2} fresh weight)
I_{game} = feeding rate for understorey feedstuffs of game animals (kg d^{-1})
TF_{game} = transfer factor feed-meat of a radionuclide for game animals (d kg^{-1})
λ_g = biological transfer rate of a radionuclide for game animals (d^{-1})
λ_r = radioactive decay rate of a radionuclide (d^{-1})

In the default data set, a value of 1.5 kg m^{-2} was applied for the yield of understorey. Values of I_{game}, TF_{game} and λ_g for different game animals and radionuclides are given in Appendix B.

[In version 4.0 of RODOS, a simplified equation is currently used. The equation will be revised in the next version of RODOS.]

From the beginning of the second growing season, the contamination of game is calculated using a transfer coefficient:

$$C_{game}(t) = TC_{game} \times A_{soil,\ dyn}(t)$$

where

$C_{game}(t)$ = activity concentration in game meat at time of hunting (Bq kg^{-1} fresh weight)

TC_{game} = nuclide dependent transfer coefficient soil - game animals (m^2 kg^{-1} fresh weight)

$A_{soil, dyn}(t)$ = bioavailable activity concentration in soil (Bq m^{-2})

Values of TC_{game} for different radionuclides are given in Appendix B.

When dietary intakes for different time points are calculated, the radioactive decay of the radionuclides in foodstuffs is corrected as follows:

$$C_{mushrooms}(t) = C_{mushrooms}(t_0) \times \exp[-\lambda_r(t-t_0)]$$
$$C_{berries}(t) = C_{berries}(t_0) \times \exp[-\lambda_r(t-t_0)]$$
$$C_{game}(t) = C_{game}(t_0) \times \exp[-\lambda_r(t-t_0)]$$

where

$C_i(t)$ = activity concentration (Bq kg^{-1} fresh weight) in mushrooms, berries or game at time of consumption, respectively

$C_i(t_0)$ = activity concentration (Bq kg^{-1} fresh weight) in mushrooms, berries or game at time of collection or hunting, respectively

$t-t_0$ = delay between collection or hunting and consumption (d)

The activity concentration at time (t_0) is fixed, by default, to the last day of the period of picking of mushrooms and berries or the last day of the hunting season. The following timing of the seasons (suggested for Central Europe) is regional and can be adapted accordingly:

Period of collection of mushrooms: 01/06 - 30/11
Period of collection of berries: 01/07 - 15/10
Hunting season: 15/09 - 31/01

2.3.2 Dose calculation

Forest gifts, and especially mushrooms and game, are rarely ingested as fresh foods. They are cooked and the radionuclide activity content of the edible fraction can be lower than in the uncooked foodstuff. For most of the culinary practices only a little variation has been found for the processing factor (R_f), which is defined as the ratio between the total activity in the processed food and the activity in the raw product.

Processing factors for different radionuclides by foodstuffs are given in Appendix B. Forest gifts often contribute very little to the average alimentary diet of the population, but there are some important variations between no consumption at all and sometimes very high levels of consumption for a restricted number of people, constituting critical groups. Two critical groups have been determined: "mushroom and berry pickers" and "hunters".

Five age groups (1, 5, 10, 15, 20 years old) represent population in the FDMF. Ingestion doses for 5 years old children and adults are transferred to the Dose Combination Module (DCM), as well as doses for hunters and mushroom and berry pickers. For vegetarians, fishermen and forest workers the same consumption rates are used as for adult members of the whole population (except for consumption of game meat by vegetarians), and the calculated doses are transferred to DCM. For the most exposed groups, only adults are considered in dose calculation.

The calculation of the internal dose through ingestion considers the time dependent radionuclide concentration in foodstuffs (for iodine, caesium, strontium and plutonium) together with an eventual delay before consumption. The consumption rates of mushrooms, berries and game in different population groups are considered together with food processing factor due to the culinary practice applied. Standard dose conversion factors are used.

The dietary intake of a radionuclide is given by

$$A_h(t) = [C_{mushrooms}(t) \times R_{f,m} \times V_{mushrooms} + C_{berries}(t) \times R_{f,b} \times V_{berries} + C_{game}(t) \times R_{f,g} \times V_{game}] \,/\, 365 \text{ d a}^{-1}$$

where

$A_h(t)$ = human intake rate of activity (Bq d^{-1})

$C_i(t)$ = activity concentration in mushrooms, berries and game at time of consumption (Bq kg^{-1} fresh weight),

$R_{f,(m, b, g)}$ = food processing factor (fraction of activity in uncooked food remaining in edible fraction of food) for mushrooms, berries or game meat, respectively

V_i = consumption rate of mushrooms, berries and game (kg a^{-1}), with individual consumption rates for critical groups of the population and average rates for the adult members of the population.

Values of consumption rates are given in Appendix B.

The dose $D_{Ing}(T)$ through ingestion of contaminated forest gifts within time T after deposition is given by

$$D_{Ing}(T) = \int_0^T A_h(t) \times g_{Ing}(t)\, dt$$

where

$D_{Ing}(T)$ = ingestion dose (Sv)

$g_{Ing}(t)$ = nuclide dependent dose conversion factor (Sv Bq^{-1})

Age-dependent dose conversion factors are applied for the 5 age groups.

2.4 External dose

The algorithms for the calculation of kerma rates are described in more detail in Golikov et al. (1999).

2.4.1 Kerma rates

A contaminated forest as a source of human external exposure is modelled with three compartments: tree crowns, trunks and soil plus understorey vegetation. Ground-layer vegetation and soil are defined as 'ground layer'. The compartment structure is basically the same as in the dynamic transfer submodule, and allows to consider the vertical distribution of activity in both the overstorey (trunk plus crown) and the ground layer. The heights of the trunk and crown layers, h_1 and h_2, the corresponding biomass densities, ρ_1 and ρ_2, and the activities, A_1 and A_2, are used in the calculation (Fig. 3). The activity distribution in soil is described by a parameter β.

The tree biomass plus air are defined as the "forest equivalent medium", FEM, with a constant elemental composition and varying density. The materials of the tree compartments are modelled as uniformly distributed in the corresponding layers. The height of the tree compartments and their mass density can vary as in real forests. The densities of the crown and trunk layers also include the contributions from understorey trees to these layers. Radionuclide concentration, biomass density and elemental composition in the forest equivalent medium (FEM) are considered uniform and effectively infinite or semi-infinite in space.

The air kerma rates at 1 m above the ground were calculated using the computer code VICAR-2 for the numeric solution of the transport equation [Nikolayev et al. 1984]. This code uses a multi-group approximation of the method of integral equations [Bergelson et al. 1970; Barkovsky and Popkov, 1990]. Calculations were performed by using a special matrix system of parameter, which was created in particular for this application [Golikov et al. 1989].

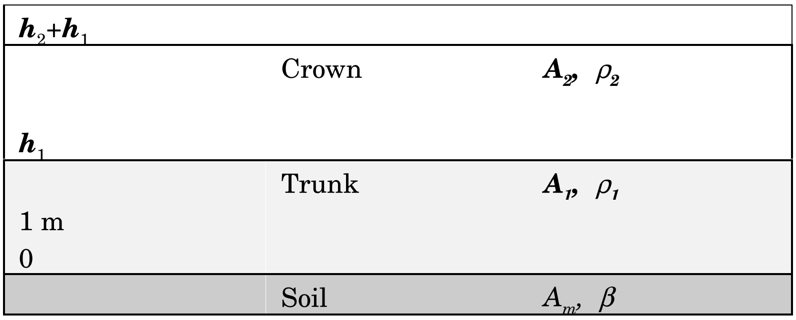

Figure 3. *Spatial structure of the forest ecosystem model for external dose calculations.*

Numeric values were calculated for the kerma rate at the height of 1 m above the ground caused by gamma radiation of plane isotropic sources located at different depths in soil and at different heights in the FEM. The kerma rate in air at the height of 1 meter above the soil surface is derived from a flat isotropic source located at specific depths ς in soil by using a simple analytical two-exponential expression.

$$K_a^{soil}(\varsigma, \rho_1) = p_1 \cdot \exp(-p_2 \cdot \varsigma) + p_3 \cdot \exp(-p_4 \cdot \varsigma),$$

where

K_a^{soil} (ς ,ρ_1) is the air kerma rate [10^{-12} (Gy s^{-1}) per (Bq cm^{-2})] at the height of 1 m above the ground with the trunk zone biomass density ρ_1 and originating from a plane isotropic source located in soil at depth ς, with

$p_1 = a_1 \cdot \exp(-a_2 \cdot \rho_1)$;
$p_2 = a_3 \cdot \exp(-a_4 \cdot \rho_1)$;
$p_3 = a_5$; $p_4 = a_6$.

The distribution of the activity in soil follows an exponential distribution:

$A_m(\varsigma) = A_a \cdot \beta \cdot \exp(-\beta \cdot \varsigma)$,

where $A_m(\varsigma)$ is the specific activity of soil (Bq·g^{-1}) at the depth ς (g·cm^{-2}) and β is the depth distribution parameter ($cm^2 \cdot g^{-1}$).

The analytical expression for the kerma rate in air at the height of 1 m above the soil is:

$$K_a^s(\beta, \rho_1) = 3.6 \cdot A_a^s \cdot \left\{ \frac{a_1 \cdot \exp(-a_2 \cdot \rho_1)}{1 + \frac{a_3 \cdot \exp(-a_4 \cdot \rho_1)}{\beta}} + \frac{a_5}{1 + \frac{a_6}{\beta}} \right\},$$

where $K_a^s(\beta, \rho_1)$ is the kerma rate (nGy·h^{-1}), A_a^s is the activity per unit area (Bq·cm^{-2})] and ρ_1 (kg·m^{-3}) is forest biomass density.

The complete set of equations to calculate the kerma rates in air from a flat isotropic source located on different heights in the FEM were approximated by the analytic expression:

$$K_a^{FEM}(E,x) = b_1 + b_2 \cdot x - b_3 \cdot \ln(x),$$

where $K_a^{FEM}(E,x)$ is the kerma rate in air at the height of 1 m above the ground from a plane isotropic source with energy E located in the FEM at height x (in units of mean free paths). Based on this expression, the analytical equations for kerma rates K_a^{tr} and K_a^{Cr}, caused by the uniform activity in the trunk zone and in the crown zone were derived:

$$K_a^{tr}(h_1,\rho_1) = A_m^{tr} \cdot \omega_1 \cdot \left[R_1 \cdot (x_0 + x_1) + R_2 \cdot (x_0^2 + x_1^2) - R_3 \cdot (x_0 \cdot \ln(x_0) + x_1 \cdot \ln(x_1))\right],$$

$$K_a^{cr}(h_2,\rho_2) = A_m^{cr} \cdot \omega_2 \cdot \left[R_1 \cdot x_2 + R_2 \cdot (x_2^2 + 2 \cdot x_1 \cdot x_2) - R_3 \cdot ((x_1 + x_2) \cdot \ln(x_1 + x_2) - x_1 \cdot \ln(x_1))\right],$$

where

$x_o = 0.12+0.11\cdot\rho_1$;
$x_1 = (0.12+0.11\cdot\rho_1)\cdot(h_1-1)$;
$x_2 = (0.12 + 0.11\cdot\rho_2)\cdot h_2$;
$\omega_1 = 0.36\cdot\rho_1/x_o$,
$\omega_2 = 0.36\cdot\rho_2\cdot h_2/x_2$.

Unit of the air kerma rate is $nGy\cdot h^{-1}$, that of the specific activity A_m $Bq\cdot g^{-1}$, h_1 and $h_2$are given in m, ρ_1 and ρ_2 is in $kg\cdot m^{-3}$ and h_1 is in m.

R_1, R_2 , R_3 are nuclide-specific parameters.

2.4.2 Effective doses

The conversion from kerma to effective dose was calculated for three energies of gamma radiation of a source, various distributions of activity in ground and uniform distributions of activity in crowns of trees. Value suggested for adults when sources are in crowns or trunks of trees was 0.7 Sv Gy^{-1} and for sources in soil 0.8 Sv Gy^{-1}. A correction function for the estimation of the influence of the size (weight) of human body was additionally derived. For a five-year old child a correction factor of 1.18 was obtained (Balonov et al. 1998).
The time people spend in forests for work or recreation is used to calculate external doses. The external dose is calculated for members of the population, 5 and 20 years of age, and for forest workers.

3 DISCUSSION

The current version of the FDMF module can be used to predict radiation doses from contaminated forests in Europe after a large-scale nuclear accident. The reliability of data varies by nuclides; the most comprehensive information on environmental transfer was available for radiocaesium. The doses through ingestion are modelled using data collected in several countries after the Chernobyl accident.

The structure of forests in Europe varies by climate and soil type as well as in the way the forests are managed. Regional model parameters are applied to all locations in that region (Müller 1998a). Many parameters in the FDMF database are regional and have to be adjusted when the model is adapted for local conditions or new radioecological regions. The current module of FDMF was kept simple enough to be easily adapted under new conditions. Long-term predictions will be materially improved when site-specific parameters are used.

In one run of the program every radioecological region can include three forest types. When the module is applied to a new area attention should be paid to forests that are most important in the context of human exposure to radiation. Only forests visited by people contribute to dietary or external doses. Berries and mushrooms are not found in dense seedling stands, and no internal dose is therefore received from them. Members of the public receive both external and ingestion doses from advanced or mature forests where they go for berry and mushroom picking or for other type of recreation. Forest workers can be exposed to radiation in many forest types, because thinning and other silvicultural work are done in stands at various development stages. The industrial structure of the region for which the module is adapted is therefore of concern.

FDMF considers the overstorey as a source of external radiation. The attenuation of radiation from the ground by trees is also taken into account. A new approach in environmental radiation assessments was used to derive the algorithm for kerma rates attenuated by the so called 'forest equivalent medium' (overstorey plus air). An issue of interest to many has been the significance of trees as a source of human exposure to radiation. Clearly, variations in the height, biomass density and, especially, the foliar biomass of tree species and stands affect the external dose, which in a short period after a deposition event can be significant.

Overstorey contamination can, in some late phase cases, also lower the doses received by people from long-lived ^{137}Cs when compared with the contamination of a bare ground (Golikov et al. 1999). In mature forests, the crowns are so far from the human subjects liable to be exposed that the doses can be lower than from ground contamination at a site without trees. However, in the early phase after deposition, there are several exposure situations in which predictions of doses from the overstorey represent a considerable fraction of the total external dose in the first days or weeks after deposition.

The user of the model should consider that each type of forest food product includes only one species or, in case of mushrooms, a group of species at a time. Spontaneous changes in human diets should also be considered in the assessments for a real fallout situation.

First version of FDMF was released in stage of intensive radioecological investigation of forests. This brings up new challenging possibilities for more versatile and reliable modelling of European forests. Validation of FDMF continues with particular emphasis on each submodule.

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The variables used in description of model calculations are defined here.

β = a parameter for definition of depth distribution of soil activity ($cm^2\ g^{-1}$)

λ_a = absorption rate of a radionuclide for crowns of trees and for understorey vegetation (d^{-1}) for the time dependent changes in activities

λ_{avail} = availability rate of a radionuclide in soil (d^{-1}) for the time dependent changes in activities

λ_g = biological transfer rate of a radionuclide for a game animal (d^{-1}) for ingestion dose calculation

λ_l = litter fall rate of a radionuclide for crowns (d^{-1}) for the time dependent changes in activities

λ_r = radioactive decay rate of a radionuclide (d^{-1})

λ_{rc} = root uptake rate of a radionuclide for crowns (d^{-1}) for the time dependent changes in activities

λ_{rem} = removal rate of a radionuclide in soil due to fixation and vertical migration (d^{-1}) for the time dependent changes in activities

λ_{rt} = root uptake rate of a radionuclide for trunks (d^{-1}) for the time dependent changes in activities

λ_{ru} = root uptake rate of a radionuclide for understorey (d^{-1}) for the time dependent changes in activities

λ_{runoff} = runoff rate

λ_{wc} = weathering rate of a radionuclide for crowns (d^{-1}) for the time dependent changes in activities

λ_{wm} = decrease rate by weathering (d^{-1}) for mushrooms for ingestion dose calculation

λ_{wt} = weathering rate of a radionuclide for trunks (d^{-1}) for the time dependent changes in activities

λ_{wu} = removal rate of a radionuclide for understorey (d^{-1}) for the time dependent changes in activities

ζ = depth of plane isotropic source in the soil ($g \cdot cm^{-2}$)

ρ_1 = biomass density of the trunk layer ($kg\ m^{-3}$)

ρ_2 = biomass density of the crown layer ($kg\ m^{-3}$)

$a_1, a_2, \ldots, a_6$ = parameter values for calculation of kerma rate from the ground layer (given in the file “Kermafac”)

A_a = activity in soil per unit area ($Bq \cdot cm^{-2}$)

$A_{ac}(t)$ = activity absorbed by the crown from deposition date up to time t, given per ground area (Bq m^{-2})

$A_b(t)$ = activity of outer bark at time t (Bq m^{-2})

$A_c(t)$ = activity in crowns at time t, given per ground area (Bq m^{-2})

$A_{d\ crowns}$ = dry deposition to crowns (Bq m^{-2})

$A_{d,\ forest}$ = dry deposition to forest (for calculation of the plume depletion)

$A_{d\ soil}$ = dry deposition to soil (Bq m^{-2})

$A_{d\ trunks}$ = dry deposition to trunks (Bq m^{-2})

$A_{d\ understorey}$ = dry deposition to understorey (Bq m^{-2})

$A_h(t)$ = human intake rate of activity (Bq d^{-1}) for ingestion dose calculation

A_i = total deposition to tree crowns, trunks, understorey and soil, respectively (Bq m^{-2})

$A_{lc}(\Delta t)$ = activity removed from crown by litter fall during time interval Δt, given per ground area (Bq m^{-2})

A_m = specific activity of trunk or crown layer (Bq·g^{-1})

$A_m(\varsigma)$ = the specific activity of soil (Bq·g^{-1}) at the depth ς (g·cm^{-2})

$A_{rc}(\Delta t)$ = activity taken up during time interval Δt from soil to crowns, given per ground area (Bq m^{-2})

$A_{rt}(\Delta t)$ = activity taken up during time interval Δt from soil to trunks, given per ground area (Bq m^{-2})

$A_{ru}(\Delta t)$ = activity taken up during time interval Δt from soil to understorey, given per ground area (Bq m^{-2})

A_{runoff} = activity removed from soil by runoff

$A_{s,dyn}(t)$ = activity in soil at time t used in calculation of root uptake, given per ground area (Bq m^{-2})

$A_{s,ext}(t)$ = activity in soil at time t for external dose calculation, given per ground area (Bq m^{-2})

$A_{sf}(t)$ = soil activity bound due to fixation and vertical migration at time t, given per ground area (Bq m^{-2})

$A_t(t)$ = activity in trunks at time t, given per ground area (Bq m^{-2})

$A_u(t)$ = activity in understorey at time t, given per ground area (Bq m^{-2})

A_w = total wet deposition (Bq m^{-2})

$A_{wc}(\Delta t)$ = activity removed from crown by weathering during time interval Δt, given per ground area (Bq m^{-2})

$A_{wt}(\Delta t)$ = activity removed from trunk by weathering during time interval Δt, given per ground area (Bq m^{-2})

$A_{wu}(\Delta t)$ = activity removed from understorey by weathering during time interval Δt, given per ground area (Bq m^{-2})
$A_{w\ crowns}$ = wet deposition on crowns (Bq m^{-2})
$A_{w\ soil}$ = wet deposition on soil (Bq m^{-2})
$A_{w\ trunks}$ = wet deposition on trunks (Bq m^{-2})
$A_{w\ understorey}$ = wet deposition on understorey (Bq m^{-2})
C_a = time-integrated concentration of radionuclides in air (Bq s m^{-3})
c_f = canopy cover fraction for wet deposition calculation
c_m = mushroom land cover at time of deposition (m^2 m^{-2}) for ingestion dose calculation
$C_{berries}$ (t) = activity concentration (Bq kg^{-1} fresh weight) in berries at time of consumption for ingestion dose calculation
C_{game} (t) = activity concentration (Bq kg^{-1} fresh weight) in game at time of consumption for ingestion dose calculation
$C_{mushrooms}$ (t) = activity concentration (Bq kg^{-1} fresh weight) in mushrooms at time of consumption for ingestion dose calculation
$C_{berries}$ (t_0) = activity concentration (Bq kg^{-1} fresh weight) in berries at time of collection for ingestion dose calculation
C_{game} (t_0) = activity concentration (Bq kg^{-1} fresh weight) in game at time of hunting for ingestion dose calculation
$C_{mushrooms}$ (t_0) = activity concentration (Bq kg^{-1} fresh weight) in mushrooms at time of collection for ingestion dose calculation
D_{Ing} (T) = ingestion dose (Sv)
flit = fraction of activity removed due to litterfall
f_{trans} = translocated activity as a fixed fraction of crown activity
fw_{crowns} = interception fraction for crowns of trees for wet deposition calculation
fw_{trunks} = interception fraction for trunks of trees for wet deposition calculation
$fw_{understorey}$ = interception fraction for understorey for wet deposition calculation
$g_{Ing}(t)$ = dose conversion factor (Sv Bq^{-1}) for ingestion dose calculation
h_1 = height of the trunk layer (m)
h_2 = height of the crown layer (m)
I_{game} = feeding rate for understorey feedstuffs of game animals (kg d^{-1}) for ingestion dose calculation

K_a^{cr} = air kerma rate (nGy·h^{-1}) from contaminated crown layer with specific activity A_m (Bq·g^{-1}) at the height of 1 m above the ground

K_a^{soil} = kerma rate in air from a source in soil (nGy·h^{-1})

K_a^{tr} = air kerma rate (nGy·h^{-1}) from contaminated trunk layer with specific activity A_m (Bq·g^{-1}) at the height of 1 m above the ground

$\mathrm{LAI}_{\mathrm{crowns}}$ = leaf area index of crowns of trees at time of deposition (m^2 m^{-2})

$\mathrm{LAI}_{\mathrm{trunks}}$ = surface area index of trunks of trees at time of deposition (m^2 m^{-2}). For trunks only the area below crown limit is considered.

$\mathrm{LAI}_{\mathrm{understorey}}$ = leaf area index of understorey at time of deposition (m^2 m^{-2})

lop = length of litter fall period (Julian days)

nof_yc = number of age classes of needles or leaves

$\mathrm{p}_{\mathrm{crowns}}$ = correction factor for retention of crowns for wet deposition calculation

$\mathrm{p}_{\mathrm{trunks}}$ = correction factor for retention of trunks for wet deposition calculation

$\mathrm{p}_{\mathrm{understorey}}$ = correction factor for retention of understorey for wet deposition calculation

R = rainfall (mm) for wet deposition calculation

R_1, R_2 , R_3 = nuclide-specific parameters for calculation of kerma rates from crown and trunk layers (given in the file "kermafac")

$\mathrm{R}_{\mathrm{f,\,b}}$ = processing factor of berries (culinary practices)

$\mathrm{R}_{\mathrm{f,\,g}}$ = processing factor of game (culinary practices)

$\mathrm{R}_{\mathrm{f,\,m}}$ = processing factor of mushrooms (culin. pract.)

S = retention coefficient of a radionuclide (mm) for wet deposition calculation

t = time since deposition event

t_0 = time of hunting, or time of harvest of berries or mushrooms

$\mathrm{T}_{\mathrm{berries}}$ = translocation factor for berries for ingestion dose calculation

$\mathrm{TC}_{\mathrm{berries}}$ = transfer coefficient for berries (m^2 kg^{-1} fresh weight) for ingestion dose calculation

$\mathrm{TC}_{\mathrm{game}}$ = transfer coefficient for game (m^2 kg^{-1} fresh weight) for ingestion dose calculation

$\mathrm{TC}_{\mathrm{mushrooms}}$ = transfer coefficient for mushrooms (m^2 kg^{-1} fresh weight) for ingestion dose calculation

$\mathrm{TF}_{\mathrm{game}}$ = transfer factor feed-meat for game animals (d kg^{-1}) for ingestion dose calculation

$V_{g\ crowns\ max}$ = dry deposition velocity for crowns (m s^{-1})

$V_{g\ soil}$ = dry deposition velocity for soil (m s^{-1})

$V_{g\ trunks}$ = dry deposition velocity for trunks (m s^{-1})

$V_{g\ understorey\ max}$ = dry deposition velocity for understorey (m s^{-1})

V_i = consumption rate of mushrooms, berries and game, respectively, for ingestion dose calculation (kg a^{1})

$Y_{mushrooms}$ = yield of mushrooms at time of harvest (kg m^{-2} fresh weight) for ingestion dose calculation

$Y_{understorey}$ = yield of understorey (kg m^{-2} fresh weight) for ingestion dose calculation

1 Deposition and Interception

Table I. *Deposition velocities for all regions. Deposition velocities for crowns, trunks, understorey and soil by groups of radionuclides for all types of forests in all regions (Belot 1977, Belot and Gauthier 1975, Bonnet and Anderson 1993, Bunzl et al. 1989, Jonas and Heinemann 1985, Müller and Pröhl 1993, Myttenaere et al. 1993, Roed 1987, Tikhomirov et al. 1993)*

	Deposition velocities (10^{-3} m s^{-1})		
	Aerosol bound radionuclides	**Elemental Iodine**	**Organic bound Iodine**
$V_{g\ crowns}$	4.5	45	0.45
$V_{g\ trunks}$	0.5	5	0.05
$V_{g\ understorey}$	2	20	0.2
$V_{g\ soil}$	0.5	3	0.05

Table II. *Leaf area indices for Central Europe. Surface area indices for understorey, for crowns of different forest types and for trunks by seasons. LAIs for overstorey are given for the forest land area and not for a single tree. The calendar should be defined according to the growth seasons of each radioecological region. Values for Central European conditions (Belot 1977; Dochinger 1980; Jonas 1984; Jonas and Heinemann 1985; Koenies 1985; Müller and Pröhl 1993; Schulze 1982).*

Compartment	**Leaf area indices (LAI) for forests at time of deposition and the maximum leaf area indices (LAI_{max})**				
	1st November - 31st March	**1st April - 31st May**	**1st June - 30th September**	**1st October - 31st October**	**LAI_{max}**
Understorey	0.5	linear interpolation	3	linear interpolation	3
Coniferous forest	10	10	10	10	10
Deciduous forest	1	linear interpolation	7	linear interpolation	7
Mixed forest	5	linear interpolation	8	linear interpolation	8
Trunks of trees	1	1	1	1	1

Table III. *Leaf area indices for Northern Europe. Surface area indices for understorey, for crowns of different forest types and for trunks by seasons. LAIs for overstorey are given for the forest land area and not for a single tree. The calendar should be defined according to the growth seasons of each radioecological region. Values for Northern European conditions (e.g. Kellomäki 1991).*

Compartment	**Leaf area indices (LAI) for forests at time of deposition and the maximum leaf area indices (LAI_{max})**				
	1st November – 30th April	**1st May – 14th June**	**15th June - 30th September**	**1st – 31st October**	**LAI_{max}**
Understorey	0.5	linear interpolation	3	linear interpolation	3
Crowns of pine-dominant forests	3.5	3.5	3.5	3.5	3.5
Crowns of spruce-dominant forests	8	8	8	8	8
Crowns of deciduous-dominant forests	0.5	linear interpolation	4	linear interpolation	4
Trunks of trees	1	1	1	1	1

Table IV. *Retention coefficients by groups of radionuclides for crowns, trunks and understorey. Default values for all types of forests in all regions (Müller and Pröhl 1993). Values can vary according to tree species and whether deposition concerns leaves or trunks of trees.*

	Retention coefficients (mm)		
	Iodine	**Caesium, zirconium, niobium, ruthenium, tellurium, cerium, plutonium, manganese, zinc**	**Strontium, barium**
S	0.15	0.3	0.6

Table V. *Correction parameters of interception of wet deposition for Central Europe. Parameters for adjusting interception fractions of understorey, crowns of different forest types and trunks. Values are compatible with other interception parameters for Central European conditions.*

	Correction factor for retention (p_i)	**Canopy cover fraction (c_f)**
Understorey	3	-
Coniferous forest	6	0.7
Deciduous forest	6	0.7
Mixed forest	6	0.7
Trunks of trees	6	-

Table VI. *Correction parameters for interception of wet deposition for Northern Europe. Parameters for adjusting interception fractions of understorey, crowns of different forest types and trunks. Values are compatible with other interception parameters for Northern Europe.*

	Correction factor for retention (p_i)	**Canopy cover fraction (c_f)**
Understorey	3	-
Crowns of pine-dominant forests	2	0.25
Crowns of spruce-dominant forests	7.5	0.3
Crowns of deciduous-dominant forests	3.8	0.3
Trunks of trees	6	-

2 Time dependent changes in forest ecosystem

Table VII. *Weathering rates for crowns, trunks and understorey. Default values for Northern and Central Europe. Values were derived for pine-dominant forests (Bergman 1994; Nygrén et al. 1994; Nylen 1996; Raitio and Rantavaara 1994).*

Compartment	**Weathering rate (d^{-1}) as a function of time after deposition**		
	< 2 months	**2-12 months**	**> 12 months**
Crowns of trees	0.0116	0.00289	0.0000693
Trunks of trees	0.05	0.004	0.00007
Understorey	0.046	0.018	0.00009

Table VIII. *Begin and end of litterfall season for different forest types. Default values for Northern and Central Europe.*

Forest type	Begin of litterfall season (Julian days)	End of litterfall season (Julian days)
Pine-dominant forests	273	304
Spruce-dominant forests	273	304
Deciduous-dominant forests	273	304

Table IX. *Default values of runoff rates for Northern and Central Europe (Nylén 1996)*.

Runoff rate (d^{-1}) by months											
1	2	3	4	5	6	7	8	9	10	11	12
0	0	0	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0	0

Table X. *Maximum fraction of soil activity removed due to runoff. Default values for Northern and Central Europe (Nylen 1996).*

Forest type	Maximum fraction of soil activity removed due to runoff
Pine-dominant forests	0.03
Spruce-dominant forests	0.03
Deciduous-dominant forests	0.03

Table XI. *Root uptake rates for crowns, trunks and understorey. Default values for Northern and Central Europe. Values were derived for pine-dominant forests (Raitio and Rantavaara 1994; Rantavaara 1990, 1996; Bergman 1994)*

Compartment	Uptake rate (d^{-1})
Crowns of trees	0.00001
Trunks of trees	0.000005
Understorey	0.00001

Table XII. *Nuclide absorption rates (d^{-1}) for crowns and understorey by forest type for Central Europe (Müller and Pröhl 1993; Watkins and Maul 1995).*

Radionuclide	Pine-dominant, deciduous and mixed forests Month				Spruce dominant forests and conifer seedling stands Month			
	11-4	**5**	**6-9**	**10**	**11-4**	**5**	**6-9**	**10**
Ag, Am, Ce, Cm, Nb, Nd, Np, Pr, Pu, Rh, Sr, Tc, Zr	0	0	0	0	0	0	0	0
Ba, La, Y	0	0	0.0007	0	0	0	0.0009	0
Sb	0	0.0009	0.002	0.0009	0	0.001	0.002	0.001
Ru	0	0.002	0.003	0.002	0	0.002	0.004	0.002
I, Mn, Mo, Te	0.0006	0.003	0.005	0.003	0.0008	0.004	0.006	0.004
Co	0.002	0.007	0.01	0.007	0.002	0.009	0.016	0.009
Cs, Na, Rb	0.0016	0.0073	0.013	0.0073	0.0021	0.009	0.017	0.009

Table XIII. *Nuclide absorption rates (d^{-1}) for crowns and understorey by forest type for Northern Europe (Müller and Pröhl 1993; Watkins and Maul 1995).*

Radionuclide	Pine-dominant, deciduous and mixed forests Month				Spruce dominant forests and conifer seedling stands Month			
	11-4	**5**	**6-9**	**10**	**11-4**	**5**	**6-9**	**10**
Ag, Am, Ce, Cm, Nb, Nd, Np, Pr, Pu, Rh, Sr, Tc, Zr	0	0	0	0	0	0	0	0
Ba, La, Y	0	0	0.0007	0	0	0	0.0009	0
Sb	0	0.0009	0.002	0.0009	0	0.001	0.002	0.001
Ru	0	0.002	0.003	0.002	0	0.002	0.004	0.002
I, Mn, Mo, Te	0	0.003	0.005	0.003	0.0001	0.004	0.006	0.004
Co	0.0002	0.007	0.01	0.007	0.0002	0.009	0.016	0.009
Cs, Na, Rb	0.0002	0.0073	0.013	0.0073	0	0.009	0.017	0.009

Table XIV. *Radionuclide removal rates (d^{-1}) in soil due to fixation and vertical migration for all forest types on mineral soil by months. Default values for Northern Europe.*

Radionuclide removal rates (d^{-1}) in soil due to fixation and vertical migration by month											
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
0	0	0	0	9.5E-5	9.5E-5	9.5E-5	9.5E-5	9.5E-5	9.5E-5	0	0

Table XV. *Availability rate (d^{-1}) of radionuclides in soil. Default value for all forest types in Northern and Central Europe.*

Compartment	**Availability rate (d^{-1})**
Soil	0.006

Table XVI. *Reciprocal of relaxation length for all forest types. Default values for Central and Northern Europe.*

Time	**Constant beta ($cm^2\ g^{-1}$)**
At deposition day	3
Ten years after deposition	0.3

3 Concentrations in foodstuffs

Table XVII. *Transfer coefficients of ^{137}Cs for mushrooms for Central Europe. Average values calculated from Bakken and Olsen 1990; Battiston et al. 1989; Block and Pimpl 1990; Byrne 1988; Henrich et al. 1990; Horyna and Randa 1988; Hove et al. 1990; IAEA 1994; Kenigsberg et al. 1995; Lambinon et al. 1988; Mascanzoni 1990; Randa et al 1990; Rantavaara 1990; Römmelt et al. 1990; Svadlenkova 1996.*

$TC_{mushrooms}$: Transfer coefficients (m^2 kg^{-1} fresh weight) of ^{137}Cs for several species of mushrooms

(Default: 0.05)

0.01	**0.05**	**0.1**	**0.5**
Agaricus arvensis	*Boletus aestivalis*	*Boletus cavipes*	*Clitocybe cavipes*
Agaricus sylvaticus	*Boletus edulis*	*Cantharellus lutescens*	*Dermocybe sp.*
Armillaria mellea	*Cantharellus cibarius*	*Cantharellus tubaeformis*	*Hebeloma sp.*
Boletus appendiculatus	*Cantharellus palens*	*Clitocybe infundibuliformis*	*Hygrophorus sp.*
Boletus elegans	*Clitocybe nebularis*	*Lactarius lignyotus*	*Hygrophorus olivaceoalbus*
Cantharellus cornucopiensis	*Collybia burhyracia*	*Lactarius quietus*	*Laccaria amethystina*
	Collybia confluens	*Lactarius torminosus*	*Laccaria laccata*
Leccinum aurantiacum	*Collybia dryophylla*	*Lactarius turpis*	*Laccaria proxima*
(Macro) Lepiota procera	*Collybia maculata*	*Leccinum scabrum*	*Lactarius sp.*
Lepista nuda	*Collybia peronata*	*Russula nigricans*	*Lactarius camphoratus*
Lepista saeva	*Hydnum repandum*	*Suillus grevillei*	*Lactarius necator*
Lycoperdon perlatum	*Kuehneromyces mutabilis*	*Tricholoma aurata*	*Lactarius porninsis*
Psalliota campestris	*Lactarius deterrimus*	*Trichomolopsis rutilans*	*Lactarius rufus*
Sarcodon imbr.	*Lactarius helvus*		*Lactarius theiogalus*
	Lactarius odoratus		*Lactarius trivialis*
	Lactarius picinus		*Rozites caperata*
	Leccinum sp.		*Russula sp.*
	Leccinum versipelle		*Russula badia*
	Lepiota naucina		*Russula erythropoda*
	Oudemansiella sp.		*Russula ochroleuca*
	Oudemansiella radicata		*Russula turci*
	Pholiota aegerita		*Suillus bovinus*
	Russula decolorans		*Suillus granulatus*
			Suillus luteus
			Suillus variegatus
			Xerocomus badius
			Xerocomus chrysenteron
			Xerocomus subtomentosus

Table XVIII. *Transfer coefficients of ^{137}Cs for mushrooms for Northern Europe (Rantavaara 1987, 1990).*

TC$_{mushrooms}$: Transfer coefficients (m^2 kg^{-1} fresh weight) of ^{137}Cs for several species of mushrooms (Default: 0.05)			
0.01	**0.05**	**0.1**	**0.5**
Armillaria borealis	*Lactarius torminosus*	*Hydnum repandum*	*Hygrophorus camarophyllus*
Boletus edulis	*Leccinum scabrum*	*H. rufescens*	*Rozites caperatus*
Cantharellus cibarius	*Russula decolorans*	*Lactarius rufus*	
Gyromitra esculenta	*Russula paludosa*	*Lactarius trivialis*	
Lactarius deterrimus	*Cantharellus tubaeformis,*	*Suillus variegatus*	
Lactarius delicious	*Cratellus cornucopioides*		
Lactarius turpis			
Leccinum versipelle			
L. vulpinum			
Ramaria flava			
Scutiger ovinus			
Suillus luteus			

Table XIX. *Transfer coefficients of ^{137}Cs for berries for Central Europe (Block and Pimpl 1990; Kenigsberg et al. 1995; Rantavaara 1987, 1990; Römmelt et al. 1990; Svadlenkova et al. 1996)*

TC$_{berries}$: Transfer coefficients of ^{137}Cs for several species of berries (m^2 kg^{-1} fresh weight)	
Species	**Average value**
Blueberry or bilberry (*Vaccinium myrtillus*)	0.003
Lingonberry (*Vaccinium vitis-idaea*)	0.002
Raspberry (*Rubus idaeus*)	0.004
Cloudberry (*Rubus chamaemorus*)	0.008
Default value	0.003

Table XX. *Transfer coefficients of ^{137}Cs for berries for Northern Europe (Rantavaara 1987, 1990).*

$TC_{berries}$: Transfer coefficients of ^{137}Cs for several species of berries ($m^2\ kg^{-1}$ fresh weight)	
Species	**Average value**
Blueberry or bilberry (*Vaccinium myrtillus*)	0.004
Lingonberry (*Vaccinium vitis-idaea*)	0.004
Raspberry (*Rubus idaeus*)	0.001
Cloudberry (*Rubus chamaemorus*)	0.008
Default value	0.004

Table XXI. *Transfer coefficients of ^{137}Cs for game for Central Europe. Average values calculated from IAEA 1994; Johanson and Bergström 1989; Johanson and Bergström 1994; Johanson et al. 1990; Johanson et al. 1994; Rantavaara et al. 1987, Rantavaara 1990; Staaland et al. 1995; Svadlenkova et al. 1996.*

TC_{game} : Transfer coefficients of ^{137}Cs for game and some domestic animals ($m^2\ kg^{-1}$ fresh weight)	
Species	**Average value**
Brown hare (*Lepus europeus*)	0.005
Mountain hare (*Lepus timidus*)	0.03
Roe deer (August-December)	0.1
Red deer	0.04
Moose	0.01
Wild boar (September-March)	0.05
Terrestrial birds	0.015
Waterfowl	0.01
Default value	0.1

Table XXII. *Transfer coefficients of ^{137}Cs for game for Northern Europe. Average values calculated from IAEA 1994; Johanson and Bergström 1989; Johanson and Bergström 1994; Johanson et al. 1990; Johanson et al. 1994; Rantavaara et al. 1987, Rantavaara 1990; Staaland et al. 1995.*

TC_{game} : Transfer coefficients of ^{137}Cs for game and some domestic animals ($m^2\ kg^{-1}$ fresh weight)	
Species	**Average value**
Brown hare (*Lepus europeus*)	0.005
Arctic hare (*Lepus timidus*)	0.03
Roe deer (August-December)	0.1
Red deer	0.04
Moose	0.01
Wild boar (September-March)	0.05
Terrestrial birds	0.015
Waterfowl	0.01
Default value	0.01

Table XXIII. *Transfer coefficients of iodine, strontium and plutonium for mushrooms, berries and game*

	Transfer coefficient of iodine ($m^2\ kg^{-1}$ fresh weight)	**Transfer coefficient of strontium ($m^2\ kg^{-1}$ fresh weight)**	**Transfer coefficient of plutonium ($m^2\ kg^{-1}$ fresh weight)**
Mushrooms	0.04	0.0001	2×10^{-4}
Berries	0.04	0.001	2×10^{-4}
Game	1×10^{-3}	2×10^{-4}	1×10^{-5}

Table XXIV. *Feeding rates and transfer factors feed-animal for game. *)Average values calculated from Howard et al. 1991; Moss and Horrill 1996; Müller and Pröhl 1993; Staaland et al. 1995.*

Species	**I_{game}: Feeding rates (kg d^{-1} fresh weight)**	**TF_{game}: Transfer factors for ^{137}Cs *) (d kg^{-1} fresh weight)**
Brown hare	0.25	0.5
Mountain hare	0.25	0.5
Roe deer	4	0.5
Red deer	7	0.5
Moose	15	0.5
Wild boar	5	0.5
Terrestrial birds	0.1	2
Waterfowl	0.1	2
Default values		
Central Europe	4	0.5
Northern Europe	15	0.5

Table XXV. *Transfer factors feed-animal of iodine, strontium and plutonium (by default, average values for domestic animals are taken)*

	Transfer factor of iodine (d kg^{-1} fresh weight)	**Transfer factor of strontium (d kg^{-1} fresh weight)**	**Transfer factor of plutonium (d kg^{-1} fresh weight)**
Game	0.01	5×10^{-3}	1×10^{-4}

Table XXVI. *Biological transfer rates λ_g (d^{-1}) by radionuclides and species of game (Müller & Pröhl 1993)*

Radionuclide	**Biological transfer rates λ_g (d^{-1}) by radionuclides and species of game Roe deer, red deer, moose, wild boar**	**Brown hare, mountain hare, terrestrial birds, waterfowl**
Caesium	0.023	0.1
Iodine	7×10^{-3}	7×10^{-3}
Strontium	7×10^{-2}	7×10^{-2}
Plutonium	1×10^{-4}	1×10^{-4}

Table XXVII. *Begin and end of collection of mushrooms and berries and of hunting. Default values for Central Europe.*

	Begin of collection or hunting season (Julian days)	**End of collection or hunting season (Julian days)**
Mushrooms	152	334
Berries	182	289
Game	259	31

Table XXVIII. *Begin and end of collection of mushrooms and berries and of hunting. Default values for Northern Europe.*

	Begin of collection or hunting season (Julian days)	**End of collection or hunting season (Julian days)**
Mushrooms	189	329
Berries	196	304
Game	245	15

4 Dose calculation

Table XXIX *Processing factors of iodine, cesium, strontium and plutonium for processing of wild food products (IAEA 1994).*

Foodstuff	**Processing factors (R_f)**			
	iodine	**cesium**	**strontium**	**plutonium**
Mushrooms	1.0	0.5	0.5	1.0
Berries	1.0	0.8	0.8	1.0
Game	0.9	0.9	0.9	1.0

Table XXX. *Consumption of wild food products by population and its sub-groups (kg a^{-1}). Default values for Central Europe (Svadlenkova et al. 1996).*

Foodstuff	**Consumption of wild food products by population and its subgroups (kg y^{-1})**						
	Population (age in years)					**Pickers**	**Hunters**
	1	**5**	**10**	**15**	**20**	**20**	**20**
Mushrooms	0	0	0	0	0.2	5	0.2
Berries	0	0	0.05	0.1	0.2	3	0.2
Game	0	0	0	0	0.5	0.5	7

Table XXXI. *Consumption of wild food products by population and its subgroups (kg a^{-1}). Default values for Northern Europe (derived from the survey data of Markkula and Rantavaara 1997)*

Foodstuff	**Consumption of wild food products by population and its subgroups (kg y^{-1})**						
	Population (age in years)					**Pickers**	**Hunters**
	1	**5**	**10**	**15**	**20**	**20**	**20**
Mushrooms	0.17	0.36	0.43	0.49	1.26	5.7	1.8
Berries	1.62	3.43	4.1	4.67	6.9	28	13
Game	0.15	0.32	0.39	0.44	0.89	1.6	13

Table XXXII. *Heights and biomass densities of crown and trunk layers of different forest types for Central European conditions (Černý 1990; The Finnish Forest Research Institute, VIII National Forest Inventory)*

Forest type/ layer	**Height (m) of the layer**	**Density (kg m^{-3}) of the layer**
Mixed forest, crowns	15.2	2.7
Mixed forest, trunks	13.7	1.9
Deciduous forest, crowns	11.3	1.24 - 1.28
Deciduous forest, trunks	8.1	1.03
Coniferous forest, crowns	15.2	2.7
Coniferous forest, trunks	13.7	1.9

Table XXXIII. *Heights and biomass densities of crown and trunk layers of different forest types for Northern European conditions (The Finnish Forest Research Institute, VIII National Forest Inventory)*

Forest type/ layer	**Height (m) of the layer**	**Density (kg m^{-3}) of the layer**
Pine advanced thinning stand, crowns	8.3	0.81
Pine advanced thinning stand, trunks	7.9	1.16
Spruce advanced thinning stand, crowns	14.5	1.36
Spruce advanced thinning stand, trunks	4.2	0.92
Pine seedling stand, crowns	3.7	0.33
Pine seedling stand, trunks	1	0.23

Table XXXIV. *Time spent in forest by subgroups of population for all types of forests. Default values for Northern Europe.*

Month	**Time spent in forest (h m^{-1}) by subgroups of population**				
	5 years old	**20 years old**	**Hunters**	**Pickers**	**Forest workers**
1	3	3	3	3	200
2	3	3	3	3	200
3	3	3	3	3	200
4	3	3	3	3	200
5	3	3	3	3	200
6	3	3	3	3	200
7	3	3	3	6	200
8	3	3	6	6	200
9	3	3	6	6	200
10	3	3	6	6	200
11	3	3	6	3	200
12	3	3	3	3	200