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EcoFood - A tool for assessment of radiation exposure in terrestrial environments impacted by airborne releases

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Abstract

The software package FDMT - Food Chain and Dose Module for Terrestrial Pathways is a component of the decision support systems, JRODOS and ARGOS, that are currently used in the Nordic countries for response to nuclear emergencies. Not all food chains that are relevant for the Nordic conditions are currently supported by FDMT and the modelling of some of the food chains is not optimal for the Nordic conditions, resulting in difficulties with the parameterization of the models. Moreover, in its current implementation FDMT is not totally transparent to users. The focus of the project was to develop a new software (EcoFood) that addresses these deficiencies and considers the findings of a gap analysis of FDMT conducted early in the project. The report presents the findings of the gap analysis, provides an overview of EcoFood´s components: the Simulator, the Model Library and the Parameter Database and a discussion on improvements and advantages inherent to EcoFood.

Key words

radionuclide, releases, atmospheric, environment, terrestrial, dose, humans

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EcoFood - A tool for assessment of radiation exposure in terrestrial environments impacted by airborne releases

Final Report from the NKS-B EcoFood (Contract: AFT/B(20)5)

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Table of contents

1. Introduction

The software package FDMT -Food Chain and Dose Module for Terrestrial Pathways (Müller et al. 2004) is a component of the decision support systems, JRODOS and ARGOS, that are currently used in the Nordic countries for response to nuclear emergencies. FDMT allows modelling the transfer of radionuclides in terrestrial food chains following an atmospheric deposition, to obtain estimates of radionuclide concentrations in foodstuffs and doses to the public from their ingestion. Not all food chains that are relevant for the Nordic conditions are currently supported by FDMT and the modelling of some of the food chains included in JRODOS is not optimal for the Nordic conditions, resulting in difficulties with the parameterization of the models. Moreover, in its current implementation FDMT is not totally transparent to users.

This report presents the results of the NKS funded project EcoFood, implemented during 2020-2021. The focus of the project was to develop a new software (EcoFood) that addresses the above-mentioned deficiencies of FDMT and considering the findings of a gap analysis of FDMT conducted early in the project. The final goal of the project was to achieve a tool suitable for the Nordic conditions and that can be used in standalone mode, i.e., outside ARGOS and JRODOS.

The report consists of six main Sections. Section 2 presents the findings and conclusions of the gap analysis. Section 3 presents an overview of EcoFood. This Section is complemented by an Appendix describing the conceptual and mathematical models included in EcoFood. Section 4 presents a discussion on improvements in EcoFood, as compared to FDMT. Conclusions and recommendations for further development of EcoFood are provided in Section 5 and references are listed in Section 6.

2. Gap analysis of FDMT

The project started with a gap analysis of FDMT. For this, the project team studied relevant accident scenarios for FDMT application in the Nordic conditions and identified food chains that need to be included in the modelling. The team then compared the food chains included in FDMT and the modelling approaches with the identified needs for the Nordic countries. The team also considered findings from international projects that have examined FDMT, including:

PardNord and EcoDoses - NKS projects - these projects addressed improvements of radioecological assessment of doses to man from terrestrial ecosystems and recommended parameter values for Nordic conditions (Nielsen and Andersson, 2006, Nielsen and Andersson, 2008).

CONFIDENCE - EC project – The project addressed the issue of uncertainties in radiological impact assessments. Also, some sub-models of FDMT were implemented in Ecolego (Brown et al. 2018, Raskob et al. 2018).

COMET – EC project - has included efforts for improving human food chain modelling through regional customization of parameter values, using Bayesian methods, and studying the long-term dynamics of soil-to-plant transfers for specific soil types and for long-lived radionuclides (Thorring et al. 2016).

The sub-sections 2.1-2.6 below present the findings in the different focus areas of the gap analysis, and sub-section 2.7 presents a summary of features and functionalities that EcoFood is expected to have.

2.1. Soil models

In the current version of FDMT, the radionuclide activity concentration available for root uptake is modelled by accounting for post-depositional processes occurring in soil, these being migration/leaching of the radionuclide out of the rooting zone and fixation in soil and subsequent desorption. The soil model is formalised as the analytical solution to a system comprising of two compartments, representing the activity available and not available (fixed) for plants, with transfers (as rate constants representing the three processes above) between and from the compartments (Müller et al., 2004). As default values, the desorption rate is set to zero in FDMT and fixation rates of 2.2×10^{-4} d^{-1} for Cs and 9×10^{-5} d^{-1} for Sr are assumed (the provenance of these values, within Müller et al. (2004), is however unclear). For other elements it is assumed that fixation is of minor importance and is set to zero. Activity concentrations in crops are derived via the multiplication of a transfer factor (commonly referred to as soil-plant concentration ratios, in units of Bq/kg (f.w. plant) per Bq/kg (d.w. soil)) by the concentration of activity (Bq kg^{-1}) in the root zone of soil at time 't' (Müller et al., 2004). The activity concentration of a given radionuclide in the root zone is synonymous with the radionuclide activity concentration available for root uptake as noted above.

It is possible to consider different soil types in a simplistic way in FDMT by altering various parameters, notably migration/leaching rate, fixation, and desorption rates, for the soil -

processes module and by modifying the soil to crop transfer factor accordingly to make them congruent with the specific soils the assessor is dealing with. If such changes are required, a collation of empirical data specific to some of these parameters for given soil types is available from publications such as IAEA (2010). However, limitations are apparent in relation to how radionuclide behaviour in soils and transfer to plant/crop is modelled within FDMT, using the empirical approach.

Long-term Assessment and hot Particles

Following severe nuclear events, a major fraction of refractory radionuclides will be released as radioactive particles, containing fission and activation products such as ^{90}Sr and ^{137}Cs as well as transuranic radionuclides. Knowledge with respect to particle characteristics and processes influencing particle weathering in soils, i.e., the transformation of solid-state radionuclide species bound in a particle matrix to dissolved species is a prerequisite for robust prognoses. Essentially, information on potentially bioavailable forms (Kashparov et al., 2004) is needed to assess long-term impact from radioactive particle contamination. The current model in FDMT involving the behaviour of radionuclides in soils is, however, not suited to modification. For example, in the case given above, there is no easy way of adapting the model to account for the presence of hot particles.

Usually, measurements of environmental radioactivity and any associated assessments assume that radionuclides are homogenously distributed throughout of the environment. However, we know that this is a crude simplification and since both releases and spatial deposition of radionuclides are prone to heterogeneity.

According to IAEA (IAEA, 2011) radioactive particles are defined as a localized aggregation of radioactive atoms that give rise to an inhomogeneous distribution of radionuclides significantly different from that of the matrix background.

The release and presence of radioactive particles have been verified and studied over many years. However, their peculiar nature has not been widely recognized and understood until after the Chernobyl accident where substantial advances with regards to the characterization and environmental behavior of such particles were made (Beresford et al., 2016).

These findings can be used to improve models employed to simulate the transfer of radionuclides along food chains and to make their prediction more robust and less uncertain.

As part of EcoFood, and to improve FDMT, a model to account explicitly for the presence of radioactive particles could be included. It can be envisaged that this will make a difference at least in relation to long-term simulations for the prediction of activity concentrations of radionuclides in crops and soil.

2.2. Models for plants

Almahayni et al. (2019) reviewed empirical (i.e. transfer factor based), semi-mechanistic and mechanistic models and assessed their fitness for the purpose of emergency preparedness and response. Some of the disadvantages in applying an empirical transfer factor approach (as used in FDMT) were noted in this review. The empirical approach predictions for a given soil-plant may vary by up to four orders of magnitude as can be evidenced by reference to IAEA (2010).

Thus, substantial uncertainty is introduced when applying this approach. Furthermore, the predictions of radiocaesium activity concentrations in plants made using a transfer factor are based on total activity concentration in soil, despite the observation that this does not represent the `bioavailable` pool of the radionuclide in soil. A proportion of the total radiocaesium in soil is strongly fixed within soil minerals (e.g. certain types of clays) and is thus unavailable for plant uptake. Additionally, the TF approach does not account for radiocaesium sorption, ageing and competition with other ions in soil solution (notably K), which greatly influence radiocaesium availability to plants (Almahayni et al., 2019). It should furthermore be supplemented that, in its current form, the soil to plant transfer model in FDMT cannot be used to evaluate the influence of various soil-based countermeasure strategies. It is known, for example, that the application of K-fertiliser can influence the fraction of radiocaesium transferable to crops as discussed by Rosén & Vinichuk (2014) and Brown et al. (2020). It would be useful to be able to model this process.

Alternatives to the transfer factor model such as the semi-mechanistic Absalom model (Absalom et al., 2001) are available. Such models have the advantage that they relate the transfer of radiocaesium in plants to the bioavailable fraction in soil and consider the influence of soil chemistry. In this regard the model accounts for competition of radiocaesium with exchangeable potassium, the distribution of radiocaesium between solution and different solid phases (soil humus and clay) and the ageing process where the amount of radicoaesium in solution changes with time as more of the radionuclide becomes 'fixed' (albeit noting that the soil model in FDMT does actually capture this last process as well). The Absalom model requires ubiquitously measured parameters as input, namely: soil gravimetric clay content (g/g), gravimetric organic content (g/g), pH and exchangeable potassium ($cmol_c$/kg). Soluble NH_4 concentration were also included as input to the original model but this was later considered to be non-essential, i.e., taken to be zero unless specifically measured (Tarsitano et al., 2011). Process-based models offer an approach to understand/cope with the high degree of variability in empirical plant-soil concentration ratios and provide predictions more relevant to a given site (Brown et al. (2020).

A final note is required on the applicability of replacing empirical models with more mechanistic-based models with regards to time following an accident. In the early phase after an accident, processes related to interception and transfer in the crop canopy are critical in determining environmental activity concentrations. As time passes, i.e. several weeks to months, processes related to soil to plant uptake become more important. In this regard, the application of process-based models would become more relevant as time progressed and when more specific questions about contaminated areas had to be answered. For providing input towards countermeasure strategies in the long-term, the application of a semi-mechanistic model might be arguably seen as being extremely important (Brown et al. 2020).

2.3. Models for animals

Lamb

Thørring et al. (2016) noted that there is a clear seasonality of lamb/sheep production in Norway. The lambs are born in March–May, released on mountain or outfield pastures during

May–June and collected in September. The slaughter period is generally September–October (which provides most of the meat used for human consumption in the following year). There is currently no possibility to include this additional information in the extant FDMT model set up. The model used for predicting radionuclide activity concentrations in lamb meat in FDMT returns values linked to specific calendar dates/time points with the tacit assumption that the animal is continuously ingesting feed from a contaminated pasture and feedstuffs derived thereof, i.e., from hay. In line with the information provided by Thørring et al. (2016), it might be useful for an assessor to have the option to select a date of lamb slaughter. This date could then subsequently be used to define the activity concentrations that are used as input to the calculation of human ingestion doses whilst accounting for decay during a storage period. In this regard, one might note that lamb meat not entering the markets soon after slaughter may be frozen for utilisation later in time. Since this process is an annual event, the model simulations could be configured to simply follow the activity concentrations in lamb meat for each subsequent new year, starting, for example, in March-May in correspondence with information provided, and introducing a recurring slaughter date at the same time each year.

Reindeer

The original configuration of ECOSYS (Müller & Pröhl, 1993) was developed for agricultural conditions in Southern Germany and it was, therefore, natural that certain types of animal husbandry, such as those more typical of boreal climates, were not included in the initial modelling remit. In Norway, the importance of reindeer herding and the potential for radiocaesium to enter the human food-chain, following the Chernobyl accident was highlighted by Skuterud & Thørring (2012). For Fennoscandia in general, Åhman (2007), noted that contamination of reindeer with radiocaesium, following the accident had an impact on many aspects of reindeer husbandry. Presumably to account for this oversight in geographical coverage, some efforts have been made, during the process of transferring the ECOSYS model to a revamped version in the form of FDMT within the JRodos decision support system (Raskob et al., 2018), to include the option of modelling radionuclide transfer to reindeer. Staudt et al. (2016) included reindeer as an animal category for boreal and alpine radioecological regions in the process of FDMT regionalisation within the HARMONE project. However, the model was parameterised by adopting the feed to animal transfer factor (d kg^{-1}) for beef cattle. There was no evidence provided to support the efficacy of so doing. Furthermore, it was assumed that the animal was grazing within an Extensive pasture (and thereby ingesting grass for which transfer would have been dictated by more organic soil types than those associated with "Intensive" pastures) as opposed to the intensive pasture used to model transfer to beef cattle and cows. Furthermore, the diet of reindeer was derived from other farm animals in boreal systems so that the ingestion of grass and hay throughout the year was adopted from beef cattle and cow with the curious exception of water intake that was reduced substantially from the source values (presumably this has something to do with increased water requirements for animals that are milked). We consider these makeshift models for reindeer to be quite inadequate. Åhman (2007) argued that reindeer diets are quite complex involving a large variety of plants species (and most notably a large component of lichen in the winter that should be adequately accounted for). Furthermore, the changes in diet and metabolism (at least the biological half-life for radiocaesium) over the year render a simplification of the sort elaborated above problematic. Ideally a bespoke model for reindeer based on, for example, the analyses conducted by Åhman (2007) might be highly germane for the augmentation of FDMT.

2.5. Food chain parameters

As mentioned earlier, FDMT is an integrated module within the two main European decision support systems, ARGOS and JRODOS which are standard tools to be used in the event of an emergency for making decisions. The reliability of these tools is dependent on the robustness of their underlying sub-systems/ modules. Earlier studies (Nielsen and Andersson, 2006 and 2008) have demonstrated the sensitivity of FDMT's outcomes to several site-specific input parameters, such as soil type, sowing and harvesting times, feeding regimes for animals and human consumption habits /dietary composition.

The ECOSYS/ FDMT model was originally developed and parametrized for Southern German conditions, so its application for other conditions, such as Nordic countries, without modifying the default parameters to reflect the new conditions would undermine the credibility of its outcomes.

For Norway, for example, one necessary modification is related to dietary compositions. The default list of food products in FDMT should be augmented with at least two Norwegian foodstuffs; brown cheese and reindeer.

Brown cheese
Brown ("whey") cheese is regarded as one of Norway's most iconic foodstuffs and is considered an important part of Norwegian gastronomical and cultural identity and heritage (https://en.wikipedia.org/wiki/Brunost). In addition to being an important foodstuff in the Norwegian diet, it has been shown that it can accumulate high levels of radiocaesium. To make brown cheese both cow's and goat's milk, or a mixture of the two, can be used. Studies conducted after the Chernobyl accident indicated that brown cheese made of goat milk is more prone for accumulating radioactive caesium (Nielsen and Andersson, 2008). Following potassium in milk and milk products, radioactive caesium will be concentrated in the whey, noting that upon production of the cheese the whey is reduced to almost a 10th of its original volume. So, any contaminants present in the whey will also be concentrated by a factor of 10 times (or more) in the final product (Nielsen and Andersson, 2008).

Reindeer
Reindeer herding is an occupational activity of cultural importance in Norway, as well as in Finland and Sweden. The dietary surveys have confirmed that reindeer meat is the main source of radiocaesium to reindeer herders, contributing about 90 % of the radiocaesium intake in central Norway (Thørring et al., 2004b).

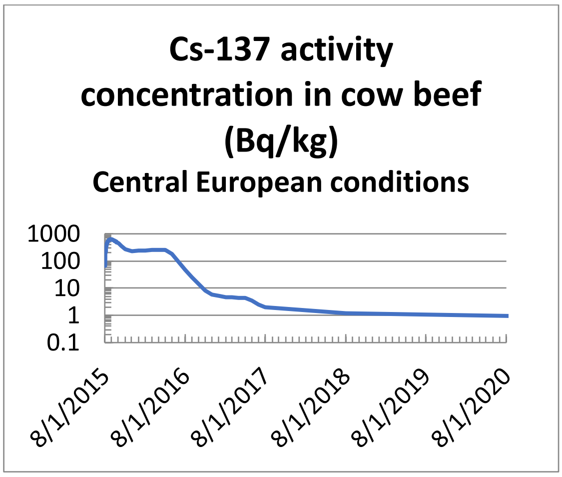
As in the case of brown cheese, reindeer meet is not part of the default diet list of ECOSYS/FDMT. DSA has conducted dietary surveys among reindeer herders in central and northern Norway (Thørring et al. (2004a) and (2004b)) that can be used in the process of adaptation of FDMT for Norwegian condition.

Lessons learn from the COMET project
One task of the COMET project was dedicated to investigating FDMT´s model parameters. It was found that FDMT´s default parameter values, taken from Central European environments, are not appropriate for Nordic and Mediterranean regions of Europe. The aim of COMET was to find in the literature parameter values that are representative for Nordic and Mediterranean terrestrial ecosystems. In this endeavour, it was important to identify parameters that have the

highest effect on the final dose assessment. Finland, Norway, Spain used FDMT in this task and France also attended with their model SYMBIOSE. Finland and Spain are JRODOS users while Norway uses ARGOS as an FDMT platform.

The focus of the work was to identify: (1) parameters of relevance to growing season and harvest periods of crops and grass including seasonal development of leaf area indices (LAI) (i.e., agricultural calendars), (2) animal feeding practice, and (3) human consumption of foodstuffs. Parameters were first collected, and some calculations were made using default parameters vs. localized parameters. Sensitivity of parameters and their contribution on doses were estimated.

The results of the study showed very different results when using the default FDMT values (for central European environments) and localized values. One example is presented in Figure 1 where results obtained using Finnish and Central European parameters are compared.



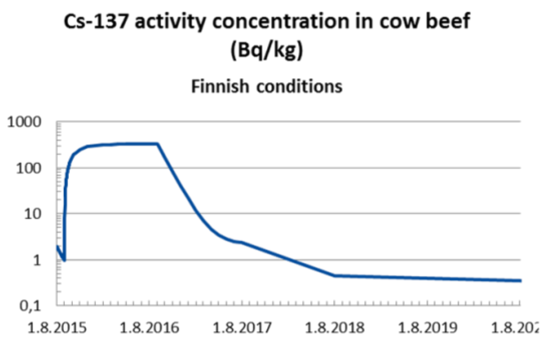


Figure 1. Cs-137 concentration in cow beef calculated with different sets of values for radioecological parameters in FDMT.

The results in Figure 1 do make sense. In Finland during the summer beef cattle does not usually graze outside and therefore the doses at the beginning are caused by inhalation. When contaminated grass (silage) is harvested and fed to animals the activity concentration in cow meet begins to increase.

According to the COMET study the following parameters can be regarded as the most important ones:

- Relevant growth periods (leaf area indices (LAI), yields, period of preparing winter feed).

- Animal parameters (animal specific feeding ratios and use of different feedstuffs during different seasons of the year).

- Human habits (age-dependent consumption rates, seasonality of consumption rates) Dietary habits may significantly change over time and that is why they must be regularly updated.

- Radioecological parameters related to the uptake by plants from the soil (transfer factors, migration rates)

It was also noted that FDMT uses grouping of different foodstuffs. However, common vegetables such as cauliflower, onions and peas do not seem to belong to any of FDMT's groups.

From feedstuffs grass silage is missing. This is not present in FDMT, but it is a crucial feedstuff in Nordic countries. During the project work STUK tried to add it to FDMT tables with no success. Also grazing of cows in outfield or in rough mountains is not considered in the model. Imported feedstuff like maize and soya are also missing from the FDMT feedstuff products, but that is probably not necessary as they are not locally produced.

From the COMET study it can be concluded that the categories should be described better in order to classify the consumer data better. There is no information about which vegetables belongs to each vegetable groups (leafy, root and fruit vegs).

Vegetables could be classified based on the part of the plant that is used for food. In FDMT, potatoes and beet have their categories. Some suggestion on what the vegetable categories should cover:

Leafy vegetables: lettuce, spinach, kale, cabbage, herbs

Fruit vegetables: tomato, eggplant, paprika, cucumber

Root vegetables: carrot, turnip, celeriac, parsnip,

Based on abovementioned classification, suggestions on what vegetable categories are missing from the FDMT list are as follows:

Legumes: peas, beans

Flower vegetables: cauliflower, broccoli, artichoke

Bulb vegetables: onions, garlic, leek

These categories could be added as new categories in the FDMT list or combined to the existing ones if the categories would be described in detail.

If the forest environment is included in EcoFood, forest mushrooms and berries could be added as their own categories as their consumption in the Nordic countries, at least in Finland, is notable.

2.6. Uncertainty analysis

Uncertainty, in general, is a concept that describes a state that arises because of having limited knowledge to estimate an outcome. It is impossible to exactly describe the existing state, a future outcome, or more than one possible outcome. So, there is uncertainty in any prediction, including predictions that are made with mathematical models, such as FDMT.

Uncertainty in model predictions can arise from several sources, including System (scenario) uncertainties, uncertainties in the mathematical models applied (Model uncertainty), and uncertainty in the values of the model parameters.

Uncertainty analysis is an important component of a radiological impact assessment using models. It can be defined as the process of identifying the sources of uncertainties, quantifying the uncertainty of the different assessment components, through a process of quantifying and propagating uncertainties through the models.

Lessons learn from the CONFIDENT project

The recently funded CONFIDENCE project (Raskob & Duranova, 2020) identified the fact that, in the context of nuclear management and long-term rehabilitation, dealing with uncertain information on the current and (predicted) evolving situation, is an intrinsic problem for decision making. The authors noted that uncertain information can result in dose assessment predictions that diverge dramatically from reality and that uncertainty forms an intrinsic component of parameter uncertainty. Furthermore, the fact that decisions based on uncertain information may lead to an outcome of "more harm than good", as evidenced by experience following the Chernobyl and Fukushima accidents, renders the necessity to reduce uncertainty a pressing issue. A key driver for the CONFIDENCE project identified by Raskob & Duranova, (2020) was the observation that uncertainty handling in simulation models, in particular decision support systems, was far from being solved.

In the context of food-chain transfer models some initial inroads into mitigating the situation regarding uncertainty handling were made in the CONFIDENCE project. Of particular note was the work of Hamburger et al. (2020) who considered the propagation of uncertainty through a modelling system involving both the atmospheric advection and dispersion of radionuclides and the subsequent transfer through an agricultural food-chain using FDMT. What this study found was that, depending on the growth season and type of radionuclide, uncertainties in the food chain model can add substantial variability to the results of dispersion models. In other words, characterising uncertainty in food-chain transfer models might be considered a constructive endeavour. As part of the underpinning effort to provide uncertainty estimates for the FDMT food-chain error propagation simulations, a literature search and data collation was performed for numerous key parameters in the FDMT model. The statistical information thus collated (see Brown et al., 2018) can from the basis for more detailed future analysis.

Lessons learn from the COMET project

It was noted in the COMET project that the behaviour of the FDMT model is not fully transparent. Moreover, the documentation of FDMT is rather old. Some of its components have been developed without updating the documentation. If somebody finds the results strange it is not easy to find out if it is a bug or a feature. Some inconsistency in results also occurred during the calculation process. That might be related to numerical issues. The results also differ between JRODOS and ARGOS which is probably caused by different (fixed) input parameters.

2.7. Summary of the gap analysis

The findings from the gap analysis concerning models, features, and functionalities that EcoFood should support can be summarized as follows:

- A generic and more flexible implementation of the FDMT models is required to ensure that they can be adapted to the Nordic conditions.

- The models and their implementation should be transparent to users.

- Several food chains models, for example reindeer, that are relevant for the Nordic countries, are missing in FDMT and should be implemented.

- Dynamic models shall be implemented for the soil that are applicable for all relevant scenarios, for example contamination with hot particles.

- It should be possible to incorporate mechanistic models for estimating highly uncertain radioecological parameter, such as soil-to-plant transfer factors and distribution coefficients.

- A database functionality shall be included that facilitates using localized values for the food chain model parameters.

- Methods for parameter sensitivity and uncertainty analyses should be included.

3. Overview of EcoFood

EcoFood is a software package for modelling the transfer in terrestrial food chains of radionuclides released to the atmosphere during a nuclear or radiological accident. EcoFood implements all FDMT sub-models (Müller et al. 2004), which are based on the ECOSYS model (Müller and Pröhl, 2006). EcoFood includes some improvements of the FDMT models and some additional models, which have been added for addressing some of the gaps identified and presented in Section 2.

From the start of the project a decision was taken to develop EcoFood using the Ecolego (http://ecolego.se) software. Ecolego is a software package for implementing dynamic models described by first order ordinary differential equations (i.e., compartmental models) and performing probabilistic simulations. Ecolego has been proved successful in several similar international projects, such as the development of the IAEA tools SAFRAN (http://safran.facilia.se) and NORMALYSA http://project.facilia.se/normalysa/software.html).

Models can be developed in Ecolego, without needing any programming, by users that have a software license. At the same time, a license of the Ecolego software is not required for setting up, assigning parameter values and running the models. This can be done using the Ecolego Player, which is free of charge and can be downloaded from the Ecolego website.

This approach of using Ecolego for the EcoFood development has the following advantages:

- The use of Ecolego functionality for creating and managing model libraries ensures that the software architecture of EcoFood allows end users to easily configure a variety of situations of exposure of individuals following a release to the atmosphere, providing essential flexibility in accounting for site specific conditions and exposure situations.

- The generic database functionality existing in Ecolego allows to create a flexible and expandable database for EcoFood, which facilitates the use of region-specific parameter values in the models.

- The models implemented in Ecolego are fully transparent to end users, who can examine all model equations and parameters.

- The powerful numerical solvers available in Ecolego ensures that any compartment model can be implemented, without requiring analytical solutions.

- Ecolego includes state of the art sensitivity and uncertainty analysis methods that can be used directly in EcoFood.

The main components of EcoFood are the Simulator program engine (Section 3.1), which is integrated with a set of program modules organized in libraries (Section 3.2) and a parameter database (Section 3.3).

3.1. The EcoFood Simulator

The EcoFood Simulator provides Graphical User Interface (GUI) capabilities, where site specific models can be created using blocks from the model libraries. The simulator has been developed based on the Ecolego Player, which can be downloaded free of charge from the Ecolego website (http://ecolego.se). The User Guide of the Player is also valid for the EcoFood Simulator.

The Simulator supports "Interaction Matrix" presentation of the conceptual model, as well as the common "Block-Scheme" presentation. An example of the "Interaction Matrix" presentation is shown in Figure 2.

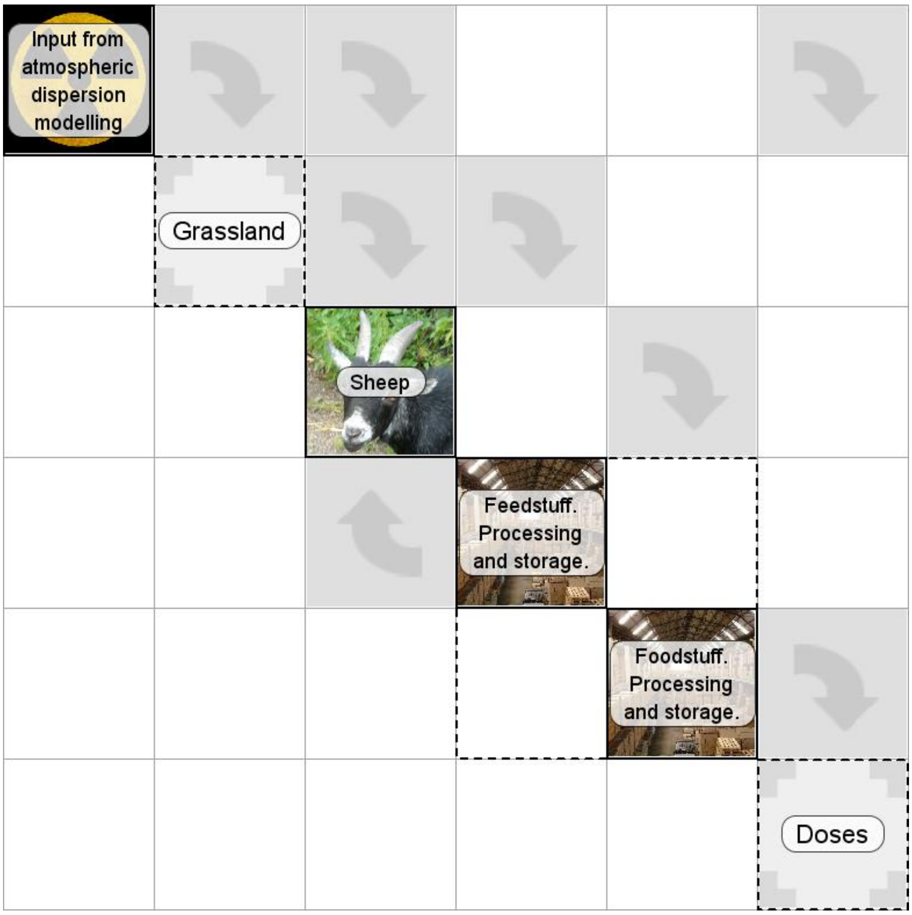


Figure 2. Interaction Matrix representation in EcoFood of the Conceptual Model. The models that are included are shown in the diagonal elements, whereas the transfer of information between them is shown with arrows in the non-diagonal elements.

This EcoFood Simulator interface allows easily:

- selecting needed models from the EcoFood Library (see Section 3.2),
- "connecting models", that is setting data exchanges between the models,
- specifying model parameter values directly in the model, importing/exporting parameter values from excel or from the EcoFood Parameter Database (see Section 3.3),

- performing deterministic and probabilistic simulations with the assembled model,
- examining outputs and analyzing simulation results (table and/or graph formats).

The EcoFood Simulator includes the simulation capabilities and functionality inherent to Ecolego software. This includes:

- built-in radionuclide database,
- powerful numerical solvers for ordinary differential equations (ODE-s), which are used in compartment models to mathematically describe radionuclide transport and transfer process,
- capabilities for probabilistic simulation, uncertainty, and sensitivity analyses,
- output data processing capabilities, including graphical presentation of modeling results,
- report generation options.

3.2. The EcoFood Model Library

The EcoFood Model Library is organized as several modules, each containing models of different components of the modelled system. Some of the models in the library are **FDMT models** as implemented in Ecolego, whereas some others are Ecolego implementations of other models described in the literature. The modules are briefly described below, and the conceptual and mathematical models are presented in the Appendix.

Module – Input

This module does the post-processing of the input from the atmospheric dispersion modelling to obtain the input required by other models to simulate the radionuclide transfer through the food chains.

	Name of model	**Short description**
	Input from atmospheric dispersion modelling	Provides the input from the atmospheric dispersion model or from measurements required by the food chains models: concentration in air, dry and wet deposition rates. Also includes calculation of the deposition rates from the integrated air concentration.

Module – Models of soils

This module includes models of the transfer of deposited radionuclide in soil and out of it.

	Name of model	**Short description**
	Analytical/FDMT Soil model	Implementation of the **FDMT model** for soils consisting of an analytical solution of 2-comparment model. Considers the processes of leaching, sorption, desorption, and fixation of radionuclides through rate constants. Calculates time dependent concentrations in the rooting zone of the soil.
	Simple dynamic	Compartment (One) dynamic model, which considers the processes of leaching, sorption, desorption, and fixation of radionuclides through rate constants. The Kd-approach (Baes and Sharp, 1983) for modelling the sorption/desorption is also included. Calculates time dependent total concentrations in the rooting zone of the soil.
	Dynamic	Implementation of the model by (Kasparov et al. 2004) for the case when there is no presence of hot particles in the deposition. Considers the processes of leaching, sorption, desorption, fixation, and remobilization of radionuclides through rate constants. The Kd-approach (Baes and Sharp, 1983) for modelling the sorption/desorption is also included. Calculates time dependent concentrations in the different fractions of the rooting zone of the soil.
	Dynamic with hot particles	Implementation of the model by (Kasparov et al. 2004) for the case when hot particles are present in the deposition. Considers the soil processes of leaching, sorption, desorption, fixation, and remobilization of radionuclides, as well as leaching from hot particles, through rate constants. The Kd-approach (Baes and Sharp, 1983) for modelling the sorption/desorption is also included. Calculates time dependent concentrations in different fractions of the rooting zone of the soil.

Module – Models of plants

This module includes models of the transfer of deposited radionuclide to plants and within the plants.

	Name of model	**Short description**
	Generic Plant	Model for a generic plant. All transfer processes are included (interception, translocation, weathering, root uptake) and can be switched on/off by the user. Various modes of harvesting and representation of growth dilution are available for selection. Calculates time dependent concentrations in raw foods and feeds.
	Grass/hay	Implementation of the **FDMT model** for grass and hay. Calculates time dependent concentrations in grass and hay.
	Type 2 Plant	Implementation of the **FDMT model** for Type 2 plants. Examples of plants: maize, beet leaves. Calculates time dependent concentrations in foods and feeds.
	Type 3 Plant	Implementation of the **FDMT model** for Type 3 plants. Examples: Leafy vegetables Calculates time dependent concentrations in foods and feeds.
	Type 4 Plant	Implementation of the **FDMT model** for Type 4 plants. Examples: Corn cobs, beet, potatoes, cereals Calculates time dependent concentrations in foods and feeds.
	Type 5 Plant	Implementation of the **FDMT model** for Type 5 plants. Examples: Root vegetables, fruit vegetables, berries. Calculates time dependent concentrations in foods and feeds.

Module - Intelligent Transfer Factors (TFs) and distribution coefficients (Kds)

This module includes models for calculation of soil-to-plant TFs and Kds based on soil and plant properties.

	Name of models	**Short description**
	Transfer Factor grass	Implementation of the model by (Absalom et al. 2001, Tarsitano et al. 2011) for calculation of Caesium TFs from soil to grass.
	Transfer Factor crops	Implementation of the model by (Absalom et al. 2001, Tarsitano et al. 2011) for calculation of Caesium TFs from soil to crops.
	Distribution coefficient	Implementation of the model by (Absalom et al. 2001, Tarsitano et al. 2011) for calculation of Caesium Kds.

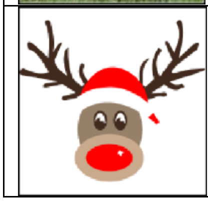
Module – Models of biotopes

This module includes integrated models of the soil-plant system for different types of biotopes. The models have been built by integrating library models for soil and plants.

	Name of model	**Short description**
	Grassland	Model of the soil-plant system for a grassland. Developed from integration of the model for Grass/hay with the Analytical Soil model. Calculates time dependent concentrations in soil and grass/hay.
	Type 2 Cropland	Model of the soil-plant system for a Type-2 cropland. Developed from integration of the model for Type 2 plants with the Analytical Soil model. Calculates time dependent concentrations in soil and foods, feeds from Type 2 plants.
	Type 3 Cropland	Model of the soil-plant system for a Type-3 cropland. Developed from integration of the model for Type 3 plants with the Analytical Soil model. Calculates time dependent concentrations in soil and foods, feeds from Type 3 plants.
	Type 4 Cropland	Model of the soil-plant system for a Type-4 cropland. Developed from integration of the model for Type 4 plants with the Analytical Soil model. Calculates time dependent concentrations in soil and foods, feeds from Type 4 plants.
	Type 5 Cropland	Model of the soil-plant system for a Type-5 cropland. Developed from integration of the model for Type 5 plants with the Analytical Soil model. Calculates time dependent concentrations in soil and foods, feeds from Type 5 plants.

Module – Models for animals

This module includes models of the intake of radionuclides by animals via inhalation and feed ingestion and their transfer to animal foods.

	Name of model	Short description
	Generic animal	Generic implementation of the **FDMT model** for animals. Considers intake of radionuclides via ingestion and inhalation. Flexible implementation of the choice of feeds and slaughtering time. Calculates time dependent concentrations in animal foods.
	Lamb Fårikål	Model implemented by parameterization of the “Generic animal” model. Calculates time dependent concentrations in raw meat from Lamb Fårikål.
	Reindeer	Implementation of the reindeer model by (Åhman, 2007). Calculates time dependent concentrations in raw meat from reindeer.

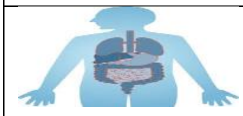
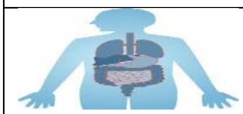
Module – Models of food storage and processing

This module includes models of changes in activity concentrations in human foods and animal feeds during storage and processing of the foods and feeds.

	Name of model	Short description
	Food processing	Implementation of the **FDMT models** of changes in activity concentrations in human foods by storage and processing of the foods. Calculates time dependent activity concentrations of radionuclides in processed/stored foods.
	Feed processing	Implementation of the **FDMT models** of changes in activity concentrations in animal feeds by storage and processing of the feeds. Calculates time dependent activity concentrations of radionuclides in processed/stored feeds.

Module – Models for calculation of doses to humans

This module includes models for calculation of doses to humans of different age groups by different exposure pathways. The module includes models for effective doses and doses to different organs.

	Name of model	Short description
	Dose to organs - food ingestion	Implementation of the **FDMT models** for calculation of doses to different organs from food ingestion. Calculates time dependent doses for different age groups.
	Effective dose - food ingestion	Implementation of the **FDMT models** for calculation of effective doses from food ingestion. Calculates time dependent doses for different age groups.
	Dose to organs - occupancy	Implementation of the **FDMT models** for calculation of doses to different organs from inhalation, external exposure from the cloud and the ground. The model considers attenuation inside buildings. Calculates time dependent doses for different age groups.
	Effective dose - occupancy	Implementation of the **FDMT models** for calculation of effective doses from inhalation, external exposure from the cloud and the ground. The model considers attenuation inside buildings. Calculates time dependent doses for different age groups.

3.3. The EcoFood Parameter Database

The EcoFood Parameter Database consists of a SQL database that can be installed locally on the user computer or on a shared server. All parameters of the models in the EcoFood Model Library have been added to the database. For each parameter multiple values can be added and tagged as desired by the user. The following data have been added to the database:

- Default values of all parameters in FDMT.
- Recommended values for Nordic conditions (NKS PardNord and ECODoses projects) of deposition parameters in FDMT.
- Relevant values for Nordic conditions of FDMT parameters collated within the EC funded projects CONFIDENCE and COMET.

It is possible to import/export parameter values from an EcoFood model, or the user can add/extract parameter values directly from the database interface. The EcoFood Parameter Database also supports import/export of parameter values from Excel.

4. Improvements implemented in EcoFood

Various improvements and additions to FDMT have been incorporated in EcoFood with the aim of addressing gaps identified in Section 2. These are described in the subsections below.

4.1. Models for soils

In FDMT the soil model is formalised as the analytical solution to a system comprising of two compartments, representing the activity available and not available (fixed) for plants, with transfers, expressed as rate constants, between and from the compartments (Müller et al., 2004). Values of these rates constants are given for Cs and Sr, whereas for other elements it is assumed that fixation is of minor importance and the rate of fixation is set to zero. Leaching of radionuclides from the rooting layer of the soil is also modelled with a rate constant.

As mentioned in Section 2, it is difficult to adapt the FDMT soil model to specific site conditions and to incorporate other processes, such as leaching of radionuclides from hot particles. Therefore, in addition to the FDMT model, three more soil models have been implemented in EcoFood (see Section 3).

The three added soil models are compartment models that are integrated numerically in EcoFood. The most complex of them (presented in Figure 3) is an implementation of the model by (Kashparov et al. 2004), which consists of 6 compartment and that can handle leaching of radionuclides from hot particles. In addition, the model considers the soil processes of sorption/desorption, fixation, remobilization and leaching of radionuclides.

The two other dynamic models are simplifications of the Kashparov model. In one of them the only difference is that Hot Particles are not considered, whereas in the simplest one instantaneous steady state is assumed between the Soil Solution and the Exchangeable fraction. Sorption and desorption process are considered implicitly in the model for the leaching from the soil, using a distribution coefficient (Kd) in the equation for the leaching rate.

Intelligent distribution coefficients (Kds)

The selection of one or another model for a specific assessment will depend on the site conditions and the availability of data. A common parameter in all three EcoFood dynamic soil models is the distribution coefficient (kd). This parameter has a large variability from site to site, depending on the soil type and composition. A promising approach for dealing with this, is to express the Kd as a function of the soil properties, i.e., by using so-called “intelligent kds”. A functionality has been added to EcoFood to be able to use “intelligent Kds” in any of the dynamic soil models available in the library. Figure 4 illustrates how models for “intelligent kds” from the EcoFood library could be linked to a dynamic model for the soil. In the current version of EcoFood, “intelligent kds” have been added only for Cs, but they can be easily added for other elements.

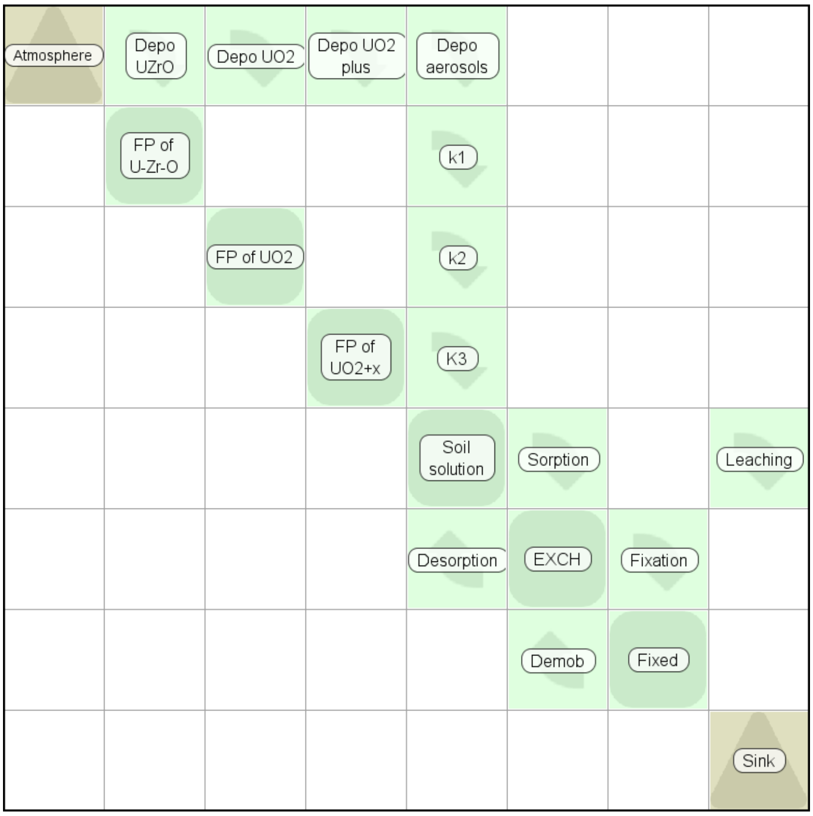


Figure 3. EcoFood dynamic soil model that supports consideration of deposited hot particles as a source of radionuclides entering the soil solution. The model considers explicitly the sorption/desorption, fixation, remobilization and leaching of the radionuclides.

Figure 4. Illustration of how "intelligent" distribution coefficients (Kd_soil) and transfer factors (TF_grass) can be added to a model created using the EcoFood model library.

4.2. Models for plants

The models in FDMT make simplifying assumptions about the transfer in the soil-plant system and the harvest of crops that differ between plant categories. As mentioned in Section 2, sometimes it is not straightforward to assign certain Nordic plant and crops to FDMT categories. For this reason, a generic plant model has been added in EcoFood, which includes all transfer processes and modes of harvesting. By making the appropriate selection of model settings, the user can tailor the model to fit any desired plant/crop. In fact, the FDMT models included in the EcoFood library have been built using this generic plant model.

Intelligent Transfer Factors (TFs)

All plant models available in EcoFood make use of soil-to-plant transfer factors (TF). It is well-known that the TFs show a large variability between sites, which contributes to the uncertainty of the model predictions. An approach for dealing with this, is to express the TF as a function of the soil and plant properties, i.e., by using so-called “intelligent TFs”. A functionality has been added to EcoFood to be able to use “intelligent TFs” in any of the plant models available in the library. Figure 4 illustrates how models for “intelligent TFs” from the EcoFood library could be linked to a plant model. In the current version of EcoFood, “intelligent TFs” have been added only for Cs, but they can be easily added for other elements.

4.3. Models for animals

The parameterization of the FDMT models varies between categories of animals/animal foods. The gap analyses performed (Section 2) showed that these models are hardly applicable for all animals and conditions that are relevant for the Nordic countries. For this reason, a generic animal model has been added in EcoFood, which has more flexibility in defining the types of feeds consumed, the slaughtering time, etc. By making the appropriate selection of model settings, the user can tailor the model to fit any desired conditions. This generic model has been used to re-create the animal models included in FDMT. It has also been used to create models for animals that are relevant for the Nordic countries and not included in FDMT. An example is the implementation of a model for Lamb Fårikål. Figure 5 illustrates how this model can be flexibly combined with other models in the EcoFood library - The generic animal model supports any combination of feeds, which is not possible in the FDMT models.

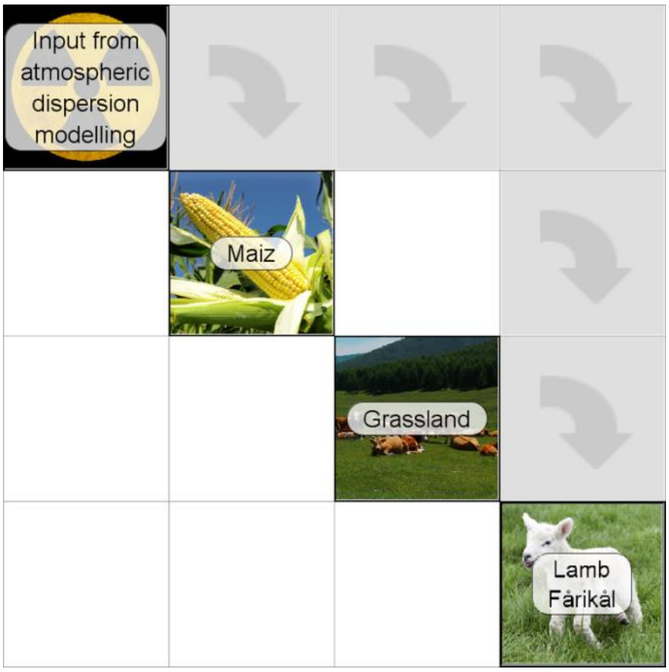


Figure 5. Illustration of how the Lamb Fårikål model is combined wih other models from the EcoFood library.

Reindeer meet is an example of animal food that is not included in FDMT. In this case, it was not possible to use the EcoFood generic model for building the reindeer model. Instead, a new library model was develop based on the model described in (Åhman, 2007).

4.4. Uncertainty and sensitivity analyses

In EcoFood uncertainty and sensitivity analyses of the models can be performed by doing probabilistic runs of the models. The process for these analyses is briefly described below.

Uncertainty analysis

Each model parameter can be assigned a Probability Density Function (PDF) to represent uncertainty in the parameter value. The parameter PDFs are then used to estimate the uncertainty of the model simulation endpoints, by propagating the uncertainties through the model. This is done by performing probabilistic simulations, where samples are taken from each parameter PDF, and the results tallied usually in the form of a PDF or Cumulative Distribution Function (CDF). This process is illustrated in Figure 6 for the case of a simple model with one input, one parameter and one endpoint.

Several techniques for sampling from input and parameters distributions are available in the literature (IAEA, 1989). EcoFood supports the conventional Monte Carlo sampling (Vose, 1996) consisting of taking random samples from the PDFs. It also supports Latin Hypercube sampling (Iman and Helton, 1988), where the input distributions are divided into intervals of equal probability and random samples are taken from within each interval.

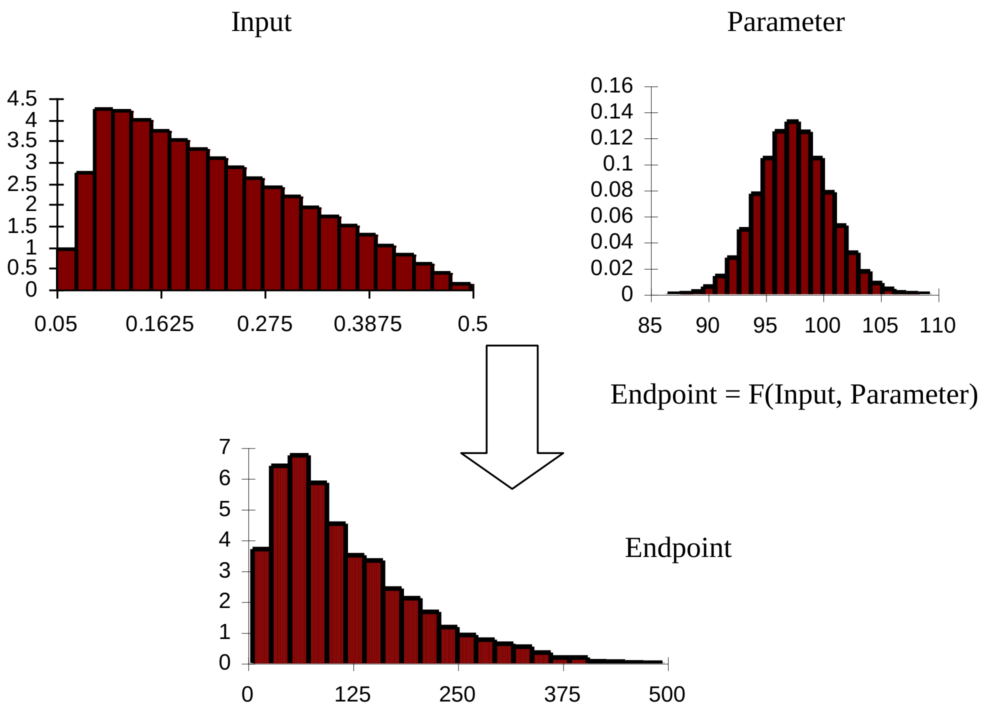


Figure 6. Illustration of the use of probabilistic simulations for propagating the uncertainties in the inputs and parameters through the model.

Sensitivity analysis

The results from the probabilistic simulations can be used for performing parameter sensitivity analyses. Sensitivity analysis is used to apportion the relative effect of the uncertainty in each model input/parameter on the uncertainty of each simulation endpoint. Several sensitivity analysis methods, of varying degree of complexity, have been proposed in the literature (Saltelli et al. 2004). The choice on an appropriate method depends on several factors such as the time required for a model simulation, the number of uncertain parameters and the type of dependency between inputs and outputs. For linear dependencies, simple methods based on correlations, such as the Pearson Correlation Coefficient (PCC) and the Spearman Rank Correlation Coefficient (SRCC) are sufficient; while for complex non-monotonic dependencies more advanced methods, based on the decomposition of the variance, are required (Saltelli et la. 2004). Both types of methods are supported by EcoFood.

The results of the sensitivity analysis can be presented in many ways, for example as tornado plots (See Figure 7). These are simple bar graphs where sensitivity statistics, for example the PCC or the SRCC, are visualized with vertical bars in order of descending absolute value. The largest the bar, the largest is the effect of a parameter on the simulation endpoint. The parameters that have positive bars (X2, X6 and X7 in Figure 7) have a positive effect on the endpoint, whereas those with negative bars (X1, X3, X4 and X5 in Figure 7) have a negative effect.

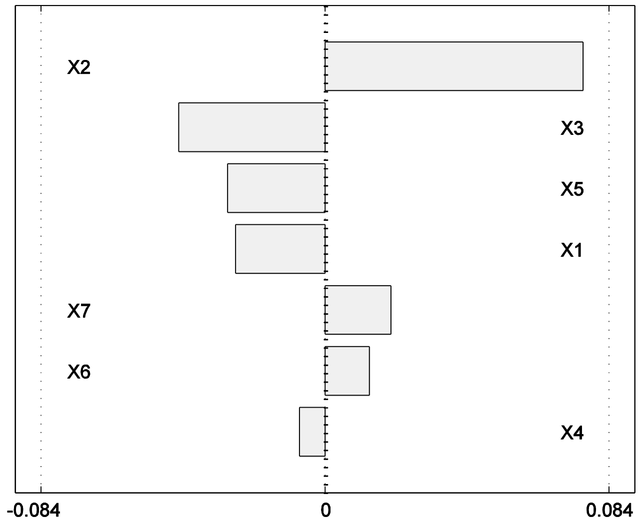


Figure 7. Example of a tornado plot representing the sensitivity statistics (values in the x-axis).

5. Conclusions and recommendations

In this project, a modern software package, EcoFood, has been developed for simulation of the transfer in food chains of radionuclides released to the atmosphere during a nuclear or radiological accident.

EcoFood includes all sub-models in FDMT, with several required improvements and extensions, identified from the gap analysis of the applicability of FDMT for the conditions of the Nordic countries:

- A more generic and flexible implementation of several FDMT´s sub-models (plants and animals), which facilitates their parameterization (use of localized parameters) and implementation of food chains typical for the Nordic conditions.

- The implementation of a database which contains representative parameters values for the Nordic conditions, obtained from previous NKS and EC projects.

- Implementation of models for food chains that are missing in FDMT, such as the reindeer food chain.

- Implementation of various dynamic models of radionuclide behaviour in soils that are suitable for incorporating some processes that might be present in some conditions, but that are missing in FDMT. An example is the leaching of radionuclides from hot particles. Also, the added dynamic models are more flexible for parameterization.

- Implementation of functionality for using intelligent Transfer Factors (TFs) and Distribution Coefficients (Kds) in the models, which is a promising way of dealing with the large uncertainty of these parameters. In this project this functionality has used for implementing intelligent TFs and Kds for Caesium.

As a software, EcoFood offers several other advantages:

- Programming is not needed for modifying and adding models to the EcoFood Model Library.

- The models are totally transparent to end users, who can inspect all equations and parameters.

- It is possible to perform parameter sensitivity and uncertainty analysis of any EcoFood model.

The following areas for further developments and improvements of EcoFood have been identified by the project team:

- Adding models of some missing food chains to the EcoFood Model Library, such as forest food chains.

- Adding models for freshwater objects (rivers and lakes).

- Adding intelligent TFs and Kds for other elements.

- Improvements in the representation of transfer processes and their parameterizations. An example is the improvements of the representation and parameterization of the translocation of radionuclides in plants using approaches described in the literature (Aarkrog et al., 1983, Aarkrog, 1994).

- Further improvements of the soil models. For example, by dividing the soil into several vertical layers, to be able to represent processes like bioturbation and surface run-off.

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Appendix. Conceptual and Mathematical Models

Conceptual model

A conceptual schematization of the overall model is shown below (Figure A1).

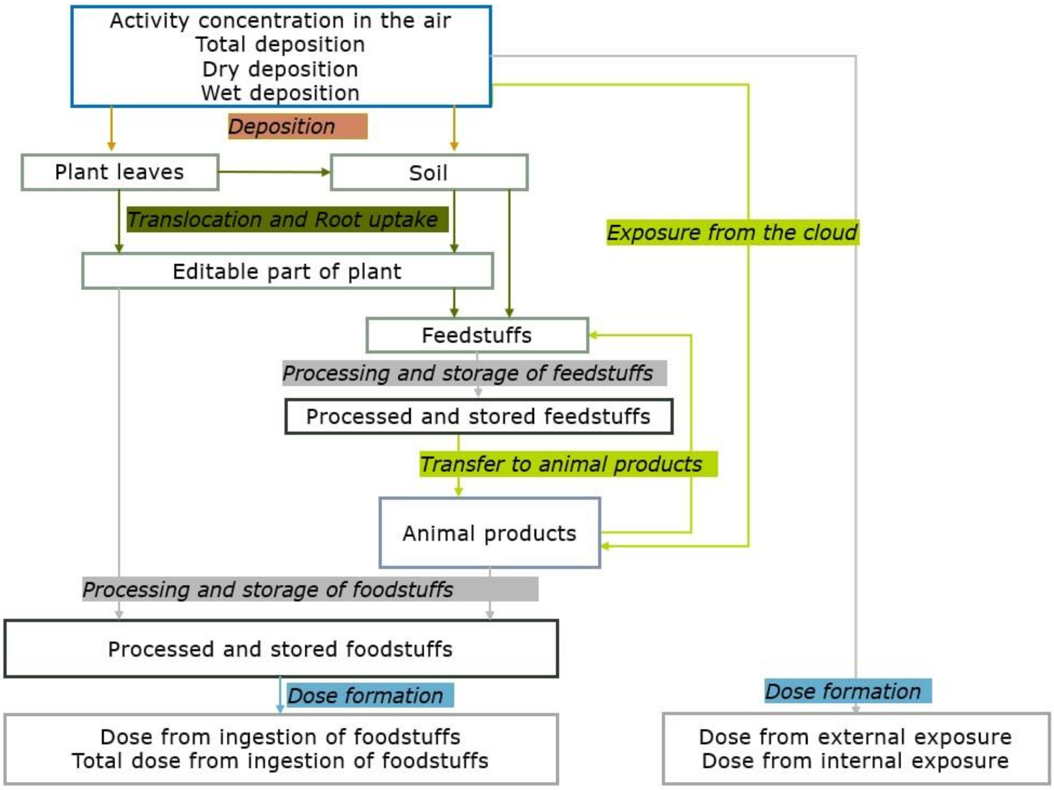

Figure A1. Schematization of radionuclides transfer in a terrestrial system

The model starts calculations from the output of the atmospheric dispersion models. The main input quantities are:

- the time-integrated activity concentration in the near ground air,
- the wet activity deposited per unit ground area,
- the amount of precipitation,
- the date of the deposition (day, month).

Contamination of plant products

The processes of the radionuclide deposition and interception by vegetation and soil are the starting point of their transfer in the food chains. Dry and wet deposition are considered separately to consider the actual circumstances as realistically as possible.

The contamination of plants is given by the activity transferred via the foliage, and the activity resulting from root uptake from the soil.

Interaction of plants with contamination is shown below:

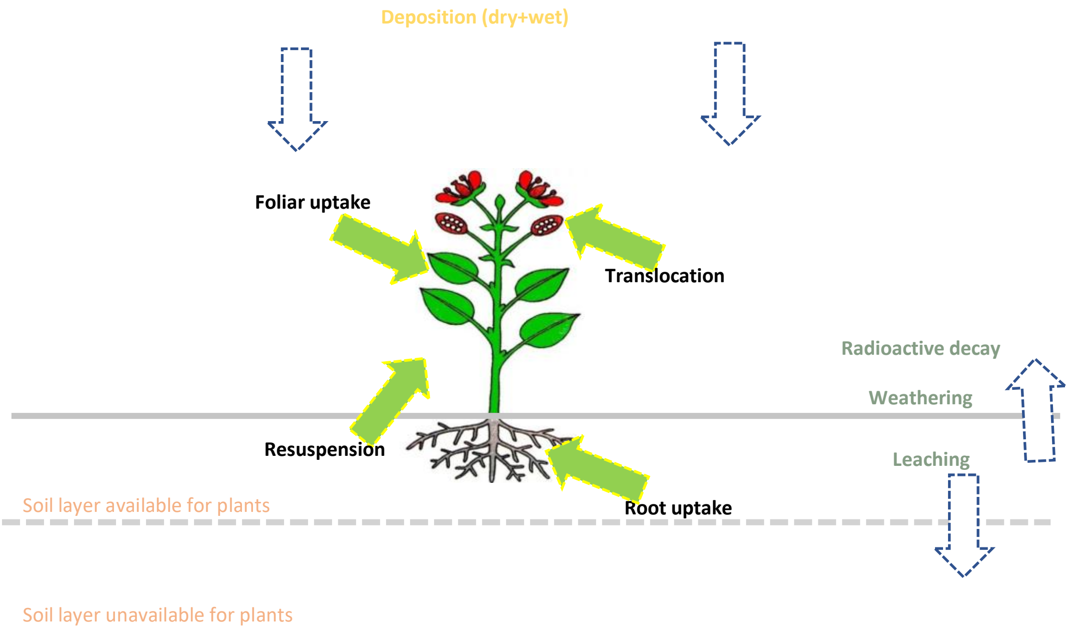

Figure A2. Conceptual model for plant interactions with the contamination

Assumptions in the model

One day deposition is assumed. Deposition occurring in a specified calendar day, at the beginning of the day.

Before deposition, it is assumed that the feed and food products are uncontaminated, i.e., radioactivity that is already existing in the environment is not considered.

Concerning the time dependency of the plant's contamination after the day of deposition, several groups of plants are considered (see Table A1).

The grass model includes the production of hay. Assumptions for the grass model are listed below:

1. Grass is harvested continuously. After some time, external contamination is no longer considered, and contamination is by root uptake only.
2. During hay harvest period the average contamination of fresh grass is calculated, and then multiplied by a factor of 5 (considering the loss of water during hay preparation).
3. The harvest period is subdivided into two intervals by a parameter giving the end of the first interval. During the first interval a special weighting factor can be defined considering the varying harvesting intensity during the whole harvest period.

For points of time after the third calendar year, no seasonal variations are considered: here only an average annual contamination is calculated.

For some plants it is assumed that they are stored for consumption in between two harvest periods. The contamination of the stored product can be calculated as: the average contamination of the preceding harvest period (type 5), or the contamination at the end of the preceding harvest period (all other types).

Table A1. Different plant categories considered in the model

Type	Used	External contamination	Stored products
1	Grass / hay	Weathering Growth dilution explicitly Translocation in root zone	Average of hay harvesting period (2 harvest intervals)
2	Maize Beet leaves	Weathering Growth dilution implicitly	As at the end of harvesting period
3	Leafy vegetables	Weathering Growth dilution implicitly	Harvest during winter time (but no growth)
4	Corn cobs, beet, potatoes, cereals, fruit	Translocation	As at the end of harvesting period
5	Root vegetables Fruit vegetables Berries	Translocation	Average of harvesting period

Foliar uptake by plants

For the assessment of the contamination of plant products after radionuclide deposition on the foliage, two types of plants are considered: those that are used “entirily” (grass, maize silage, leafy vegetables) and those from which only a certain part is eaten or fed to animals (e.g., cereals, potatoes).

In the first case, the contamination at time of harvest is calculated as initial contamination at time of deposition. Losses of activity by weathering (by rain and wind) and by growth dilution during the time between deposition and harvest are considered.

For leafy vegetables and maize, the dilution by increasing biomass is considered implicitly by dividing the deposition onto the foliage at time of deposition by the yield at time of harvest.

The approach for pasture grass is different due to the continuous harvesting. Here the deposited activity is divided by the yield at time of deposition. The increase of biomass is considered by the dilution rate. It is assumed that phloem mobile elements (such as caesium and iodine) are partly translocated to the root zone and transported to the leaves at later times. This is described by a rate constant.

The concentration of activity in hay and grass silage is taken as a weighted mean concentration in grass harvested between begin and end of hay harvesting period. The first half of that period is weighted 70% and the second 30% to reflect the relative monthly growth of pasture grass.

For plants which are only partly consumed, the translocation of radionuclides from the leaves to the edible part is considered. This is important only for nuclides which are mobile in the phloem (see Table A2), but not for immobile elements. The translocation is dependent on the stage of development of the plants. It is quantified by the translocation factor which gives the fraction of activity deposited on the leaves which is recovered in the edible part of the plant at time of harvest. It depends on the time elapsed between deposition and harvest. For immobile elements only the direct deposition onto the edible parts of the plant is of relevance; this contribution is also included in the translocation factor.

Table A2. Mobile and immobile nuclides in the phloem

Mobile elements	Immobile elements
Co, Cs, I, Mn, Mo, Na, Rb, Sb, Tc, Te	Ag, Am, Ba, Ce, Cm, La, Nb, Nd, Np, Pr, Pu, Rh, Ru, Sr, Y, Zr

This approach is also used for fruits and berries. This is a rough approximation, since due to lack of adequate data the translocation to and storage in stems and branches is not considered.

The interception of wet deposited radionuclides is calculated from the leaf area index (LAI), the interception coefficient and the amount of rainfall of the precipitation event. The LAI is strongly dependent on the time of year. For every plant species considered, a specific tabulated function of the LAI is assumed.

The interception coefficient distinguishes between grains (grass, cereals, maize) and all other plants.

Root uptake

The estimation of the root uptake of radionuclides assumes that the radionuclides are well mixed within the entire rooting zone. The concentration of activity due to root uptake is calculated from the concentration of activity in the soil using the transfer factor which gives the ratio of concentration of activity in plants (fresh weight) and soil (dry weight).

Two soil compartments are included to the model. They are representing the activity available and not available for plants (this approach considers sorption (fixation process and desorption from the soil particles process). The concentration of activity in soil is calculated from the total (dry and wet) deposited activity assuming a homogeneous distribution over the rooting zone and considering the decrease of activity by radioactive decay, by leaching to deeper soil layers, by fixation to and desorption from soil particles.

The calculation of the root uptake of plants is based on the total (dry and wet) deposition onto soil and vegetation.

If the deposition occurs during the growing period less than 50 days before harvest, a reduced root uptake is assumed for the first harvest. The reduction factor is the ratio of the time span from deposition to harvest and 50 days (or the length of the whole growing period if it is less than 50 days).

Resuspension

Resuspension of radionuclides results also in a transfer of activity from soil to the above ground parts of the plant. Plant contamination due to resuspension is proportional to the activity in the soil.

The plant contamination due to resuspension is estimated from the mass of the soil that is attached to the plant and an element-dependent enrichment factor that is defined as the ratio of the activity concentration in the resuspended soil and the average concentration of the soil.

For grass and forage the soil intake of cattle is considered. This parameter is defined as the amount of soil that is ingested by cattle per unit of grass or forage intake. Since during the soil ingestion of animals, no fractionation occurs as during the resuspension, it is assumed that the contamination of the soil ingested is equal to the mean activity in the soil. Therefore, the enrichment factor is not applied. The resuspension and soil ingestion by cattle is formally used as the transfer factor for root uptake.

Contamination of animal products

Primary contamination of animal products

The concentration of activity in animal products (milk, meat, and eggs) results from the intake of activity by the animals, considering the kinetics of the radionuclides in the animal metabolism.

The conceptual model of radionuclides interaction with cattle is shown below.

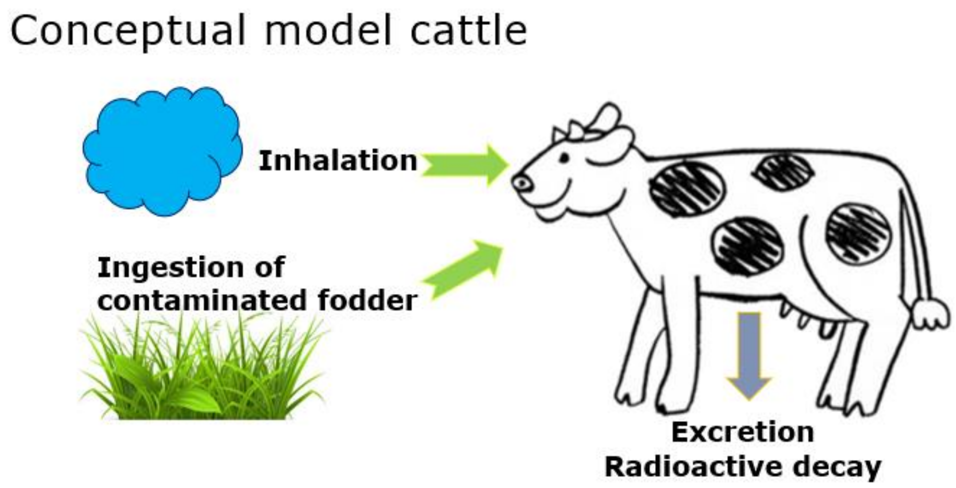

Figure A3. Conceptual model of the animal products

The amount of activity ingested by the animals is calculated from the concentration of activity in the different feedstuffs. For the inhaled activity, the same transfer factor to animal products as for ingested activity is assumed. This assumption is justified since for most elements the same or very similar resorption factors for inhalation and ingestion is used in the metabolic models for deriving dose conversion factors.

Plants or products processed from plants or animal products can be feedstuffs for animals. For a realistic dose assessment in emergency situations, the feeding regimes must be adapted to the season-dependent feed compositions of the specific region under consideration.

Ingestion of soil by grazing cattle is included in the feedstuff contamination. The soil intake of animals is quantified in the model parameters by a factor which is defined as the amount of soil (dry weight) per unit fresh weight of crop. This factor can be given for each of the plants separately. It varies widely depending on the grazing management and the condition of the pasture.

Inhalation of radionuclides by the animals is considered; this pathway may be relevant for early contamination of animal products in certain cases (deposition during wintertime), but it is relatively unimportant for the total resulting doses.

The time-dependent transfer to the animal products is described by the transfer factor fodder-animal product and the retention function. The transfer factor fodder-animal product gives the ratio of concentration of activity in the animal product and the daily intake of activity by the animal for equilibrium conditions.

Change of activity concentration by storage and processing

The contamination of human foodstuffs and of the animals' fodder is calculated considering the activity enrichment or dilution during processing and culinary preparation as well as processing and storage times.

The concentration of activity decreases during storage and processing due to radioactive decay.

The contamination of the processed product is expressed by the processing factors which are defined as the ratio of concentrations in the final processed product to that of the primary product.

Calculation of doses by food ingestion

The intake of activity by the reference person is calculated from the time-dependent concentrations of activity in foodstuffs and the human consumption rates.

Foodstuffs are assumed to be locally produced, i.e., the calculated ingestion doses represent potential doses for people producing all their food locally. Age-dependent consumption rates of the average population are applied.

Calculation of doses from occupancy

Doses from occupancy consider the following exposure pathways:

- Inhalation during cloud passage.
- External exposure due during cloud passage.
- Inhalation of suspended soil particles.
- External dose from radionuclides deposited on the ground.
- Exposure from contamination of closes and skin.

For calculation external dose from the ground, it is assumed that the deposited activity is homogeneously distributed on an infinite meadow. Different deposition patterns and shielding at different locations are taken into consideration by a correction factor.

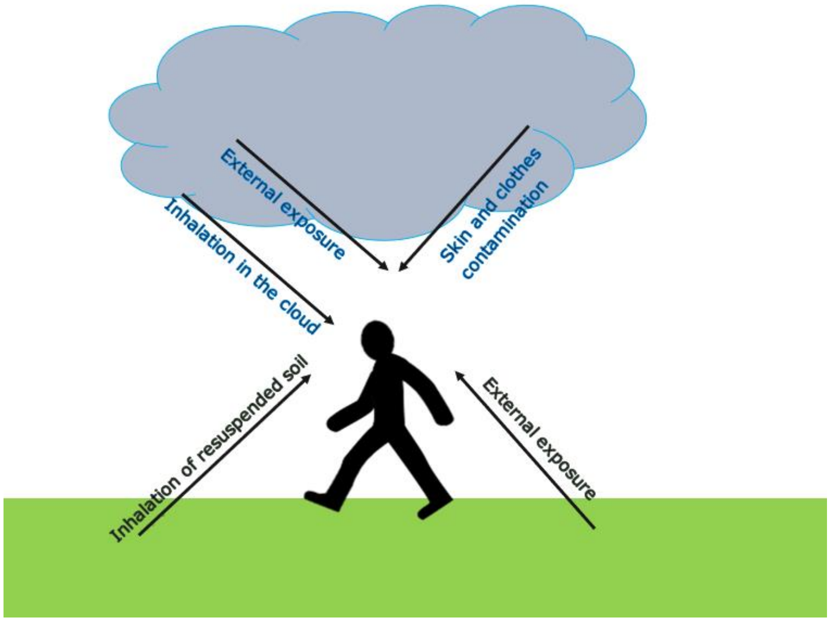

Figure A4. Conceptual model for calculation of doses from occupancy

The following assumptions are made for calculations of doses from contamination of skin and clothes:

- The deposition velocity for dry skin is same as for clothes. As default, a value of 1E-3 m s^{-1} is assumed.
- Indoors, the dry deposition is reduced by the factor which is also applied to estimate the indoor inhalation dose.
- For the estimation of wet deposition on clothes and skin, the interception factor 0,1 is applied. Wet deposition is only assumed for the time fraction people spent outdoors.
- For the fraction of the skin that is covered by clothes is set up to 0,8.
- The residence time of radionuclides on skin and clothes is the same. As default 24 h hours are assumed. During this time, the activity is lost by radioactive decay only.
- The contamination of skin causes an exposure by alpha-, betta- and gamma-radiation, whereas the contamination of clothes causes only an exposure due to gamma-radiation. The dose factors for skin and clothes contamination were taken from Jacobi et al. (1989). The values for skin represent the dose in skin averaged over a depth in skin of 50-100 µm.

Mathematical model

Input from atmospheric dispersion modelling

The contamination of soil is given by the sum of dry and wet deposition on soil. Total deposition on soil is calculated by:

$$A_{\text{soil total}} = \text{Depo}_{\text{soil,WET}} + \text{Depo}_{\text{soil,DRY}}$$

Where

$A_{\text{soil total}}$	Total deposition on soil [Bq/m^2];
$\text{Depo}_{\text{soil, WET}}$	Wet deposition on soil [Bq/m^2];
$\text{Depo}_{\text{soil, DRY}}$	Dry deposition of nuclides on soil [Bq/m^2];

Wet deposition on soil is calculated by:

$$\text{Depo}_{\text{soil,WET}} = \text{Wet}_{\text{deposition}}$$

Where

$\text{Wet}_{\text{deposition}}$ Initial wet deposition [Bq/m^2].

Dry deposition of nuclides on soil is calculated by:

$$\text{Depo}_{\text{soil,DRY}} = C_{\text{integrated,air}} \cdot V_{\text{g,max,soil}} \cdot \text{seconds}_{\text{per,hour}}$$

Where

$C_{\text{integrated, air}}$	The time-integrated activity concentration in air [Bq·h/m^3];
$V_{\text{g, max, soil}}$	Maximum deposition velocity on soil [m/s];
$\text{seconds}_{\text{per, hour}}$	Conversion hours to seconds [s/h].

Maximum deposition velocity on soil is constant value ($5.0 \cdot 10^{-4}$) for all nuclides, except Iodine. For Iodine the next equation is used:

$$V_{\text{g,max,soil[I]}} = 5.0 \cdot 10^{-4} \cdot \text{DV}_{\text{soil,Particle}} + 0.003 \cdot \text{DV}_{\text{soil,Elemental}} + 5.0 \cdot 10^{-5} \cdot \text{DV}_{\text{soil,Organic}}$$

Where

DV_{soil} Fraction of iodine in the form of particles, elemental and organic [unitless].

Mathematical equations for contamination of plants products

The initial contamination of the plants results from dry deposition onto the foliage of the plants and from the fraction of wet deposition which is initially retained by the foliage.

$$Depo = Depo_{DRY} + Depo_{WET}$$

Where

$Depo$	Total deposition of radionuclides onto the foliage [Bq/m^2];
$Depo_{DRY}$	Total dry deposition on the plant of radionuclide [Bq/m^2];
$Depo_{WET}$	Total wet deposition on the plant of radionuclide [Bq/m^2].

Radionuclide wet deposition on plant:

$$\mathrm{Depo}_{\mathrm{WET}} = \mathrm{Wet}_{\mathrm{deposition}} \cdot f_{\mathrm{wi,2}}$$

Where

$\mathrm{Wet}_{\mathrm{deposition}}$	Total wet deposition of radionuclide i [Bq/m^2];
$f_{wi,\,2}$	Interception fraction [unitless].

The interception of wet deposited radionuclides is calculated as:

$$f_{\mathrm{wi}} = (((B_{\mathrm{j,time}}(\mathrm{calendar\_day\_in\_year}) \cdot \frac{S_{\mathrm{ij}}}{\mathrm{Amount}_{\mathrm{of,rainfall}}}) \cdot (1 - e^{-(\ln(2) \cdot \frac{\mathrm{Amount}_{\mathrm{of,rainfall}}}{3 \cdot S_{\mathrm{ij}}})})))$$

$$\text{if } \mathrm{Amount}_{\mathrm{of,rainfall}} = 0,\ f_{\mathrm{wi}} = 0$$

Where

f_{wi}	Interception fraction [unitless];
$\mathrm{Amount}_{of,\,rainfall}$	Amount of rainfall of the precipitation event [mm];
$B_{j,\,time}$	Leaf area index of plant type j at time T [unitless];
S_{ij}	Retention coefficient of radionuclide i on plant type j [mm].

Interception fraction could not be higher than 1.

$$f_{\mathrm{wi,2}} = \begin{cases} 1, & \text{if } f_{\mathrm{wi}} > 1; \\ f_{\mathrm{wi}}, & \text{elsewhere.} \end{cases}$$

The contamination of plant with radionuclide is given as:

$$C_{\mathrm{plant}} = C_{\mathrm{plant,dep}} + C_{\mathrm{plant,rootUptake}}$$

Where

$C_{plant,\,dep}$	Concentration in plant from deposition onto foliage [Bq/kg];
$C_{plant,\,rootUptake}$	Concentration in plant from root uptake [Bq/kg].

The concentration of activity in grass is given by:

$$C_{\text{plant,dep}}(t) = \frac{Depo}{E_g} \cdot \left\{(1 - a_i) \cdot e^{-(\lambda_{vn}+\lambda_{wi}+\lambda_r)} + a_i \cdot e^{-(\lambda_t+\lambda_r)}\right\}$$

Where

$Depo$	Total deposition of nuclide i on the grass [Bq/m^2];
E_g	Yield of grass at time of deposition (time-dependent) [kg/m^2];
a_i	Fraction of activity, which is translocated to the root zone [unitless];
λ_{wi}	Weathering rate of nuclide i [d^{-1}];
λ_{vn}	Growth dilution rate dependent on the month of year [d^{-1}];
λ_t	Rate constant representing translocation to the root zone and subsequent remobilization [d^{-1}];
λ_r	Radioactive decay constant [d^{-1}].

For Type 2 and Type 3 the contamination at time of harvest is given by the initial contamination at time of deposition, by loss of activity by weathering (by rain and wind):

$$C_{\text{plant,dep}}(t) = \frac{Depo}{E_j} \cdot e^{-(\lambda_{wi}+\lambda_r)\cdot t}$$

Where

$Depo$	Total activity of nuclide deposited on the foliage of plant, [Bq/m^2];
E_j	Yield of plant at time of harvest [kg/m^2];
λ_{wi}	Weathering rate of nuclide i [d^{-1}];
λ_r	Radioactive decay constant [d^{-1}].

For Type 4 and Type 5 plants the translocation of radionuclides from the leaves to the edible part is considered as:

$$C_{\text{plant,dep}}(t) = \frac{Depo}{E_j} \cdot Tr_f(\Delta t) \cdot e^{-\lambda_r t}$$

Where

$Depo$	Total activity of nuclide deposited on the foliage of plant, [Bq/m^2];
E_j	Yield of plant at time of harvest [kg/m^2];
$Tr_f(\Delta t)$	Translocation factor for nuclide and plant type, depends on time Δt between deposition and harvest;
λ_r	Radioactive decay constant [d^{-1}].

Concentration in grass from root uptake is calculated by:

$$C_{\text{Plant rootUptake}} = TF_{soil,plant} \cdot C_{\text{soil,total}}$$

Where

$TF_{soil, plant}$	Transfer factor from soil to plant [unitless];
$C_{soil, total}$	Total radionuclide activity in soil [Bq/kg].

Transfer factor from soil to plant includes root uptake, contamination of the plant by resuspension and ingestion of soil by cows

$$\mathrm{TF}_{\mathrm{soil,plant}} = \mathrm{TF}_{\mathrm{rootUptake}} + f_{\mathrm{e}} \cdot R_{\mathrm{j}} + S_{\mathrm{j}}$$

Where

$TF_{rootUptake}$	Soil-plant transfer factor by root uptake [unitless];
f_e	Enrichment factor [unitless];
R_j	Mass load of soil on plant [g/g];
S_j	Soil intake by grazing animal [g/g].

The concentration of activity in soil is calculated from the total (dry and wet) deposited activity assuming a homogeneous distribution over the rooting zone, and taking into account the decrease of activity by radioactive decay, by leaching to deeper soil layers, by fixation to and desorption from soil particles. The following analytical approach is applied:

$$C_{\mathrm{soil,total}} = \frac{\mathrm{Depo}}{L \cdot \rho} \cdot \left[\{a_s \cdot e^{-b1 \cdot t} + (1 - a_s) e^{-b2 \cdot t}\} \cdot e^{-\lambda_r t}\right]$$

where

Depo	Total deposition of radionuclides (dry + wet) on soil [Bq/m^2];
a_s	Coefficient representing distribution of nuclides in soil [unitless];
L	Depth of rooting zone for pasture or arable soil [m];
ρ	Soil density for pasture [kg/m^3];
b1 and *b2*	Coefficients which represent loss processes [d^{-1}].

Coefficient a_s is calculated by:

$$a_{\mathrm{s}} = \frac{\lambda_{\mathrm{fi}} - \lambda_{\mathrm{di}} + \lambda_{\mathrm{ai}} + \mathrm{RR}}{2 \cdot \mathrm{RR}}$$

Where

λ_{fi}	Fixation rate of nuclide i (pasture or arable soil) [d^{-1}];
λ_{di}	Desorption rate of the nuclide i from the (pasture or arable) soil [d^{-1}];
λ_{ai}	Leaching rate of nuclide i (pasture or arable soil) [d^{-1}];
RR	Coefficient [d^{-1}].

Coefficients b1 and b2 are calculated by:

$\mathrm{b1} = \frac{\lambda_{\mathrm{fi}} + \lambda_{\mathrm{di}} + \lambda_{\mathrm{ai}} + \mathrm{RR}}{2}$ and $\mathrm{b2} = \frac{\lambda_{\mathrm{fi}} + \lambda_{\mathrm{di}} + \lambda_{\mathrm{ai}} - \mathrm{RR}}{2}$

Where

RR Coefficient [d^{-1}].

The RR coefficient is calculated by:

$$\mathrm{RR} = \lambda_{\mathrm{fi}} - \lambda_{\mathrm{di}} + {\lambda_{\mathrm{ai}}}^{2} + 4 \cdot \lambda_{\mathrm{fi}} \cdot {\lambda_{\mathrm{di}}}^{\frac{1}{2}}$$

The grass model includes the production of hay: During another harvest period the average contamination of fresh grass is calculated, and then multiplied by a factor of 5 (considering the loss of water during hay preparation). The harvest period is subdivided into two intervals by parameters giving the end of the first interval. During the first interval a weighting factor can be defined considering the varying harvest intensity during the whole harvest period.

Example: If the harvest interval for hay is from 1st June till 30th September, the end of first interval is 1st August, and the weighting factor of the first interval is 2, then it is assumed that 2/3 of the whole harvest is produced in the first half of the harvest period.

Radionuclide concentrations in hay:

$$\mathrm{Hay} = 5 \cdot e^{-(\mathrm{time} - \mathrm{Date}_{\mathrm{of\,deposition}}) \cdot \mathrm{lambda}} \cdot \begin{cases} \mathrm{Harvest}_{\mathrm{first,period}}, & \text{if } \mathrm{time}_{\mathrm{of,year}} >= t_{\mathrm{harvest,begins}} \; and \; \mathrm{time}_{\mathrm{of,year}} <= t_{\mathrm{harvest,middle}}; \\ \mathrm{Harvest}_{\mathrm{second,period}}, & \text{elsewhere.} \end{cases}$$

Concentration of radionuclides during first harvest period:

$$\mathrm{Harvest}_{\mathrm{first,period}} = \mathrm{Grass}_{\mathrm{Mean}}$$

Where

$\mathrm{Harvest}_{\mathrm{first,\,period}}$	Concentration gathered during harvest period [Bq/kg];
$\mathrm{Grass}_{\mathrm{Mean}}$	Mean concentration of grass during harvest period [Bq/kg];

Mean radionuclide concentration in grass during harvest period:

$$\mathrm{Grass}_{\mathrm{Mean}} = \frac{\mathrm{Grass\ Integrator}}{\mathrm{days}_{\mathrm{integrated}}}$$

Where

Grass Integrator	Preparation of grass during first harvest period which will be used for production of hay[Bq];
$days_{integrated}$	Calculation of harvest interval length [d].

Harvest_second_period:

$$\text{Harvest}_{\text{second,period}} = \text{Grass}_{\text{Mean,Snapshot}} + (\text{Grass}_{\text{Mean}} - \text{Grass}_{\text{Mean,Snapshot}}) \cdot (1 - \frac{\text{weight}_{\text{factor}} - 1}{\text{weight}_{\text{factor}} + 1})$$

Where

$Harvest_{second,\ period}$	RN concentration in grass during second period of hay preparation [Bq/kg];
$Grass_{Mean,\ Snapshot}$	Mean radionuclide concentration in grass at the middle of the harvest period [Bq];
$Grass_{Mean}$	Mean Rn concentration in grass during harvest period[Bq/kg];
$weight_{factor}$	Weight factor for the first period for hay [unitless].

Mathematical equations for animal product contamination

Total activity concentration of radionuclides in animal products summed over biological transfers is calculated as:

$$\text{Farm}_{\text{animals,products}} = \sum_{\text{Biological Transfer}} \text{Farm}_{\text{products}}$$

Where

$Farm_{products}$	Activity concentration of radionuclides in animal products [Bq/kg].

Activity concentration of radionuclides in animal products is calculated as

$$\text{Farm}_{\text{products}} = \text{TF}_{\text{ik,farm}} \cdot \lambda_{\text{bio,farm}} \cdot \text{Farm}_{\text{products,corrected}}$$

where

$\text{TF}_{\text{ik,farm}}$	Transfer factor fodder (farm animals) [d/kg];
$\lambda_{\text{bio,farm}}$	Biological transfer rate [d^{-1}];
$Farm_{products,\ corrected}$	Activity of radionuclides in farm products corrected by animal time life [Bq].

Activity of radionuclides in farm products corrected by animal time life is calculated as:

$$\mathrm{Farm}_{\mathrm{products,corrected}} = (\mathrm{Farm\ feeding} + \ \mathrm{Inhalation}\ ) -$$

$$-\left(\ \mathrm{Farm}_{\mathrm{Products,Dly}} + \ \mathrm{Inhalation}_{\ \mathrm{Dly}}\right) \cdot e^{-(\lambda_{\mathrm{bio,farm}}+\lambda_r)\cdot\ \mathrm{Time}_{\ \mathrm{life,farm,animals}}}$$

Where

Farm feeding	Radionuclide activity in animal products obtained by feeding [Bq];
Inhalation	Radionuclide activity in animal products obtained by inhalation [Bq];
$\mathrm{Farm}_{\mathrm{Products,Dly}}$	Correction for feeding taking into account animal time life [Bq];
$\mathrm{Inhalation}_{\mathrm{Dly}}$	Correction for inhalation taking into account animal time life [Bq];
$\lambda_{\mathrm{bio,farm}}$	Biological transfer rate [d^{-1}];
λ_{r}	Physical decay constant [d^{-1}];
$\mathrm{Time}_{\mathrm{life,\ farm,\ animals}}$	Lifetime of animals [d].

Radionuclide concentration in animal products obtained by feeding of farm animals is calculated as:

$$\frac{d\mathrm{Farm\ feeding}}{\mathrm{dt}} = \mathrm{Farm\ feeding} + \mathrm{Intake}_{\mathrm{feed}} - \mathrm{Farm\ an\ feeding} \cdot\ \lambda_{\mathrm{bio,farm}}$$

Where

Farm an feeding	Radionuclides concentration in animal products obtained by feeding [Bq];
$\mathrm{Intake}_{\mathrm{feed}}$	The intake from feeding [Bq/d];
$\lambda_{\mathrm{bio,farm}}$	Biological transfer rate (excretion) [d^{-1}].

Intake by feeding is calculated as:

$$\mathrm{Intake}_{\mathrm{feed}} = \ A_{\ \mathrm{am}} \cdot \ a_{\ \mathrm{ij,farm,an}}$$

Where

A_{am}	The intake of activity from feedstuffs by animal [Bq/d];
$a_{ij,\ farm,\ an}$	Fraction of biological transfer for farm animals [unitless].

The intake of activity from feedstuffs by animal is calculated as

$$A_{\ \mathrm{am}} = \sum_{\mathrm{feedstuff}} C_{\ \mathrm{i,feed}} \cdot \ I_{\ \mathrm{feed}}$$

$C_{i,feed}$	Concentration of activity of radionuclide i in feedstuff [Bq/kg];
I_{feed}	Intake rate of feedstuff by the farm animal [kg/d].

Radionuclide activity in animal products obtained by is calculated as:

$$\frac{d\text{Inhalation animals}}{\text{dt}} = \text{Inhalation animals} + \text{Intake}_{\text{inhalation}} - \text{Inhalation animals} \cdot \text{Lambda}_{\text{bio,farm}}$$

Where

Inhalation animals	Radionuclide activity in animal products obtained by inhalation [Bq];
$\text{Intake}_{\text{inhalation}}$	Intake by feeding [Bq/d];
$\text{Lambda}_{\text{bio,farm}}$	Biological transfer rate [d^{-1}].

Intake by inhalation for animal is calculated as:

$$\text{Intake}_{\text{inhalation}} = \text{Animal}_{\text{inhalation}} \cdot a_{\text{ij,farm,an}}$$

Where

$a_{ij,farm,an}$	Fraction of biological transfer for animal product [unitless].

Activity of radionuclides inhaled by animal during cloud passage (24 hours) is calculated as:

$$\text{Animal}_{\text{inhalation}} = C_{\text{integrated,air}} \cdot \text{Inh}_{\text{rate}}$$

Where

$\text{Animal}_{\text{inhalation}}$	Activity of radionuclides inhaled by animal [Bq];
$C_{\text{integrated,air}}$	The time-integrated activity concentration in air [$Bq \cdot h/m^3$];
Inh_{rate}	Inhalation rate of animal k [m^3/h].

Storage and processing of foodstuff and feedstuff

In case of time after deposition is lower than storage time concentration in foodstuff is equal to 0.

The concentration of activity decreases during storage and processing due to radioactive decay

$$C_{\text{RN,After,Storage}} = C_{\text{iq}} \cdot e^{-\lambda_r \cdot t_{\text{storage,processing}}}$$

Where

$C_{\text{RN, After, Storage}}$	Concentration of activity of radionuclide i in foodstuffs or feedstuff at time t after processing and storage [Bq/kg];
C_{iq}	Concentration of activity of RN i in the processed product q [Bq/kg];
λ_r	Physical decay constant [d^{-1}];

$t_{\text{storage,processing}}$	Storage and processing time of food- or feedstuff [d].

The contamination of the processed product is expressed as:

$$C_{\text{iq}} = V_{\text{ipq}} \cdot \text{Concentration}_{\text{raw product p}}$$

Where

V_{ipq}	Processing factor of nuclide i for production of the processed product q from the primary products p [unitless];
$\text{Concentration}_{\text{raw product p}}$	Activity concentration in raw product p (cropland plants, animal farm products and plants) [Bq/kg].

Effective dose from foodstuff ingestion

Radiation exposure due to ingestion of the foodstuff for referenced person is calculated as:

$$\frac{d\text{Dose}}{\text{dt}} = \text{Concentration}_{\text{for,ingestion}} \cdot V_{\text{n}} \cdot \text{DCC}_{\text{ing,food}} \cdot \text{mSvperSv}$$

Where

Dose	Radiation exposure due to ingestion of the foodstuff n [mSv];
$\text{Concentration}_{\text{for, ingestion}}$	Radionuclide i concentration in foodstuff n after storage and processing [Bq/kg];
Vn	Consumption rate of foodstuff n at time t [kg/d];
$\text{DCC}_{\text{ing, food}}$	Dose conversion factor for ingestion of nuclide i at time t [Sv/Bq];
mSvperSv	Amount of mSv in 1 Sv [mSv/Sv];
$\text{hours}_{\text{per, day}}$	Conversion days to hour [h/d].

Effective dose from ingestion of foodstuff summed over the radionuclides is calculated as:

$$\text{Dose}_{\text{ingestion,RN,food}} = \sum_{i=1}^{n} \text{Dose}_{Rn}$$

Where

Dose_{Rn}	Dose from ingestion of foodstuff contaminated by nuclide i
n	Number of radionuclides

Doses from occupancy

Dose from inhalation during cloud passage

The dose $Dose_{inh, cloud}$ due to inhalation of radionuclides during the passage of the radioactive cloud is calculated from the time-integrated activity concentration in the near ground air, the inhalation rate, and the age-dependent dose factor for inhalation In addition, a reduction factor can be applied taking into account the lower activity in air inside houses:

$$\mathrm{Dose}_{\mathrm{inh,cloud}} = C_{\mathrm{integrated,air}} \cdot I \cdot \mathrm{DCC}_{\mathrm{inh,cloud}} \cdot r_{\mathrm{inh,summ,cloud}} \cdot \mathrm{mSvperSv}$$

Where

$Dose_{inh, cloud}$	Inhalation dose [mSv];
$Date_{of, first, deposition}$	Date when deposition happened [d];
$C_{integrated, air}$	The time-integrated activity concentration in air [Bq*h/m^3];
I	Age-dependent inhalation rate [m^3/h];
$DCC_{inh, cloud}$	Dose conversion factor for inhalation of radionuclide i [Sv/Bq];
$r_{inh, summ, cloud}$	Summed reduction factor for staying indoors [unitless];
mSvperSv	Amount of mSv in 1 Sv [mSv/Sv].

Summed reduction factor for staying indoors:

$$r_{\mathrm{inh,summ,cloud}} = \sum_{\mathrm{Locations}} r_{\mathrm{inh}}$$

Where

r_{inh} Reduction factor for staying indoor [unitless].

Reduction factor for staying indoor

$$r_{\mathrm{inh}} = f_{\mathrm{ui}} \cdot c_{\mathrm{Lij,cloud}}$$

Where

r_{inh}	Reduction factor for staying indoor [unitless];
f_{ui}	Relative occupancy time at location j during passage of cloud [unitless];
$c_{Lij, cloud}$	Filtering factor for nuclide i and environment j [unitless];

Dose from external exposure during cloud passage

External exposure from radionuclides in the cloud is calculated by:

$$D_{\mathrm{w,i}} = C_{\mathrm{integrated,air}} \cdot \mathrm{DCC}_{\mathrm{external,cloud}} \cdot r_{\mathrm{w,i,summ}} \cdot \mathrm{mSvperSv}$$

Where

$D_{w,i}$	External exposure from radionuclides in the cloud [mSv];
$C_{integrated,\ air}$	The time-integrated activity concentration in air [$Bq \cdot h/m^3$];
$DCC_{external,\ cloud}$	Dose factor for external exposure from cloud [$Sv \cdot m^3 \cdot Bq^{-1} \cdot h^{-1}$];
$r_{w,\ i,\ summ}$	Summed reduction factor [unitless];
mSvperSv	Amount of mSv in 1 Sv [mSv/Sv];

The summed reduction factor:

$$r_{\mathrm{w,i,summ}} = \sum_{\mathrm{Locations}} r_{\mathrm{w,i}}$$

Where

$r_{w,\ i}$ Reduction factor for staying at different locations [unitless].

Reduction factor for staying at different locations:

$$r_{\mathrm{w,i}} = f_{\mathrm{ui}} \cdot c_{\mathrm{wij}}$$

Where

$r_{w,\ i}$	Reduction factor for staying at different locations [unitless];
f_{ui}	Relative occupancy time at location j during passage of cloud [unitless];
c_{wij}	Environment factor for cloud exposure at location j [unitless].

Dose of external exposure from the ground

Dose from radionuclides in the ground is calculated by:

$$\frac{d\mathrm{Dose\ ext\ ground}}{\mathrm{dt}} = \mathrm{Dose\ ext\ ground} + \mathrm{Ground}_{\mathrm{depo,time}} \cdot r_{\mathrm{bi,summ}} \cdot \mathrm{DCC}_{\mathrm{external,ground}} \cdot \mathrm{seconds}_{\mathrm{per,hour}} \cdot \mathrm{hours}_{\mathrm{per,day}} \cdot \mathrm{mSvperSv},$$

Where

Dose ext ground	Dose from radionuclides in the ground [mSv];
$Date_{of,\ first,\ deposition}$	Date of deposition [d];
$Ground_{depo,\ time}$	Total deposition on ground as function of time [Bq/m^2];

$r_{bi, summ}$	Reduction factor for staying at different locations [unitless];
$DCC_{external, ground}$	Age dependent dose factor for exposure from ground (Sv/s)*(m^3/Bq) [GSF-12/90][Sv*m^2*Bq^{-1}*s^{-1}];
$seconds_{per, hour}$	Conversion hour to seconds [s/h];
$hours_{per, day}$	Conversion days to hour [h/d];
mSvperSv	Amount of mSv in 1 Sv [mSv/Sv].

Reduction factor for staying at different locations:

$$r_{\mathrm{bi,summ}} = \sum_{\mathrm{Locations}} r_{\mathrm{bi}}$$

Where

r_{bi} Reduction factor for staying at different locations[unitless]

Reduction factor for staying at different locations:

$$r_{\mathrm{bi}} = f_{\mathrm{ui}} \cdot c_{\mathrm{bij}}$$

Where

r_{bi}	Reduction factor for staying at different locations [unitless];
f_{ui}	Relative occupancy time at location j during passage of cloud [unitless];
c_{bij}	Environment factor for cloud exposure at location j [unitless].

Total deposition on ground (soil + lawn) as function of time is calculated by

$$\begin{aligned}\mathrm{Ground}_{\mathrm{depo,time}} = \mathrm{Lawn}_{\mathrm{depo,total}} \cdot (\frac{\mathrm{a1}}{\mathrm{lambda}_{1} + \mathrm{lambda}} \\ \cdot (e^{-(\mathrm{lambda}_{1}+\mathrm{lambda})\cdot(\mathrm{time}-\mathrm{Date}_{\mathrm{of,first,deposition}}-1)} \\ - e^{-(\mathrm{lambda}_{1}+\mathrm{lambda})\cdot(\mathrm{time}-\mathrm{Date}_{\mathrm{of,first,deposition}})}\end{aligned}$$

Where

$Ground_{depo, time}$	Total deposition on ground as function of time [Bq/m^2];
$Date_{of, first, deposition}$	Date of deposition [d];
$Lawn_{depo, total}$	RN total deposition on lawn [Bq/m^2];
a1	Contribution fractions of the migration rates [unitless];
$lambda_1$	Migration rates [d^{-1}];
lambda	Physical decay constant [d^{-1}];
a2	Contribution fractions of the migration rates [unitless];
$lambda_2$	Migration rates [d^{-1}].

Radionuclides total deposition on lawn that is used in external exposure calculations.

$$\mathrm{Lawn}_{\mathrm{depo,total}} = \mathrm{Depo}_{\mathrm{soil,TOTAL}} + \mathrm{Lawn}_{\mathrm{Dry,deposition}}$$

Where

$\mathrm{Lawn}_{\mathrm{depo,\ total}}$	RN total deposition on lawn[Bq/m^2]
$\mathrm{Depo}_{\mathrm{soil,\ TOTAL}}$	Total deposition Bq/m^2[Bq/m^2]
$\mathrm{Lawn}_{\mathrm{Dry,\ deposition}}$	Dry deposition onto lawn [Bq/m^2]

Dose in organ k due to skin contamination

Dose in organ k due to skin contamination is calculated by:

$$\mathrm{Dose}_{\mathrm{in,organ,from,skin,contamination}} = (C_{\mathrm{integrated,air}} \cdot \mathrm{seconds}_{\mathrm{per,hour}} \cdot V_{\mathrm{g,H}} \cdot C_{\mathrm{H}} + f_{\mathrm{H,N}} \cdot \mathrm{Wet}_{\mathrm{deposition}} \cdot f_{\mathrm{F}}) \cdot \mathrm{DCC}_{\mathrm{Skin,to,organs}} \cdot A_{\mathrm{H}} \cdot \left(\frac{1 - e^{-\mathrm{lambda} \cdot \frac{t_{\mathrm{H}}}{\mathrm{hours}_{\mathrm{per,day}}}}}{\mathrm{lambda}}\right) \cdot \mathrm{seconds}_{\mathrm{per,hour}} \cdot \mathrm{hours}_{\mathrm{per,day}} \cdot \mathrm{mSvperSv}$$

Where

$\mathrm{Dose}_{\mathrm{in,\ organ,\ from,\ skin,\ contamination}}$	Dose in organ k due to skin contamination [mSv];
$C_{\mathrm{integrated,\ air}}$	The time-integrated activity concentration in air [Bq*h/m^3];
$\mathrm{seconds}_{\mathrm{per,\ hour}}$	Conversion hour to seconds [s/h];
$V_{\mathrm{g,\ H}}$	The deposition velocity for dry skin [m*s^{-1}];
C_{H}	Reduction factor for staying indoors [unitless];
$f_{\mathrm{H,\ N}}$	Interception factor [unitless];
$\mathrm{Wet}_{\mathrm{deposition}}$	Wet deposition activity [Bq/m^2];
f_{F}	Fraction of time spent outdoors [unitless];
$\mathrm{DCC}_{\mathrm{Skin,\ to,\ organs}}$	Dose rate in the organ k after skin contamination [Sv*s^{-1}/Bq];
A_{H}	Total area of skin [m^2];
lambda	Physical decay constant [d^{-1}];
t_{H}	Skin exposure time [h];
$\mathrm{hours}_{\mathrm{per,\ day}}$	Conversion days to hour [h/d];
mSvperSv	Amount of mSv in 1 Sv [mSv/Sv].

External dose from radionuclides deposited on skin and clothes

$$\mathrm{Dose}_{\mathrm{to,skin}} = ((C_{\mathrm{integrated,air}} \cdot V_{\mathrm{g,H}} \cdot \mathrm{seconds}_{\mathrm{per,hour}} \cdot C_{\mathrm{H}} + f_{\mathrm{H,N}} \cdot \mathrm{Wet}_{\mathrm{deposition}} \cdot f_{\mathrm{F}}) \cdot (g_{\mathrm{H,H,gamma}} \cdot \mathrm{m2}_{\mathrm{per,cm2}} \cdot \mathrm{seconds}_{\mathrm{per,hour}} \cdot f_{\mathrm{K}} + g_{\mathrm{H,H}} \cdot \mathrm{m2}_{\mathrm{per,cm2}} \cdot \mathrm{seconds}_{\mathrm{per,hour}} \cdot (1 - f_{\mathrm{K}})) \cdot (\frac{1}{\frac{\mathrm{lambda}}{\mathrm{hours}_{\mathrm{per,day}}}}) \cdot (1 - e^{-\frac{\mathrm{lambda}}{\mathrm{hours}_{\mathrm{per,day}}} \cdot t_{\mathrm{H}}})) \cdot \mathrm{mSvperSv}$$

Where

$\mathrm{Dose}_{\mathrm{to,\ skin}}$	Dose of skin [mSv];
$C_{\mathrm{integrated,\ air}}$	The time-integrated activity concentration in air [Bq·h/m^3];
$V_{\mathrm{g,\ H}}$	The deposition velocity for dry skin [m·s^{-1}];
$\mathrm{seconds}_{\mathrm{per,\ hour}}$	Conversion hour to seconds [s/h];
C_{H}	Reduction factor for staying indoors [unitless];
$f_{\mathrm{H,\ N}}$	Interception factor[unitless];
$\mathrm{Wet}_{\mathrm{deposition}}$	Wet deposition activity [Bq/m^2];
f_{F}	Fraction of time spent outdoors [unitless];
$g_{\mathrm{H,\ H,\ gamma}}$	Gamma-component of the dose rate in skin [Sv·s^{-1}·Bq^{-1}·cm^2];
$\mathrm{m2}_{\mathrm{per,\ cm2}}$	Conversion cm^2 to m^2 [m^2/cm^2];
f_{K}	Fraction of the skin that is covered by clothes [unitless];
$g_{\mathrm{H,\ H}}$	Total dose rate in skin after skin contamination [Sv·s^{-1}·Bq^{-1}·cm^2];
lambda	Physical decay constant [d^{-1}];
$\mathrm{hours}_{\mathrm{per,\ day}}$	Conversion days to hour [h/d];
t_{H}	Skin exposure time [h];
mSvperSv	Amount of mSv in 1 Sv [mSv/Sv].

Inhalation dose from resuspended soil particles

$$D_{\mathrm{inh,resusp,i}} = C_{\mathrm{L,r}} \cdot I \cdot \mathrm{DCC}_{\mathrm{inh}} \cdot r_{\mathrm{inh,summ}} \cdot (\mathrm{time} - \mathrm{Date}_{\mathrm{of,first,deposition}}) \cdot \mathrm{hours}_{\mathrm{per,day}}$$

Where

$D_{\mathrm{inh,\ resusp,\ i}}$	Inhalation dose from resuspended soil particles [Sv];
$C_{\mathrm{L,\ r}}$	Activity concentration in the air due to resuspension [Bq·m-3];
I	Age-dependent inhalation rate [m^3/h];
$\mathrm{DCC}_{\mathrm{inh}}$	Dose conversion factor for inhalation of radionuclide i [Sv/Bq];
$r_{\mathrm{inh,\ summ}}$	Summed reduction factor for staying indoors [unitless];
$\mathrm{hours}_{\mathrm{per,\ day}}$	Conversion days to hour [h/d].

Activity concentration in the air due to resuspension:

$$C_{\mathrm{L,r}} = \mathrm{Soil}_{\mathrm{depo,total}} \cdot K_{\mathrm{r,time}}$$

Where

$C_{L,r}$	Activity concentration in the air due to resuspension [Bq·m^{-3}];
$\mathrm{Soil}_{depo,\ total}$	Total deposition [Bq/m^2];
$K_{r,\ time}$	Time-dependent resuspension factor [m^{-1}];

Time-dependent resuspension factor:

$$K_{\mathrm{r,time}} = \mathrm{R1} \cdot e^{-\mathrm{R2}\cdot(\mathrm{time} - \mathrm{Date}_{\mathrm{of,first,deposition}})} + \mathrm{R3}$$

Where

$K_{r,\ time}$	Time-dependent resuspension factor [m^{-1}];
R1	Resuspension factor immediately after deposition [m^{-1}];
R2	Decrease rate of K_r after deposition [d^{-1}];
$\mathrm{Date}_{of,\ first,\ deposition}$	Date when deposition happened [d];
R3	Long-term resuspension factor [m^{-1}].

Summed reduction factor for staying indoors

$$r_{\mathrm{inh,summ}} = \sum_{\mathrm{Locations}} r_{\mathrm{inh,soil}}$$

Where

$r_{inh,\ soil}$	Reduction factor for staying indoor [unitless]

Reduction factor for staying indoors:

$$r_{\mathrm{inh,soil}} = f_{\mathrm{ui}} \cdot c_{\mathrm{Lij}}$$

Where

$r_{inh,\ soil}$	Reduction factor for staying indoor [unitless];
f_{ui}	Relative occupancy time at location j during passage of cloud [unitless];
c_{Lij}	Filtering factor for nuclide i and environment j [unitless].

Bibliographic Data Sheet **NKS-449**

Title	EcoFood - A tool for assessment of radiation exposure in terrestrial environments impacted by airborne releases
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Abstract	The software package FDMT - Food Chain and Dose Module for Terrestrial Pathways is a component of the decision support systems, JRODOS and ARGOS, that are currently used in the Nordic countries for response to nuclear emergencies. Not all food chains that are relevant for the Nordic conditions are currently supported by FDMT and the modelling of some of the food chains is not optimal for the Nordic conditions, resulting in difficulties with the parameterization of the models. Moreover, in its current implementation FDMT is not totally transparent to users. The focus of the project was to develop a new software (EcoFood) that addresses these deficiencies and considers the findings of a gap analysis of FDMT conducted early in the project. The report presents the findings of the gap analysis, provides an overview of EcoFood´s components: the Simulator, the Model Library and the Parameter Database and a discussion on improvements and advantages inherent to EcoFood.
Key words	radionuclide, releases, atmospheric, environment, terrestrial, dose, humans

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