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1 Introduction

The objective of forest radioecology modelling is to mathematically simulate the distribution, cycling and sinks of radionuclides in forests, including the wildlife inhabiting the forest. The focus of this Deliverable is on describing the parameters needed to develop models for the cycling of radionuclides in forest ecosystems. There is a dual purpose to this type of modelling:

- Research modelling: understanding the role of trees as 'biological pumps' cycling radionuclides along with the water. This involves implementing the governing equations of processes controlling the movement of water (e.g. evapotranspiration, groundwater flow, sap flow) and energy (e.g. solar irradiation, changes in temperature). Then, it is necessary to link radionuclide transport to these fluxes.
- Assessment modelling: Calculating the pathways of radionuclides intercepted by the forest, providing a basis for calculating the dose to man and the environment. The calculation of doses to humans through external exposure and ingestion of forest foodstuffs relies on the prediction of radionuclides transfer dynamics within forest compartments (Rantavaara, Calmon et al. 2001).

In developing a forest model for radionuclides, it is important to capture the essential processes regulating the entry, circulation, storage and exit of substances to the trees – in other words, the biogeochemical cycling. A schematic, based on the IAEA Biomass report (IAEA 2003), is given in Figure 1 below.

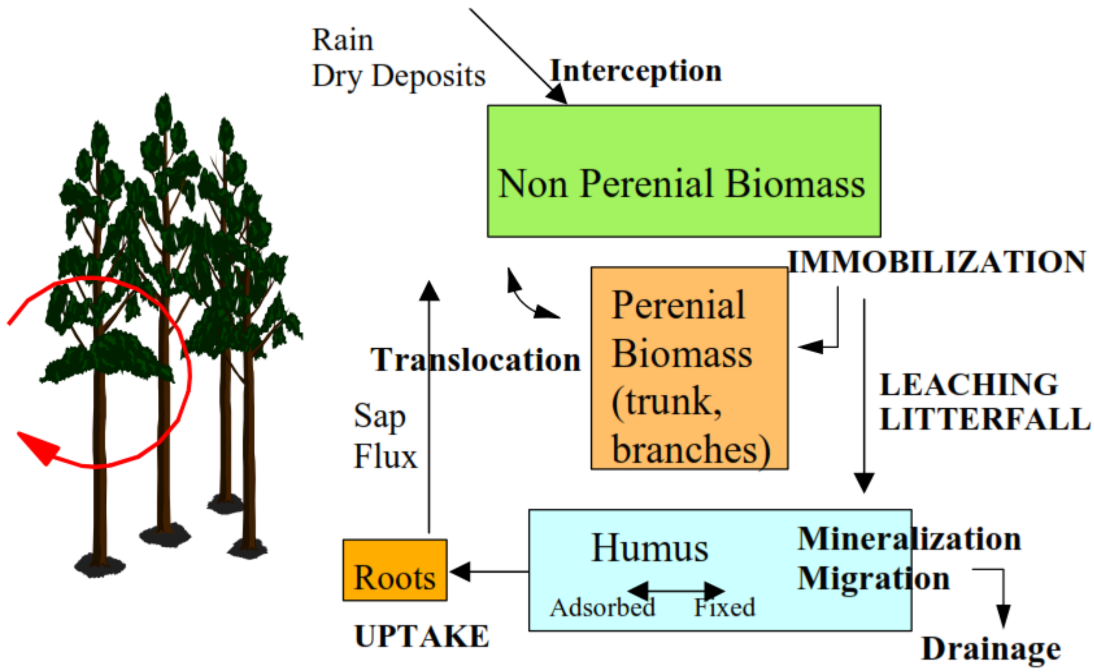

Figure 1: Processes regulating the cycling of radionuclides by forest vegetation
In both cases, there are three main areas to consider:

- The transfer of radionuclides from the unsaturated zone of the soil. This is important when the source of radioactivity is in the soil, e.g. ground disposal of radioactive waste. Another situation of interest is long-term (i.e. years to decades) prediction of contamination in forest systems contaminated by atmospheric deposits (for which memory of the initial input is progressively lost).
- The interception by the trees of radionuclides from the atmosphere (important for accidents).
- The deposition of radionuclides transported by the litterfall to the forest floor, leading to exposure to forest products and to man.

The parameter requirements of a forest radioecology model vary greatly depending on the degree of complexity of the model, which in turn is dictated by the model's purpose. Therefore, there is no "one size fits all" parameter list. Research models require a higher number of parameters, carrying information closely linked to the governing equations used to describe the processes. This can include physical, biological (i.e. ecophysiological) and chemical parameters which need to be derived from observations and field measurements in contaminated environments, alongside laboratory experiments, because it is virtually impossible to trace down every single parameter in the equations to basic physical or chemical constants.

On the other hand, assessment-type models tend to be simpler, with many being systems of linear, first order differential equations $\frac{dC_i}{dt} = \sum_i(inputs\ to\ C_i) - \sum_i(outputs\ from\ C_i)$ in which the exchange between compartments is mathematically represented by first-order kinetics. This means that there is a 'rate equation' with a constant transfer rate which is generally an empirical or semi-empirical parameter. A 'box model' can be constructed, which is very simple and has a reasonably small number of these rate constants. Note however that this is an approximation; one may have transfer rates that can be parametrised as a function of environmental co-variables/co-factors (like time series of meteorological data or biomass fall, etc.) and the transfer between compartments does not necessary follow a first order kinetics representation in every case.

2 Parameter requirements for a simple forest 'box' model

A good example of a typical 'box model' of the type that could be used in assessments is the model of ^{36}Cl cycling in a coniferous stand (Van den Hoof and Thiry 2012), developed at SCK•CEN (Belgium). This is a model with rates of transfer k_{ij} between compartments C_i and C_j. Although there are many types of such simple box models, it often (but not always) shares the fundamental characteristics for a model of this complexity, such as (a) it is dynamic, with the fluxes of biomasses, energy or nutriments following first-order kinetics, (b) the behaviour of the radionuclide is similar to the behaviour of the stable element (c) the transfer rates are time-independent, (d) the fluxes between compartments are controlled by the element content in the donor compartment and (e) as an initial condition, sometimes all the model compartments except the initial source term are generally assumed to be empty (although

ODE based models can be started/run from a pre-existing contamination in the forest system). The model structure is indicated in Figure 2.

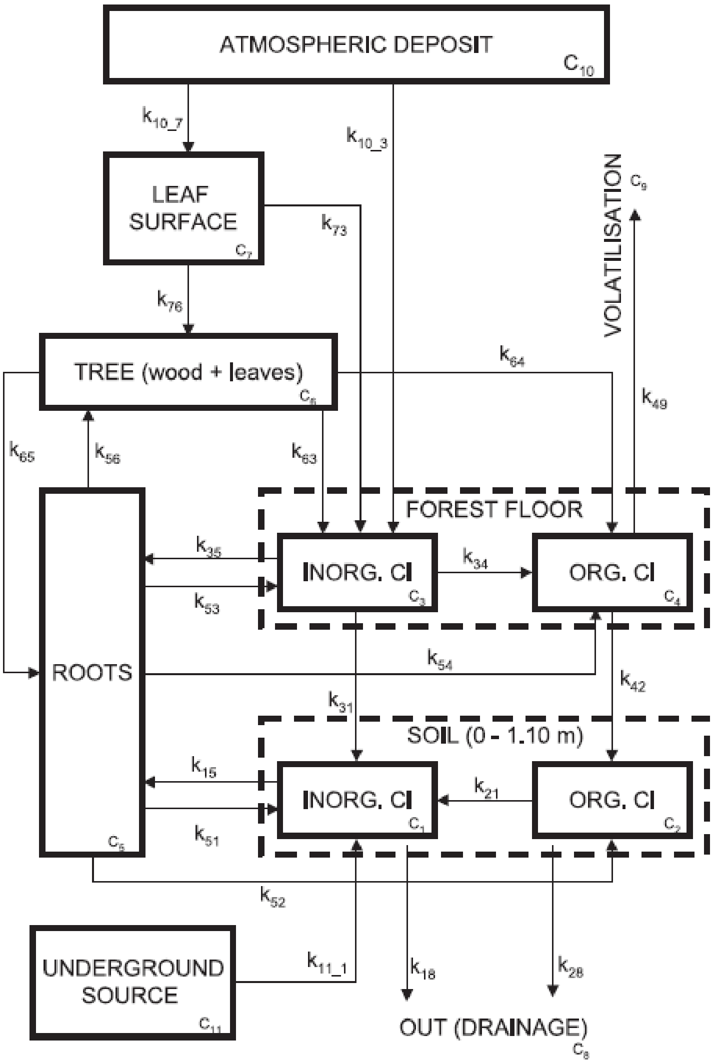

Figure 2: Schematic of box model for ^{36}Cl cycling in a coniferous stand (Van den Hoof and Thiry 2012)

The key parameters for the ^{36}Cl model are the rate constants k_{ij} representing the following processes:

- Atmospheric deposition onto leaf surface (k_{10_7}) and forest floor inorganic radionuclide pool (k_{10_3}).
- Transfer from leaf surface to above-ground tree biomass (k_{76}).
- Leaching from leaf surface to forest floor inorganic Cl pool (k_{73}).
- Transfer from tree to forest floor of organic (k_{64}) and inorganic Cl pool (k_{63}).
- Transfers from the inorganic to the organic phase in the forest floor (k_{34}) and from the organic to the inorganic phase in the soil (k_{21}).

- Transfers of inorganic (k_{31}) and organic chlorine (k_{42}) from the forest floor to the soil.
- Leaching of inorganic (k_{18}) and organic radionuclide from the soil (k_{28}).
- Volatilisation of organic radionuclide from the forest floor (k_{49}).
- Transfers from soil and forest floor to roots (k_{15} and k_{35}) and from roots to soil and forest floor (k_{53}, k_{54}, k_{51} and k_{52}).
- Translocation from roots to above-ground tree biomass (k_{56}) and the reverse (k_{65}).

Some of these parameters can be deduced but some need to be derived experimentally. Full details are given elsewhere (Van den Hoof and Thiry 2012). The rate constant k_{76} can be determined by field experiments on radionuclide translocation in plants. k_{63} and k_{64} by measuring fraction of the organic radionuclide content controlled by the annual litterfall rate and the total element content in the tree. k_{34} and k_{28} can be derived from measurements of the amount of inorganic and organic element in the soil in relation to the total, and same for drainage water. k_{21} is the ratio between the mineralisation rate and the organic radionuclide content of the soil; experiments on the mineralisation process of radionuclides from the litterfall are very useful here.

The rate constant k_{31} can be derived from hydrological modelling but the necessary inputs are needed from experiment: fraction of silt, clay, organics in the soil i.e. soil characterisation; precipitation and parameters for evapotranspiration calculation (temperature, humidity, light intensity, leaf area index). k_{42} requires determination of the humus stock. k_{53}, k_{54}, k_{51} and k_{52} require knowing the fraction of radionuclide in roots and other parts of the tree. k_{56} is a very important translocation parameter and it requires the radionuclide distribution pattern in trees including the growing tissues (twigs, needles) other living (sapwood, roots) and dead parts (bark, litterfall). For k_{65}, it is useful to measure the decrease in radionuclide concentration in pine needles during senescence prior to leaf fall.

Based on the above, we venture the following wish list of modelling requirements to experimentalists in the case of simple, 'box-type' assessment forest models, like that of van den Hoof and Thiry (2012).

Table 1: Parameter requirements for 'box-type' assessment forest models

Parameter	**Importance**	**Experiment**
Annual litter-fall rate	★★★	Litter collection trays
Initial conditions for radionuclide concentration in trees including the growing tissues (twigs, needles) other living (sapwood, roots) and dead parts (bark, litterfall).	★★★(★)	Field sampling: biomass, tree cores. For needles consider the senescence period prior to leaf fall. Radiometric measurements.
Initial conditions for radionuclide concentration in soil and humus	★★★	Radiometric measurements.

Tree to leaf surface concentration ratio at steady state	★★	Field experiments on radionuclide translocation in plants. This concentration ratio is not a constant, so this is not always accessible by field experiment.
Fraction of organic radionuclide in the above and in drainage water	★ (only for radionuclides with a significant organic fractionation)	Field sampling
Mineralisation rate	★★	Lab experiments on the mineralisation process of radionuclides from the litterfall
Soil characterisation: fraction of silt, clay, organics in the soil, distribution coefficient K_d in the particular conditions of the soil i.e. composition, bulk density and porosity, degree of moisture and geochemical conditions).	★★★(★)	Field sampling, radiometric analysis of pore water and soil to determine experimentally the K_d, which is a parameter with a high degree of uncertainty.
Main parameters for evapotranspiration calculation (temperature, atmospheric pressure, wind speed, relative humidity, precipitation, net solar energy input in Wm^{-2}, leaf area index). These are used by the model to calculate water flux through the tree.	★★★	Field monitoring – rain gauges, PAR sensors, etc.
Biomass data (mass of a whole tree, number of trees per Ha, tree height, tree diameter ? at breast height)	★★★	Site surveys

Another example of a typical assessment model is given by TREE4 model - Transfer of Radionuclides and External Exposure in FORests (Calmon, Thiry et al. 2009, Calmon, Gonze et al. 2014). In the course of the 4th European Commission framework programme (1995-1999), the French Institute for Radiological Protection and Nuclear Safety (IRSN) and the Finnish

Radiation and Nuclear Safety Authority (STUK) designed and developed a forest module for the RODOS system (Ehrhardt and Weis 2000). The development of the model relied on post-Chernobyl observations made in western European forests. The objective was to develop a rather simple approach to help decision-making by rapidly estimating the consequences of accidental atmospheric fallout, with a special emphasis on the short-term phase (i.e. first few months). This dynamic model accounts for the physical and biological processes that control the fate of radiocaesium during the short-term phase: dry deposition onto vegetation and forest floor, interception of wet deposit by vegetation and vegetation depuration through litterfall, throughfall and stem flow. The approach has been tested in the frame of IAEA research programmes BIOMASS, 1997-2001 and EMRAS, 2003-2007, dedicated to forest models inter-comparison and parameters review (IAEA 2002, Shaw, Venter et al. 2005, Calmon, Thiry et al. 2009, IAEA 2010). Preliminary results obtained with the TREE4 approach on radiocaesium transfer and ambient dose rate in Fukushima forest biotopes have been recently reported (Calmon, Gonze et al. 2014, Gonze, Calmon et al. 2014, Gonze, Renaud et al. 2014, Calmon, Gonze et al. 2015).

The evolution of radionuclide inventories in each forest pool (expressed in Bq m^{-2}) is calculated along with mass fluxes between them (Bq m^{-2} s^{-1}). The approach relies on the resolution of mass balance equations with mathematical parameterisations specific to each process considered in the conceptual model. Parameter values are tabulated for three different types of forests: deciduous broadleaf, evergreen and mixed forests, the latter being characterised by the percentage of deciduous and evergreen.

Especially for assessment models, a difficulty is often to manage uncertainty/variability in the parameter values. One major point is that for each parameter, there is a set of environmental characteristics that determine its numerical value. Therefore, the transfer parameter values are conditioned by physico-chemical, biological and ecological characteristics of the forest ecosystem considered, and thus are intrinsically site-specific. The most influencing environmental factors are known to be the local meteorological conditions (e.g., rainfall and snowfall time series, mainly) and the vegetation characteristics (e.g., stand density and age, tree species composition, tree component biomasses or area indexes and biomass dynamics at both intra-annual and inter-annual scales).

Therefore, part of this variability/uncertainty can be better resolved by introducing parameterisations that explicitly account for environmental conditions/co-factors (ex: throughfall rate driven by the effective rainfall rate) and a sub-model dedicated to the description of the forest structure and functioning, through for example allometric relationships and population density dynamic models. These kind of refinements were shown to significantly increase the realism of such assessment model predictions and its capability to capture the spatio-temporal variability of radionuclide dynamics in Fukushima contaminated forests (Gonze, Calmon et al. 2016).

Based on the above, the wish list of modelling requirements in the case of flux-based models, like TREE4 (Calmon, Thiry et al. 2009, Calmon, Gonze et al. 2014), is very similar to that described above for the ^{36}Cl box-model. Some further parameters are required and listed in the following table.

Table 2: Parameter requirements for flux-based models

Parameter	**Importance**	**Experiment**
Ecophysiological parameters describing the forest structure : - Growth and litterfall season - Specific Leaf Area of foliage, branch and trunk (m^2 kg $(dm)^{-1}$) - Allometric relationships for foliage, branch and trunk - Water retention capacity of the tree canopy (m) - Time-dependent litterfall rate (kg (dm) m^{-2} s^{-1})	★★★	Most of these data can be found in forestry literature for common tree species. Site surveys may be required for very specific sites.
Time-dependent meteorological data including rainfall time series (m)	★★★	Site surveys
Dry deposition velocity of airborne radionuclides onto the canopy, trunk and soil compartments (m s^{-1})	★★	Field monitoring (meteorological tower)
Throughfall and stem flow rates (s^{-1})	★★★(throughfall) ★ (stem flow)	Water collectors

3 Parameter requirements for a research 'process-based' model

A good example of a process-based box model of the type that could be used for research is the model of element cycling in a coniferous stand considering soil-vegetation-atmospheric (SVAT) interactions, ECOFOR (Vives i Batlle, Vandenhove et al. 2014). The model structure is indicated in Figure 3. This model assumes a simplified representation of the hydrology with water infiltration, Darcy flow and the Lucas-Washburn equation which describes capillary flow in a bundle of parallel cylindrical tubes, rather than adopting the general but more complex representation by the Richards' equation, which is difficult to solve numerically.

The movement of water through the soil layers is then modelled using a 'tipping bucket' approach in which the soil column is represented by ten computational layers and water flows from to and from a layer are controlled by a an algorithm based on the above hydrological equations and each layer's actual volumetric water content, total porosity and field capacity, with excess water exiting to groundwater recharge.

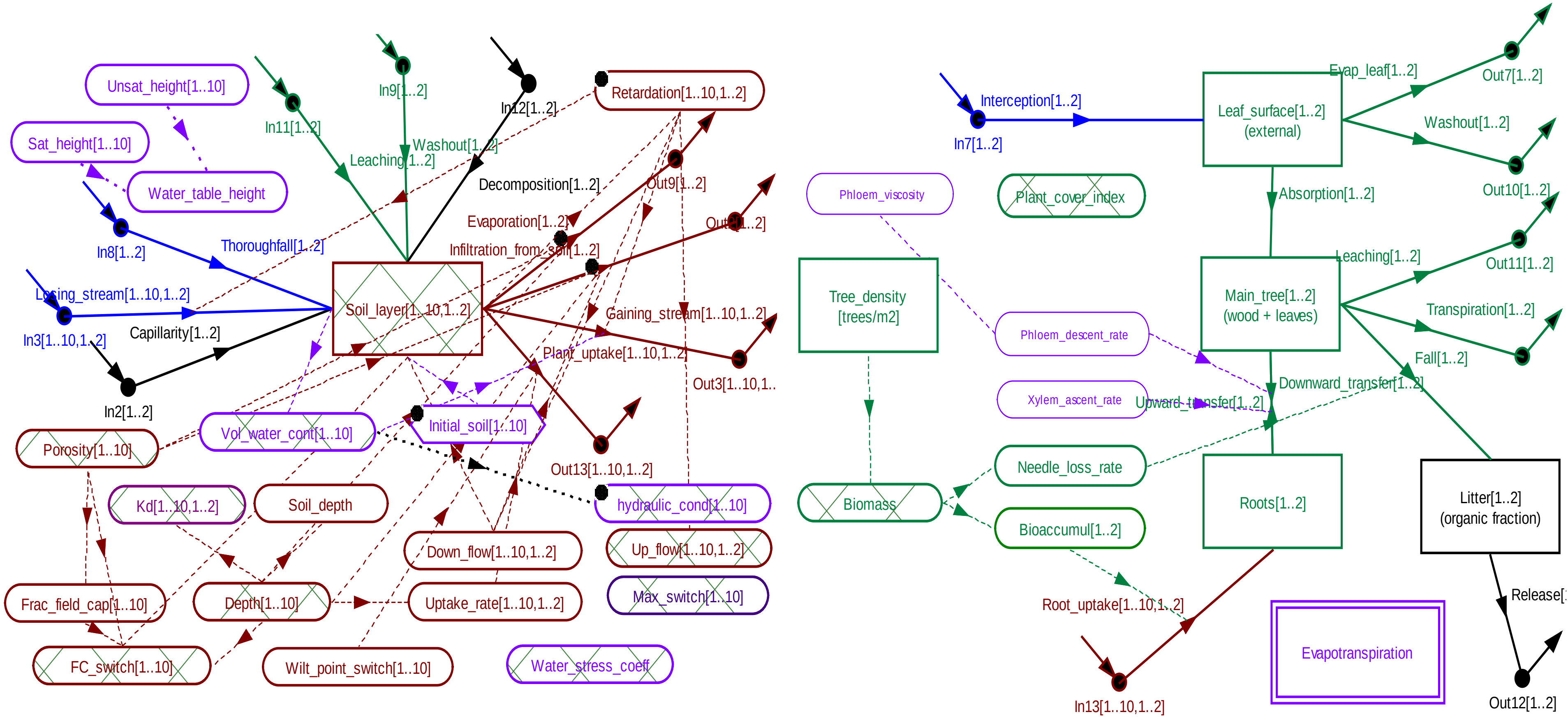

Figure 3: Schematic of ECOFOR model as set-up in ModelMaker 4, including hydrological (left) and vegetation (right) main sub-models. The meaning of the symbols is as follows: Compartments (rectangle), variables (rounded rectangle), sub-model (double rectangle), flow (arrow) and influence (dotted arrow).

The hydrological model is coupled to a plant sub-model where water uptake via roots is driven by evapotranspiration as calculated by the Monteith model (Monteith and Unsworth 2007) and fluids circulate through the plant upwards (xylem upflow governed by the Poiseuille equation) and downwards (phloem downflow along an osmotic pressure gradient) allowing translocation of the radionuclides with these flows. Water interception by the canopy, washout, absorption and leaching are considered as transfer factors and litterfall plus litterfall decomposition are modelled by an empirically-derived linear transfer rate. Element transport is linked to water via retardation processes in soil (with link to the K_d of the element, assumed to be dependent on soil moisture) whilst empirically-derived selectivity coefficients link element fluxes to the water fluxes in plants in an approach similar to the BioRUR model (Casadesus, Sauras-Yera et al. 2008).

ECOFOR, whilst more complex and process-based than our previous examples, is not as complicated as some forest models that include plant biology and chemical processes at the molecular level (Deckmyn, Verbeeck et al. 2008, Deckmyn, Campioli et al. 2011). It represents a research model of the type sufficiently complex to be realistic and sufficiently simple to be practical for future use in environmental assessments.

Of all the components of the model, it is the hydrology that is most difficult to simplify. In the ideal case one would have to solve Richard's Equation which depends on very few parameters but is very complex to solve mathematically. By adopting simpler strategies, the model is more practical and requires less parameters and computational effort, but a price is paid in terms of reducing the applicability range of the model because of the use of some approximations (such as the aforesaid Darcy flow and Lucas-Washburn capillarity equations, for example).

Based on a study of parameter requirements presented in the COMET International Workshop on Models and Data Fit for Purpose (Vives Batlle 2016), we venture the following wish list of modelling requirements to experimentalists in the case of a more sophisticated research model for radionuclides in forests (parameters already mentioned for the case of a simpler box model are indicated in italics).

Table 3: Parameter requirements for a more sophisticated research model

Parameter	**Importance**	**Experiment**
Total soil column depth and surface area	★★★	Physical characterisation on soil samples.
Soil characteristics for all soil 'horizons' considered by the model: • Volumetric water content at residual and at saturation value • K_d for saturated soil (depends on	★★★(★)	Field sampling, radiometric analysis of pore water and soil to determine experimentally the K_d, which is a parameter with a high degree of uncertainty.

composition, degree of moisture and geochemical conditions) • Saturated hydraulic conductivity • Soil layer clay, sand, organic fractions • Soil layer thicknesses • Soil layer bulk density • Soil layer particle density • Soil layer porosity		
Radionuclide concentration in trees including the growing tissues (twigs, needles) other living (sapwood, roots) and dead parts (bark, litterfall). Plant selectivity coefficients for relevant radionuclides can be derived from the above.	★★★(★)	Studies of element distribution in different parts of the tree for the specific site or borrowing data from a similar site.
Radionuclide concentration in soil and humus.	★★★	Sampling, radiometric analysis
Tree physiology: Height, trunk diameter, tot. mass, above/below ground mass ratio, wood density, moisture content of wood, bark and needles.	★★★(★)	Site surveys
Mass fraction of the compartments: needles, bark, litter, roots, wood.	★★★(★)	Sampling on site
Annual litter-fall rate	★★★	Litter collection trays
Plant water interaction coefficients: absorption, interception and washout factors, leaching rates.	★★★(★)	These are important parameters but they cannot be easily measured for each case. One would like to have some 'rain in the greenhouse ' where indicative values of these parameters are determined for different

		types of trees and radionuclides (pine, oak, poplar, beech, etc.)
Anaerobiosis parameter (root waterlogging limit), fractional wilting point.	★★	See comment above
Root model parameters: extinction coefficient (for exponential model).	★★★	Literature, textbooks
Sap characteristics: Phloem concentration, density and drag coefficient, sap sucrose content, phloem and xylem vessel radii, xylem pressure differential.	★★★	Literature, textbooks
Litterfall parameters: bark and needle fall rate, litter decomposition rate.	★★★	Field sampling
Main parameters for evapotranspiration calculation (temperature, atmospheric pressure, wind speed, relative humidity, precipitation, net solar energy input in Wm^{-2}, leaf area index).	★★★	Field monitoring – rain gauges, PAR sensors, etc.
Biomass data (mass of a whole tree, number of trees per Ha, tree height, tree perimeter at breast height).	★★★	Site surveys

4 Conclusions

Different types of forest models implement processes in a different way and require different types and numbers of parameters. The problem is compounded by the fact that in developing a model for forests, it is necessary to couple processes in three domains: soil, the vegetation and the atmosphere. The hydrological problem in particular is not amenable to easy mathematical representation. This complex situation requires approximations and simplifications. Under these conditions, it is not possible to give a 'one size fits all' wish list of modelling parameters for the modelling of radionuclides in forests.

However, some generalisations can be made, and in the present document, we have approached the challenge by describing parameter requirements with three examples ranging from simple box models for assessments to more advanced research models, from which the basic parameter requirements according to model type, their importance and the sources of information have been deduced and presented in Tables 1 - 3.

With respect to sources of information, in current monitoring programmes, it is often the case that data on radionuclide concentrations in tree parts and surrounding soils and their associated biomasses are determined, but the principal 'accompanying parameters' describing the environment (soil hydrological characterisation, soil K_ds, evapotranspiration controlling parameters) are often missing. A lot of what is referred to as model uncertainty is caused by not measuring these 'hidden' variables and thus being unable to explain differences that would be quantified by integrating this ancillary information in the model. This can be addressed by complementing regular sampling (to measure radionuclides) along with ongoing monitoring of these parameters, using monitoring stations with data logging capabilities linked to basic instruments (e.g. pluviometers, photosynthetically active radiation (PAR) sensors, sap flow meters, feed from a local meteorological station, soil moisture sensors and piezometers). This is the approach used in a recent study (Gielen, Vives i Batlle et al. 2016), soon to be adapted for the NORM-contaminated Belgian site at Kepkensberg.

When attempting a predictive modelling approach for forests, it may well be the case that all the required site-specific parameters are not available. The following process can then be attempted. In the first instance one should try to utilise bibliographic reference parameters, whereupon by literature search one may hopefully be able to find a range for the parameters (minimum, maximum and median). Starting with the median value, the modeller can vary each parameter within the permitted interval and, through this calibration process, assert the optimum value that fits best the model output to the available reference data. If no reference data are available, it is at least possible to calculate an uncertainty band for the model predictions.

If the model output does not fit observation unless the parameters are outside their permitted interval, then there is a need to change the structure of the model. Usually, the problem is that the actual model representation is too complex. The only solution then is to simplify by reducing the model's scope and complexity/level of detail (model abstraction), because simple models require less data and the results are easier to interpret since the structure of the model is better understood. Model simplifications should always be down to a level that still maintains sufficient accuracy for addressing the modelling objectives.

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