A systematic approach to the migration of $^{137}\text{Cs}$ in forest ecosystems using interaction matrices

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Abstract

The migration of radionuclides in the environment is complex and involves multiple biotic and abiotic components and interactions. When developing conceptual and mathematical models of such processes, there is a risk that important components and interactions are omitted or underestimated. This risk can be reduced if a systematic approach to model development is applied. In this paper, a systematic method using interaction matrices is applied for development of a conceptual model of the migration of $^{137}\text{Cs}$ in forest ecosystems. A method for derivation of the most dominant radionuclide migration pathways in the system is proposed. This method is illustrated by a pathway analysis of $^{137}\text{Cs}$ accumulation by fungi. The application of interaction matrices for studies of cause–effect relationships, for showing the state of knowledge and for identification of research priorities is also discussed. © 1999 Elsevier Science Ltd. All rights reserved.

1. Introduction

The migration of radionuclides in the environment is complex and involves multiple biotic and abiotic components and interactions. When developing conceptual and mathematical models of such processes, there is a risk that important components and interactions are omitted or underestimated. This risk can be reduced if a systematic approach to model development is applied.

In the present work a method developed by Hudson (1992) for systematic studies of processes in rock engineering systems is applied to the development of a conceptual model of $^{137}\text{Cs}$ long-term migration in forest ecosystems. In this method, interaction matrices are used to represent the mechanisms responsible for the behaviour of the
system. A similar method has been applied for development of conceptual biosphere models and scenarios for performance assessments of high-level radioactive waste repositories (BIOMOVS II, 1996). The use of this method for development of ecological models has, however, not been reported in the literature. For this reason, in this paper we have put emphasis on the description of the method and illustration of its possibilities for ecological modelling.

To form a conceptual model is one of the early steps in the creation of a mathematical model, but it might also have a meaning of its own. The conceptual model can be considered as a list of components of importance to the problem in focus, but it also shows how these components are connected by means of interactions. In this work, interaction matrices are firstly used to develop the conceptual model and afterwards used as a diagram of the conceptual model itself. An example that illustrates how to derive the most dominant pathways from the conceptual model is presented in the paper. The application of the matrix diagram of the conceptual model to identify cause–effect relationships in the system and for showing the state of knowledge are also discussed.

2. Description of the method

The essence of the method is to study processes occurring in a system using an $n \times n$ interaction matrix $[x_{ij}]$, where “$i$” is the row number and “$j$” is the column number of each element of the matrix. In such a matrix the components of the systems in question are elements in the leading diagonal ($i = j$) and the interactions between them are the off-diagonal elements ($i \neq j$). The matrix should be read clockwise. An element with $j > i$ denotes how the diagonal element $x_{ii}$ influences the diagonal element $x_{jj}$ while an off-diagonal element with $j < i$ denotes how the diagonal element $x_{jj}$ influences the diagonal element $x_{ii}$. The number of diagonal elements is a measure of the matrix resolution. If the number of leading diagonal terms increases, then the number of possible interaction terms and the matrix resolution also increase. For a matrix with “$n$” diagonal terms, there are $n(n - 1)$ interaction terms.

A key question is the selection of the diagonal elements and the optimal resolution based on the knowledge about the system. There is no universal objective method for this and thus the choice strongly depends on the expert judgement of the person building the matrix. A way to gain in “objectivity” is to involve several experts, for instance a multidisciplinary group (BIOMOVS II, 1996). To make the matrix more useful for studies of cause–effect relationships, pathway analysis, etc., the diagonal elements should be selected in such a way that as many binary interactions as possible are placed in off-diagonal elements. The resulting matrix can be checked for completeness by assuming that each binary interaction is in principle possible, and by a comparison with information on interactions found in the literature.

When the diagonal elements and the binary interactions have been identified, it is possible to “code the matrix”, i.e. to rank the interactions in order of importance. Hudson (1992) discussed five different methods for matrix coding: from a simple binary, i.e. interactions are switched on and off, to a complete numerical analysis of
the interactions. In this paper we use the “expert semi-quantitative method”, which is an extension of the binary method to five categories of the interactions ranging from zero to four. This corresponds to “no”, “weak”, “medium”, “strong” and “critical” interactions, respectively. Also here a multidisciplinary group can be used to improve the trust in the ranking. The coded interaction matrix can be used as a diagram of the conceptual model of the studied process.

3. The conceptual model

The radionuclide migration and redistribution in forest ecosystems vary in time and can be divided into two main phases (Tikhomirov & Shcheglov, 1994). In the first phase, lasting a few years after an atmospheric contamination, the mechanisms of decontamination, foliar uptake and redistribution of the radionuclides inside the plant are dominant. The second phase follows the radionuclide transfer from the phytomass into the forest litter and then into the soil root zone, and is characterised by a predominance of root uptake also followed by redistribution of the radionuclides. In this paper, we will focus on the study of the second phase. No influence of man on the system or dramatic perturbations of the system, like forest fires, were considered in the present study.

The process for development of the conceptual model consisted of iteratively creating an interaction matrix. As a basis for the matrix, a list of interactions of $^{137}$Cs migration in forest ecosystems was collected using our own experience and the existing literature, especially review publications (Fraiture, 1992; Myttenaere, Schell, Thiry, Sombre, Ronneau, & Van der Stegen de Schrieck, 1993; Thiry & Myttenaere, 1993; Tikhomirov & Scheglov, 1994; Nimis, 1996). Firstly, a simple version of the matrix, shown in Fig. 1, with a small number of diagonal elements corresponding to some major components of the ecosystem, was built. In this matrix several interactions had, however, to be assigned to a number of the diagonal boxes, especially the ones corresponding to the tree, soil-litter and understorey layers (components). In order to have most of the binary interactions in off-diagonal elements the matrix resolution was afterwards increased to 9 by fragmenting some diagonal elements (Fig. 2).

The tree layer was divided into leaves (needles) and other parts, the soil layer into litter, organic soil and mineral soil. Some years after a deposition most of $^{137}$Cs is in the soil-litter layer (Myttenaere et al., 1993; Tikhomirov & Scheglov, 1994; Hubbard, Wallberg, & Moberg, 1996), where multiple interactions lead to its vertical distribution and transfer to plants. To place all the interactions occurring in this layer in off-diagonal elements, we would need to include many more diagonal elements. A matrix representing the whole ecosystem would then be too big to be useful in practice. As a compromise, the mechanisms of root uptake and vertical migration include the sorption/desorption interactions occurring in the soil-litter layer. A possible alternative would be to represent the soil-litter layer in an independent matrix connected to the main matrix.
The choice of fungi as an independent diagonal element is motivated by its central role in the migration of $^{137}$Cs in forest ecosystems. Fungi have a high capacity to accumulate $^{137}$Cs (Kiefer & Maushart, 1965; Roehleder, 1967; Seegel & Schweinshaut, 1981; Eckel, 1986; Nimis, Giovani, & Padovani, 1986; Mascanzoni, 1987, 1990; Byrne, 1988; Heinrich, 1992; Strandberg, 1994). Olsen, Joner, & Bakken (1990) estimated theoretically that about 30% of $^{137}$Cs could be fixed by soil fungal biomass. Fungi through mycorrhizae also play an important role in the uptake of $^{137}$Cs by higher plants (Guillitte, Melin, & Wallberg, 1990, 1994; Wirth, Hiersche, Krajewska, Kressel, Mahler, & Römmelt, 1994). The mycorrhizae associations are considered in the matrix as interactions between fungi and plants related to the processes of root uptake.

The matrix in Fig. 2 includes the interactions found in the literature search. The strength or importance of the interactions is, however, different for different phases of...

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<table>
<thead>
<tr>
<th>Atmosphere</th>
<th>interception rainfall snowfall</th>
<th>interception rainfall snowfall</th>
<th>interception rainfall snowfall</th>
<th>inhalation interception</th>
</tr>
</thead>
<tbody>
<tr>
<td>transpiration burning</td>
<td>leaves fall weathering interception fertilisation</td>
<td>weathering interception mycorrhizae</td>
<td>ingestion</td>
<td></td>
</tr>
<tr>
<td>resuspension</td>
<td>root uptake rainsplash</td>
<td>Soil/litter percolation diffus/adv. litter decomp. sorption/desorption</td>
<td>uptake, rainsplash</td>
<td>ingestion</td>
</tr>
<tr>
<td>transpiration burning</td>
<td>root uptake (mycorrhizae)</td>
<td>leaves fall weathering interception fertilisation</td>
<td>Understorey translocation root uptake (mycorrhizae)</td>
<td>ingestion</td>
</tr>
<tr>
<td>consumption</td>
<td>fertilisation</td>
<td>consumption</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig. 1. Interaction matrix with 5 diagonal elements describing the long-term migration of $^{137}$Cs in a forest ecosystem.
the contamination history. The matrix in Fig. 3 shows the ranks, from 0 to 4, of the interactions according to their importance for $^{137}$Cs migration in the forest during the long-term phase of the contamination, i.e. for the time period beginning a few years after the deposition.

The first step for coding the matrix was to select the critical (most important) interactions with rank 4. The selection of the critical interactions was based on the following knowledge: (i) root uptake is the dominant transfer process in this phase (Tikhomirov & Shcheglov, 1994; Nimis, 1996); (ii) the root uptake of $^{137}$Cs is mainly from the organic layer of the soil (Andolina & Guillitte, 1990; Römmelt, Hiersche, Schaller, & Wirth, 1990); (iii) an important part of the root uptake of $^{137}$Cs by trees is through the mycorrhizae (Guillitte et al., 1990; Wirth et al., 1994); (iv) the ingestion of

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**Fig. 2.** Interaction matrix with 9 diagonal elements describing the long-term migration of $^{137}$Cs in a forest ecosystem.

<table>
<thead>
<tr>
<th>Atmosphere (Air)</th>
<th>interception</th>
<th>interception</th>
<th>interception</th>
<th>interception</th>
<th>interception</th>
<th>interception</th>
</tr>
</thead>
<tbody>
<tr>
<td>transpiration</td>
<td>rainfall</td>
<td>snowfall</td>
<td></td>
<td></td>
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<tr>
<td>burning</td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
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<tr>
<td><strong>Tree leaves</strong></td>
<td>translocation</td>
<td>leaves fall</td>
<td>weathering</td>
<td></td>
<td></td>
<td>ingestion</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>interception</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Tree other</strong></td>
<td>weathering</td>
<td>interception</td>
<td>Fertilisation</td>
<td>Fertilisation</td>
<td>mycorrhizae</td>
<td>ingestion</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>weathering</td>
<td></td>
</tr>
<tr>
<td>resuspension</td>
<td>rain splash</td>
<td>Litter</td>
<td>Decomposition</td>
<td>Percolation</td>
<td>root uptake</td>
<td>ingestion</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>root uptake</td>
<td></td>
</tr>
<tr>
<td>root uptake</td>
<td>Soil organic</td>
<td>organic</td>
<td>Fertilisation</td>
<td>Fertilisation</td>
<td>Fertilisation</td>
<td>ingestion</td>
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<tr>
<td></td>
<td></td>
<td>mineral</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>root uptake</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>ingestion</td>
</tr>
<tr>
<td>transpiration</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>burning</td>
<td>leave fall</td>
<td>weathering</td>
<td>Fertilisation</td>
<td>Fertilisation</td>
<td>mycorrhizae</td>
<td>ingestion</td>
</tr>
<tr>
<td></td>
<td></td>
<td>interception</td>
<td></td>
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<tr>
<td>fertilisation</td>
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<td>ingestion</td>
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</table>

Wild animals

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fungi is one of the main pathways of accumulation of $^{137}\text{Cs}$ by forest wild animals (Karlen, Johansson, & Bergström, 1991; Johanson & Bergström, 1994; Strandberg & Knudsen, 1994; Kiefer, Pröhl, Müller, Lindner, Drissner, & Zibold, 1996).

The second step was to rank the interactions in each column in order of their significance with respect to the critical interactions. The same procedure was applied to the rows. It is clear that the obtained ranking cannot be completely “objective” and it will always to some extent reflect the views of the person who did it. (We repeated this procedure several times analysing the system from different points of view, but the sum of the rows and columns did not vary by more than $\pm 2$.)

The coded matrix in Fig. 3 can be used as a diagram of a conceptual model of $^{137}\text{Cs}$ long-term migration in forest ecosystems. It shows the main components of the

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Fig. 3. Coded matrix — Diagram of the conceptual model of the long-term migration of $^{137}\text{Cs}$ in a forest ecosystem. (Critical — 4, Strong — 3, Medium — 2, Weak — 1, No interaction — 0).
system, the interactions between them and the relative strength of these interactions. One advantage of this conceptual model is that all known interactions that might take place in the system have been jointly and systematically considered during its development. This reduces the risk that relevant interactions are omitted or underestimated. It provides a general picture of the migration of the radionuclide in the system and it does not focus on the radionuclide accumulation in any particular component of the system.

4. Pathway analysis

The purpose of a model is often to predict the radionuclide concentration in one or more components of the system. In this case, it is necessary to identify the migration pathways ending in one or several particular components. The migration pathways can be seen as multiple interactions in the system, i.e. as combinations of the binary interactions in the interaction matrix. Any multiple interaction that does not include a binary interaction coded as “0” is in principle possible. The sum of the ranks (in the coded matrix) of the binary interactions involved can be used to rank the pathways in order of strength or importance. However, to compare the strength of pathways that involve different numbers of binary interactions one should use normalised ranks, which can be derived by dividing the sum of the ranks of the binary interactions involved by their number.

Table 1 shows the normalised ranks of the pathways ending in fungi obtained from the diagram of the conceptual model in Fig. 3. Examples of conceptual models of $^{137}$Cs accumulation in fungi that include all pathways with a normalised rank higher than or equal to 4.0 or 3.0 are presented in Fig. 4. There is a large number of pathways with a normalised rank between 2 and 3. This means that further addition of pathways could significantly increase the model complexity and the number of model parameters. This could result in an increase of the uncertainty of the model predictions.
Fig. 4. Diagram of a conceptual model of $^{137}$Cs accumulation in fungi — all pathways with a normalised rank higher or equal to 4.0 (a) or 3.0 (b) are included (the sources and sinks are not indicated).

Fig. 5. A plot of the cause–effect relationships in a forest ecosystem.
5. Other applications

5.1. Description of cause–effect relationships in the system

The sum of a row of the coded matrix represents the way in which a particular component affects all other components of the system and is termed the “cause” (C). The sum of a column represents the effect that other components of the system have on the component corresponding to this column and is termed the “effect” (E). A plot in (C, E)-space is a graphic representation of the cause–effect relationships of the system. Fig. 5 shows a cause–effect plot corresponding to the conceptual model in Fig. 3.

The position of the points in the cause–effect plot indicates the mode of interaction of each component with other components of the system. The longer the distance of a component from origin along the 45° diagonal the higher is the sum C + E and thus the higher is the degree of interaction of this component with other components of the system. From Fig. 5 it can be seen that the components can be divided into three groups of different degrees of interactivity. Fungi show the highest values and mineral soil, atmosphere and tree leaves the lowest. Understorey vegetation, forest litter, organic soil, parts of trees (other than leaves) and wild animals have an intermediate position.

The distance between the diagonal and the points corresponding to different components is an indicator of the degree of dominance or subordinance of the components. The components situated on the left side of the diagonal influence the system less than the system influences them (subordinate components). The components on the right side of the diagonal influence the system more than the system influences them (dominant components). In the example studied (Fig. 5), most components, with the exception of leaves and wild animals, are situated in the plot close to the main diagonal. This means that they influence the system approximately as much as the system influences them. This is an indication that the long-term behaviour of $^{137}$Cs in forest ecosystems is characterised by near to steady-state conditions. Leaves and wild animals are correspondingly the most dominant and subordinate components.

The models of radionuclide migration in the environment are often compartment models. One disadvantage of such models is that the parameter values have to be obtained for each specific site. The parameters often include several processes, which makes it difficult to estimate them from empirical data. A possible way to improve such models is to describe some key interactions in a mechanistic way, i.e. at a process level. The cause–effect plots can be useful for the selection of these interactions since they give an idea of the role of different components in the studied process. The degree of interactivity, dominance and subordinance could indicate priorities for modelling at a process level. In the case studied, fungi being the most interactive component could be treated as part of a distributive pool of the available caesium in the system. This solution was applied in the models of $^{137}$Cs migration in forest ecosystems proposed by Shaw, Mimikhin, Dvornik, Zhuchenko (1996).
5.2. Presentation of the state of knowledge

The development of models is strongly influenced by the state of knowledge of the modelled processes. Often, for example, important pathways cannot be included in the model because of lack of knowledge. The representation of the knowledge of the studied system in an interaction matrix could be helpful for identification of these pathways. In the matrix in Fig. 6 we have summarised our judgement on the knowledge of the migration of $^{137}$Cs in forest ecosystems. The state of knowledge is here classified in three categories: good, medium and bad. The analysis of this matrix, together with the coded matrix (Fig. 3), shows that there is a rather poor knowledge of

![Interaction Matrix](image)

Fig. 6. Judgement of the state of knowledge of the migration of $^{137}$Cs in a forest ecosystem. (Good—G, Medium — M, Bad — B, No interaction — 0).
several critical and strong interactions. This information can be used for identification of research priorities; design of model-oriented monitoring programmes, etc.

6. Concluding comments

The method discussed in this paper can be used as a tool for systematic ecological studies. We have shown its possibilities for one example dealing with the migration of $^{137}$Cs in forest ecosystems. One of its main advantages lies in the starting assumption that interactions between two components are possible. In this way, it is assured that the relevant interactions are included in the analysis. The application of this method for identification of the most dominant pathways can bring clear benefits, especially for complex systems and poor knowledge about the processes. When using this method it is important to take into account the element of subjectivity inherent to it. A way to increase the objectivity is to involve several experts in creating and coding the interaction matrices.

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References


