MODELLING OF RADIONUCLIDE TRANSPORT IN FORESTS: REVIEW AND FUTURE PERSPECTIVES

G. SHAW
Imperial College of Science,
Berkshire, United Kingdom

W. SCHELL, I. LINKOV
University of Pittsburgh
Pittsburgh, United States of America

1. INTRODUCTION

Ecological modeling is a powerful tool which can be used to synthesize information on the dynamic processes which occur in ecosystems (1). Models of radionuclide transport in forests were first constructed in the mid-1960's, when the consequences of global fallout from nuclear weapons tests and waste disposal in the environment were of great concern. Such models were developed based on site-specific experimental data and were designed to address local needs (2-4). These models had a limited applicability in evaluating distinct ecosystems and deposition scenarios. Given the scarcity of information, the same experimental data sets were often used both for model calibration and validation, an approach which clearly constitutes a methodological error. Even though the early modeling attempts were far from being faultless, they established a useful conceptual approach in that they tried to capture general processes in ecosystems and thus had a holistic nature. Later, radioecological modeling attempted to reveal ecosystem properties by separating the component parts from the whole system, as an approach to simplification. This method worked well for radionuclide transport in agricultural ecosystems, in which the biogeochemistry of radionuclide cycling is relatively well understood and can be influenced by fertilization. Several models have been successfully developed and applied to human dose evaluation and emergency response to contaminating events in agricultural lands (5-7).

## 2. RECENT FOREST ECOSYSTEM MODELS FOR RADIONUCLIDES

The Chernobyl accident provided valuable information for calibration and validation of models where the lack of a major synthesis of usable information was clearly demonstrated(8). Developments in techniques for sampling and analysis and recent computer software improvements have allowed radioecologists to implement integrated field and modeling programs in which ecosystems of interest can be partitioned both experimentally and conceptually, and empirical fluxes of radionuclide contaminants determined. However, attempts at incorporating these parameters have sometimes led to increasing complexity of the models. In addition, many of the parameters needed in the models are difficult to measure and the experimental values have a wide range, and therefore a large uncertainty. For example, in an attempt to reduce uncertainty in soil-to-plant transfer factors for radionuclides, a working group of the International Union of Radioecologists defined standard conditions for field measurements (9). The resulting values for agricultural crops, however, still have uncertainties of some two orders of magnitude. Forest ecosystems are much more complex and are likely to have even greater ranges of values. This large variability complicates the use of transfer factors in forest ecosystems. Documentation shows that natural ecosystems have even higher parameter uncertainties than agricultural ecosystems due to site variability, the layered structure of soils and diversity of plant cover. It is not surprising that attempts to apply the complex models developed for agricultural ecosystems to natural environments have not been very fruitful.

At least five recently developed models ECORAD (10), FORESTLIFE (11), RIFE (12) Biotic model (13) and FORESTPATH (14) have been used in fitting sample data collected from the Chernobyl zone and then deriving factors for the inter-compartment transfer of radionuclides, (Figure 1). This approach provides site-specific information which can be used in further general model development. An interesting finding in comparing a forested region only 7 km from the Chernobyl reactor with a forest area in Ireland shows that ^{137}Cs is much more mobile in the soil in Ireland than adjacent to Chernobyl (15). A possible explanation is that the initial deposition near Chernobyl was low-solubility "hot" particles and the Irish fallout was soluble and thus more readily available for root uptake. In using these data for predictive model development, transfer factors between compartments and the use of advection and diffusion coefficients in the soil layers have been discussed. Coefficients defining transport of ^{137}Cs through the upper soil layers have been deduced from such measurements (16). A problem faced by forest modelers is the complex dynamics in the system and the time dependent variability in the transfer of radionuclides. This large variability complicates the use of transfer factors in forest ecosystems. A model for radionuclide cycling in vegetation and uptake by animals relates the primary production, growth and turnover of ^{137}Cs (13). This model focuses on the biotic system, in contrast to other models which are generally driven by transport in soil (16).

Another useful approach employs a spread sheet to define parameters and to make probabilistic calculations on the time distribution of radionuclides in the forest compartments as well as radiation doses received by man as a result of a wide variety of exposure pathways (17). This screening model, FORM, has limited applicability in that it is specifically designed to assist in the development of criteria for clean-up of contaminated forests. It begins to address the many technical and economic issues in a comprehensive approach which includes use of forest products, dose to workers, cost/benefit analysis and management options. One major value of this approach is that it provides a useful package in which appropriate parameter values are compiled and synthesized for use by the non-specialist.
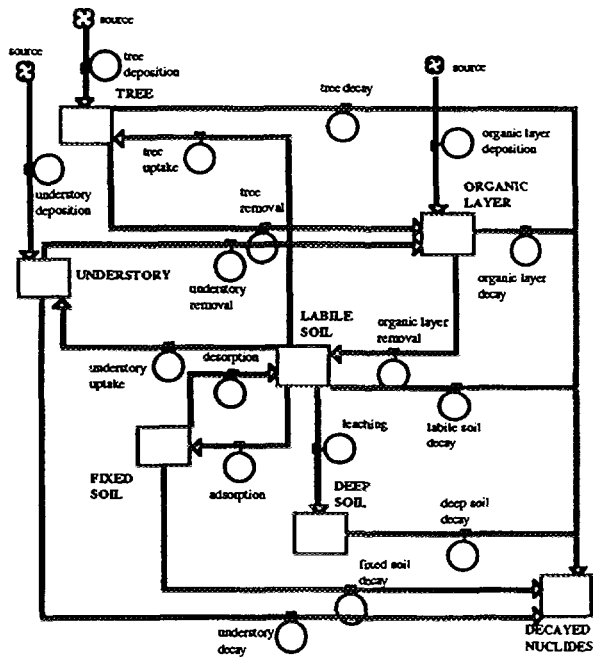
3. A GENERIC MODEL - FORESTPATH

In this paper, we advocate a holistic approach to radioecological modeling. However, forest ecosystems are so complex that it is impossible to separate many of the interacting components and processes controlling radionuclide transfers and storages. Our current knowledge of forest radioecology requires development of generic models to be used as tools to synthesize the available information and to guide future experimental programs. The FORESTPATH model describes the major kinetic processes and pathways of radionuclide migration in forests and natural ecosystems (Figure 1). The model can be used to predict future radionuclide concentrations by calculating the time-dependent radionuclide concentrations in different compartments of the forest ecosystem based on the information available on residence half-times in two forest types: coniferous and deciduous (14,18). Results of model simulations in Figure 2 show that forests can efficiently accumulate the radioactivity released to the environment and that the understory, tree and organic layer are the major sink compartments contributing to human radiation dose. The FORESTPATH model reproduces well the radionuclide cycling pattern found in the literature for deciduous and coniferous forests. This model also provides a method for evaluating human and ecological radiation doses. The model simulations can be used for quantitative evaluation of the effectiveness of different remedial actions. As a demonstration of its practical usefulness, it has already been applied to guide a comprehensive sampling program in the forests contaminated by the Chernobyl NPP accident (19). The results of the measurements are shown in Figure 3.
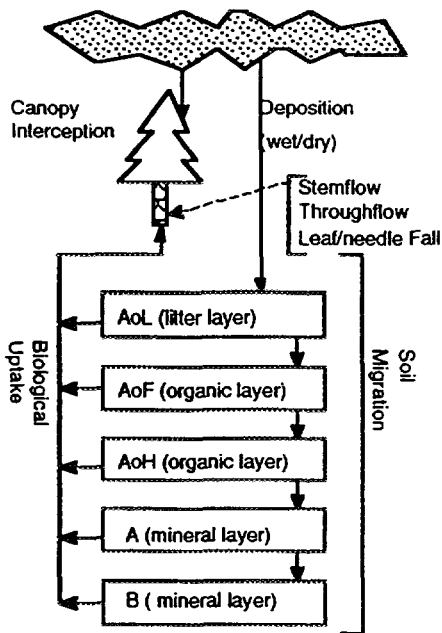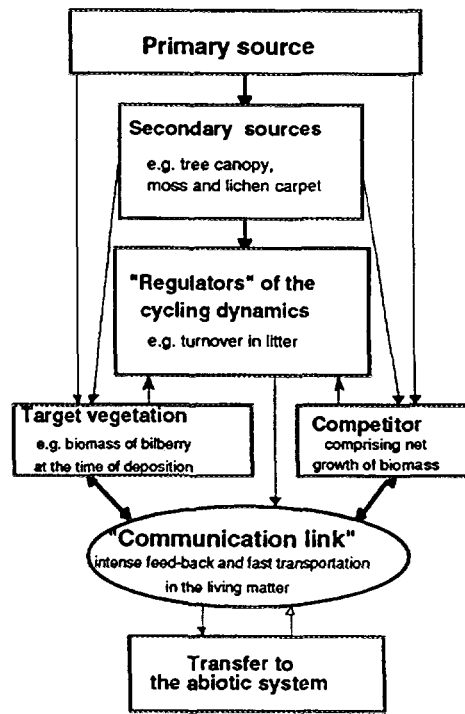
(a) ECORAD
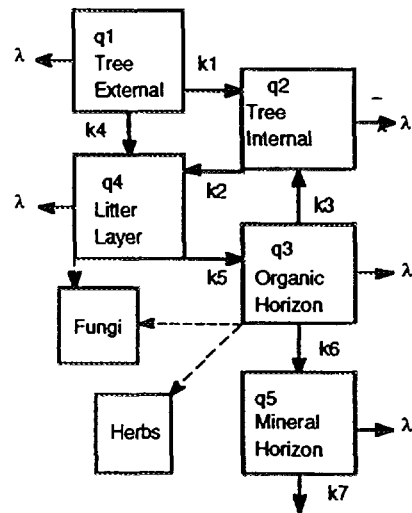
(b) RIFE

(c) FORESTPATH

(d) Biotic model

Figure 1. Framework for modeling radionuclide behavior in forest ecosystems:
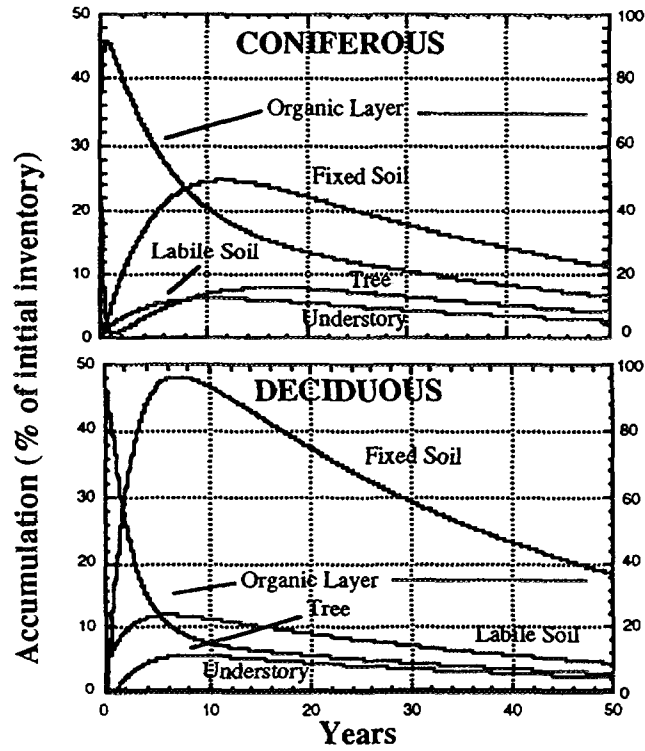a) ECORAD, b) RIFE, c) FORESTPATH, d) Biotic model.

Figure 2. Results of generic model runs for predicting ^{137}Cs distribution in forests using FORESTPATH.
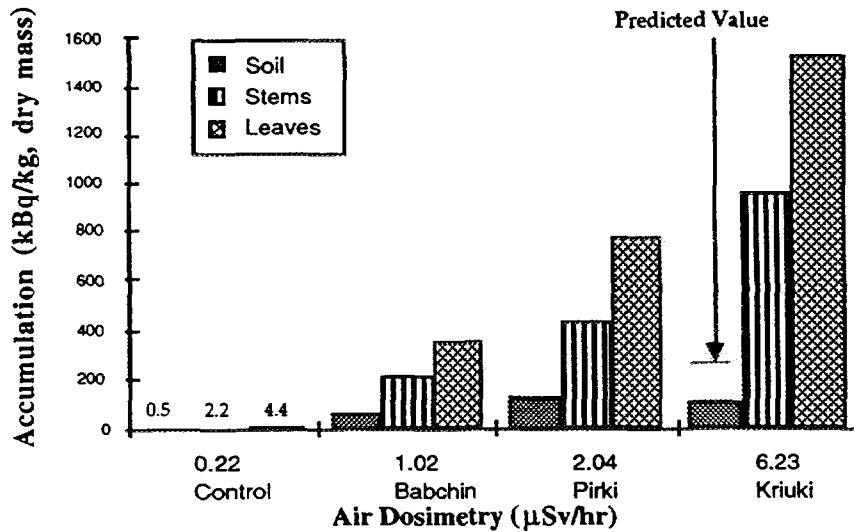

Figure 3. Accumulation of ^{137}Cs by fern in Chernobyl area coniferous forests, July 1994, at sites with different dosimetric levels 1m above the soil. Samples measured by M. Gerzabek, F. Strebl and V. Karg, Austrian Research Center, Seibersdorf.

4. CONCLUSIONS

Future model development requires accurate definition of key components of the generic forest ecosystem, while taking into consideration the interactions with neighboring interface ecosystems such as aquifers, catchment basins, marshlands, and rivers. These conceptual models can be tested using data from the literature. If coherence is found between these tests and site specific information, then the model has credibility and further information is required to validate it. The validation process is undertaken to identify the most important variables which control the output predictions, i.e., sensitivity analysis. If these variables are not known within reasonable error limits, then a field sampling and analysis program should be undertaken. The final approach to the model is to use one ecosystem where the model functions well and then use independent information from another ecosystem which is located in a different area. After adjusting for such features as soil types, organic layer, biomass distribution, temperature, species, etc., a validated model should be able to predict radionuclide concentrations over a time period following contamination. After the basic dynamic predictions are validated, then the model can be used to evaluate other social, economic, political, dose reconstruction, and site remediation activities which may be considered in the aftermath of a nuclear contamination event. The process of modeling radionuclide behavior in natural ecosystems is progressing slowly but with strong implications for both ecology and for risk identification and assessment purposes. However, for semi-natural ecosystems, we still cannot confidently answer the question: When once contaminated by radionuclides, how long will it take to restore a contaminated zone into productive use by the affected population?

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