BY0000223

Modelling Radiocaesium Fluxes in Forest Ecosystems

Results from the ECP-5 project conducted under the Agreement for International Collaboration on the Consequences of the Chernobyl Accident between the European Commission and the Ministries for Chernobyl Affairs in Belarus, Russia and Ukraine

G. Shaw: Centre for Analytical Research in the Environment, Imperial College at Silwood Park, Ascot, Berkshire, SL5 7TE, United Kingdom
A. Kliashtorin, S. Mamikhin, A. Shcheglov: Radioecology Laboratory, Soil Science Faculty, Moscow State University, Moscow, 119899 Russian Federation
B. Rafferty: Radiological Protection Institute of Ireland, 3 Clonskeagh Square, Clonskeagh Road, Dublin 14, Ireland
A. Dvornik, T. Zhuchenko: Byelorussian Research Institute of Forestry, Gomel, Belarus
N. Kuchma: 'Pripyat' Research and Industrial Association, 1-a B. Khmelnitsky Street, Chernobyl, 255620 Ukraine

Abstract: Monitoring of radiocaesium inventories and fluxes has been carried out in forest ecosystems in Ukraine, Belarus and Ireland to determine distributions and rates of migration. This information has been used to construct and calibrate mathematical models which are being used to predict the likely longevity of contamination of forests and forest products such as timber following the Chernobyl accident.

1. Introduction

Little information on radionuclide migration processes within forest ecosystems existed before the Chernobyl accident. Yet in countries such as Belarus, where approximately 20% of the national forest cover is contaminated to levels in excess of 15 Ci km^{-2} (555 kBq m^{-2}), the post-contamination management of forests is a highly important economic and social problem [1].

During the period 1992 - 1995 forest sites contaminated by the Chernobyl accident in Ukraine, Belarus and Ireland have been monitored by ECP-5 to determine the magnitudes of radionuclide fluxes (principally radiocaesium) between the major components of the forest ecosystems concerned. A range of sites was chosen for this study which represents a variety of forest types receiving a wide range of initial contamination inventories from the Chernobyl pulse.

The aim of this collaborative study has been to provide dynamic data which can be used to develop prototype mathematical models of forest contamination to be employed in accident emergency response and post-accident forest management. This paper describes, first, the philosophy underlying the approach to measurement and evaluation of radionuclide fluxes in contaminated forest ecosystems and, secondly, the development and implementation of three mathematical models by members of ECP-5.

2. Conceptual Framework for Forest Monitoring & Modelling

Analyses of the fluxes and storage of isotopes such as ^{137}Cs in and between discrete ecological compartments can provide useful information for subsequent numerical analysis and modelling of radionuclide fate and persistence [2]. Such analyses are required not just for ecological curiosity but because they provide an unavoidable starting point to the problem of estimating individual and collective effective doses to potentially large groups of people following nuclear contamination events.

The general framework adopted in this study for the compartmental analysis of radiocaesium behaviour in forests is shown in Figure 1. Deposition of radionuclides from the Chernobyl plume was predominantly dry in the immediate vicinity of the ChNPP itself, whereas further afield (particularly in western Europe and Scandinavia) wet deposition resulted in highly localised 'hot spots' of contamination. However, as deposition from Chernobyl can be considered to approximate a single 'pulse' in the long term the most important consideration in flux modelling of forests is the initial total deposit per unit ground area and the relative interception of this by the tree canopy. Losses of contamination from the tree canopy can be rapid, effected by stemflow, throughfall and the loss of leaves or needles. These processes transfer contamination to the litter layer on the forest floor, after which underlying soil horizons become contaminated at a rate which is controlled by soil migration. Ultimately radionuclides may be lost to the drainage waters flowing from forests, but Tikhomirov *et al.* [3] have ascertained that such losses are trivial in forests of the Chernobyl 30 km zone. More important is the return of radionuclides, especially ^{137}Cs, to the standing biomass via biological uptake processes which completes the cycle of radionuclide movement within the ecosystem.

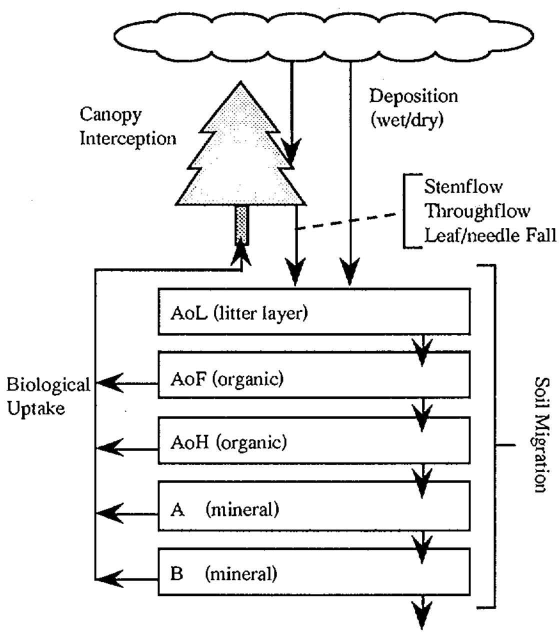

Figure 1: Conceptual framework for measurement and modelling of radiocaesium fluxes in contaminated forest ecosystems.

For the radiologically important isotope ^{137}Cs, with a radioactive decay half life of ~30 years, the primary question of interest is whether the persistence of the contaminant within the forest ecosystem will be controlled by physical decay or by ecological self decontamination processes. If self decontamination of the system as a whole is slow then it is relevant to ask whether certain components of the ecosystem will accumulate a greater proportion of the total ^{137}Cs inventory than others. If so, this has important implications for assessment and aversion of effective doses.

3. Modelling Approaches

Three forest models have been developed by groups working as part of ECP-5. These are ECORAD (Moscow State University), FORESTLIFE (Belorussian Forest Institute) and RIFE (Imperial College, London). Each of the models is based on a compartmental approach which can readily be fitted to the conceptual framework shown in Figure 1. Each model identifies the soil and the tree compartments as being the major components of the forest ecosystem. Both ECORAD and FORESTLIFE use a diffusion based approach to model radiocaesium movement in the soil which Mamikhin [4] has previously described for

ECORAD. In FORESTLIFE a quasi-diffusion equation is used to describe vertical migration to any depth, x, in the forest soil

$$\frac{dq}{dt} = D \cdot \frac{d^2q}{dx^2} \qquad (1$$

where q is the activity and D is the diffusion coefficient for radiocaesium. In order to describe observed distributions of radionuclides within forest soils in Belarus 'fast' and 'slow' diffusion coefficients must be applied which approximate to advection and diffusion components of migration, respectively. Following the prediction of migration in the soil profile ECORAD and FORESTLIFE calculate radiocaesium distributions within the tree component of the forest ecosystem based on transfer coefficients measured after the Chernobyl accident at a series of calibration sites. For ECORAD, four of these sites are in Russia (in the Bryansk and Kaluga regions) and four of are in the Ukraine, situated within the 30km exclusion zone. For FORESTLIFE, 13 monitoring plots in forests in SE Belarus were used to monitor intensively radiocaesium within soils and vegetation between 1992 and 1994. These plots contained pine stands of different ages allowing a relationship between tree age and transfer coefficient to be determined which demonstrated that young trees (10 - 20 years) can accumulate up to 7x more radiocaesium than older trees (70 - 80 years) at the same soil activity concentration.

The RIFE model consists of five compartments which represent the major radiocaesium storages within a forest ecosystem. The general equation describing fluxes within the compartmental system can be written as

$$\frac{dQ_x(t)}{dt} = I_x + \sum_{x \neq y} k_{yx} Q_y - Q_x \left\{ \sum_{x \neq y} k_{xy} + k_x + \lambda \right\} \qquad (2$$

where Q_x (t) is the activity of radiocaesium in compartment x at time t (Bq), I_x is the rate of radiocaesium input into compartment x (Bq t^{-1}), k_{yx} is the transfer coefficient from compartment y to x (t^{-1}), k_x is the loss rate coefficient from compartment x (t^{-1}) and λ is the physical decay rate of the isotope under consideration (t^{-1}). The data on which RIFE is based are derived from 'near-field' sites within the Chernobyl 30km zone as well as from a 'far-field' site in Ireland and the model provides a framework within which experimental field data may be evaluated.

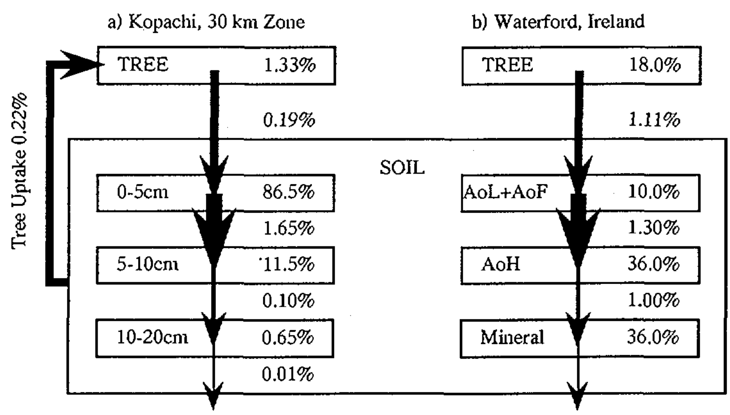

Figure 2: Summary of radiocaesium inventory distributions and annual fluxes at Ukrainian and Irish forest sites in 1992/1993.

4. Measurement & Modelling of Radiocaesium Fluxes in Forest Ecosystems

Field monitoring carried out by ECP-5 at forest sites in the Chernobyl 30km zone (Kopachi) and in Ireland (Waterford) has been aimed at quantifying radiocaesium fluxes along the major pathways shown in Figure 2. These two sites were selected to represent 'near-field' and 'far-field' scenarios, respectively, with the former site receiving a significant number of hot particles. Two major discrepancies are evident between the results for each site. The first is that downwards migration of the radiocaesium inventory into the mineral soil has been much higher at Waterford than within the 30km zone, probably reflecting the influence of hot particles in retarding the leaching of radiocaesium. The second major difference is in the fraction of the total radiocaesium inventories at each site present within the trees. At Waterford this fraction is 0.18, while at Kopachi it is 0.013. Again, this major difference between sites is most probably due to the difference in the physico-chemical form in which the radiocaesium was deposited; at Waterford the bioavailability of Chernobyl-derived radiocaesium is evidently much higher than at Kopachi.

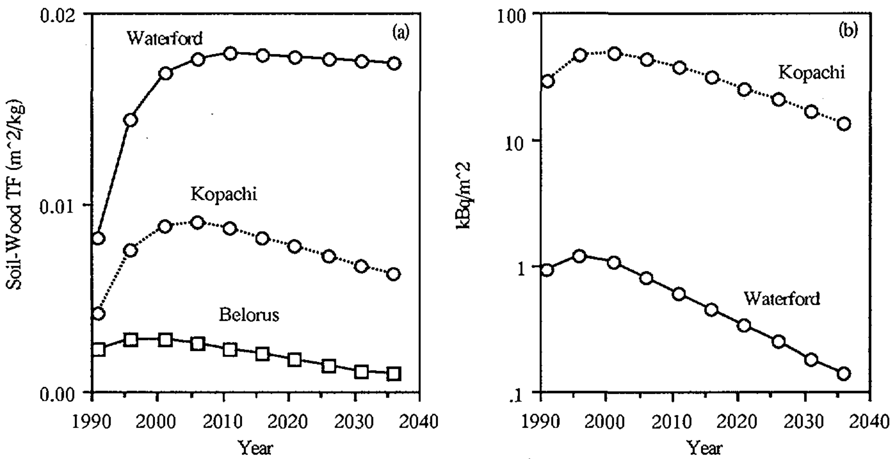

Figure 3: (a) Predicted soil-to-pine wood transfer factors (m^2 kg^{-1}) at Kopachi and Waterford (RIFE) and for 20-40 year-old trees in Belarus (FORESTLIFE). (b) RIFE predictions of absolute pine wood contamination (kBq m^{-2}) at Kopachi and Waterford.

A major goal of ECP-5' s forest modelling studies is to predict the likely contamination of wood and the effective decontamination half times of timber following peak contamination. Figure 3(a) shows predictions of soil-to-pine wood transfer factors made using the RIFE and FORESTLIFE models. Both models predict similar time courses for Kopachi and for the Belorussian pine forests, with peak contamination occurring between 1995 & 2005 and similar wood decontamination rates at each site. For Waterford the predicted decline in soil-to-pine wood transfer factor is slower due to the more bioavailable radiocaesium at this site being recycled within the standing biomass. However, Figure 3(b) shows that the absolute contamination of pine wood at Waterford declines more quickly than at Kopachi (effective half times 16 years and 24 years) due to the loss of mobile radiocaesium from the tree rooting zone by leaching. This loss by leaching is retarded by hot particles in the 30km zone.

5. References

1. Crick, M. (1994) Reflections on Forestry in Belarus. Presented at VAMP, IAEA, Vienna. Nov. 1994.
2. Heal, O. W. and A. D. Horrill (1983) The terrestrial ecosystem: an ecological context for radionuclide research. pp. 31 - 46 in: Ecological Aspects of Radionuclide Release, Blackwell Scientific Publications, UK.
3. Tikhomirov, F. A., A. I. Shcheglov and V. P. Sidorov (1993) Forests and forestry: radiation protection measures with special reference to the Chernobyl accident zone. Sci. Tot. Environment, 137, 289 - 306.
4. Mamikhin, S. V. (1995) Mathematical model of ^{137}Cs vertical migration in a forest soil. J. Environ. Radioactivity, 28(2), 161 - 170.