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Mathematical model of ^{137}Cs dynamics in the deciduous forest

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Abstract

A mathematical model of ^{137}Cs behaviour in the forest ecosystem is presented. The behaviour of this radionuclide is assumed to obey the same regularities as the behaviour of its stable chemical analogue, potassium. Radionuclide dynamics are considered in parallel with the dynamics of the phytomass. Radionuclides contained in the vegetation are pooled into two basic compartments: external and internal contamination, with separate analysis of each. The model was verified using the data obtained in the 30-km zone of the Chernobyl NPP in 1986–1994. The algorithm described was found to be the most efficient in terms of ^{137}Cs behaviour in the forest environments. © 1999 Elsevier Science Ltd. All rights reserved.

1. Introduction

Mathematical modelling is an effective method to study and forecast the consequences of radioactive contamination of the biosphere due to nuclear weapons testing and accidents at nuclear installations. The studies of the consequences of the Chernobyl NPP accident have promoted the intensive development of mathematical modelling of radionuclide behaviour in the environment. Existing models are characterised by a variety of approaches. The above can be illustrated by the models, developed in the framework of the Agreement for International Collaboration on the Consequences of the Chernobyl Accident between the European Commission and Ministries for Chernobyl Affairs in Belarus, Russia and the Ukraine (Shaw, Mamikhin, Dvornik & Zhuchenko 1996a), and early models (for example: Olson, 1963; Anokhin, 1974; Crout Neil, Beresford, Howard & Unsworth, 1990; Van Voris, Cowan, Cataldo, Wildung & Shugart, 1990; Muller & Prohl, 1993; Alexakhin, Ginsburg,

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Mednic & Prokhorov, 1994; Sundblud & Mathiasson, 1994). A variant of the model is presented in this article. Initial data were obtained due to our original studies of the radionuclide dynamics within the so-called 30-km Exclusion Zone of Chernobyl NPP in 1986–1994 (Tikhomirov, Shcheglov & Mamikhin, 1995; Shaw et al., 1996b, Shaw, Mamikhin, Dvornik, Rafferty, Shcheglov & Kuchma, 1996c; Mamikhin, Tikhomirov & Shcheglov, 1997). Analysis and formalisation of the present information on radionuclide behaviour in terrestrial ecosystems were realised within the framework of the informational-predictive system ECORAD (Mamikhin, 1996). The model includes the following main processes running in the system "vegetative cover-soil":

- natural decontamination (plant self-decontamination as a result of the fall of leaves, needles, branches, generative organs, external bark, and washing off by atmospheric precipitation);
- downwards radionuclide transport in woody plants (from assimilative organs and bark to roots);
- radionuclide release into the soil with the root discharges;
- root uptake of radionuclide and upwards transport from the soil to the above-ground phytomass.

A range of approaches to mathematical modelling of radionuclide behaviour in the environment was developed. The most efficient algorithm describing ^{137}Cs migration is based on the following assumptions:

(1) The behaviour of ^{137}Cs principally obeys the same regularities as the behaviour of its stable chemical analogue, potassium.

(2) Radionuclide dynamics is considered in close association with the corresponding dynamics of the phytomass.

(3) The radionuclide content of the vegetation is analysed separately for each of two principal groups: (1) external and (2) internal contamination. The reason for this division is the radionuclide pathway to the plant structures. Internal contamination is due to radionuclide transfer from the soil to plant via the root system (root uptake) or radionuclide redistribution within the plant (from the more contaminated parts of the plant to the less contaminated ones). The external contamination is fully determined by direct radionuclide fallout onto the above-ground organs of the exposed plants. As an example, we consider a model of the long-term dynamics of ^{137}Cs in the deciduous forest ecosystem.

2. Description of the model

Mature oak forest (40–80 years old) was chosen as the ecosystem to be modelled. The model simulates the ecosystem contamination as a result of fallout of radionuclides in the form of particles less than 10 μm in diameter. This scenario generally corresponds to the situation that has taken place just after the Chernobyl accident in 1986, which makes it possible to calibrate and verify the model using the available direct data.The topological structure of the model is presented in Fig. 1. The functions of radioactive decay of ^{137}Cs contained in the ecosystem components are not shown.

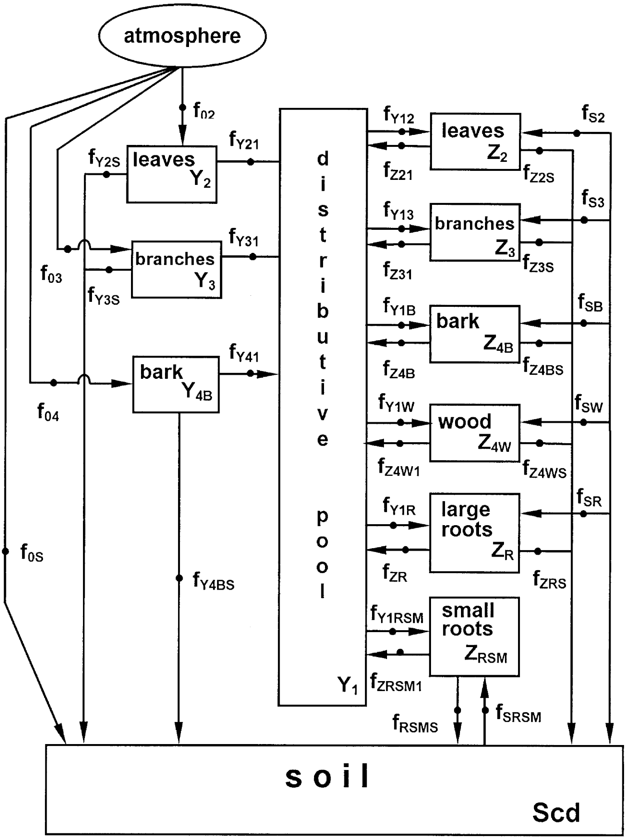


Fig. 1. Flow diagram of radiocaesium migration in a deciduous forest.

2.1. Driving variable

Atmosphere — deposition of radioactive matter from the atmosphere.

2.2. State variables

The following state variables are included in the model:

2.2.1. Vegetation

organic matter content (absolute dry weight) — X_i; content of stable potassium (^{39}K) — K_i; content of ^{137}Cs (Bq per kg of dry weight): Z_i — internal contamination, Y_i — external contamination, E_i — total contamination. Soil contamination — Scd. Total contamination of plant and soil cover – Cd. Index *i* corresponds to the structural parts of plants: 2 — foliage, 3 — branches, 4*w* — trunk wood, 4*b* — trunk

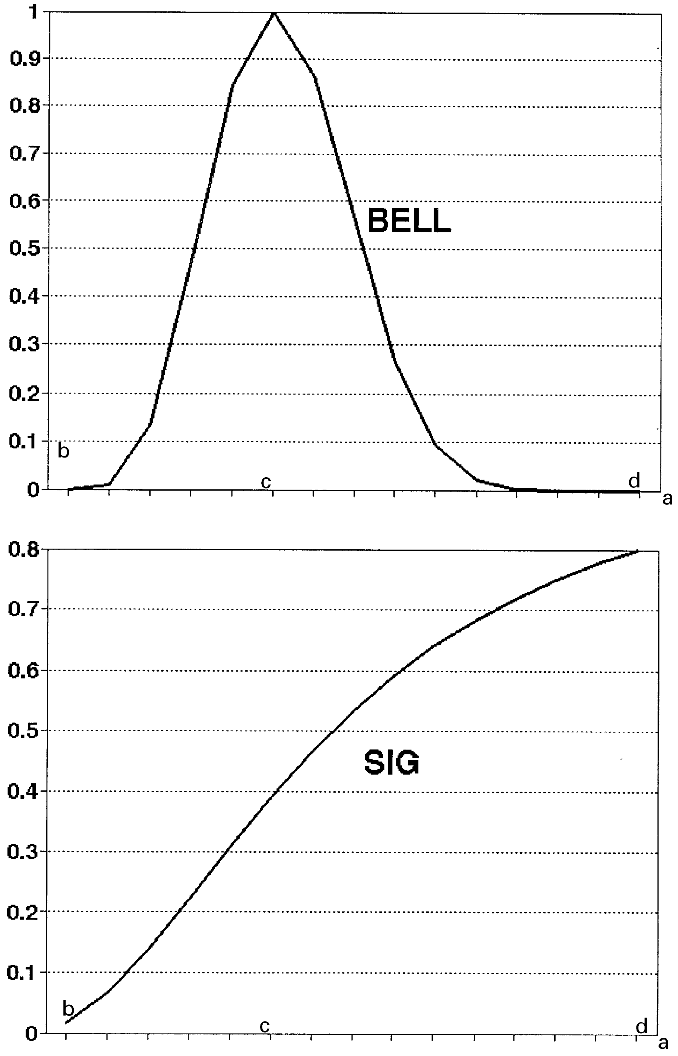


Fig. 2. General shape of the auxiliary variables BELL and SIG.

bark, *r* — large roots, *rsm* — small roots. Y_1 — distributive pool, fictional part intended only to collect and distribute ^{137}Cs fluxes in plants. The sum of the input fluxes for the unit Y_1 is equal to the sum of the output fluxes.

2.3. Auxiliary variables

Auxiliary variables BELL and SIG (Fig. 2) are included to account for the influence of such factors as temperature, humidity, size of particles and so on in the equations of the transfer functions. They describe an asymmetric dependence of a transfer process on the value of the factor. BELL is a Pirson's curve;

$$\mathrm{BELL}(a, b, c, d) = ((a - b)/(c - b))^{e*}((a - d)/(c - d))^{e*((d - c)/(c - b))}.$$

Parameter e causes bell width. The second variable SIG is given by the formula:

$$\mathrm{SIG}(a, b, c) = (a - b)/(((c - b)/2 - b) + (a - b)).$$

Since seasonal (less then one year) dynamics are not considered in the given variant of the model, the mass of organic matter in the components is computed using the following equation:

$$X_i(t + 1) = X_i(t) + P_i - O_i,$$

where $X_i(t + 1)$ is the biomass of a given year, $X_i(t)$ the biomass of the previous year, P_i the gross increment for a year, O_i the annual litterfall. Then, the potassium inventory in the structural components of the plant cover (K_i) and the gross increment (KP_i) are computed: $K_i = X_iC_i; KP_i = P_iC_i$, where C_i is the specific content of potassium (g/g of dry matter) in the component i.

2.4. Transfer functions

2.4.1. External contamination

Interception of ^{137}Cs by foliage:

$$f_{y02} = a_1(1 - \mathrm{SIG}(\mathrm{psize}, 0, 1000))(X_{2f} + 0.1)/X_2 finp,$$

where a_1 is the absorption factor of foliage, psize is the size of particles (in micrometers), X_{2f} is the mass of foliage at the time of radioactive fallout (T km^{-2}), and finp is the ^{137}Cs contamination density (kBq km^{-2}). Interception of ^{137}Cs by branches and trunk bark:

$$f_{y0i} = a_{(i-1)}(1 - \mathrm{SIG}(\mathrm{psize}, 0, 1000))\mathrm{finp},$$

where $a_{(i-1)}$ is the retaining ability factor. Function SIG reflects the inverse dependence of fraction retaining ability on the size of fallout particles in this case.

Litterfall:

$$f_{yis} = b_i(Y_i - f_{yi1}),$$

where b_i is the litterfall factor (the parameter reflecting the rate of self-decontamination of the fraction from the external contamination).

Radioactive decay:

$$f_{yid} = \mathrm{dc}Y_i,$$

where dc is the fraction of ^{137}Cs decaying per year.

The contribution of the structural parts to the distributive pool:

$$f_{yi1} = c_iY_i,$$

where c_i is the proportion of external ^{137}Cs contained in the fraction i entering the pool.

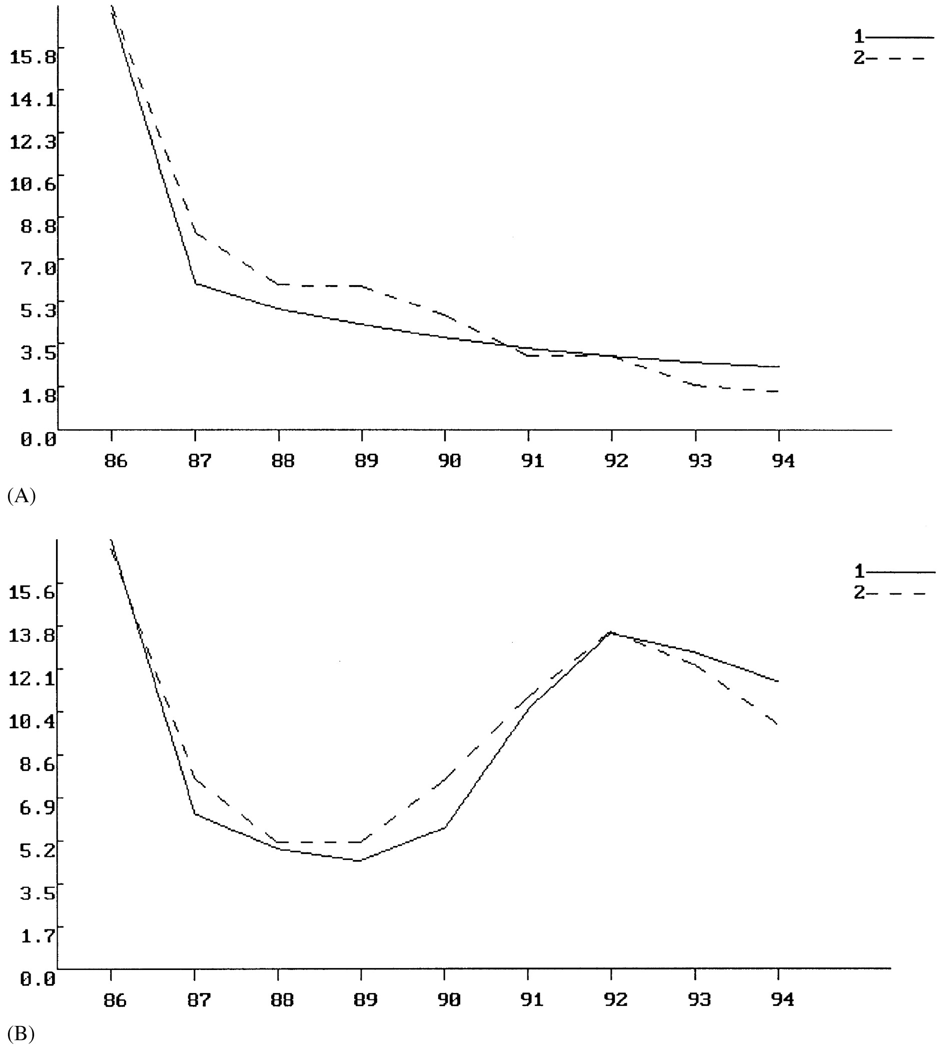


Fig. 3. Dynamics of ^{137}Cs (% of total contamination, 1986–1994) in the above-ground part of the plant cover in landscapes with contrasting moisture regimes (A — automorphic; B — hydromorphic; —— Computed by model; - - - - field data).

2.4.2. Internal contamination

Deductions of ^{137}Cs from fractions into the distributive pool:

$$f_{zi1} = h_i Z_i,$$

where h_i is the part of the internal ^{137}Cs contained in fraction i entering the pool.

The distribution of ^{137}Cs from the pool into the fractions is assumed to be directly proportional to the ^{39}K content in the fraction:

$$f_{y1zi} = Y_1 K_i / K_{sum},$$

where K_{sum} is the total K content in vegetation.

^{137}Cs uptake by plants from soil:

$$f_{sp} = a_6 a_7 \mathrm{BELL}(ny, 1, 5, 100, 5) Scd,$$

where a_6 is a factor for the ecosystem moisture status (hydromorphism), a_7 is the factor for the maximum biological availability of ^{137}Cs for a particular type of soil, BELL is the function for the dependence of the dynamics of ^{137}Cs biological availability on the time passed from the moment of fallout.

Distribution of ^{137}Cs transferred from the soil into plants by fractions: in this case it is assumed that the distribution takes place proportionally to the content of potassium in the gross increment of some fraction:

$$f_{si} = f_{sp} KP_i / KP_{sum},$$

where KP_{sum} is the total content of K in the gross increment of the vegetation.

Removal of the accumulated ^{137}Cs from plants to soil with litterfall: it is assumed this value is directly proportional to the litterfall mass:

$$f_{is} = Z_i O_i / X_i.$$

The export of some proportion of ^{137}Cs into the distributive pool before the litterfall is taken into account for the foliage compartment.

The model parameters were obtained using original field and laboratory data and a range of literature data. Original data on the radionuclide distribution amongst the components of vegetation in 1986–1989 were used to calibrate the model (Tikhomirov & Shcheglov, 1994; Mamikhin et al., 1997). Fig. 3 displays the model predictions and field data indicating the dynamics of total contamination in the above-ground part of the vegetative cover in the landscapes with contrasting moisture regimes (automorphic and hydromorphic).

3. Validation of the model

Validation of the model was achieved made using the data on radionuclide dynamics in the tree components in the oak forest ecosystem mainly within the 30-km Zone of the Chernobyl NPP in 1986–1994 (Mamikhin et al., 1997). Figs. 4 and 5 compare the experimental (obtained from field observation) and calculated data on ^{137}Cs dynamics in the tree components. The similarity between the field and computed values is rather satisfactory. Some disagreements are likely caused by spatial variability of the field data, since a large-scale sampling of model trees is necessary to obtain statistically confident information. The corresponding replication is difficult to carry-out under field conditions in the contaminated zone.

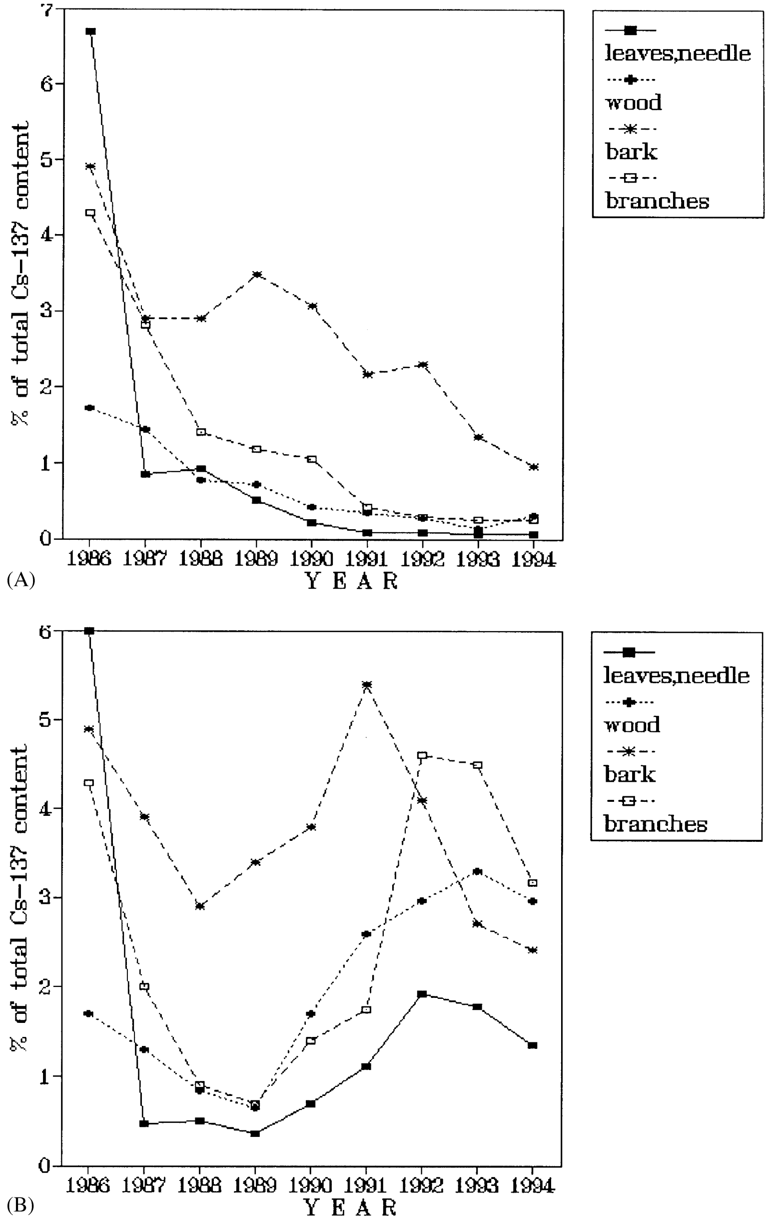
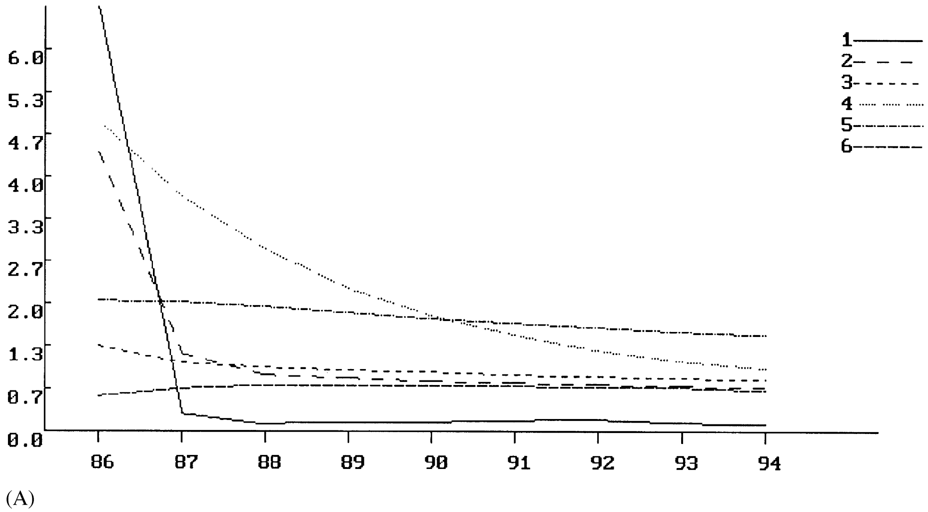
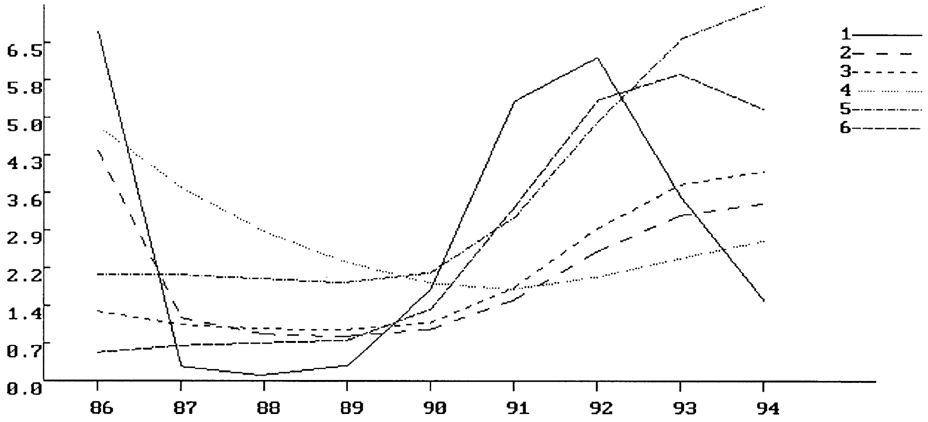


Fig. 4. Dynamics of ^{137}Cs content (% of total contamination) in the components of trees in eluvial (A) and accumulative (B) landscapes (with automorphic and hydromorphic regimes, respectively) in 1986–1994 in the 30-km zone around Chernobyl NPP (Mamikhin et al., 1997).

The values for the automorphic landscapes calculated using our model were collated with the field data on ^{137}Cs distribution in the above-ground phytomass in Oak Ridge, 30 years after the fallout (Table 1).



(A)



(B)

Fig. 5. Computed dynamics of ^{137}Cs content (% of total contamination) in the different fractions of the stand in eluvial and accumulative landscapes (with automorphic and hydromorphic regimes, respectively) under conditions of a single fallout event (1 — leaves, 2 — branches, 3 —wood, 4 — bark, 5 — large roots, 6 — small roots).

Table 1
Distribution of ^{137}Cs in the trees' above-ground biomass, % (Van Voris et al., 1990)

Component:	Oak Ridge	Model (30 years)
Leaves	2.7	3.3
Branches	22.6	29.7
Wood + bark	74.7	67

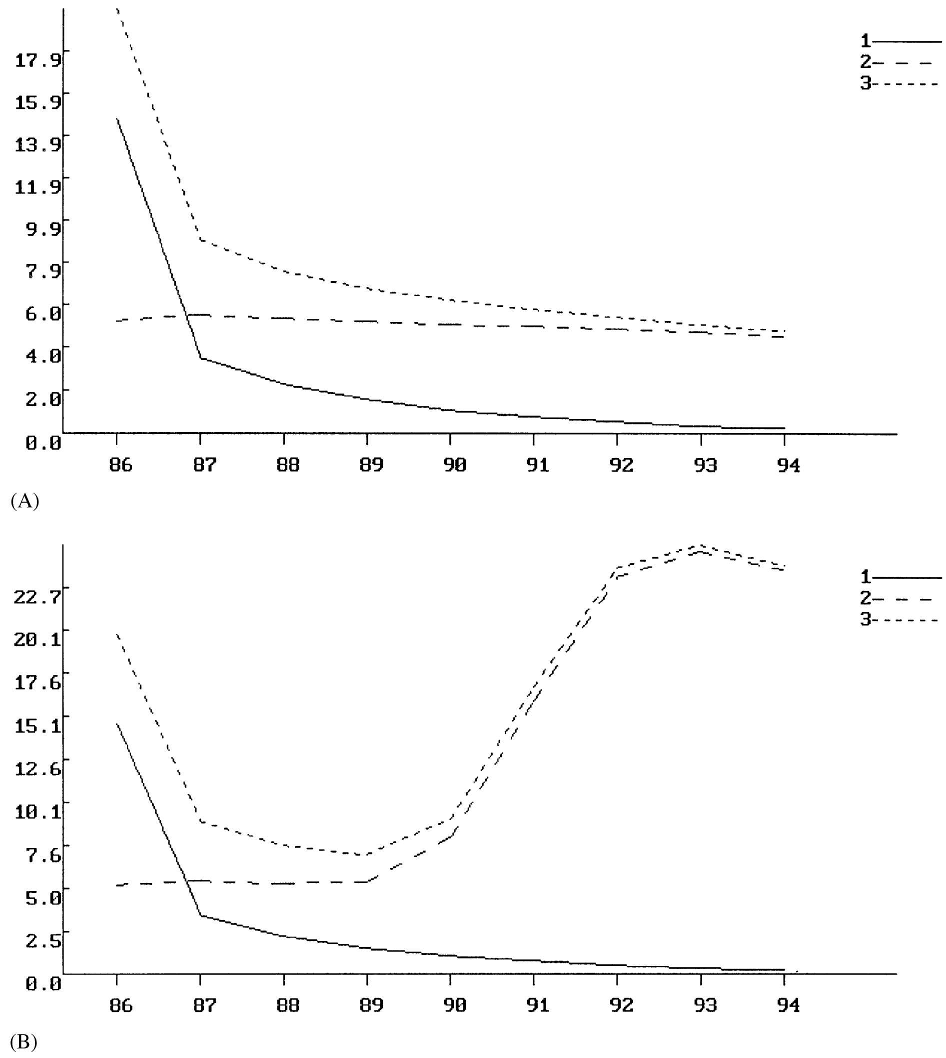


Fig. 6. Computed 10-year dynamics of ^{137}Cs content (% of total contamination) in the total above-ground phytomass in eluvial (A) and accumulative (B) landscapes under conditions of a single fallout event (1 — external, 2 — internal, 3 — total contamination).

4. Results

The model allows simulation of the long-term dynamics of the ^{137}Cs content in the components of deciduous forest ecosystems of landscapes with different degrees of moisture status and in different conditions of fallout of small-size radioactive precipitation.

Figs. 5 and 6 present the computed 10-year dynamics of the ^{137}Cs content in different components of trees and in the total phytomass (total contamination and with division into external and internal contamination) in eluvial and accumulative landscapes under conditions of a single fallout event. The calculations made it possible to clarify the individual contribution of different tree components and specific pathways to the total contamination in the forest ecosystems. Use of the model principally enables us to obtain the information on radionuclide dynamics in the underground phytomass, which is practically impossible to determine by direct measurements.

A range of simulative experiments (repeated fallout, continuous fallout, etc.) has been performed using the model. In part, the situation of the same release 10 years after was simulated. Figs. 7–9 present a forecast of the ^{137}Cs behaviour in the vegetative cover for 20 years ahead based on our model. Some problems attributed to the modelling of radionuclide dynamics in forest ecosystems were revealed in the course of model development. Of particular importance in our opinion is to take into account the biological availability of the radionuclides when describing ^{137}Cs uptake by plants. This task was accomplished only to a first approach, by introducing the time function of this parameter (availability dynamics). This somewhat limits the range of the model application. A more general description of ^{137}Cs root uptake can be obtained by taking into account the effect of physico-chemical soil properties on the processes of radionuclide sorption by soil.

Another problem is a lack of field data for model validation. We do not know a data pool on long-term ^{137}Cs migration in the components of the forest ecosystem that is similar to the one used to calibrate this model. At the same time, the present model-calculated dynamics of the root contamination cannot be considered as fully reliable because of the lack of experimental (field) data to calibrate the model and verify the adequacy of the simulation.

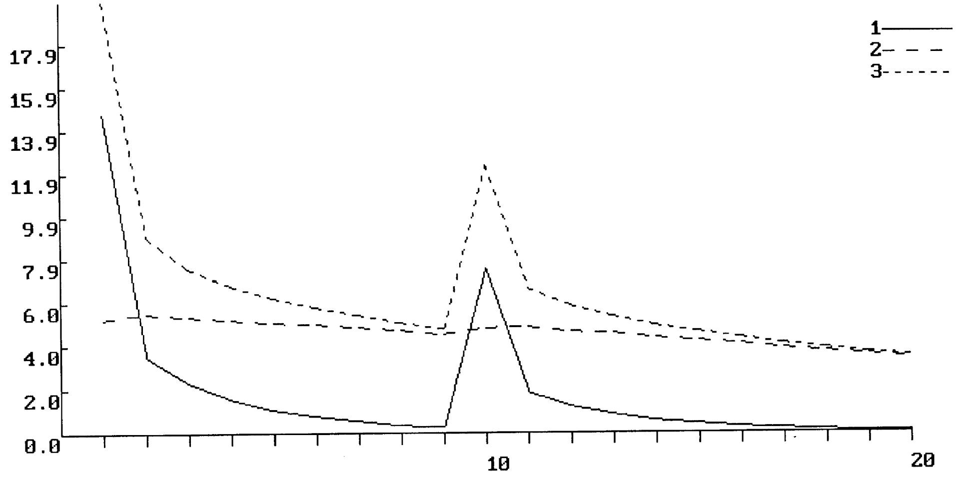


Fig. 7. Computed 20-year dynamics of ^{137}Cs content (% of total contamination) in the total above-ground phytomass in an eluvial landscape under conditions of a twofold fallout event (1 — external, 2 — internal, 3 — total contamination).

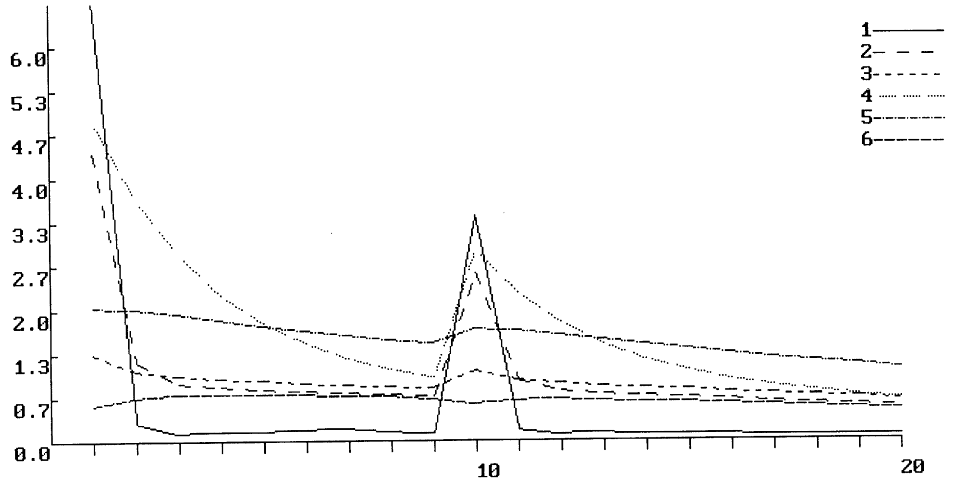


Fig. 8. Computed 20-year dynamics of ^{137}Cs content (% of total contamination) in the different fractions of stand in an eluvial landscape under conditions of a twofold fallout event (1 — leaves, 2 — branches, 3 — wood, 4 — bark, 5 — large roots, 6 — small roots).

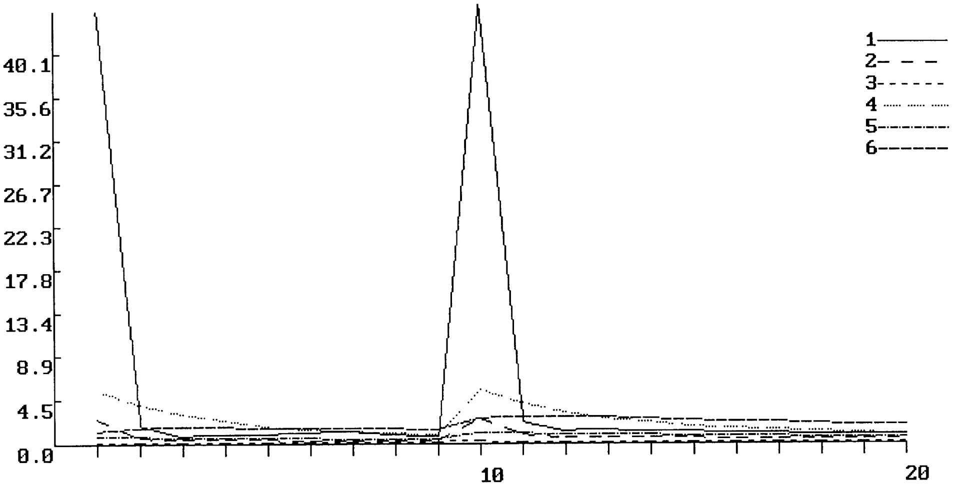


Fig. 9. Computed 20-year dynamics of ^{137}Cs content (kBq kg^{-1} of absolute dry mass) in the different fractions of stand in an eluvial landscape under conditions of a twofold fallout event (1 — leaves, 2 — branches, 3 — wood, 4 — bark, 5 — large roots, 6 — small roots).

5. Conclusion

The model algorithm presented in the paper makes it possible to simulate reliably the conditions of forest ecosystem contamination by radioactive caesium as a result of an emission of radioactive matter to the atmosphere (pulse or over a range of years). Now the model is under further development and upgrading. The function of biological accessibility is being modified. The range of application of the model is broadening by including the fuel component into the list of state variables. This will make it possible to simulate radioactive fallout in the form of large particles as well as small (aerosol) ones. A family of similar models will be developed to describe radionuclide behaviour in coniferous and mixed forests.

It is also necessary to simulate the situation of repeated seasonal, annual and more continuous fallout events. A model of the seasonal (less then one year) dynamics of the ^{137}Cs content in the components of the forest ecosystem is in progress. Such a model should include special blocks to simulate the seasonal dynamics of the phytomass and a range of relevant abiotic factors. This is being developed on the basis of the present model of the seasonal dynamics of organic matter (carbon) in oak forests (Mamikhin, 1990,1997).

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