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Simulation of the Dynamics of Different Forms of Radiocesium in Soils of Terrestrial Ecosystems

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Abstract—A refined imitational model of the seasonal dynamics of radiocesium in soils of forest ecosystems is suggested. This model has been used to predict the dynamics of biologically available and unavailable forms of radiocesium in an artificially contaminated sandy soddy-podzolic soil of an oak ecosystem for a period of 50 years.

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INTRODUCTION

The dynamics of different forms of radionuclides in soil are the decisive factor determining their uptake by plants. With the beginning of large-scale pollution of the biosphere with technogenic radionuclides, considerable attention has been paid to the study of this phenomenon. The accumulation of factual data made it possible to develop mathematical models describing the behavior of radionuclides in soil. After the Chernobyl NPP accident, the particular attention was paid to ^{137}Cs as the major and the most hazardous radioactive pollutant at that moment. Several models were elaborated that suggested different algorithms for describing the forms of radiocesium occurrence in soils [1, 8, 9, 11, 12]. Above all, this was caused by the necessity of taking into account temporal changes in the biological availability of ^{137}Cs and the declining rate of its uptake by plants in order to predict the dynamics of contamination of the vegetation cover with this pollutant.

Approaches suggested by various researchers differ both in the level of detail and in the algorithms describing the particular processes. It should be noted that in this field, as well as in radioecological modeling in general, the lack of quantitative data on the parameters of these processes poses the main obstacle for creating reliable models. Under these conditions, some integral approach to the description of the object should be applied. The practice of mathematical modeling in biology proves that this approach is quite feasible, as it allows one to obtain an adequate picture of the dynamics of studied indices, including the dynamics of the radioactive contamination. This approach turned out to be valid for the models of the long-term ^{137}Cs dynamics [4, 5]. However, models of the annual dynamics require a more detailed study of the radionuclide behavior in soil and the revision of the earlier applied algorithm.

OBJECTS AND METHODS

An oak-forest ecosystem developed on a soddy-podzolic sandy soil was chosen as the study object. In mature forest ecosystems of the middle latitudes, the upper soil layer usually represents a developed forest litter. It is in the litter where the radioactive fallout onto the soil surface from the atmosphere and from the surface vegetation undergoes various physicochemical transformations. After that, radionuclides penetrate the underlying soil horizons, where the bulk of fine sucking roots supplying plants with water and mineral nutrients occur. Radionuclides may also enter the soil with root exudates and root residues. The subsequent fate of radionuclides depends on their transformation, i.e., their release from fuel particles and plant residues subjected to mineralization, their immobilization in the soil adsorption complex, etc. For radiocesium, these processes develop rather quickly. Direct studies of the forms of Chernobyl-derived ^{137}Cs in soils demonstrated that its distribution by separate fractions was close to that of stable cesium and radiocesium of the global fallout already in 1992. The contents of both water-soluble and exchangeable radiocesium in soils of natural ecosystems contaminated after the Chernobyl accident ranged within 3–24% of the total ^{137}Cs content depending on the soil type [7].

An algorithm for describing the dynamics of radiocesium in soil was developed within the framework of an imitational model of the daily dynamics of ^{137}Cs in the broad-leaved forest ecosystem Ecorad_D_II [6]. For this purpose, we adapted an already existing model of the hourly dynamics of organic matter in the broad-leaved forest ecosystem [3, 4]. This model consists of seven blocks describing the meteorological conditions, solar irradiation, soil water and temperature regimes, and the dynamics of carbon reserves in the particular components of woody and herbaceous vegetation and in the soil. It was supplemented with the radioecological block developed on the basis of the earlier suggested model of the long-term dynamics of radiocesium [4]. However, the latter model was substantially revised; in particular, new rules of the redistribution of radiocesium between different components of vegetation were introduced. It was supposed that radiocesium does not enter these components directly from the soil, but rather through a so-called distributive pool, from which its further redistribution takes place. An algorithm describing the uptake of radiocesium by plants from the soil was also significantly modified.

The radioecological block was further complemented with necessary data on the organic carbon pools, the intensity of plant falloff and respiration, and the character of phenological cycle. This block simulated the dynamics of potassium and radiocesium contents in the aboveground vegetation and in the soil with a time step of one day. The work with this model proved this step to be sufficient for the purposes of our study.

Hypotheses concerning the particular processes governing the behavior of radiocesium were verified via including special functions describing these processes in the algorithm and subsequent numerical experiments with the model. Numerical values of the parameters included in the model equations were selected on the basis of the factual data on the radionuclide behavior in forest ecosystems that were collected by staff members of the Laboratory of Radioecology (at present, the Department of Radioecology and Ecotoxicology) within the 30-km zone around the Chernobyl NPP and in the adjacent areas [2, 10, 13], as well as from the data published by other researchers.

AN ALGORITHM TO SIMULATE THE DYNAMICS OF DIFFERENT FORMS OF RADIOCESIUM

The current version of the algorithm is based on the assumption that the pool of ^{137}Cs in soil can be conventionally subdivided into two groups with respect to the bioavailability of ^{137}Cs, i.e., (a) available (ionic and exchangeable forms, *Sbac*) and (b) unavailable (fixed) ^{137}Cs. In turn, the second group may be subdivided into two parts, including (1) temporarily unavailable ^{137}Cs contained in fuel particles and in dead organic matter (*Stnc*) and (2) virtually unavailable ^{137}Cs fixed in the soil adsorption complex (*Sbnc*).

In addition to the mentioned variables, the density of soil contamination with ^{137}Cs (*Sd*) was also included in the model for its checking and convenient balance calculations.

Figure 1 shows the topological structure of the subprogram describing the dynamics of these forms of radiocesium in soil. Soil contamination with radiocesium is described in our model by the following system

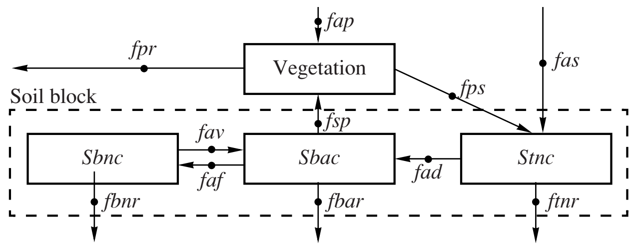

Fig. 1. Soil block in the imitation model of the daily dynamics of ^{137}Cs Ecorad_D_II.

of simple finite-difference equations with a one-day time step:

$$\Delta Sd = (finp(ny, nd) - fap) - fsp + fps - rd \times Sd,$$

$$\Delta Stnc = (finp(ny, nd) - fap) + fps - fad - ftnr,$$

$$\Delta Sbac = ad \times Stnc + fav + faf - fsp - fbar,$$

$$\Delta Sbnc = af \times Sbac - fav - fbnr.$$

These equations include several functions describing the main fluxes of radiocesium in an ecosystem as follows:

finp(*ny*, *nd*) is the input of radiocesium from the atmosphere (radioactive fallout). This value is calculated in the model before the beginning of the work of the radioecological block taking into account a particular scenario selected by the user. For the Chernobyl scenario, it was tentatively decided that the ^{137}Cs fallout occurred in equal doses for ten days after the accident. In order to reproduce various radiation situations, the calculated values were stored in a two-dimensional data massif marked by the following indices: *ny* (indicating a year) and *nd* (indicating the day number in the year).

fap is the fallout absorbed by the plant cover. It represents the sum of functions for radiocesium capture by the particular components of the stand with due account for their biomass at the moment of the fallout and their absorption properties. For instance, for leaves, this function appears as $fy02 = a1 \times (1 - si(prize, 0, 1000)) \times si(x2a(ny, nd), 0, 210) \times finp(ny, nd)$, where *a1* is the species-specific coefficient of the retention of ^{137}Cs; *psize* is the fallout particle size (μm); *si* (*psize*, *0*, *1000*) is the function describing the decrease in the absorption of ^{137}Cs the growing particle size; *x2a*(*ny*, *nd*) is the leaf biomass; and *si*(*x2a* (*ny*, *nd*), *0*, *210*) is the function for the growth in the absorption of ^{137}Cs with an increase in the biomass of leaves (which reaches its maximum on the 210th day); $0 \le si \le 1$.

fsp is the radiocesium uptake by the plants from the soil. It is described by the following equation:

$$fsp = ap \times tba(x12) \times Sbac,$$

where *ap* is the species-specific uptake coefficient for the particular tree stand and the landscape type, and *x12*

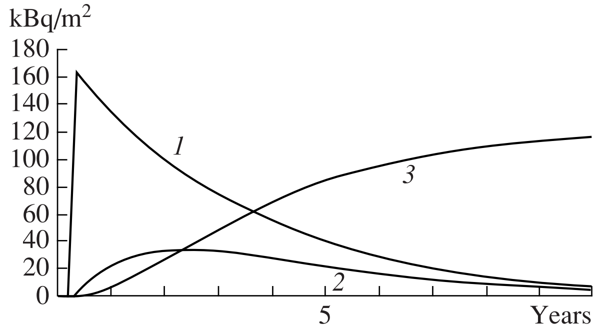

Fig. 2. Dynamics of different forms of ^{137}Cs in soil: (*1*) temporarily unavailable forms (fuel particles and plant falloff), (*2*) available forms (ionic and exchangeable forms), and (*3*) virtually unavailable (fixed) ^{137}Cs.

is the phenological time calculated from the difference between the average monthly temperature for the particular year and the long-term average monthly temperature. It is assumed that increased (compared to the long-term average) monthly air temperatures in the first half of the year accelerate the phenological cycle, whereas increased monthly temperatures in the second half of the year decelerate it with a coefficient of 0.05 per one degree of temperature difference. Similarly, the lower temperature slows down the phenological cycle in the first half of the year and accelerates it in the second six months with the same coefficient. *tba* stands for the function of the biological activity described by the following equation: $tba(x12) = bell(x12, 1, 210, 360, 5)$, where *bell* is the Pearson curve of type I: $BELL\ (a, b, c, d, e) = ((a - b) / (c - b))^{e}((a - d)/(c - d))^{e((d - c)/(c - b))}$. This variable describes the bell-shaped dependence of the process on argument *a*; it is equal to 0 at $a \le b$ and $a \ge d$ and gains its maximum (1) at $a = c$. Argument *e* characterizes the width of the bell; the smaller its value, the wider the bell.

fps sums up the functions of the radionuclide input into the soil with plant falloff (including both aboveground and underground falloff), its washout from the plant components, and its input with root exudates and other intravital plant excreta.

The input of the radionuclide with plant falloff is a function of the ratio between the daily falloff and the total biomass of the particular component of plants. For example, for fine roots, this function has the following form:

$$frsms = zrsm \times orsd(nd)/rsma(ny, nd),$$

where *zrsm* is the content of ^{137}Cs in the roots, *orsd*(*nd*) is the amount of the roots dying off in a day, and *rsma*(*ny*, *nd*) is the root biomass. For leaves, the integral function of the radionuclide washout and its release with intravital excreta is described by the linear function.

The input of the radionuclide with exudates of fine roots is described by the following function:

$$fzrsms = aw \times tba(x12) \times zrsm,$$

where *aw* is the washout coefficient.

The input of the radionuclide during the destruction of fuel particles and the mineralization of plant residues and the processes of its sorption–desorption in the soil adsorption complex are described by simple linear equations:

$$fad = ad \times Stnc; \quad fav = av \times Sbnc;$$

$$\text{and} \quad faf = af \times Sbac,$$

where *ad* and *af* are coefficients of the destruction and sorption determined by the iteration method, and *av* is the release of the radionuclide calculated proceeding from the *af* value and the equilibrium reserves of the available (*Sbac*) and adsorbed (*Sbnc*) ^{137}Cs.

The radioactive decay functions are described by the following equations:

$$fbar = rd \times Sbac; \quad ftnr = rd \times Stnc;$$

$$\text{and} \quad fbnr = rd \times Sbnc,$$

where *rd* is the coefficient of radioactive decay (the portion of ^{137}Cs decayed per day).

Distribution of different forms of ^{137}Cs in the soil after 50 years

^{137}Cs	Temporarily biologically unavailable	Biologically active	Biologically unavailable
% of the soil contamination	0.022	1.916	98.062
% of the total contamination	0.021969	1.91326	97.921771

DISCUSSION

The presented algorithm is rather simple and does not reveal the actual mechanisms of radiocesium transformation in soil; nevertheless, it can be applied to predict the plant cover contamination, i.e., to calculate the content of the biologically available radionuclide. The use of this algorithm in the simulation model of the daily dynamics of ^{137}Cs permitted us to obtain distribution patterns of the biologically active, temporarily inactive, and completely inactive ^{137}Cs in soil (Fig. 2). The results of our simulation agree with the experimental data obtained by other researchers. The calculations were performed for the Chernobyl scenario; the initial density of the radioactive contamination was taken equal to 200 kBq/m^2. The numerical experiments performed with the model pointed to the sustainable operation of its soil block. The predicted distribution of different forms of ^{137}Cs in the soil is shown in the table.

Earlier, to describe the radionuclide uptake by plants, we used a complex discontinuous function based on the Pearson curve of the first type and on many parameters that had to be determined by the iteration method. The results of this determination were not always unambiguous [5]. This was the only possible option for the models of the long-term dynamics of ^{137}Cs with a time step of one year. A model described in this paper considers different functional groups of radiocesium separately with a time step of one day. As a result, the model has become simpler, and the number of parameters to be determined is less than that in the previous versions of the model.

An adequate simulation of the dynamics of radiocesium in soil has been proved for the daily dynamics of ^{137}Cs in the oak-wood ecosystem developed on the soddy-podzolic sandy soil. It should be noted that the values of the parameters included in the equations are to be determined once again when applying this algorithm for other ecosystems with other soils.

The approaches presented in this paper can be applied not only in the radioecological models but also in the models describing the biological cycle of mineral elements (first of all, potassium) and changes in soil fertility upon the application of mineral fertilizers.

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