Mathematical modelling in radioecological studies

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This paper describes the history of development and the main directions of studies on mathematical modelling in the Russian Institute of Agricultural Radiology and Agroecology in Obninsk.

Studies on mathematical modelling of the behaviour of radioactive substances in agroecosystems and farming on technogenously contaminated territories were initiated at the RIARAE physico-chemical department in 1974 by Professor A.A.Ter-Saakov, G.V.Kozmin and L.G.Chernyaeva. These were primarily directed at evaluating the influence of physical factors on the components of agroecosystems and the development of models for the behaviour of radionuclides in different forms in living organisms.

In the late 70s, when researchers Yu.A. Tomin, V.Yu. Topychkanov, and S.A. Geraskin came to the Institute the direction of the work has changed. The high qualifications and experience of these specialists made it possible to embark on the development of a comprehensive simulation model for plant production in situations of radioactive contamination. In the framework of this model for the first time the impact of the main factors, e.g. meteorological, organisational, etc. that indirectly influence the severity of consequences of radioactive contamination was considered on the production of agricultural foodstuffs.

Since 1983, RIARAE has been actively developing radioecological models describing the behaviour in the environment of radioactive matters and their effects on the biospheric critical components. Since the real ecological situation is characterized by simultaneous exposure of living organisms to low doses and concentrations of factors of different (physical, chemical and biological) nature, the Institute has developed and applied to the analysis of particular experimental material a system of principles and methods for a quantitative assessment of the biological system's response to a combined effect of toxics. These are oriented to complex real situations which involve a large number of simultaneously acting factors, the presence of the nonlinear (antagonism, synergism) effects of damages interactions, slight exceeding of the background values for some agents and small amounts of information available for a researcher. Simultaneously, a complex of models have been developed that describe the effects of ionising radiation at different levels of organisation of living organisms [3].

An important step was the elaboration of a model describing the radiation injury and postradiation development of forest ecosystems. Within the context of this model, which formed the basis for S.I. Spiridonov's thesis, the ideas of the ecological mechanisms that define the influence of ionising radiation on natural ecological systems have been developed for the first time. This model summarized the long-term research in the South Urals on the evaluation of ionising radiation effects on forest ecosystems [6].

Specialists from RIARAE took active part in the International Program of International Scientific Committee on Problems of Environment (ISCPE). Under this program the first nonclassified studies were conducted related to the global nuclear conflict. In Russia, these studies were initiated by academicians E.P. Velikhov, A.A. Dorodnitsin, Professor Yu.M. Svirezhev. Dr. S.V. Fesenko and Dr. S.I. Spiridonov from RIARAE were the first to make assessments of the consequences of a nuclear war for agriculture and forest ecosystems. The results of their studies reported at the ISCPE International Conference in Moscow, March 21-26 1988, as well as in the monograph "Mathematical Models for Ecosystems. Ecological and Demographic Consequences of a Nuclear War" edited by A.A.Dorodnitsin [4] and adequately depicting the views of Soviet scientists as to the consequences of the global nuclear conflict had an important influence on the development of this problem. A significant contribution to the solution of this problem was made by a team of researchers supervised by Dr.O.K.Vlasov. They made assessments of the major factors responsible for the consequences of severe biospheric catastrophes for agriculture.

Later on, in 1989-1991, the studies of Dr. B.I. Yatsalo and Dr. O.A. Mirzeabasov contributed significantly to these studies. They have developed a range of models for predicting consequences for agriculture of the biospheric balance disturbances [2]. These studies included:

- mathematical modelling of the consequences of significant man-made exposures;
- development of original models within the limits of global biospheric processes modelling;
- development of software and databases for studying different scenarios of man-made effects at regional-global level.

On the whole, the investigations carried out by the RIARAE specialists in this area were consonant to those by Yu.M. Svirezhev, A.M. Tarko, V.F. Krapivin on modelling the global biospheric processes and by M. Harwell et al. on possible consequences of nuclear war, and were of great practical importance for building up the public opinion on the restriction of nuclear weapons.

Of great significance were a range of studies performed by the Institute's specialists on evaluating impacts of normalized and accidental releases from nuclear enterprises on agricultural and forestry. These calculations made under the direction of Dr. S.V. Fesenko for 5 NPPs in Russia (Novovoronezh, Leningrad, Rostov, Bashkir and Gorky) enabled the evaluation of a potential risk from NPPs with different types of reactors. The results derived were used for the examination of operating and being constructed NPPs in Russia.

New and relatively complex tasks associated with predicting the behaviour of the major dose-forming radionuclides ^{137}Cs and ^{90}Sr in agricultural and semi-natural ecosystems were posed by the Chernobyl accident. It should be noted that the main regularities of the behaviour of these radionuclides in the environment were identified well before this accident (in studies of consequences of environmental contamination from global testing of nuclear weapons). Simultaneously the corresponding mathematical models were devised. At the same time, special features of global fallout, such as radionuclide releases into the atmosphere over prolonged periods of time, fallout in the form of readily soluble finely dispersed particles, made it impossible to extrapolate the derived data in full measure to the situation found after the Chernobyl accident. Accordingly, the models used to predict radionuclide migration and estimates based on these models had large uncertainties, thereby causing a need for new more elaborate models providing long-term prediction of changes in the biological availability of radionuclides in agroecosystems and their accumulation in farm products. The development of such models which took into account possible uncertainties of both the parameters and the application conditions had been in progress since 1987. This enabled a reliable prediction to be made of the contamination of farm products for different scenarios of land use in affected areas [5, 7].

Of paramount importance in radioecology is to identify the mechanisms governing the behaviour of radionuclides and chemical toxics in food chains. From the point of view of their studying and appropriate models developing, the Chernobyl situation provided a unique situation. Some results obtained in the accidental zone, such as an abnormally high radionuclide mobility in the environment, are beyond our traditional knowledge. Besides, these studies have revealed poor adequacy of criteria and models for the assessment of biological availability. To explain the above effects and for long-term prediction of ^{137}Cs accumulation in food and fodder crops, a number of models have been developed that describe changes in the biological availability of this radionuclide in the soil-plant system. The models devised provided a means for the long-term forecast of ^{137}Cs leaching from the root layer of different types of soil, changes in ^{137}Cs availability in areas with different contribution of fuel particles. The results from these studies widely covered in the domestic journals ("*Proceedings of the Russian Academy of Agricultural Sciences*", "*Soil Science", "Radiation Biology. Radioecology*") and foreign journals ("*The Science of the Total Environment*", "*Journal of Environmental Radioactivity*") [1, 3, 10] greatly influenced the development of our knowledge of ^{137}Cs biochemistry in agricultural and semi-natural ecosystems.

One of the trends of research being currently actively developed at the Institute is the elaboration of methods for reconstructing doses of irradiation of the population living in the regions contaminated as a result of nuclear weapons testing (Semipalatinsk Test Site). In the framework of these studies supervised by Dr. O.K. Vlasov models have been devised allowing one to compare different pathways of exposure and correct assessments have been made of the consequences of these tests for rural population, which was very essential for granting relevant privileges and paying compensations.

It should be noted when considering a range of problems connected with the rehabilitation of the radiation affected territories that much of these have to do with the provision of rational ways of farming in unfavourable ecological situations. These problems are multifactoral and multioptional. It is therefore necessary that methods and software be developed and put into practice that provide informational and analytical support of works on the organisation of agricultural production in the contaminated areas including the creation of both databases that contain information necessary for decision making and computer systems for analyzing possible variants of farming and application of countermeasures.

The development of special databases on the contamination of agricultural lands and products in the Chernobyl affected area was one of the key problems while assessing the effectiveness of countermeasures in the accidental zone. The major radiation accidents showed that the identification of a range of problems related to the organization of rational farming in affected areas is of crucial importance for safe residence of the population. At the same time, the development of systems for agricultural production in contaminated areas must be based on the analysis of radiological situation in the agroindustrial complex and identification of trends in its variation. Such an assessment can only be done based on the data on the contamination levels, scales and times of countermeasures, dynamics of farm produce contamination, as well as on the information about the rate of natural geochemical processes responsible for changes in the biological availability of radionuclides in food chains.

Studies on the development of databases on radioactive contamination of farmlands and products were initiated in 1987 at the department of mathematical agroecology (head Dr. O.K. Vlasov). In an early stage these included data on the contamination of farmlands. Then, owing to the efforts of a team of researchers headed by Dr. O.N. Bakalova and Dr. V.A. Likuev, extensive information was gathered on the ecologo-economic situation in the affected area. Since 1990, these works have been focused in the laboratory for modelling radioecological processes headed by Dr. S.V. Fesenko. By 1993, this information was supplemented by data on the radionuclide dynamics in farm products and by 1995, by data on the TF dynamics in the soil-plant system. The results from the radiation-ecological monitoring of agroecosystems carried out by several RIARAE departments were the base of these databanks.

The availability of comprehensive information systematized within the RIARAE databases allowed a number of major practical and scientific problems to be solved. The regularities of variations in the radionuclide content in farm products in regions with different scales of countermeasure application were studied, as well as the contribution of countermeasures and natural biogeochemical processes to the decrease in products contamination was assessed [1, 9].

The first prototype of a decision support system, program system "OKC", was developed in 1989-1990 by S.V. Fesenko, V.A. Polozov, L.G. Chernyaeva, and O.A. Mirzeabasov. Despite an insufficient PC power, as early as in 1989 this system had the main features of the modern decision support systems and was actively employed for solving national economic tasks associated with the justification of variants of farming in the Chernobyl affected area.

In 1991, studies were started under the supervision of Dr. S.V. Fesenko on the development of a complicated local decision support system FORCON [8]. The system included:

- Analysis of the radiological situation and estimation of possible trends of countermeasure application for areas to be rehabilitated.
- Modelling of countermeasures with the account of existing conditions. Scenarios of their application. Calculation of costs of countermeasures and changes in the contamination levels of farm products after their application.
- Analysis of the effectiveness of the scenarios specified and choice of rational ways of organisation of agricultural production with taking into account the possibilities for countermeasure implementation (availability of necessary resources, money, etc.).

The distinctive feature of this system was that it offered the analysis of both countermeasure options and strategy of their application after radiation accidents.

In 1992-1996, it was precisely this system that was widely used to justify the rational variants of agricultural production on farms located in the contaminated regions of Russia. The results derived were utilized for the preparation of the Recommendations on Agricultural Production in the Contaminated Areas of the Kaluga Region (1992, 1995), Recommendations on the Use of the Abandoned Areas (Recommendations on Maintenance of Soil Fertility and Safe Phytosanitary Situation on Farm Lands Temporarily Excluded from Land Use, 1994), etc.

In 1994, a start was made at the Institute on the development of decision support systems based on the geoinformation technologies. To this end, in 1994 a sector was established at RIARAE for applying computer systems in radioecology headed by Dr.B.I. Yatsalo. The key features of the system being developed, PRANA, which make it different from those similar in purpose are:

- use of GIS technologies; vector map of land use and related databases are one of the key system's components;
- different levels of investigation and of detail in assessing the consequences of radioactive contamination, choice of intervention strategies, as well as the effectiveness of countermeasures (regional, local levels).

It should also be noted that since 1991, the works on the creation of the decision support systems FORCON and PRANA have been done in collaboration with a number of famous European research centres: NRPB (Great Britain) and CEPN (France) under the international EC/CIS program on the mitigation of consequences of the Chernobyl NPP accident. PRANA is being developed in the framework of the international ISTC (International Scientific and Technical Centre) project in close cooperation with scientists from the Kurchatov Institute and Institute of Biophysics (Moscow), as well as the Russian Federal Nuclear Centre Arzamas-16. This system was officially presented at the International Conference "Radiological Consequences of the Chernobyl Accident", Minsk, 1996 and at the IRPA International Congress, Vienna, 1996 [11].

Since 1993, specialists from RIARAE have been actively participating in the IAEA expert groups on validating the models for the radionuclide behaviour in the environment (S.V. Fesenko) and on improving the levels of intervention in the event of a radiation accident (B.I. Yatsalo).

Currently, the problems connected with the development of models for pollutants migration in agricultural and semi-natural ecosystems, their effects on the critical components of agroecosystems and development of relevant software are being solved at RIARAE in one laboratory and two sectors. Among the priorities in research are:

1. Development of models and methods for risk evaluation of technogenous contamination of agricultural lands.
2. Study of theoretical fundamentals and development of models describing the mechanisms of the behaviour of radionuclides and chemical toxics in agrolandscapes and their effects on the critical components of agroecosystems.
3. Elaboration of decision support systems on farming in technogenously contaminated areas with the account of landscape details.

References

1. **Alexakhin R.M., Fesenko S.V., Sanzharova N.I., Spiridonov S.I., Vorobiyov G.T., Yakovleva N.A.** On the decrease in ^{137}Cs content in plant products affected by the Chernobyl NPP accident *RAAS Proc*., 1995. 3:20-21 (1995) (in Russian).
2. **Gaidukov O.Yu., Tarko A.M., Yatsalo B.I.** Modelling of agricultural production and population dynamics after a nuclear conflict. *Problems of Environment and Natural Resources*. 12:25-30 (1988) (in Russian).
3. **Geraskin S.A., Sarapultsev B.I.** A stochastic model of induced genome instability. Radiation Biology. *Radioecology*, 35(4):451-462 (1995) (in Russian).
4. *Mathematical models. Ecological and Demographical Consequences of Nuclear War*, Ed. A.A.Dorodnitsin. Moscow: Nauka, 1986, 176 p. (in Russian).
5. *Agricultural Radioecology*/Eds. Alexakhin R.M., Korneyev N.A. Moscow: Ecology, 1992, 400 p. (in Russian).
6. **Spiridonov S.I., Fesenko S.V., Alexakhin R.M., Spirin D.A.** Mathematical modelling of consequences of acute radiation exposure of the woody story of forest biogeocenosis. *Radiobiology*. 29(4):544-549 (1989) (in Russian).
7. **Fesenko S.V., Chernyaeva L.G., Sanzharova N.I., Alexakhin R.M.** Probabilistic methods for predicting the contamination of farm products. *Atomic Energy*. 74(6):507-513 (1993) (in Russian).
8. **Fesenko S.V., Sanzharova N.I., Wilkins B.T., Nisbet A.F.** FORCON: Local Decision Support System for the Provision of Advice in Agriculture. - Methodology and Experience of Practical Implementation*. Radiation Protection Dosimetry*, 64(1/2):157-164 (1996).

9. **Fesenko S.V., Alexakhin R.M., Spiridonov S.I., Sanzharova N.I.** Dynamics of ^{137}Cs Concentration in Agricultural Products in Areas of Russia Contaminated as a result of the Accident at the Chernobyl Nuclear Power Plant. *Radiation Protection Dosimetry*. 60(2):289-298 (1996). .
10. **Sanzharova N.I., Fesenko S.V., Alexakhin R.M., Anisimov V.S., Kuznetsov V.K., Chernyayeva L.G.** Changes in the Forms of ^{137}Cs and its Availability in Plants as Dependence on Properties of Fallout after Chernobyl Nuclear Power Plant Accident. *The Science of the Total Environment*, 154: 9-22 (1994).
11. **Yatsalo B.I., Mirzeabasov O.A.** Computer DSS for assessment of countermeasure strategy in the long-term period of liquidation of the consequences of a nuclear accident (agrosphere). *Proc. of the IRPA Congress*, Vienna, 2:747 (1996).