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Radioecological Studies in Russia

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Abstract—Main events in the formation and development of the Russian radioecological school are reviewed, from the first basic doctrines proposed by V.I. Vernadsky and V.N. Sukachev, through the experimental radiation biogeocenology developed by N.V. Timofeeff-Ressovsky, V.M. Klechkovskii, and their followers, to recent studies in the zones of nuclear accidents, including the Chernobyl accident, which has global significance.

The history of the development of radioecology in our country is inseparable from the history of world science in general. However, radioecology has certain specific features: some of its fields had been concealed from the scientific community for a relatively long time. Our task was to describe the formation of the national school of radioecologists, its outstanding representatives, and fruitful ideas that were first developed in Russia and contributed to world science.

A special role in the formation of radioecology belongs to V.I. Vernadsky. In his works, he formulated the theory of living matter and the Earth biosphere, which demonstrated long-term coevolutionary development of the biota and inert matter and had a dramatic impact on the general concept of the world (Vernadsky, 1926). The idea of the orderliness of the biosphere was brilliantly developed by V.N. Sukachev in his studies on biogeocenoses as elementary units of the biosphere (Sukachev, 1947). Vernadsky (1929) was the first to perform radioecological experiments on analyzing trends in radium accumulation by living organisms.

Large-scale efforts undertaken in the world in the mid-1950s to create nuclear weapons resulted in the release of a great amount of artificial radioactive materials into the atmosphere. The world scientific community realized that a new global ecological factor appeared on the Earth, namely, artificial radionuclides and ionizing radiation emitted by them. The importance of understanding interactions of living organisms with each other and with the environment under conditions of radioactive contamination and a higher level of background radiation induced the development of a new scientific field named radiation biogeocenology, or radioecology. The name of this science and definitions of its principal objectives and tasks appeared almost simultaneously and independently of one another in papers published by Russian (*O povedenii...*, 1956; Timofeeff-Ressovsky, 1957; Peredel'skii, 1957) and American scientists (Odum, 1957; Platt, 1957). Radioecology, or radiation biogeocenology, completed the orbit of research fields dealing with radiation effects on biological objects. It developed in two interrelated directions: in the first, attention was focused on radionuclide accumulation, migration, and distribution in natural biogeocenoses, and in the second, on effects of ionizing radiation on populations, communities, and ecosystems.

These were the objectives of studies initiated by N.V. Timofeeff-Ressovsky in 1947 in the laboratory B of the enterprise known as PO Box 0215 and continued since 1955 at the Institute of Biology (Ural Division, USSR Academy of Sciences). Research developed on the basis of his concept of experimental radiation biogeocenology (Timofeeff-Ressovsky, 1957, 1962). Regarding radioactive isotopes as "labeled" atoms, Timofeeff-Ressovsky and his colleagues carried out numerous studies on radionuclide behavior in simplified systems. The results of these studies allowed them to classify radionuclides according to the type of their behavior in ecosystems and to identify factors determining their mobility. In that period, the work largely concentrated on the role of living organisms in the accumulation of radionuclides and their redistribution over principal components of biogeocenoses. The limits of accumulation proved to be extremely wide as concerns both different elements and different biological species (Timofeeff-Ressovsky, 1962; Timofeeva-Ressovskaya, 1963; *Radioaktivnost'*..., 1966).

Special tests on model communities of terrestrial plants, soil microorganisms, and freshwater periphyton exposed to radioactive contamination revealed typical alterations in these complexes, which ranged from radiostimulation to disturbances in their species composition and structure (Timofeeff-Ressovsky *et al.*, 1957; Kulikov, 1957). Note that studies of radiosensitivity and radiopathology of living organisms belong to the field of radiobiology, and the fundamentals of this science are addressed here only as far as they concern radioecology.

The first institution dealing with problems of the behavior of artificial radionuclides in the agrosphere was the Biophysical Laboratory of the Timiryazev Agricultural Academy in Moscow, organized in 1948.

The laboratory was headed by V.M. Klechkovskii, one of the founders of agricultural radioecology and the leader of experimental research on the soil chemistry of artificial radionuclides and their delivery to plants (*O povedenii..*, 1956; Gulyakin and Yudintseva, 1962; Aleksakhin, 1963). On A.F. Ioffe's initiative, a similar laboratory was also organized at the Agrophysical Institute of the Lenin All-Union Academy of Agricultural Sciences (VASKhNIL) in Leningrad. Studies performed in this laboratory by M.K. Mel'nikova, Ya.A. Kokotov, V.M. Prokhorov, A.S. Frid, and other scientists dealt with a broad spectrum of problems related to the migration of biologically important radionuclides and the important role of diffusion in their transfer in different media (Prokhorov, 1981).

In autumn 1957, an accident at the PO Mayak (nuclear industry enterprise), subsequently called the Kyshtym accident, resulted in the release of over two million Ci of radioactive substances into the atmosphere. Settling to the soil and plant cover, these airborne radionuclides formed the Eastern Ural Radioactive Trace (EURT). In this connection, in 1958 an experimental research station was organized at PO Mayak, which was initially headed by G.A. Sereda and subsequently by E.A. Fedorov, N.A. Korneev, and G.N. Romanov. V.M. Klechkovskii continuously coordinated all the studies performed at the station. The group of researchers working under his leadership was awarded State Prize in 1974 for investigations in the EURT territory. Unfortunately, information on the situation with radioactive contamination in the Urals was classified and became fully available to radioecologists only after the Chernobyl accident (*Itogi...*, 1990).

In the late 1950s, one more center of radioecological studies appeared at the Institute of Biology of the Komi Branch of the USSR Academy of Sciences, in a special department founded on P.P. Vavilov's initiative. The department was headed by V.I. Maslov and, later, by A.I. Taskaev, and researchers were consulted by leading specialists, such as I.N. Verkhovskaya, A.M. Kuzin, R.M. Aleksakhin, F.I. Pavlotskaya, and others, who also participated in field and experimental work. This scientific team, working under severe conditions of the taiga and tundra zones, organized and performed comprehensive studies on natural biogeocenoses with naturally and technogenically increased levels of background radioactivity, which were distributed over a vast territory. The abundant factual data obtained in these studies allowed researchers to reveal principal trends in the behavior of natural radionuclides in both inert and living components of ecosystems (*Radioekologicheskie issledovaniya v prirodnykh biogeotsenozakh*, 1972; *Radioekologicheskie issledovaniya pochv ...*, 1983). They also initiated unique studies on the effects of small radiation doses on plant and animal populations in natural and model communities, which provided the basis for the modern views on this problem (*Tyazhelye ...*, 1990).

The subsequent strategy of radioecological research was determined by large-scale nuclear weapons tests. Investigations were mainly aimed at revealing principles of migration, distribution, and biological action of radioactive substances in different ecosystems of land, inland waters, and seas, developing the scientific basis for predicting the consequences of radioactive contamination of the biosphere, setting ecological standards for the contents of these contaminants in different components of the environment, and reducing their adverse effects. Their authors widely used the systemic landscape-geochemical approach based on the idea of the interrelationship between living and inert environmental components and between individual biogeocenoses.

Ideological leaders of these studies were scientists working at the Vernadsky Institute of Geochemistry and Analytical Chemistry and headed by V.I. Baranov. The first data on the levels of soil and plant contamination with radionuclides within the borders of the former Soviet Union were obtained by F.I. Pavlotskaya, E.B. Tyuryukanova, R.M. Aleksakhin, M.A. Naryshkin, F.A. Tikhomirov, and others (Tikhomirov, 1972; Pavlotskaya,1974; Aleksakhin and Naryshkin, 1977). They revealed zones of dispersion and secondary accumulation of radionuclides in the environment and assessed the effects of local ecological conditions on the rate of radionuclide migration and passage along the food chains to human diet (Tyuryukanova, 1974; Moiseev and Ramzaev, 1975; Kulikov and Molchanova, 1975). In those years, numerous comparative studies on radiosensitivity of dozens of plant and animal species were carried out, and their results provided the basis for the first prognoses of radiation effects on biocenoses (Preobrazhenskaya, 1971; Krivolutskii, 1983). The accumulation of radioecological information on specific features of the behavior of radionuclides in different environments of living organisms resulted in differentiation of radioecology into several special research fields, such as agricultural, forest, marine, and continental radioecology.

The current task of agricultural radioecology is to study the principles of migration of radionuclides (released mainly by enterprises of the nuclear fuel cycle) in the agroindustrial sphere to develop a complex of agrotechnological, agrochemical, and stockbreeding measures aimed at reducing the content of radionuclides in agricultural production. The All-Union Research Institute of Agricultural Radioecology, headed by Member of the VASKhNIL R.M. Aleksakhin, is the main scientific center developing research in this field in our country. The most important achievements in agricultural radioecology were described in numerous papers, reviews, and fundamental monographs (*Radioekologia oroshaemogo zemledeliya*, 1985; *Sel'skokhohozyaistvennaya radioekologiya*, 1991).

Forest radioecology concentrates on features specific for forest ecosystems. Different forest types have a great retention capacity with respect to radionuclides, and self-purification of the aboveground forest phytomass proceeds slowly. This retards circulation of chemical elements and creates conditions for chronic irradiation of forest plants and animals. The results of corresponding studies provide valuable material for constructing models of spatiotemporal redistribution of radionuclides in forest biocenoses, which, in their turn, are necessary for issuing scientifically valid recommendations on forest management in territories with an increased radionuclide content (Tikhomirov, 1972; Aleksakhin and Naryshkin, 1977; Yushkov, 1987; *Deistvie ioniziruyushchei radiatsii...*, 1988; *Radiatsionnoe vozdeistvie...*, 1990, *Vliyanie...*, 1996).

The main task of marine radioecology is to study the dynamic states of marine communities in relation to radioactive load created by global emissions, radioactive waste discharge, and contaminated river runoff, and the assessment of ecological mechanisms providing for their self-purification from contaminants (Polikarpov, 1964; Polikarpov and Egorov, 1986; Matishov *et al.*, 1994).

Based on the foundation laid by N.V. Timofeeff-Ressovsky and on vast experimental material, the concept of continental radioecology as radioecology of land ecosystems and inland water bodies was formulated (Kulikov and Molchanova, 1975; Aleksakhin, 1982; Kulikov and Chebotina, 1988; Chebotina *et al.*, 1992). The main tasks in this field include the comprehensive analysis of radionuclide migration in inert and living components of land and freshwater biogeocenoses and the assessment of radiation effects on them, taking into account all the types of intraspecific variation and the modifying effects of biogenic and abiogenic environmental factors (*Radiochuvstvitel'nost'...*, 1989; Pozolotina,1996).

Experience gained in different fields of radioecological research and methodology developed in its course were applied to long-term comprehensive studies in the zone of the EURT. The situation in this area was aggravated in 1967 by wind transfer of radionuclides from the coastal zone of Lake Karachai, which served as a natural reservoir of radioactive waste dumped from PO Mayak. The territory of the EURT virtually became a range for the experiment in nature that had no analogues in the world. Scientists from several institutes of the USSR Academy of Sciences actively participated in studies performed at the Experimental Station. These were Dokuchaev Soil Science Institute, Zoological Institute, Komarov Botanical Institute, Laboratory of Forest Science, Severtsov Institute of Evolutionary Morphology and Animal Ecology, and Vavilov Institute of General Genetics. Other scientists were from institutions affiliated with the VASKhNIL, State Hydrometeorological Service, and Moscow State University.

In the course of this work, specialists performed for the first time large-scale mapping of contaminated territories (V.L. Andronikov), which was supplemented by geobotanical studies (E.G. Smirnov), and analyzed the distribution of radionuclides in soils depending on the complex of conditions existing in natural biogeocenoses (B.S. Prister, N.P. Arkhipov, and A.V. Egorov). New methods of quantitative determination of different radionuclides, plutonium isotopes in particular (M.N. Fedorova), methods of ecological dosimetry, and principles of registering biological effects of radiation on different plant and animal species were elaborated (G.N. Romanov and F.A. Tikhomirov). The data obtained also concerned the role of animals and plants in radionuclide migration in natural ecosystems, primary changes occurring in populations of different species exposed to radiation and secondary effects associated with disturbances of biogeocenotic relationships in these populations (V.E. Sokolov, E.A. Fedorov, F.A. Tikhomirov, A.I. Il'enko, D.A. Krivolutskii, A.D. Pokarzhevskii, D.A. Spirin *et al.*), the assessment of the potential for recovery in populations and ecosystems, and the analysis of remote consequences of radioactive contamination (V.A. Shevchenko, F.A. Tikhomirov *et al*). The results of these works were partially described in papers (without indicating the site and conditions of contamination) and, more completely, in collective monographs (*Deistvie ioniziruyushchei radiatsii na biogeotsenoz*, 1988; *Ekologicheskie posledstviya...*, 1993).

In addition to the Kyshtym accident, PO Mayak is also responsible for the critical situation in the Techa River into which it discharged unpurified radioactive waste in the first years after being put in operation. As a result, water, bottom sediments, the biota, and floodplain landscapes of the Techa River were heavily contaminated with long-life radionuclides. Full-scale radioecological studies of this river ecosystem began only after 40 years. Their results showed that current levels of radioactive contamination of the Techa River and the adjoining floodplain landscapes are still very high. According to calculations, the major proportion of discharged radionuclides is concentrated in the system of reservoirs in the upper reaches of the Techa River, and about 15% is concentrated in the river proper and floodplain soils. Over 1 TBq of radioactive materials formed a radioactive trace in the Ob'–Irtysh river system and migrated to northern seas (Trapeznikov *et al.*, 1993).

After the Chernobyl accident, the world's worst nuclear accident, a characteristic peak of radioactivity was registered over both land and sea, in terrestrial and aquatic organisms. The USSR Academy of Sciences had to develop and implement the program of detailed studies on the effects of the accident and its consequencies for the animal and plant world, water, and atmosphere in order to issue current and prognostic recommendations for the maintenance of normal activities in areas exposed to radioactive contamination. Virtually all departments of the Academy participated in this program. Specialists from the Institute of Biology of the Komi Research Center were the first to begin large-scale investigations, and the combined radioecological expedition of the Academy, headed by V.E. Sokolov, followed them in 1987. The experience gained by radioecologists during studies in the EURT and other radioactively contaminated zones proved to be invaluable in this situation.

The specific radioecological situation in the zone of the Chernobyl accident was accounted for by a complex radionuclide composition, physicochemical properties of radioactive fallout, and the diversity of natural and meteorological conditions (*Informatsiya...*, 1986). Radioecological studies showed that direct radiation impact was lethal for the most radiosensitive species of plants, invertebrates, and vertebrates in the central zone. On the remaining territory, no direct signs of radiation damage to biological objects were revealed, whereas indirect effects manifested themselves in all their variety. This raised the urgent problem of analyzing on a large scale the effects of so-called small doses of radiation on living organisms.

Studies on redistribution of radionuclides in ecosystems provided the data on the dependence between their physicochemical properties, on the one hand, and migration and accessibility for living organisms, on the other, and to assess the roles of their transmission by air, through roots, and in other ways in radionuclide uptake by plants. The results of the ten-year work were described in hundreds of scientific papers and a series of monographs (*Radiatiotsionnoe vozdeistvie...*, 1990; *Radioekologicheskie posledstviya...*, 1991; Kozubov and Taskaev, 1994; Maslova *et al.*, 1994; *Vozdeistvie Radioaktivnogo...*, in two volumes, 1996; *Vliyanie...*, 1996). The global impact of the Chernobyl accident accounted for the unprecedented openness of radioecological studies, the accessibility of their results, including formerly classified data on previous accidents, and for large-scale scientific collaboration (UNSCEAR, 1988; *Comparative Assessment...*, 1991). Cooperation among specialists from different countries contributed to both fundanmental radioecology and the methodology of radioecological research and allowed scientists to reach a new level in the understanding of problems associated with radiation effects on the environment.

Radiation hazard, which attracted the attention of radioecologists as soon as this science began to develop, has not decreased with time but, on the contrary, progressively increases: the development of nuclear technologies results in the production of fissionable materials in great amounts and is associated with risk of nuclear accidents. In the context of general ecology, this means that the topical problems of radiation biogeocenology (in addition to traditional), now concern radiation safety, the development of ecological norms, setting ecological standards, and predicting the delayed effects of exposure to small doses of radiation on the biota.

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