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Some Indices of Biological Cycle of ^{137}Cs and ^{39}K in Forest Ecosystems of Bryansk Woodland in the Remote Period after Chernobyl Fallouts

A. I. Shcheglov, O. B. Tsvetnova, and A. A. Kasatskii
e-mail: shchegl@mail.ru
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Abstract—The features of the biological cycle of ^{137}Cs and ^{39}K in the remote period after Chernobyl fallouts are considered on the example of forest ecosystems of Bryansk woodland. It is demonstrated that the maximum amount of ^{137}Cs in the total phytomass is concentrated in wood, the minimum amount of ^{137}Cs, in the external bark layers; for the annual production, in assimilating organs and the external bark layers, respectively. The distribution of ^{39}K in the total phytomass and the annual production is almost identical to that of ^{137}Cs. The arrival of ^{137}Cs to the soil with litter in pine and birch forests has recently been equal approximately to 50% of the capacity of the biological cycle. It mostly arrives with the assimilating organs (needles and leaves). In pine forests the return of ^{39}K into the soil with litter is closest to that observed for ^{137}Cs.

Keywords: biological cycle, radionuclides, ^{137}Cs, ^{39}K, phytomass stock, annual production, litter.
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INTRODUCTION

Biogeochemical migration of radionuclides is the main process determining the redistribution of radioactive elements in the biosphere. Studies into this field by means of the example of model experiments of global and Kyshtym fallouts have been developed by V.M. Klechkovskii and N.V. Timofeev-Resovskii [6, 13]. The elaborations of their students and followers, R.M. Aleksakhin and M.A. Naryshkin, N.V. Kulikov, F.A. Tikhomirov, E.B. Tyuryukanova, and A.N. Tyuryukanov, et al. [1, 7, 8, 14, 15] have made it possible to formulate the main principles of biogeochemistry of technogenic radionuclides and show the features of biological cycle of these elements. The role of vegetative cover in retaining the primary aerosol fallouts was revealed; the features of the secondary redistribution of radionuclides over structural components of the phytomass were ascertained, and the features of their accumulation in supraterraneous and subterranean phytomass were noted [1, 8].

This direction of radioecology has been intensely developed, in particular, in the post-Chernobyl period. In natural experiments it was confirmed that up to 90% of the laid-down activity is retained by tree crowns [5, 9–11, 18, 20, 21, etc.]. Its main part is currently concentrated in soil, most likely in the upper surface layers. The latter fact differentiates the distribution of technogenic radionuclides, in particular, ^{137}Cs, from its chemical analog, potassium, which is known to be distributed more uniformly over the entire root-inhabited mass. The earlier studies also demonstrated that the biological cycle (BC) of ^{137}Cs at the initial stages after radioactive fallouts is characterized by a considerable prevalence of descending radionuclide flows over the ascending flows. Thus, during the first years, the arrival of ^{137}Cs within vegetation litter was higher than its root consumption by more than an order of magnitude. It was assumed that the BC indices for ^{137}Cs and ^{39}K will subsequently level off. However, the data obtained attest to the fact that an increase in the specified differences, rather than smoothing of them, is noted in the dynamics in forest ecosystems of the forest–steppe zone that underwent radioactive contamination [17, 19, 20]. In this connection the present work aims at revealing the features of the biological cycle of ^{137}Cs and ^{39}K in the main types of forest ecosystems on the European part of the territory of the Russian Federation that underwent radioactive contamination as a result of the Chernobyl Nuclear Power Plant accident (1986). In this study, the results of surveys carried out in forest ecosystems of Bryansk woodland are presented.

OBJECTS AND METHODS OF STUDY

The surveys were carried out in 2008–2010 at two sites of forest ecosystems of Bryansk oblast (Krasnogorsk forestry, Krasnogorsk district) that were characterized by the highest density of radioactive contamination in the Russian Federation [1].

The sample plots (50 × 50 m) were set in pine green-moss forest (70 years old) and gramineous grassland birch forest (50 years old), which had been

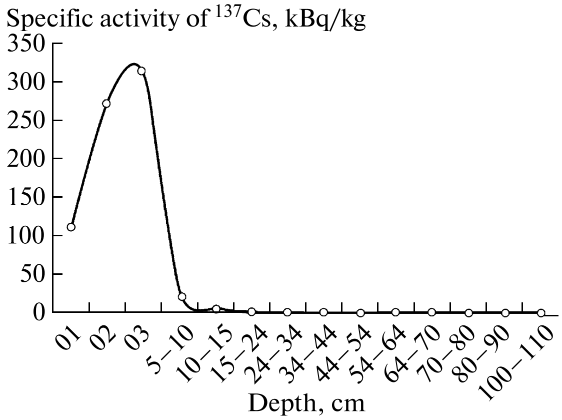

Fig. 1. Vertical distribution of the specific activity of ^{137}Cs in the profile of soils under study.

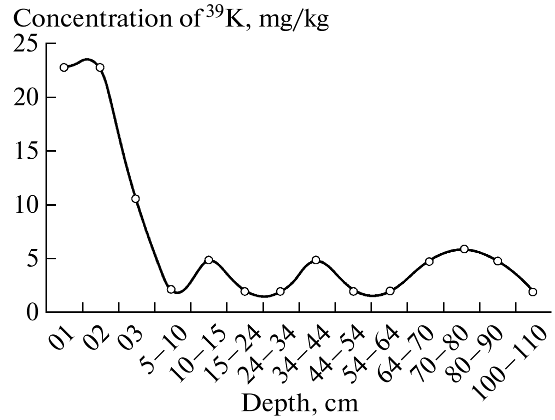

Fig. 2. Vertical distribution of exchangeable potassium in the profile of soils under study.

formed on sandy podzolic soils. The plots were separated only by a ridge. The indices of the biological cycle were studied according to procedures that have conventionally been used in this field [3, 12, etc.]. The experimental material for estimating the indices of the biological cycle of an organic compound and the elements under study (^{137}Cs and ^{39}K) were obtained directly on the sample plots. The sampling in the tree layer was performed from model trees, which were selected with allowance for the mensurational description. A model tree with parameters that were close to the average tree for the given age category was sawn down and divided into structural parts: leaf/needle growth during the current formation year, needles from earlier years, large branches (>1 cm thick), and small branches (<1 cm thick). The average sample for each of the components specified was formed using the entire crown. The samples of the external bark (cork), internal bark (phloem), and wood were collected from cuts made at different height values of the trunk: near the top, the middle, and the stem base [18, 21].

In order to determine the degree of soil contamination with ^{137}Cs and the content of mobile potassium, sections were made on the plots under study; soil samples were taken layer-by-layer, taking into account the genetic horizons. The stock of phytomass and yearly production within the tree layer were calculated based on the experimental material and mathematic dependences obtained for the phytocenoses of Bryansk oblast in the preliminary studies [18, 21]. The quantitative estimation of the arrival of organic compound within litter was performed using litter traps (with an area of 1 × 1 m), which were mounted at each plot, repeated ten times. Litter was collected once per year, in late autumn, immediately after the mass defoliation had ended.

The preparation of soil and plant samples for the analysis and measurement of specific activity of ^{137}Cs was carried out using the standard procedures on a scintillation gamma-spectrometer, the amplitude spectrum of impulses was processed using the Progress software [16]. Potassium content was determined using conventional methods: exchangeable potassium was determined in soil and in plants according to Kirsanov or on a flame photometer after wet combustion [4].

RESULTS AND DISCUSSION

The performed surveys demonstrated that the densities of contamination of soils of pine and birch tree phytocenoses with ^{137}Cs are close and equal to approximately 9300 kBq/m^2. The indices of content and distribution of ^{137}Cs radionuclide in the soil profile at both plots show no significant differences: the maximum specific activity and its stock (up to 90%) were observed in the substrate (O3 subhorizon) and the adjacent 0- to 5-cm-thick mineral layer (Fig. 1).

Concentration of exchangeable potassium in soil varies from 0.2 to 2.3 mg/100 g; as already mentioned, its distribution over the profile as compared with that of ^{137}Cs is characterized by a different type. Thus, biogenic accumulation of the element is observed in the organogenic horizon of the forest floor; its content, considerably decreasing in mineral layers, is appreciably uniformly distributed over the entire mass under study and increases near the parent rock to a certain extent (Fig. 2).

Analysis of the production processes attests to the fact that pine and birch forests differ insignificantly in terms of the total phytomass and the yearly production. The stock of phytomass and is equal to 2130–2350 q/ha; the stock of yearly production for pine and birch forests is equal to 5100 and 5700 kg/ha (Table 1). The main difference consists in the indices of return of organic matter into soil. Thus, almost 52% of the yearly growth arrives to the soil in birch forests, whereas for pine forests this value is smaller by 10%.

As is well known, the chemical composition of plants primarily represents the elemental composition of soil medium. Meanwhile, a number of factors have

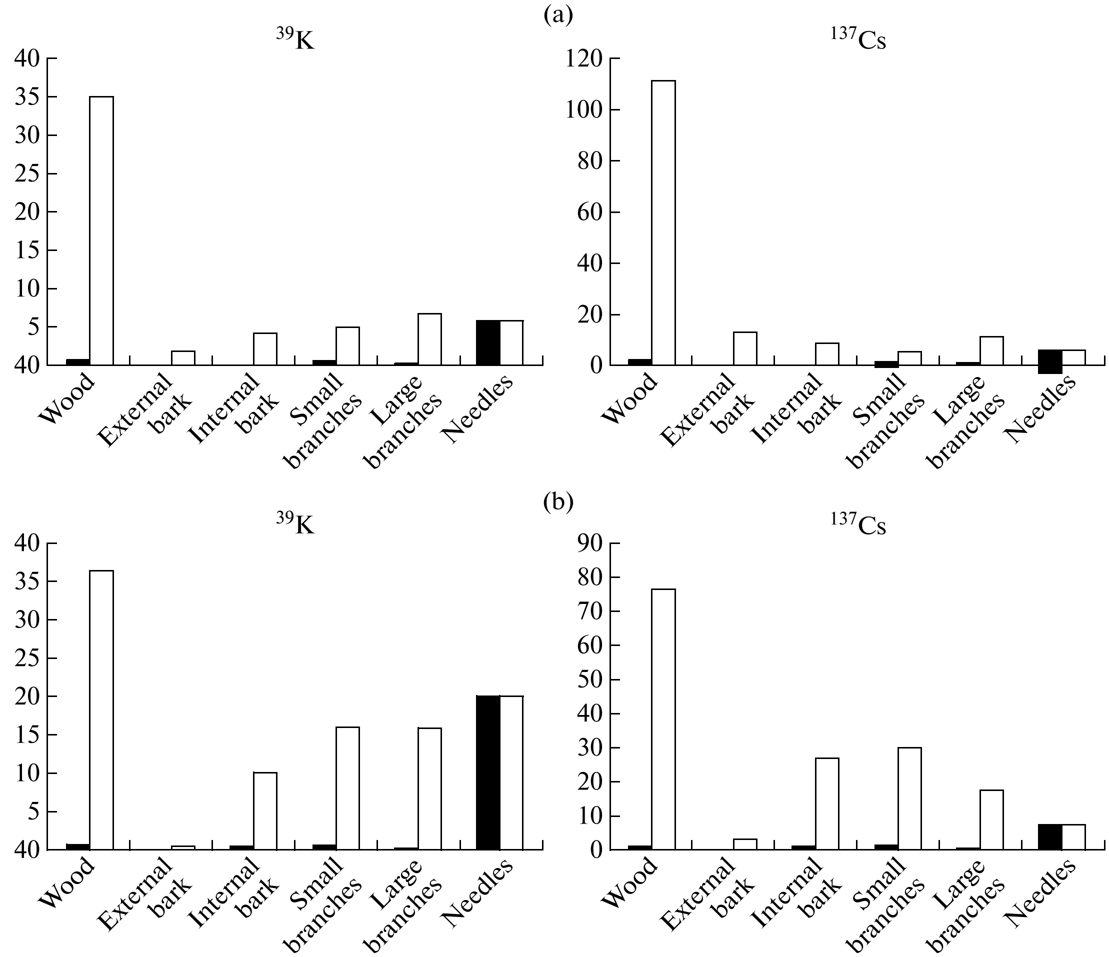

Fig. 3. Stocks of ^{39}K (kg/ha) and ^{137}Cs (kBq/m^2) in the total phytomass (light bars) and yearly production (black bars) of pine forests (a) and birch forests (b).

also an effect on this index; therefore, the content of stable elements in plants varies appreciably and fluctuates over a wide range depending on climatic conditions, position of an ecotope within the landscape, biological features of the species, the structural part and return of the plant, physiological role of the consumed element, etc. In addition, under conditions of contamination, including radioactive contamination, the accumulation of the elements in plants depends directly on the level of soil contamination.

As demonstrated by our studies, concentration of stable potassium in structural components of pine and birch trees varies within the 0.01–1.0% range, which corresponds to the data obtained by other authors in their studies devoted to the biological cycle in forest ecosystems [8, etc.] (Table 2).

The specific activity of ^{137}Cs in the components of wood species under study is also nonuniform and fluctuates almost in the same range: 4.2–38.0 kBq/kg (pine tree) and 0.35–6.4 kBq/kg (birch tree) (Table 2).

Table 1. Cycle of organic matter in forest phytocenoses of Bryansk woodland

Phytocenosis	Phytomass stock, 100 kg/ha	Biological cycle indices					
		yearly growth		retained in phytomass		arrives to soil with litter and debris	
		100 kg/ha/yr	%	100 kg/ha/yr	%	100 kg/ha/yr	%
Pine forest	2100	51.50	100	30.00	58.25	21.50	41.75
Birch forest	2350	57.00	100	27.50	48.25	29.50	51.75

Table 2. Specific activity of ^{137}Cs and concentration of stable potassium in components of the tree stage of pine and birch biogeocenoses

Structural component of the forest	Pine		Birch	
	^{137}Cs, kBq/kg	^{39}K, %	^{137}Cs, kBq/kg	^{39}K, %
Wood	4.2	0.02	6.4	0.02
Internal bark	18.5	0.07	33.4	0.17
External bark	4.30	0.01	13.4	0.03
Large branches	9.9	0.09	8.4	0.05
Small branches	27.0	0.15	22.3	0.25
Current year growth/leaves	38.0	1.0	34.6	0.35
Needles of the past years of formation	30.0	0.25	–	–
Litter	18.0	0.14	16.0	0.17

The fact is notable that, upon root arrival, the distribution of ^{137}Cs in general corresponds to that of its nonisotopic analog, potassium, the following series of accumulation in structural parts being typical of it: current year growth/leaves > needles of the past years of formation > internal bark > small branches > large branches > wood > external bark. According to our data, the correlation coefficients between the distribution of potassium and ^{137}Cs over the components of birch and pine trees are equal to 0.84 and 0.86, respectively ($P = 0.95$).

Thus, similarly to potassium, cesium is accumulated in physiologically active organs and tissues (in assimilating organs of the current year of formation, in current year sprouts, in the external parts of cambium, etc.). However, the biological features of the species and the structure of the external layers of the bark that predetermine the levels of plant contamination at the stage of aerial fallouts have a considerable effect on the distribution of this radionuclide.

In biological cycle the return of elements with litter is a significant index. It has been ascertained in our surveys that potassium concentration in litter is lower than that in the assimilating analogs by a factor of 1.5–3, which is associated with the outflow of the element before litter and leaching. The values of activity of the litter in the biogeocenoses under study are close and not higher than 14–18 Bq/kg (Table 2).

The balance calculations of stock of ^{137}Cs and potassium have shown that, in accordance with the organic matter value and concentration of the elements, wood makes the maximum contribution to the total phytomass, whereas the contribution of the external bark layers is minimal (Fig. 3). In yearly production and growth, the highest content of the elements is observed in the assimilating organs of the current year of formation (growth and leaves) and the minimum content is observed in the external bark as well.

As already mentioned, active root consumption of ^{137}Cs by plants with its accumulation in structural organs of the forest has been recently observed on the territory under study. In this connection, the flow of radionuclides that arrive annually to the soil surface with vegetation litter is appreciably high. Thus, the litter mass in phytocenoses under study varies from 0.21 kg/m^2 in pine forests to 0.29 kg/m^2 in birch forests. The main contribution to the arrival of vegetation litter to the soil is made by assimilating organs, leaves and needles. The second place is held by small branches and fragments that it is difficult to morphologically identify and isolate (with diameter <2 mm) (the so-called "miscellaneous" fraction).

The flow of radionuclides to the soil is determined not only by its mass, but also by the specific activity of ^{137}Cs in various fractions. According to our data, it is maximal in the "miscellaneous" fraction (21.5 kBq/m^2) and in small branches (18.0 kBq/m^2), with assimilating organs being contaminated to a smaller extent (11.6 kBq/m^2). The decrease in the specific activity of ^{137}Cs in litter components as compared with the vegetating analogs is connected with its leaching during the falling process. These regularities of formation of the chemical composition of the litter are typical of potassium as well, which additionally points to the similarity between the behaviors of the elements under study.

The data obtained attest to the fact that the indices of the cycle of K and ^{137}Cs in pine and birch forests of Bryansk woodland currently almost coincide and, within the yearly cycle, are characterized by an insignificant excess of the amount of elements that are retained in phytomass over their return to the soil (Fig. 4). Thus, in pine forests the arrival of ^{137}Cs and K to soil with litter is equal to 47 and 45%, respectively. Therefore, the amount of radionuclides retained in the phytomass is equal to 53 and 55% of the BC capacity, respectively. In birch forests, 49% of cesium and 40% of potassium arrives to the soil within litter; i.e., 51% of ^{137}Cs and 60% of potassium (of the BC capacity) is retained in the phytomass. This is associated with the fact that the intensity of leaching of these elements from the phytomass of litter-forming structures is dif-

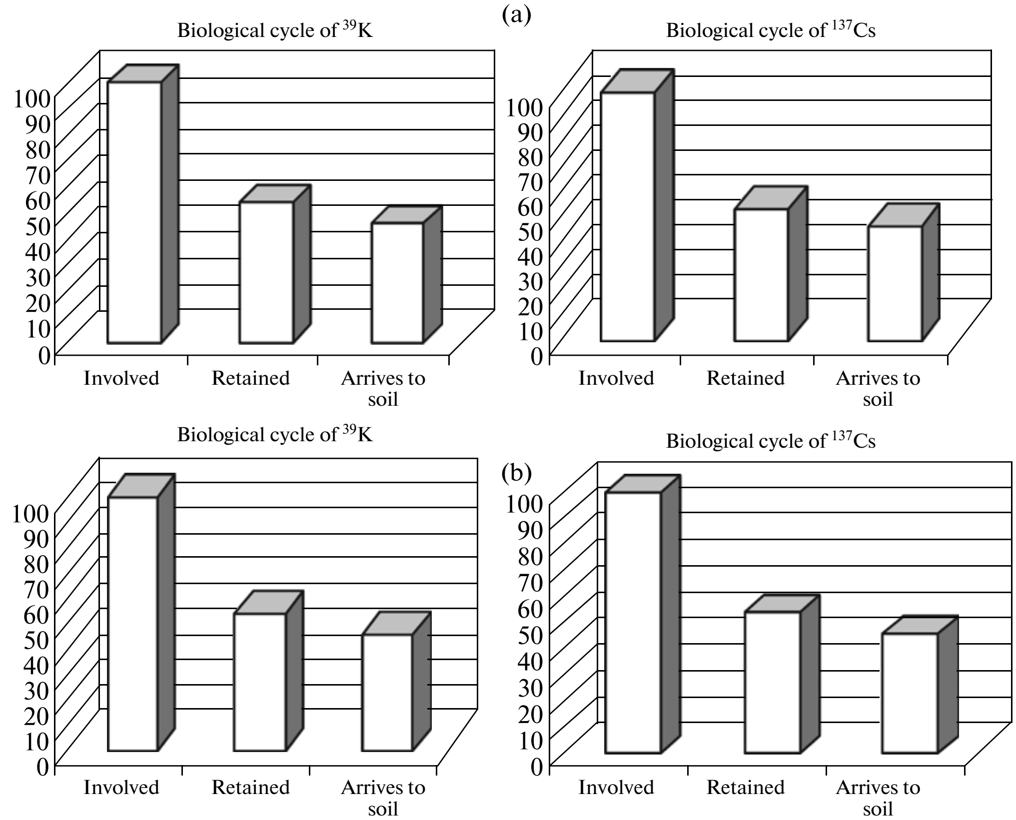

Fig. 4. The features of biological cycle of ^{137}Cs and ^{39}K in pine (a) and birch (b) forests.

ferent: it is higher in birch forests, being in the lead for potassium.

The analysis of indices of ^{137}Cs BC at the initial and remote periods after the fallouts allows stating that during the initial period, the arrival of the element to soil with the litter was higher than its consumption from the soil almost by a factor of 10 [18, 21]. The indices of ^{137}Ce BC in the forests of Bryansk woodland on sandy podzolic soils currently almost coincide with those for its chemical analog, potassium. This considerably differentiates the biological cycles of ^{137}Cs and ^{39}K in the forests of the nearest fallout zone. Out surveys demonstrated that, during the remote period after the Chernobyl fallouts (more than 20 years), the biological cycle of ^{137}Cs on dark gray forest soils of eluvial landscapes of the remote fallout zone (Tula oblast, Russia) differs from the biological cycles of potassium isotopes and is still characterized by a considerable domination of descending flows of the element [17, 20].

CONCLUSIONS

• The density of soil contamination in forest ecosystems of Bryansk woodland that underwent radioactive contamination as a result of the Chernobyl Nuclear Power Plant accident (1986) currently is equal to 9300 kBq/m^2 with respect to ^{137}Cs. The main activity is concentrated in the forest floor and in the 0- to 5-cm substratum.

• The specific surface of ^{137}Cs in structural components of pine and birch forests varies from 4 to 38 kBq/kg and decreases in the series N > IB > SB > EB > LB > W in pine forests and L > SB > IB > LB > EB > W in birch forests (Fig. 3). Potassium concentration in structural components of the forests under study varies from 0.01 to 1% and for the analyzed series varies similarly to that for ^{137}Cs. The average correlation coefficient between distribution of ^{39}K and ^{137}Cs over structural components is equal to 0.85 at $P = 0.95$.

• The adequacy of distribution of ^{137}Cs and its chemical analog, potassium, over structural components of the forests under study attests on the uniformity of their arrival (via roots) and the similarity of absorption by plants.

• The content of ^{39}K and ^{137}Cs in structural components of pine litter is lower than that in vegetating analogs by a factor of 1.5–2. In birch forests, these differences are stronger and attain twofold values for cesium and sevenfold for potassium. The intensity of their leaching from phytomass of litter-forming structures is different for the phytocenoses under study: it is higher in birch forests and is higher for potassium if comparing the elements.

• The maximum stock of ^{137}Cs within the total phytomass in phytocenoses under study is concentrated in wood; the minimal stock is concentrated in the external bark layers. The maximum stock of ^{137}Cs in the yearly production is concentrated in assimilating organs, whereas the minimum stock was observed in the external bark layers. The distribution of potassium stock over the total phytomass and the yearly production is almost identical to that of ^{137}Cs.

• The arrival of ^{137}Cs to soil with litter currently is equal to 47 (in pine forests) and 49% (in birch forests) of the BC capacity. This element mostly arrives with assimilating organs (needles and leaves). In pine forests the return of potassium to the soil with litter is close to that of cesium and is equal to 45%, this index being lower for birch forests (40%).

REFERENCES

1. Aleksakhin, R.M. and Naryshkin, M.A., *Migratsiya radionuklidov v lesnykh biogeotsenozakh* (Radionuclides Migration in Forest Biogeocenosis), Moscow: Nauka, 1977.
2. *Atlas zagryazneniya Evropy tseziem posle chernobyl'skoi avarii* (Atlas of Europe Contamination by Cesium Caused by Chernobyl Catastrophe), Belgorod, 1998.
3. Bazilevich, N.I., Titlyanova, A.A., Smirnov, V.V., et al., *Metody izucheniya biologicheskogo krugovorota v razlichnykh prirodnykh zonakh* (The Ways to Research the Biological Cycle in Different Nature Areas), Moscow: Mysl', 1978.
4. Vorob'eva, L.A., *Khimicheskii analiz pochv* (Chemical Analysis for Soils), Moscow: MGU, 1998.
5. Dvornik, A.M., Radio-Ecological Estimation of Forest Ecosystems after Nuclear Accidents: Methodology, Simulation, Prediction, *Extended Abstract of Doctoral Sci. (Biol.) Dissertation*, Gomel: Institut lesa NAN Belarusi, 1998.
6. Klechkovskii, V.M., *O povedenii radioaktivnykh produktov deleniya v pochvakh, ikh postuplenii v rasteniyakh i nakoplenii v urozhae* (On Radioactive Fission Products Behavior in Soils, there Receipt into Plants and Accumulation in the Crop), Moscow: ANSSR, 1956.
7. Kulikov, N.V. and Piskunov, L.I., On Plants Role in Vertical Migration of ^{90}Sr and ^{137}Cs in Soil, *Agrokhimiya*, 1970, no. 7.
8. Makhonina, T.N., Timofeev-Resovskii, N.V., Titlyanova, A.A., and Tyuryukanov, A.N., ^{90}Sr and ^{137}Cs Distribution over Biogeotsenosis Components, *Dokl. Akad. Nauk SSSR*, 1961, vol. 140, no. 5, pp. 1209–1212.
9. Orlov, A.A., Krasnov, V.P., and Kossinskii, V.P., Features of ^{137}Cs Biogeochemistry in Oligotrophic Bog Ecosystems, in *Radioaktivnost' posle yadernykh vzryvov i avarii* (Radioactivity after Nuclear Explosions and Accidents), St. Petersburg, 2005, pp. B30–B31.
10. Parfenov, V.I., Yakushev, B.I., Martinovich, B.S., et al., *Radioaktivnoe zagryaznenie rastitel'nosti Belarusi (v svyazi s avariei na Chernobyl'skoi AES)* (Radioactive Contamination of Belarus Flora (in Connection with Chernobyl Catastrophe)), Minsk: Nauka i Tekhnika, 1995.
11. Perevolotskii, A.N., *Raspredelenie 137Cs i ^{90}Sr v lesnykh biogeotsenozakh* (^{137}Cs and ^{90}Sr Distribution in Forest Biogeotsenosis), Gomel, 2006.
12. Rodin, L.E. and Bazilevich, N.I., *Dinamika organicheskogo veshchestva i biologicheskii krugovorot zol'nykh elementov i azota v osnovnykh tipakh rastitel'nosti zemnogo shara* (Organic Matter Dynamics and Biological Cycle in the Main Types of World Vegetation), Moscow: Nauka, 1965.
13. Timofeev-Resovskii, N.V., On Biosphere Radioactive Contamination and Contamination–Proof Measures, in *Trudy instituta biologii Ural'skogo filiala AN SSSR* (Scientific Works of Institute of Biology of the Ural Branch of the Russian Academy of Sciences), 1962, issue 22.
14. Tikhomirov, F.A., Aleksakhin, R.M., and Fedorov, E.A., Radionuclide Migration in Forests and Ionized Radiation Impact onto Forests, *Peaceful Uses Atomic Energy*, Vienna: IAEA, 1972, vol. 11, pp. 675–684.
15. Tyuryukanova, E.B., Belyaeva, L.I., Levkina, N.I., and Emel'yanov, V.V., *Landshaftno-geokhimicheskie aspekty povedeniya Sr–90 v lesnykh i poimennykh biogeotsenozakh poles'ya* (Landscape–Geochemical Aspects of ^{90}Sr Behavior in Forest and Flood Biogeocenosis of Woodlands), Moscow: GK po ispol'zovaniyu atomnoi energii USSR, 1973.
16. Khomutinin, Yu.V., Kashparov, V.A., and Zhebrovskaya, E.I., *Optimizatsiya otbora i izmereniya prob pri radioekologicheskom monitoringe* (Samples Optimization and Selection under Radioecological Monitoring), Kiev, 2001.
17. Tsvetnova, O.B. and Shcheglov, A.I., Biological Cycle Features of ^{137}Cs and Potassium Isotopes in Forest and Forest–Steppe Agrophytocenosis for the Distant Period after Chernobyl Falls, in *Problemy radioekologii i pogranichnykh distsiplin* (Problems of Radioecology and Boundary Disciplines), Yekaterinburg, 2009, issue 12, pp. 299–331.
18. Shcheglov, A.I., *Biogeokhimiya tekhnogennykh radionuklidov v lesnykh ekosistemakh* (Biogeochemistry of Induced Radionuclides in Forest Ecosystems), Moscow: Nauka, 1999.
19. Shcheglov, A.I. and Tsvetnova, O.B., Features of Biological Cycle Dynamics of Induced Radionuclides and Macroelements in Forest Ecosystems, in *Materialy V Vserossiiskogo obshchestva pochvovedov* (Proc. V All–Russian Soils Scientists Society), Rostov-on-Don, 2008, p. 66.
20. Shcheglov, A.I., Tsvetnova, O.B., and Kuchma, N.D., Long–Term Dynamics of ^{137}Cs and ^{90}Sr Transition Coefficients into Structural Components of Forest Stand, *Problemy ekologii lesov i lesopol'zovaniya v Poles'e Ukrainy* (Ecology Problems of Forests and Forest Exploitation in the Ukrainian Polesye), Zhitomir, Volhynia, 2004, issue 4 (10), pp. 62–76.
21. Schcheglov, A.I., Tsvetnova, O.B., and Klyashtorin, A.L., *Biogeochemical Migration of Technogenic Radionuclides in Forest Ecosystems*, Moscow: Nauka, 2001.