ISSN 1028-334X, Doklady Earth Sciences, 2024, Vol. 519, Part 2, pp. 2356–2361. © Pleiades Publishing, Ltd., 2024.
ISSN 1028-334X, Doklady Earth Sciences, 2024. © Pleiades Publishing, Ltd., 2024.

GEOECOLOGY

Radionuclides (^{40}K, ^{232}Th, ^{226}Ra, ^{137}Cs, and ^{90}Sr) in Agroecosystems of the Central Chernozem Region

S. V. Lukin[a,b,*] **(ORCID: 0000-0003-0986-9995)**

Presented by Academician V.I. Kiryushin June 18, 2024

Received June 18, 2024; revised July 17, 2024; accepted July 24, 2024

Abstract—Studies were conducted in 2023–2024 at reference sites of Belgorod oblast. The study procedure is conventional in the agrochemical service. The purpose of this work is to study the specific activity of natural and artificial radionuclides in the soils and the plants of certain agroecosystems. These studies have shown that the average specific activity of ^{40}K does not vary significantly in the leached (539 Bq/kg), typical (544 Bq/kg), and ordinary (573 Bq/kg) arable chernozems, while in the residual carbonate chernozems, this parameter (207 Bq/kg) is 2.60–2.77 times lower. The average specific activity of ^{232}Th in the leached (39.2 Bq/kg), typical (42.9 Bq/kg), and ordinary (46.7 Bq/kg) chernozems is 1.97–2.35 times higher than in the residual carbonate (19.9 Bq/kg) chernozems. The average specific activity of ^{226}Ra in the soils studied do not differ significantly, staying within 17.3–18.9 Bq/kg. In the soils of the western and eastern areas of the region, the specific activity of ^{137}Cs ranges within 5.9–19.6 and 16.3–87.2 Bq/kg, respectively. The specific activity of ^{90}Sr in the soils of the western regions is below 3, whereas for the eastern, it is below 5 Bq/kg. In the plant products studied, the average specific activity of ^{40}K varies within 111–597 Bq/kg, while those of ^{232}Th and ^{226}Ra do not exceed 6 and 8 Bq/kg, respectively. The specific activity of ^{137}Cs is less than 3, and that of ^{90}Sr is 2 Bq/kg, which is significantly lower than the established maximum levels for this parameter.

Keywords*:* natural radionuclides, artificial radionuclides, specific activity, chernozem, winter wheat, sainfoin

DOI: 10.1134/S1028334X24603134

INTRODUCTION

The most important natural factor that plays a significant role in human life is the natural radiation background. Its magnitude largely depends on the content of long-lived natural radionuclides (NRNs) in the soils. The main representatives of NRNs, the specific activity of which is determined during ecological monitoring of soils, include ^{40}K, ^{232}Th, and ^{226}Ra (an intermediate decay product of ^{238}U), with half-lives of 1.27×10^9, 1.39×10^9, and 1.6×10^3 yr, respectively [1, 2].

After the accident at the Chernobyl Nuclear Plant in 1986, most of Central Russia was subjected to radioactive contamination by artificial radionuclides (ARNs). The main contaminants were ^{137}Cs and ^{90}Sr with half-lives of 30.2 and 28.8 yr, respectively [3–5]. ARNs were primarily deposited in soils, including soils of agricultural designation. Russian legislation has not established the maximum permissible levels of specific activity for ^{137}Cs and ^{90}Sr in soils; however, a system of territorial zoning has been approved depending on the density of contamination with ^{137}Cs (a critical radionuclide): 1–5 Ku/km^2 (37–185 kBq/m^2), the zone of residence with preferential social and economic status; 5–15 Ku/km^2 (185–555 kBq/m^2), the optional evacuation zone; and >15 Ku/km^2 (555 kBq/m^2), the evacuation zone [6].

In food products and animal foodstuff, only the content of ARNs ^{137}Cs and ^{90}Sr is regulated. For example, the maximum permissible levels of specific activity of ^{137}Cs and ^{90}Sr in grain intended for food purposes are 60 and 11 Bq/kg, while for feed grain they are 180 and 100 Bq/kg, respectively [7].

Despite the fact that 38 years have passed since the Chernobyl accident, and most of the ARNs have already decayed, to determine their specific activity in soils and plants is an important part of agroecological monitoring conducted by the agrochemical service of Russia.

The aim of this work is to study the specific activity of natural and artificial radionuclides in the soils and

[a]*Belgorod Center for Agrochemical Service, Belgorod, 308015 Russia*
[b]*Belgorod State National Research University, Belgorod, 308015 Russia*
**e-mail: serg.lukin2010@yandex.ru*

Fig. 1. Cartogram of the study zone with sampling sites.

plants of the Central Chernozem Region by the example of Belgorod oblast.

STUDY PROCEDURE

The studies were conducted in the southwestern part of the Central Chernozem Economic Region on the territory of Belgorod oblast. In the forest–steppe part of the region, typical and leached chernozems prevail, while ordinary and residual-carbonate chernozems occur in the steppe area. Leached, typical, and ordinary chernozems formed on loess-like loams and clays, and residual-carbonate chernozems developed on the chalk eluvium [8].

As part of the baseline monitoring, typical virgin chernozem samples were collected in the Yamskaya Steppe area at Belogorye State Nature Reserve located in the municipal formation (MF) of Gubkinskii Urban Okrug, while ordinary chernozem was sampled from the protected area of the Gniloe district near the village of Viktoropol in Veidelevskii District MF (Fig. 1). In the 10- to 20-cm layer of typical virgin chernozem, the contents of physical clay (particles smaller than 0.01 mm), organic matter, and pH of the water extract (pH_{H_2O}) were 57.3%, 10.1%, and 7.0, respectively, while for ordinary chernozem, they were 66.3%, 9.5%, and 7.0, respectively.

Samples of leached and typical chernozems, used in agricultural production, were collected from the reference sites on the territory of Rakityanskii district MF, while ordinary chernozems were sampled in Veidelevskii district MF, and residual-carbonate chernozems, in Rovenskii district MF. For each subtype of chernozem, 20 samples were taken from the soil layer of 0–25 cm. Soil and plant samples were collected according to the procedure established in the agrochemical service [9]. In arable leached chernozems, the average contents of physical clay, organic matter, and pH_{H_2O} were 53.9%, 5.4%, and 6.3; for typical chernozems, these values were 55.1%, 5.5%, and 6.6; for ordinary chernozems, they were 72.5%, 5.6%, and 7.8; and for residual-carbonate chernozems, they were 62.1%, 4.0%, and 8.3, respectively.

All analyses were carried out at the accredited testing laboratory of Belgorod Center for Agrochemical Service. The specific activities of ^{226}Ra, ^{232}Th, ^{40}K, and ^{137}Cs in all objects, as well as of ^{90}Sr in plant production samples were determined according to the procedure FP.1.38.2011.10033 “Procedure for Measuring the Specific Activity of Natural Radionuclides, Cesium-137 and Strontium-90 in Samples of Environmental Objects and Products of Enterprises Using an MKGB-01 RADEK Gamma Beta Radiation Spectrometer-Radiometer and an MKSP-01 RADEK Gamma Spectrometer. The specific activity of ^{90}Sr in the soil was determined according to GOST R 54041-2010 Soils: Method for Determining ^{90}Sr.

RESULTS AND DISCUSSION

Radionuclides in soils. The concentration and distribution of NRNs in soils depend on many factors, including the granulometric and mineralogical composition, acidity of the soil solution, content, and quality of organic matter, and the moisture pattern, among others [10]. As a rule, the specific activity of ^{40}K, ^{232}Th, and ^{226}Ra increases at an increase in the content of physical clay; therefore, this parameter is lower in sandy and sandy-loam soils compared to clayey and loam soils [3].

In the typical virgin chernozem, natural radionuclides form a decreasing order of specific activity (Bq/kg): ^{40}K(523) > ^{232}Th(38.2) > ^{226}Ra(18.2), and in ordinary virgin chernozem, the order is ^{40}K(537) > ^{232}Th(37.9) > ^{226}Ra(20.0).

The average specific activity of ^{40}K did not reveal any significant differences for leached (539 Bq/kg), typical (544 Bq/kg), and ordinary (573 Bq/kg) arable chernozems; however, this parameter had a trend to increase in ordinary chernozems, since the latter had a higher content of physical clay. The average specific activity of ^{40}K in these subtypes of chernozems was 2.60–2.77 times higher than in residual-carbonate chernozems (207 Bq/kg). This is related to the lower total potassium content in the soils formed on the chalk eluvium compared to chernozems, where loess-like loams and clays are the soil-forming rocks (Fig. 2). The ratio of ^{40}K/^{39}K in the environment is constant across the planet [1].

The average specific activity of ^{232}Th in leached (39.2 Bq/kg) and typical (42.9 Bq/kg) chernozems did not differ significantly, while in ordinary chernozems (46.7 Bq/kg), it was higher than in leached chernozems. The average specific activity of ^{32}Th was 1.97–2.35 times higher in these subtypes of chernozems than in residual-carbonate chernozems (19.9 Bq/kg). The established differences are caused by the properties of the soil-forming rocks.

The studied subtypes of chernozems did not show significant differences in the average specific activity of ^{226}Ra. This parameter was within 17.3–18.9 Bq/kg, varying in the range from 11.3 to 28.6 Bq/kg.

In the studies performed on gray forest soils in Vladimir oblast with a physical clay content of 34%, the average value of this parameter was within 490–582 Bq/kg, which is quite consistent with the specific activity of this radionuclide in leached, typical, and ordinary arable chernozems of Belgorod oblast [5]. At the same time, the average specific activity of ^{40}K in arable chernozems of southern Volgograd oblast was 625 Bq/kg, varying within 523–798 Bq/kg, which is somewhat higher than the value we determined in our studies [2]. In the same soils, the specific activity of ^{232}Th was 40.2 Bq/kg, varying from 29.0 to 52.6 Bq/kg, and that of ^{226}Ra was 21.1 Bq/kg, varying within 13.1–39.8 Bq/kg, which is quite consistent with the values of these parameters in leached, typical, and ordinary chernozems of Belgorod oblast.

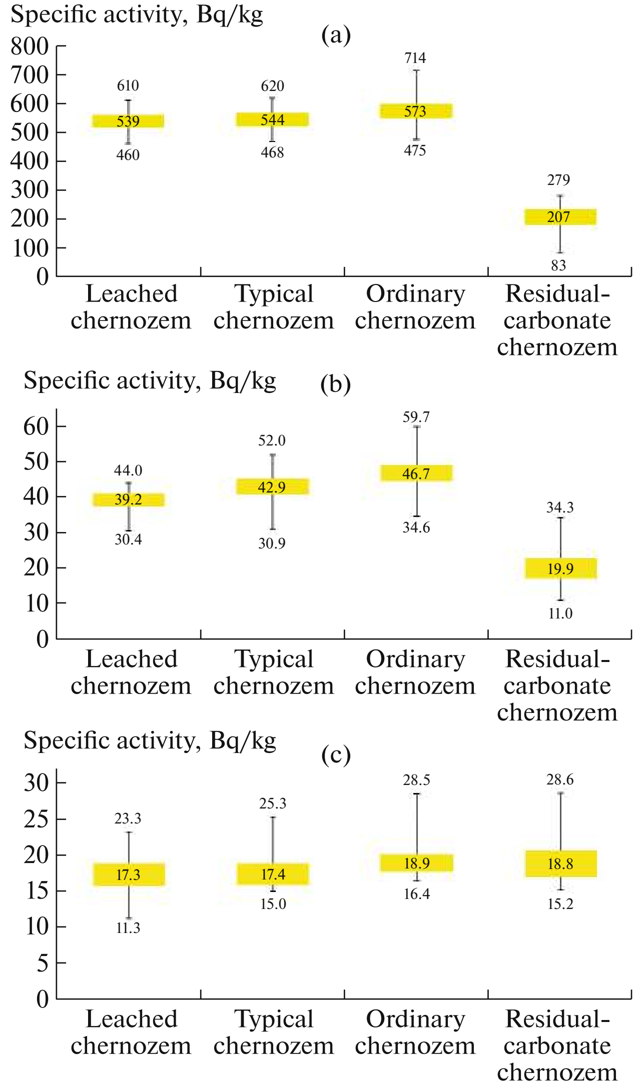

Fig. 2. Specific activity of natural radionuclides (a) ^{40}K, (b) ^{232}Th, and (c) ^{226}Ra in the top soil, Bq/kg.

According to the estimates [1], the average specific activity of ^{40}K, ^{232}Th, and ^{226}Ra in the chernozems of Russia is 500, 31.7, and 23.1, respectively; the standard interval is 390–610, 22–42, and 12–34 Bq/kg. For soils in the planet, the average specific activity of ^{40}K, ^{232}Th, and ^{226}Ra is 370, 26, and 26, with a typical

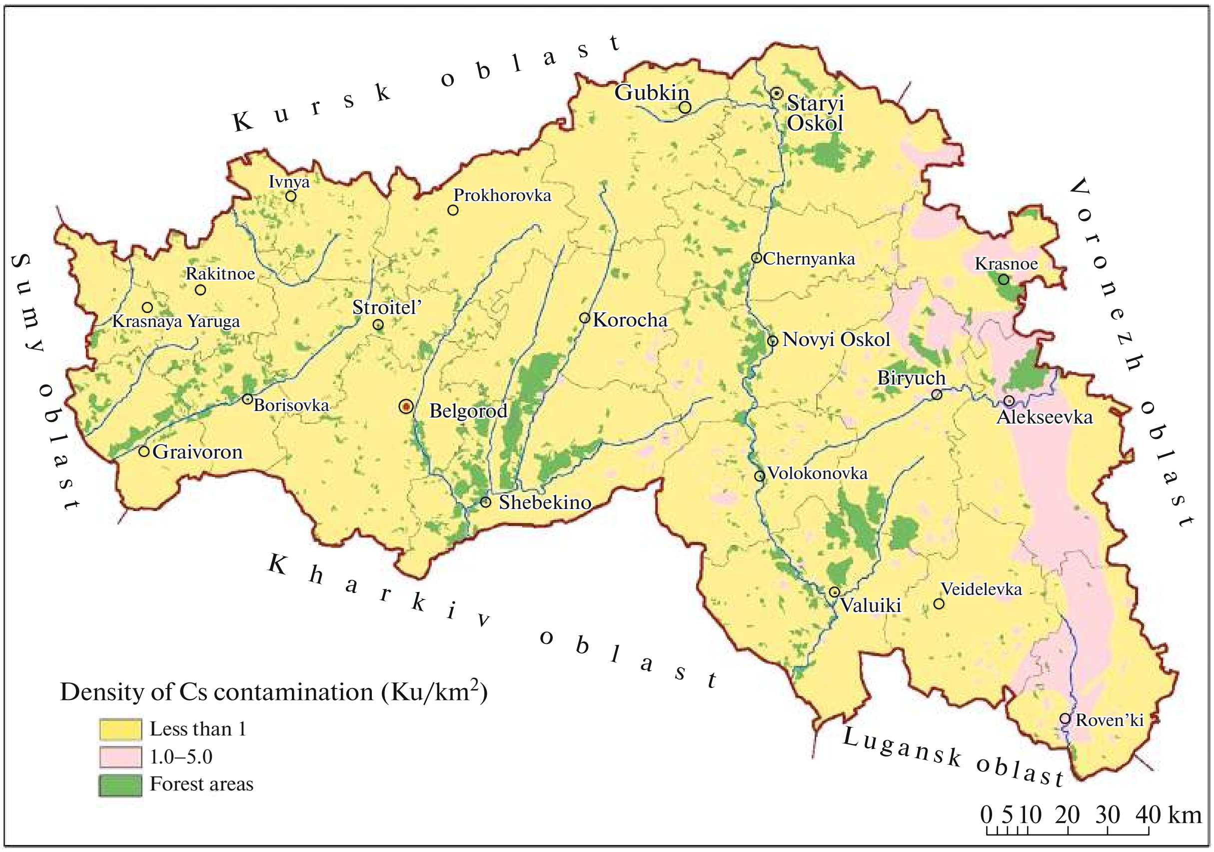

Fig. 3. Cartogram of ^{137}Cs contamination of agricultural lands in Belgorod oblast (as of January 1, 2004).

interval of 110–740, 7–48, and 11–52 Bq/kg, respectively [11].

The peculiarity of radioactive contamination of the soil with ^{137}Cs as a result of the Chernobyl accident is patchiness and high inhomogeneity [3, 5]. In Belgorod oblast, approximately 140000 ha of agricultural land were found to be contaminated with ^{137}Cs in the range of 37–185 kBq/m^2. These lands are located primarily in the eastern districts of the region and are characterized by higher variability of specific activity of ARNs than the soils in the western districts (Fig. 3).

According to the archival data from Belgorod Center for Agrochemical Service, prior to the Chernobyl accident in 1985, the gamma dose rates ranged within 7–12 μR/h at the reference sites. After the accident in 1986, in the western part of the region, this parameter was 9–52 μR/h at the reference sites, while in the eastern part, e.g., in the Alekseevskii urban okrug, it reached 130–200 μR/h. Therefore, the contaminated fields were plowed to a depth of 30 cm, and some fields were plowed deeply with subsoil plows (>40 cm) to bury ARNs and shield the emitted radiation. By 1987, the gamma dose rate was already equal to 11–24 μR/h. The specific activity of ^{137}Cs in the soils of the western districts was 15–96 Bq/kg, while ^{90}Sr was 9–24 Bq/kg. In the soils of the eastern district, the specific activity of ^{137}Cs was 99–279 Bq/kg and that of ^{90}Sr equaled 13–32 Bq/kg.

According to the results of the radiological survey conducted in 2023–2024, the gamma dose rate at the reference sites ranged within 8–14 μR/h. In the western part of the region (Rakityanskii district MF), the average specific activity of ^{137}Cs in typical and leached chernozems was 11 Bq/kg, varying within 5.9–19.6 Bq/kg, while the specific activity of ^{90}Sr was less than 3 Bq/kg. In the eastern part of the region, the average specific activity of ^{137}Cs in ordinary chernozems (Veidelevskii district MF) was 35.3 Bq/kg, varying from 22.2 to 43.8 Bq/kg, and in residual-carbonate chernozems (Rovenskii district MF), it was 39.4 Bq/kg, varying from 16.3 to 87.2 Bq/kg. In the eastern part of the region, the specific activity of ^{90}Sr in the soils of the reference sites was less than 5 Bq/kg.

Radionuclides in plants. The specific activity of radionuclides in plants varies over a wide range and is determined by the chemical properties of the radionuclides themselves, the biological characteristics of various species and varieties of plants, the conditions of growth, and the ecological and agrochemical characteristics of soils, particularly the contents of their radionuclides and antagonistic elements.

Table 1. Specific activity of ^{40}K in the plant products, Bq/kg of absolutely dry matter

Soil	Crop	Variation-statistical characteristics			
		$\bar{x} \pm t_{05}s\bar{x}$	lim	V, %	n
Ordinary chernozem (plowland)	Wheat, grain	111 ± 5	90–130	10.2	21
	Winter, straw	182 ± 16	136–231	19.7	21
	Sainfoin (hay)	597 ± 55	316–811	20.4	20
Ordinary chernozem (virgin soil)	Miscellaneous herbs (hay)	375 ± 28	286–470	16.1	20
Residual-carbonate chernozem (plowland)	Sainfoin (hay)	402 ± 52	222–598	27.6	20

The average specific activity of ^{40}K was 375 varying within 286–470 Bq/kg in ordinary chernozems in virgin miscellaneous herbs represented by feather grass, sheep fescue, cocksfoot, smooth brome, couch grass, and some other species of steppe vegetation. The specific activity of this radionuclide in the soil was 1.43 times higher than in the plants (Table 1).

In arable ordinary chernozems, the average specific activity of ^{40}K in sainfoin hay was 597 Bq/kg, varying within 316–811 Bq/kg. This value was almost equal to the specific activity of ^{40}K in the soil (573 Bq/kg). The average specific activity of this NRN in winter wheat grain was 111 Bq/kg, varying within 90–130 Bq/kg. The specific activity of ^{40}K in the straw was 1.6 times higher than in the grain of this crop. The specific activity in the soil was 5.2 and 3.1 times higher than in the grain and straw of winter wheat, respectively. According to the published data, the average specific activity of ^{40}K in wheat grain is 128 Bq/kg [12].

The average specific activity of ^{40}K in sainfoin grown on residual-carbonate chernozems was 402 Bq/kg, which was almost 1.5 times lower than in ordinary chernozems. The specific activity of this NRN in this crop was 1.9 times higher than in the soil.

In the plants of Northwestern Altai, the specific activity of ^{40}K varies from 6 to 3985 Bq/kg with an average value of 740 Bq/kg. The specific activity of this NRN in the plants is higher than in the soils (487 Bq/kg), which is related to the biogenic properties of the element [12]. In the plants of the dry steppe zone of Rostov oblast, this parameter varies within 28–516 Bq/kg, with an average value of 149 Bq/kg. The specific activity of ^{40}K in the plants is almost three times lower than in the soils [13]. In the southern part of Tyumen oblast, the specific activity of ^{40}K in perennial grass hay varies from 23.9 to 3977 Bq/kg [14].

In 2023–2024, the levels of specific activity of ^{232}Th and ^{226}Ra in the plant products did not exceed 6 and 8 Bq/kg, respectively. According to the published data, the levels of specific activity of ^{232}Th and ^{226}Ra vary in a wide range. For example, in the southern part of Tyumen oblast, the specific activity of ^{232}Th in perennial grass hay varied from 18.7 to 296 Bq/kg, and ^{226}Ra, from 7.3 to 340 Bq/kg [14]. In the plants of the dry steppe zone of Rostov oblast, the specific activity of ^{232}Th and ^{226}Ra varies within 10.9–98.3 and 10.3–82 Bq/kg, respectively [13]. In the plants of Northwestern Altai, the specific activity of ^{232}Th varies from 1 to 50 and equals 8.13 Bq/kg, on average [12]. A summary of the data from different regions of the world shows that, in the plants grown in soils with normal background, the specific activity of ^{232}Th varies from 0.5×10^{-5} to 2.8 Bq/kg, while in the soils with high concentrations of the element (thorium provinces), it is 0.058–80 Bq/kg [15, 16].

In 1986, in the less contaminated western regions of the area, the specific activity of ^{137}Cs and ^{90}Sr ranged within 9.3–91.8 and 0.3–4.5 Bq/kg in the grain of winter crops, while in the worst affected eastern regions, it was 10.1–190 and 2.0–5.5 Bq/kg, respectively. Such a high level of product contamination was likely related to the radioactive fallout getting directly on the growing plants. However, as early as 1987, in the western regions of the area, the specific activity of ^{137}Cs and ^{90}Sr in the grain of winter and spring crops was 1.3–3.4 and 0.8–1.4 Bq/kg, while in the eastern regions it equaled 1.4–5.9 and 1.1–4.6 Bq/kg, respectively, which is not above the permissible levels established for food products. In subsequent years, the radiation monitoring of the plant products did not reveal exceedance of the maximum allowable levels of specific activity of ^{137}Cs and ^{90}Sr. In 2023–2024 the level of specific activity of ^{137}Cs and ^{90}Sr in the plant products did not exceed 3 and 2 Bq/kg, respectively.

CONCLUSIONS

Thus, the studies established that the average specific activity of ^{40}K in the leached (539 Bq/kg), typical (544 Bq/kg), and ordinary (573 Bq/kg) arable chernozems did not show significant differences, while in the residual-carbonate chernozems, this parameter (207 Bq/kg) was 2.60–2.77 times lower. The average specific activity of ^{232}Th in the leached (39.2 Bq/kg), typical (42.9 Bq/kg), and ordinary (46.7 Bq/kg) chernozems was higher than in the residual-carbonate soils (19.9 Bq/kg) by a factor of 1.97–2.35. The studied soils did not differ significantly in the average specific activity of ^{226}Ra, which ranged within 17.3–18.9 Bq/kg. In the western regions of the area, the specific activity of ^{137}Cs in the soils varied within 5.9–19.6 Bq/kg, while in the eastern regions, it was 16.3–87.2 Bq/kg. The specific activity of ^{90}Sr in the soils of the western regions was below 3, and in the eastern regions, below 5 Bq/kg. In the plant products studied, the average specific activity of ^{40}K varied within 111–597 Bq/kg, while that of ^{232}Th and ^{226}Ra did not exceed 6 and 8 Bq/kg, respectively. The specific activity of ^{137}Cs was less than 3 Bq/kg, and that of ^{90}Sr was 2 Bq/kg, which is significantly lower than the established maximum levels for this parameter.

FUNDING

This work was supported by ongoing institutional funding. No additional grants to carry out or direct this particular research were obtained.

CONFLICT OF INTEREST

The author of this work declares that he has no conflicts of interest.

REFERENCES

1. P. M. Orlov, V. G. Sychev, and N. I. Akanova, Mezhd. S-kh. Zh., No. 4, 62–67 (2020). https://doi.org/10.24411/2587-6740-2020-14074
2. B. F. Aparin, E. V. Mingareeva, E. Y. Sukhacheva, and N. I. Sanzharova, Eurasian Soil Sci. **50** (12), 1395–1405 (2017). https://doi.org/10.1134/S106422931712002X
3. P. M. Orlov, O. V. Gladysheva, M. I. Lunev, and N. I. Akanova, Mezhd. S-kh. Zh., No. 1, 37–42 (2018).
4. V. S. Voskresenskii, Vestn. Ross. Univ. Druzhby Narodov, Ser. Ekol. Bezop. Zhiznedeyatel'nosti, No. 1, 69–73 (2009).
5. A. A. Utkin, Radiats. Biol. Radioekol. **63** (2), 199–210 (2023). https://doi.org/10.31857/S0869803123020121
6. The Russian Federation Law No. 1244-1 "On Social Protection for People Who Were Radiated during the Chernobyl Accident," May 15, 1991. https://www.consultant.ru/document/cons_doc_LAW_5323/. Cited April 8, 2024.
7. *Tekhnicheskii reglament Tamozhennogo soyuza* (Technical Regulations of the Customs Union), No. TRTS015/2011: On Grain Safety" (with Changes up to Sept. 15, 2017). Technical Regulations of the Customs Union No. 015/2011, December 9, 2011. docs.cntd.ru›document/902320395. Cited April 10, 2024.
8. V. D. Solovichenko, *Belgorod Soils: Fertility and Rational Utilization* (Otchii Dom, Belgorod, 2005) [in Russian].
9. V. G. Sychev, A. N. Aristarkhov, I. V. Volodarskaya, et al., *Methodological Recommendations for Complex Monitoring Soil Fertility of the Arable Lands* (Russian Agriculture Ministry, Moscow, 2003) [in Russian].
10. N. G. Rachkova, I. I. Shuktomova, and A. I. Taskaev, Eurasian Soil Sci. **43** (6), 651–658 (2010). https://doi.org/10.1134/S1064229310060050
11. The United Nations Scientific Committee on the Effects of Atomic Radiation, *Report for 1977 to the General Assembly with Annexes. The Sources and Effects of Ionizing Radiation* (New York, 1978), Vol. 1, pp. 233–260.
12. I. A. Egorova, Yu. V. Kislitsina, and A. V. Puzanov, Vestn. Altaisk. Gos. Agrarn. Univ., No. 11 (61), 32–38 (2009).
13. E. A. Buraeva and O. S. Bezuglova, Arid. Ekosyst. **13** (1), 65–73 (2023). https://doi.org/10.1134/S2079096123010031
14. V. Z. Burlaenko and S. P. Igasheva, Samar. Nauchn. Vestn. **9** (3), 32–36 (2020).
15. S. V. Fesenko and E. S. Emlyutina, Radiats. Biol. Radioekol. **62** (4), 434–445 (2022). https://doi.org/10.31857/S086980312204004X
16. R. Kritsananuwat, S. K. Sahoo, H. Arae, and M. Fukushi, Radioanal. Nucl. Chem. **303**, 2571–2577 (2015).

Translated by L. Mukhortova