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^{137}Cs REMOVAL FROM CONTAMINATED SOIL BY PERENNIAL BLUEGRASS HERBS DEPENDING ON MINERAL NUTRITION AND SOIL WATER AVAILABILITY

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Abstract

The expansion of zones of anthropogenically affected agricultural lands and soil pollution pose a serious environmental threat. Radionuclides with long half-lives of fallout from the anthropogenic nuclear disasters are among the most dangerous pollutants. At present, the world scientific literature has accumulated extensive data on the effect of ameliorants, organic and mineral fertilizers on the yield and biological removal of ^{137}Cs from the soil by crops. This paper is our first report on the influence of natural and anthropogenic factors on ^{137}Cs migration from the contaminated soil to bluegrass forage plants many years following the Chernobyl accident (South-West of the Bryansk region, 2009-2011). Our subjective was to study ^{137}Cs removal from the soil depending on plant species and doses of full fertilizers. The soil of the site was alluvial meadow sandy, with pH_{KCl} = 5.2-5.6, 3.08-3.33 % humus, 620-840 mg/kg mobile phosphorus, 133-180 mg/kg exchangeable potassium, and ^{137}Cs contamination of 493-872 kBq/m^2. Effects of $N_{90}P_{60}K_{90}$, $N_{90}P_{60}K_{120}$, $N_{90}P_{60}K_{150}$, $N_{120}P_{60}K_{120}$, $N_{120}P_{60}K_{150}$, and $N_{120}P_{60}K_{180}$ used as ammonium nitrate, granulated superphosphate, and potassium chloride on monospecies crops of perennial bluegrasses *Dactylis glomerata* L., *Festuca pratensis* Huds., and *Phalaroides arundinacea* L. were compared. Fertilizers were used annually, with N and K applied in equal amounts at the first and second mowing and P full dose applied at the first mowing and P full dose applied at the first mowing. The period of vegetation in 2010 was characterized by increased radiation balance. In 2011, bioclimatic conditions were optimal for plant growth and development. The period between the first and the second mowing differed from that before the first mowing in the increased radiation balance and evaporability. The deficiency of soil moisture during the time from beginning of plant growth to the first mowing did not affect water supply of plants because of close groundwater after periodic flooding of the plain. We determined transpiration, transpiration coefficient, a relative transpiration, the rate of decrease in 137Cs specific activity of the biomass, intensity of ^{137}Cs removal from the soil to justify an inverse relationship of ^{137}Cs specific activity in the biomass from a dose of full mineral fertilizer. It has been shown that the intensity of ^{137}Cs bio-removal depends on a dose of full mineral fertilizer. The intensity of ^{137}Cs removal is the smallest in *Dactylis glomerata* and the greatest in *Phalaroides arundinacea*. The main mechanism of biological removing ^{137}Cs from the soil is relative transpiration which determines the availability of soil moisture for plant roots and Pe value reflecting the ratio of diffusion and convection in the moisture flow. The relationship between Pe and relative transpiration in the three studied bluegrass species is high (r = 0.8-0.9). We propose the equation of ^{137}Cs bio-removal by perennial bluegrass with the use of mineral fertilizers, which expresses essential pattern of ^{137}Cs activity in the biomass as influenced by the fertilizers and is fair for the studied species of bluegrass herbs.

Keywords: alluvial meadow sandy soil, ^{137}Cs, removal rate, perennial bluegrass herbs, tran-

spiration, relative transpiration, NPK fertilizers

Natural forage lands, which are one of the main sources of coarse and succulent feed for livestock breeding, also play a multifunctional role in the formation of a sustainable agricultural landscape. Therefore, the study of mechanisms to increase their productivity and recovery after anthropogenic damage is of great interest [1-5]. In the conditions of radioactive contamination, along with increasing the productivity of hayfields and pastures, it becomes important to obtain the feed that meets the standard for the permissible content of radionuclides [6-9].

A large amount of data has been accumulated on the effect of ameliorants, organic and mineral fertilizers on the yield and biological removal of ^{137}Cs from the soil by agricultural crops [10-13]. It has been experimentally proved that potassium fertilizers reduce the specific activity of ^{137}Cs of plant products [14-18]. The introduction of potassium fertilizers has become the main agrochemical method in the conditions of radioactive soil contamination. When studying different doses of N, P, and K as part of a complete mineral fertilizer, it was found that the transition of ^{137}Cs from the soil to plant production depends not only on the dose of potassium, but also on the ratio of the doses of potassium and nitrogen, as well as the amount of nitrogen in the composition of the complete mineral fertilizer [19-21].

For the first time in the distant period after the Chernobyl accident, we investigated the role of natural and anthropogenic factors in the process of ^{137}Cs migration in the soil-plant system (by the example of the use of different types of *Poaceae* as feed) and proposed a mechanism that regulates the biological removal of ^{137}Cs from the soil through relative transpiration, which determines the availability of soil moisture for plants.

The aim of the work was to study the effect of different doses of full mineral fertilizer on the availability of soil moisture for the root system and the intensity of the process of biological removal of ^{137}Cs from the soil by monospecies crops of perennial bluegrass.

Techniques. The studies were conducted in the southwestern part of the Bryansk Region on the meadow section of the central floodplain of the Iput River. The soil of the experimental plot is alluvial meadow shallow medium-humic, sandy on sandy loam alluvium with the following division of the profile into genetic horizons: A_d (0-4 cm), A_1 (4-18 cm); B_1 (18-40 cm); B_g (40-60 cm), Cg (60-90 cm). The agrochemical characteristics of the soil are as follows: pH_{KCl} 5.2-5.6, hydrolytic acidity 2.6-2.8 mEq/100 g of soil, the amount of absorbed bases 11.3-13.1 mEq/100 g of soil, cation exchange capacity 12.9-15.9 mEq/100 g of soil, base saturation of 81-82%; humus content 3.08-3.33% (according to Tyurin), mobile phosphorus 620-840 mg/kg, exchange potassium 133-180 mg/kg (according to Kirsanov). The contamination density of the ^{137}Cs experimental site during the period of the work was 493-872 kBq/m^2.

The intensity of ^{137}Cs bio-removal from the soil at different doses of full mineral fertilizer was studied on monospecies crops of perennial bluegrass plants. Against the background of two-tier plowing, cocksfoot grass (*Dactylis glomerata* L., cultivar VIC 61), meadow fescue grass (*Festuca pratensis* Huds., cultivar Dedinovska) and reed canary grass (*Phalaroides arundinacea* L., cultivar Pripyatsky) were sown; the seeding rates of all seeds were 15 kg/ha. The scheme of the experiment: I — the control without fertilizers, II — $N_{90}P_{60}K_{90}$, III — $N_{90}P_{60}K_{120}$, IV — $N_{90}P_{60}K_{150}$, V — $N_{120}P_{60}K_{120}$, VI — $N_{120}P_{60}K_{150}$, VII — $N_{120}P_{60}K_{180}$. Ammonium nitrate, simple granulated superphosphate, and potassium chloride were used. Fertilizers were introduced annually: nitrogen and potassium ones in two doses (half of the calculated dose for the first mowing, the second half – for the second mowing), phosphate – one full dose for the first mowing. The sown area was 63 m^2, the harvesting area was 24 m^2, and the experiment was conducted with threefold repetition.

The yield of grass was calculated by the method of total sampling for weighting and the selection of the sample bundle. Two cuts were carried out per year (the first mowing – from June 1 to 10, the second mowing – from August 23 to September 1).

The transpiration value was determined by the formula of Penman [22], evaporation – by Budyko [23]. The transpiration coefficient was calculated as $C_t = \Sigma_g E_t / Y$ (1), where $\Sigma_g E_t$ is the total transpiration during the growing season, mm; Y is yield of air-dry phytomass of grass, t/ha. Relative transpiration was calculated using the formula: $\alpha = \Sigma_g E_t / \Sigma_g E_0$ (2), where $\Sigma_g E_t$ and $\Sigma_g E_0$ are the total transpiration and evaporation, respectively, during the growing season.

The specific activity of ^{137}Cs in the studied plant samples was determined using the Gamma Plus universal spectrometric complex (Scientific Production Enterprise Doza, Russia), the established measurement error of not more than 10%.

The daily average values of the short-wave part of the radiation balance were conducted according to urgent observations using the trapezoidal method [24]. To calculate the average daily values of the total radiation balance, empirical coefficients were used [25, 26]. The daily average values of photosynthetically active radiation (PAR) were calculated in accordance with the description [27].

The obtained data were subjected to the analysis of variance using the Excel 7.0 and Statistic 7.0 software (StatSoft, Inc., USA). The mean values are presented (*M*). The significance of differences with the control and between the variants was evaluated by the least significant difference (LSD_{05}). The differences were considered statistically significant when going beyond the borders of the LSD.

Results. Table 1 shows the phytoclimatic and meteorological indicators for the duration of the experiments. The vegetation season of 2010, in comparison with other years, was characterized by an increased radiation balance. Phytoclimatic conditions, optimal for the growth and development of crops from the first to second mowing developed in 2011. The period from the first mowing to the second mowing differed from that before the first mowing by a higher radiation balance and, correspondingly, greater evaporation.

1. Phytoclimatic conditions of spring-summer vegetation of bluegrass crops by mowings and years of observation (Bryansk Region)

Indicator	2009		2010		2011	
	1	2	1	2	1	2
The sum of the average daily values of the radiation balance during the growing season, MJ/m^2	394	569	439	688	432	485
The sum of average daily values of photosynthetically active radiation during the growing season, MJ/m^2	266	460	268	426	256	336
Air temperature, °C	13.9	19.4	16.2	25.0	16.3	21.1
Specific heat of evaporation, MJ/kg	2.47	2.46	2.47	2.45	2.47	2.45
Evaporation during the growing season, mm	160	231	178	281	175	198
Amount of precipitation during the growing season, mm	75.8	155.3	86.7	200.7	84.1	169.1
Moisture deficit during the growing season, mm	–84	–76	–91	–80	–91	–29
Humidity coefficient	0.47	0.67	0.49	0.71	0.48	0.85

N o t e. 1 — before the first mowing; 2 — from the first to the second mowing.

The deficit of soil moisture during the period from the resumption of the growing season to the first mowing did not affect the water regime of grass crops due to the close standing of groundwater after periodic flooding of the floodplain.

In the period from the first to the second mowing, a particularly large moisture deficit was in 2010, the minimum in 2011. The decrease in groundwater level and soil moisture deficit affected the water regime of crops and, as it appeared, the productivity of bluegrass plants in the period before the second mowing.

The transpiration coefficient is equal to the transpiration moisture consumption for the formation of 1 ton of hay of bluegrass plants. As it follows from Table 2, prior to the first mowing, when the soil moisture is sufficient, the values of C_t were determined by the phytoclimatic conditions of cultivation and did not depend on the species characteristics of the crops. Species features were manifested given the lack of soil moisture in 2010, caused by a decrease in groundwater level, an increase in radiation balance, evaporation and air temperature during the growing season from the first to second mowing. Under these conditions, only the reed canary grass reduced PAR absorption and water consumption for yield formation.

2. Transpiration coefficient C_t for perennial bluegrass plants by year and vegetation period (Bryansk Region)

Plants	2009	2010	2011
From the resumption of vegetation to the first mowing			
Cocksfoot grass	452	500	515
Meadow fescue grass	450	500	510
Reed canary grass	450	500	510
From the first to the second mowing			
Cocksfoot grass	472	490	444
Meadow fescue grass	472	497	439
Reed canary grass	472	465	442

In the experimental plot, the initial non-uniformity of ^{137}Cs contamination was observed. In the plots occupied by cocksfoot grass, meadow fescue grass, and reed canary grass, the density of ^{137}Cs contamination of the arable horizon of soil varied within the limits of 725-837, 615-671 and 493-631 kBq/m^2, respectively. Such values of the density of surface contamination ^{137}Cs are characterized as high [28].

3. Contamination density ^{137}Cs (kBq/m^2) **in the arable horizon of soil under the studied crops according to the variants of the experiment and years of research** (Bryansk Region)

Variant	Cocksfoot grass			Meadow fescue grass			Reed canary grass		
	2009	2010	2011	2009	2010	2011	2009	2010	2011
Control	726	726	725	668	669	667	493	493	493
$N_{90}P_{60}K_{90}$	842	839	841	650	649	651	629	631	629
$N_{90}P_{60}K_{120}$	790	785	785	637	634	633	541	541	539
$N_{90}P_{60}K_{150}$	812	809	809	667	668	671	524	526	522
$N_{120}P_{60}K_{120}$	837	840	834	670	670	667	546	542	545
$N_{120}P_{60}K_{150}$	800	794	803	678	679	669	498	496	496
$N_{120}P_{60}K_{180}$	764	766	761	615	609	622	510	502	537

The highest yields of bluegrass plants in all experimental variants in the first mowing were obtained in 2010 with a PAR value of 268 MJ/m^2 and C_t = 500. In the period from the first to second mowing, the highest crop yields in all variants were noted in 2011 with a PAR value of 336 MJ/m^2 and C_t = 442. In all cases in the first and second mowing, hay yield was higher given an increase in the dose of mineral fertilizer from 150 to 210 kg of active matter per 1 ha. Table 5 shows the specific activity of ^{137}Cs obtained in the experiment of air-dry phytomass of bluegrass plants. As follows from the data in Tables 4 and 5, an inverse proportion was revealed between the yield and specific activity of ^{137}Cs of hay: an increase in crop yield with increasing doses of mineral fertilizers led to a decrease in the specific activity of ^{137}Cs in the phytomass.

4. Yield (t/ha) **of the air-dry mass of perennial bluegrass plants according to the variants of the experiment and years of research** (Bryansk Region)

Variant	Cocksfoot grass				Meadow fescue grass				Reed canary grass			
	2009	2010	2011	on average	2009	2010	2011	on average	2009	2010	2011	on average
The first mowing												
Control	1.12	2.43	1.75	1.77	1.17	2.34	1.9	1.80	1.23	2.48	1.86	1.86
$N_{45}P_{60}K_{45}$	3.96	8.94	7.8	6.90	4.25	8.91	8.51	7.22	4.37	9.32	8.78	7.49
$N_{45}P_{60}K_{60}$	3.98	9.48	7.87	7.11	4.44	8.42	8.6	7.15	4.51	9.55	8.86	7.64
$N_{45}P_{60}K_{75}$	4.28	9.62	8.06	7.32	4.43	9.72	9.27	7.81	4.69	9.77	9.31	7.92
$N_{60}P_{60}K_{60}$	4.55	9.33	8.59	7.49	4.87	9.38	8.9	7.72	4.89	9.41	9.14	7.81
$N_{60}P_{60}K_{75}$	5.02	5.58	8.61	6.40	5.22	9.67	9.16	8.02	5.59	9.72	9.26	8.19
$N_{60}P_{60}K_{90}$	5.06	9,82	9,31	8,06	5,47	9,96	9,33	8,25	6,12	10,23	9,45	8,60
LSD_{05}	4.26	4,35	4,04	4,18	3,98	3,84	4,44	4,12	3,89	4,08	4,26	4,16
The second mowing												
Контроль	0.61	1.14	0.96	0.90	0.64	1.21	0.93	0.93	0.67	1.28	1.02	0.99
$N_{45}K_{45}$	1.97	3.09	3.7	2.92	2.04	3.15	3.67	2.95	2.10	3.20	4.05	3.12
$N_{45}K_{60}$	2.06	3.35	3.85	3.09	2.09	3.37	3.77	3.08	2.18	3.40	4.18	3.25
$N_{45}K_{75}$	2.16	3.49	3.94	3.20	2.33	3.46	3.89	3.23	2.23	3.51	4.25	3.33
$N_{60}K_{60}$	2.23	3.42	4.22	3.29	2.38	3.54	4.25	3.39	2.45	3.62	4.51	3.53
$N_{60}K_{75}$	2.59	3.57	4.37	3.51	2.54	3.61	4.59	3.58	2.54	3.69	4.75	3.66
$N_{60}K_{90}$	2.62	3.76	4.44	3.61	2.59	3.78	4.67	3.68	3.86	3.81	5.21	4.29
LSD_{05}	1.29	0.98	1.24	1.47	1.26	1.48	1.67	1.51	1.58	1.36	1.72	1.56

5. Specific activity of ^{137}Cs (Bq/kg) **of the air-dry mass of perennial bluegrass plants according to the variants of the experiment and years of research** (Bryansk Region)

Variant	Cocksfoot grass				Meadow fescue grass				Reed canary grass			
	2009	2010	2011	on average	2009	2010	2011	on average	2009	2010	2011	on average
The first mowing												
Control	2990	2866	2952	2936	2880	2796	2877	2851	2325	2296	2378	2333
$N_{45}P_{60}K_{45}$	1322	1318	1338	1326	1215	1208	1231	1218	1208	1186	1227	1207
$N_{45}P_{60}K_{60}$	845	809	848	834	834	811	842	829	736	698	744	726
$N_{45}P_{60}K_{75}$	479	437	461	459	440	421	456	439	398	363	418	393
$N_{60}P_{60}K_{60}$	469	479	492	480	476	422	467	455	426	412	458	432
$N_{60}P_{60}K_{75}$	280	286	313	293	312	285	321	306	259	238	268	255
$N_{60}P_{60}K_{90}$	275	268	297	280	289	256	286	277	255	231	258	248
LSD_{05}	56	68	55	50	42	56	55	45	66	59	75	45
The second mowing												
Control	2862	2788	2966	2872	2910	2655	2793	2786	2264	2196	2308	2256
$N_{45}K_{45}$	1308	1285	1301	1298	1290	1213	1262	1255	1309	1195	1210	1238
$N_{45}K_{60}$	802	776	798	792	754	708	743	735	717	637	698	684
$N_{45}K_{75}$	347	345	352	348	363	312	342	339	330	308	337	325
$N_{60}K_{60}$	434	437	452	441	446	409	453	436	436	411	437	428
$N_{60}K_{75}$	376	381	368	375	352	388	361	367	359	318	385	354
$N_{60}K_{90}$	305	333	346	328	315	302	352	323	310	296	342	316
LSD_{05}	84	76	68	63	105	98	87	95	63	57	66	69

6. Coefficients of ^{137}Cs accumulation in the air-dry mass of perennial bluegrass plants according to the variants of the experiment and years of research (Bryansk Region)

Variant	Cocksfoot grass			Meadow fescue grass			Reed canary grass		
	2009	2010	2011	2009	2010	2011	2009	2010	2011
The first mowing									
Control	1.03	0.99	1.02	1.08	1.04	1.08	1.18	1.16	1.20
$N_{45}P_{60}K_{45}$	0.39	0.39	0.40	0.47	0.47	0.47	0.48	0.47	0.49
$N_{45}P_{60}K_{60}$	0.27	0.26	0.27	0.33	0.32	0.33	0.34	0.32	0.34
$N_{45}P_{60}K_{75}$	0.15	0.14	0.14	0.17	0.16	0.15	0.19	0.17	0.20
$N_{60}P_{60}K_{60}$	0.14	0.14	0.15	0.18	0.16	0.18	0.20	0.19	0.21
$N_{60}P_{60}K_{75}$	0.09	0.09	0.10	0.12	0.11	0.12	0.13	0.12	0.14
$N_{60}P_{60}K_{90}$	0.09	0.09	0.10	0.12	0.11	0.12	0.13	0.12	0.12
The second mowing									
Control	0.87	0.96	1.02	1.09	0.99	1.05	1.15	1.11	1.17
$N_{45}K_{45}$	0.39	0.38	0.39	0.50	0.47	0.49	0.52	0.48	0.48
$N_{45}K_{60}$	0.26	0.25	0.25	0.30	0.28	0.29	0.33	0.30	0.32
$N_{45}K_{75}$	0.11	0.10	0.11	0.14	0.12	0.13	0.16	0.15	0.16
$N_{60}K_{60}$	0.13	0.13	0.14	0.17	0.16	0.17	0.20	0.19	0.20
$N_{60}K_{75}$	0.12	0.12	0.12	0.13	0.15	0.14	0.18	0.16	0.19
$N_{60}K_{90}$	0.10	0.11	0.11	0.13	0.12	0.14	0.18	0.17	0.19

The calculation of ^{137}Cs accumulation coefficients in the air-dry mass of bluegrass plants according to the experimental variants (Table 6) made it possible to establish an inversely proportional relationship between these coefficients and the yield, as well as the doses of mineral fertilizers. To reveal the mechanism of such a dependence, we calculated the values of relative transpiration ($\Sigma_g E_t/\Sigma_g E_0$) according to the experimental variants in the first and second mowing in different years. Relative transpiration is used to determine the degree of water supply for crops, as well as the period of irrigation of crops. This value characterizes the availability of soil moisture to the root system of the plant. Mineral fertilizers increase the transpiration of crops [29, 30] and, correspondingly, the value of $\Sigma_g E_t/\Sigma_g E_0$. Under optimal conditions of the water regime, the relative transpiration of crops is 0.70-0.85 [31].

7. Relative transpiration of crops of perennial bluegrass plants according to the variants of the experiment and years of research (Bryansk Region)

Variant	2009			2010			2011 год		
	1	2	3	1	2	3	1	2	3
From the resumption of vegetation to the first mowing									
$N_{45}P_{60}K_{45}$	1.12	1.21	1.24	2.51	2.51	2.62	2.29	2.50	2.58
$N_{45}P_{60}K_{60}$	1.12	1.26	1.27	2.66	2.36	2.68	2.31	2.50	2.61
$N_{45}P_{60}K_{75}$	1.21	1.26	1.32	2.7	2.73	2.74	2.37	2.73	2.74
$N_{60}P_{60}K_{60}$	1.29	1.50	1.38	2.62	2.63	2.65	2.53	2.62	2.69
$N_{60}P_{60}K_{75}$	1.42	1.47	1.58	1.57	2.71	2.73	2.53	2.68	2.73
$N_{60}P_{60}K_{90}$	1.43	1.55	1.73	2.76	2.8	2.88	2.74	2.74	2.78
From the first to the second mowing									
$N_{45}K_{45}$	0.40	0.42	0.43	0.55	0.55	0.56	0.83	0.55	0.91
$N_{45}K_{60}$	0.42	0.43	0.45	0.59	0.59	0.6	0.86	0.59	0.93
$N_{45}K_{75}$	0.44	0.48	0.45	0.62	0.61	0.62	0.88	0.61	0.93
$N_{60}K_{60}$	0.45	0.48	0.50	0.60	0.62	0.64	0.94	0.62	1.01
$N_{60}K_{75}$	0.53	0.52	0.52	0.63	0.64	0.65	0.98	0.64	1.07
$N_{60}K_{90}$	0.54	0.53	0.79	0.66	0.67	0.67	1.00	0.67	1.17

Note. 1 — cocksfoot grass, 2 — meadow fescue grass, 3 — reed canary grass.

During the growing season before the first mowing, the value of relative transpiration in all variants exceeded 1.0 (Table 7). These data indicate that the crops experienced an excess of moisture caused by a close occurrence of groundwater after flooding in the floodplain in April. From the first to second mowing, this figure exceeded 1.0 only in 2011. In 2009 and 2010, with a large moisture deficit of 76-80 mm, relative transpiration did not reach the optimum value in any variant of crops. The meteorological and phytoclimatic conditions were optimal for the growth and development of crops in 2011, when the seeds developed in the conditions of abundance of soil moisture.

The calculation results (see Table 7) show that with an increase in the dose of complete mineral fertilizer, the relative transpiration value increases with a lack and excess of soil moisture. Electrolytes that are part of mineral fertilizers, causing compression of double electric layers on the walls of soil capillaries, reduce the proportion of adsorbed ions ^{137}Cs in the solution flow to the plant root system [24]. An increase in the dose of mineral fertilizer increases the availability of soil moisture for plant roots, reduces the Pe value, and leads to a decrease in the specific activity of ^{137}Cs in the phytomass of grasses. Relative transpiration, which determines the bioavailability of soil moisture and the Pe number at different levels of mineral nutrition, is one of the main reasons for the inverse proportion between the specific activity of ^{137}Cs and the phytomass yield in bluegrass plants.

The data on the specific activity of ^{137}Cs in the phytomass of bluegrass plants (see Table 5) reflect the relationship between the specific activity in the control and the use of different doses of mineral fertilizers. This relationship is described by the following formula: $A_i = A_k \times \exp(-\lambda \Sigma b E_T)$ (3), where A_i and

A_k are the specific activity of ^{137}Cs in the phytomass, respectively, in the variant *i* and in the control, Bq/kg; ΣbE_T is transpiration during the growing season, mm; λ is the relative intensity of bio-removal (a constant value for certain conditions; the larger the value of λ, the lower the specific phytomass activity in the variant *i* is, compared to the control). With an increase in the dose of full mineral fertilizers above 195 kg of active matter per 1 ha, the difference in the values of λ is 0 or very small. These data confirm the exponential dependence of the specific activity of the phytomass of herbs in the variant *i* on transpiration and the adequacy of formula (3) to the real process of bio-removal.

It should be noted that under equal conditions of cultivation in each of the six experimental variants in the first and second mowing, changes in the intensity of ^{137}Cs bio-removal by cultures depending on the species were noted, as reported by other authors [5, 32-35]. In our experiment, cocksfoot grass had the lowest intensity of ^{137}Cs biological removal, and reed canary grass the highest one.

8. Relative intensity (λ) of ^{137}Cs bio-removal from the soil by the phytomass of perennial bluegrass plants according to the experimental variants and years of research (Bryansk Region)

Variant	2009 год			2010 год			2011 год		
	1	2	3	1	2	3	1	2	3
From the resumption of vegetation to the first mowing									
$N_{45}P_{60}K_{45}$	5.7	5.0	4.7	2.3	2.3	1.8	2.4	2.1	1.8
$N_{45}P_{60}K_{60}$	8.3	7.4	6.6	3.2	3.4	3.0	3.6	3.1	3.0
$N_{45}P_{60}K_{75}$	10.8	10.8	9.7	4.4	4.3	3.9	4.7	4.2	3.7
$N_{60}P_{60}K_{60}$	9.7	8.5	9.0	4.5	4.4	4.1	4.5	4.2	3.8
$N_{60}P_{60}K_{75}$	11.4	10.5	9.4	9.3	5.2	4.7	5.6	5.1	4.3
$N_{60}P_{60}K_{90}$	11.4	10.3	10.0	5.3	5.2	4.8	5.2	5.2	4.5
From the first to the second mowing									
$N_{45}K_{45}$	12.8	12.0	9.8	7.7	7.7	6.8	7.5	7.1	5.4
$N_{45}K_{60}$	14.9	14.7	12.9	8.4	8.4	7.7	7.8	7.9	6.7
$N_{45}K_{75}$	20.3	18.9	21.3	11.6	11.6	12.3	11.6	11.0	10.3
$N_{60}K_{60}$	18.8	15.9	14.8	11.3	11.2	10.0	9.6	9.4	7.8
$N_{60}K_{75}$	21.6	21.1	22.0	13.5	13.8	12.2	11.3	10.7	9.0
$N_{60}K_{90}$	21.8	21.9	15.3	13.3	13.9	12.3	12.2	10.6	8.7

Note. 1 — cocksfoot grass, 2 — meadow fescue grass, 3 — reed canary grass.

Therefore, the formula (3) can be used for a comparative assessment of ^{137}Cs bio-removal from the soil by different species of bluegrass plants when applying mineral fertilizers.

Thus, an analysis of the results of field experiments conducted on monospecies crops of bluegrass forage plants revealed the following features of the process of ^{137}Cs bio-removal from the soil. The transpiration coefficient of the studied grass species with sufficient moisture supply does not depend on the dose and type of fertilizer, but with a lack of moisture, it depends on the radiation balance and the type of plant. One of the main reasons for the inverse proportion between the specific activity of ^{137}Cs and the yield of grass phytomass is an increase in relative transpiration with increasing doses of complete mineral fertilizer and a decrease in the proportion of adsorbed ions ^{137}Cs in the soil moisture flow to the root system caused by the compression of double electric layers on the walls pores and a decrease in the Pe value with increasing convection in the flow. We suggest the equation of ^{137}Cs bio-removal from the soil by the phytomass of perennial bluegrass plants using mineral fertilizers, which expresses the pattern of change in the specific activity of ^{137}Cs phytomass under the influence of introduced fertilizers and is valid for the studied species of bluegrass plants. It was revealed that the intensity of ^{137}Cs bio-removal from the soil to the first mowing differs from that in the period from the first to the second mowing, which is characterized by a significantly greater decrease in ^{137}Cs bio-removal by sowing of grass due to low relative transpiration and low bioavailability of moisture, which is accompanied by a decrease in the intensity of convective flow of moisture to the root system.

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