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POTASSIUM FERTILIZERS TO REDUCE ^{137}Cs ACCUMULATION AND INCREASE FODDER CROP HARVESTING ON THE RADIONUCLIDE-POLLUTED FLOODPLAIN PASTURES

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Abstract

Protective measures on the radionuclide-polluted rural territories after the Chernobyl accident are known to reduce agricultural production which is not corresponding to standards for radiation safety and a common radiation dose. On natural floodplain pastures in the southwest of the Bryansk region, we studied fodder crop yield and specific radioactivity as influenced by mineral fertilizers with regard to their total doses and potassium to nitrogen portion. The soil of the pastures was alluvial sod-gley sandy with 3.08-3.33 % humus, 620-840 mg/kg P_2O_5 , 133-180 mg/kg K_2O , and pH_{KCl} 5.2-5.6. After the Chernobyl disaster, the post-accidental ^{137}Cs pollution of the soils was 1221-1554 kBq/m² in 2000-2008 and 559-867 kBq/m² in 2009-2014. A mix of *Bromus inermis* (8 kg/hectare), *Festuca pratensis* (8 kg/hectare), *Phleum pratense* (5 kg/hectare), *Phalaris arundinacea* (5 kg/hectare), *Alopecurus pratensis* (5 kg/hectare) was used for sowing in 2000-2008, and in 2009-2014 *Festuca pratensis* (6 kg/hectare), *Alopecurus pratensis* (5 kg/hectare) and *Phalaris arundinacea* (7 kg/hectare) mix was examined. Ammonium nitrate, simple granular superphosphate and potassium chloride were as fertilizers. According to the protocol, $1/2$ doses of N and K along with full P dose were pre-applied to soil at the first mowing, and $1/2$ doses of N and K were applied after mowing. Minimum aboveground green biomass possessing the greatest specific radioactivity was observed when no mineral fertilizers used. In 2000 to 2008 the highest crop yield of 30.9 t/hectare was harvested when $\text{N}_{60}\text{P}_{90}\text{K}_{60}$ applied. An increase in N, P, K and their fractions did not lead to a significant rise in green mass production. However, at $\text{N}_{60}\text{P}_{90}\text{K}_{60}$ dose and nitrogen to potassium ratio as 1:1 the nitrogen increased a specific radioactivity of forage which did not correspond to radiation safety standard. Therefore in the areas polluted at 1221-1554 kBq/m² we recommend applying NPK fertilizers with N to K ratio of 1:1.5 to grow green biomass which possesses the specific radioactivity not exceeding the admissible level. In 2009 to 2014 $\text{N}_{45}\text{P}_{60}\text{K}_{75}$ were optimal for high productivity and admissible quality of the fodder crops. With no fertilizer used the correlation between yield and specific radioactivity level was weak and positive, whereas application of fertilizers at N:K portion as 1:1, changed the correlation to weak, but negative. Further increase in K fraction strengthened the correlation. Our findings of decrease in ^{137}Cs specific radioactivity level in green fodder confirm that the K fertilizers are mainly effective for a rehabilitation of soil radioactive pollution on pastures. ^{137}Cs migration from forages to animal husbandry production was also calculated. So, it is shown that the K fertilizers are the main factor limiting ^{137}Cs transition from soil to plants and thus lowering ^{137}Cs specific radioactivity in animal husbandry products and a corresponding internal exposure dose in human.

Keywords: potassium fertilizers, fodder grounds, ^{137}Cs , green biomass, milk, meat, internal radiation dose

The Chernobyl accident led to a sharp increase in the content of artificial radionuclides in the environment, including the main dose forming radionuclide ^{137}Cs . The uniqueness of this accident is due not only to the scale of the release of radioactive substances and areas exposed to intense radioactive contamination, but also to the consequences for agriculture, and material and technical costs required for mitigation [1-3].

Currently, in the Bryansk region of the Russian Federation, the area of agricultural land with ^{137}Cs soil contamination density over 37 kBq/m² is 422.4

thousand hectares, including 271.7 thousand hectares of arable land and 150.7 thousand hectares of hayfields and pastures [4-6]. Manufacture of food products with permissible and lower radionuclide level is a priority, because internal exposure due to consumption of radionuclide contaminated food dominates in the formation of exposure doses in the remote period after the accident [7-9].

Protective measures on the radionuclide-polluted rural territories reduce agricultural production which does not meet the standards for radiation safety and the total radiation exposure (10-12). Over the post-accident period, Russian, Ukrainian and Belarusian scientists have conducted numerous studies of radionuclide migration in agro-ecosystems. Based on these, guidelines on the management of agricultural production have been issued [13-15].

Prediction of crop contamination on automorphic soils of light granulometric composition has a sufficiently high certainty, since it is based on extensive practical data [16-18]. At the same time, floodplains are the critical landscapes as radionuclide accumulation is constantly going on there [19-21]. As a consequence, a detailed study of the relationship between the accumulation of radionuclides, the use of chemicals, and forage land productivity remains topical [22-24]. Natural land is the main source of feed for cattle in the farms where most of the milk with the excess of permissible ^{137}Cs level is produced. The amount of excessively radioactive contaminated products remains high.

Exceeding the standards for radionuclide levels in the products is the main criterion for determining the need for protective measures in agriculture [25, 26]. To assess the justification for such measures, these measures costs and the risk of radiation exposure effects (collective dose) that can be prevented should be considered [27, 28]. An in-depth study of the state and opportunities to use radioactively contaminated areas allows to prove adequate options for agricultural production in the areas with high content of soil radionuclides [29, 30].

We were the first to perform long-term comprehensive studies of the effectiveness of potassium fertilizers and their various combinations with other mineral fertilizers to increase the productivity of seeded bluegrass mix under the conditions of natural floodplains and substantiated the application rates of potassium optimal to reduce ^{137}Cs entering the production in the soil-plant-animal-human system.

The purpose of this study was to investigate the role of potassium fertilizers in the rehabilitation of radioactively contaminated forage lands.

Technique. Stationary experiment was conducted in Novozybkov district of the Bryansk region in the years of 2000-2014. Experimental plot soil was alluvial sod-gley sandy with 3.08-3.33 % humus, 620-840 mg/kg P_2O_5 , 133-180 mg/kg K_2O , and pH_{KCl} 5.2-5.6. After the Chernobyl disaster, the post-accidental ^{137}Cs pollution of the soils was 1221-1554 kBq/m² in 2000-2008 and 559-867 kBq/m² in 2009-2014. Agro-technical measures envisaged disking (BDF-2,4 harrows, Russia) and plowing using plow PN-3-35 (Russia), followed by planting bluegrass mixes typical of the region.

In 2000-2008, a mix of perennial bluegrass including *Bromus inermis* (8 kg/hectare), *Festuca pratensis* (8 kg/hectare), *Phleum pratense* (5 kg/hectare), *Phalaris arundinacea* (5 kg/hectare), and *Alopecurus pratensis* (5 kg/hectare) was used. In 2009-2014, the mix included *Festuca pratensis* (6 kg/hectare), *Alopecurus pratensis* (5 kg/hectare), and *Phalaris arundinacea* (7 kg/hectare).

Ammonium nitrate, simple granular superphosphate, and potassium chloride (Russia) were used as fertilizers. Doses of fertilizers in 2000-2008 were as follows: control (no fertilizers), $\text{P}_{90}\text{K}_{120}$, $\text{P}_{120}\text{K}_{180}$, $\text{N}_{120}\text{P}_{90}\text{K}_{120}$, $\text{N}_{120}\text{P}_{90}\text{K}_{180}$, $\text{N}_{120}\text{P}_{90}\text{K}_{240}$, $\text{N}_{180}\text{P}_{120}\text{K}_{180}$, $\text{N}_{180}\text{P}_{120}\text{K}_{270}$, $\text{N}_{180}\text{P}_{120}\text{K}_{360}$; in 2009-2014: control (no fertilizers), $\text{P}_{60}\text{K}_{90}$, $\text{P}_{60}\text{K}_{120}$, $\text{N}_{90}\text{P}_{60}\text{K}_{90}$, $\text{N}_{90}\text{P}_{60}\text{K}_{120}$, $\text{N}_{90}\text{P}_{60}\text{K}_{150}$, $\text{N}_{120}\text{P}_{60}\text{K}_{120}$,

$N_{120}P_{60}K_{150}$, $N_{120}P_{60}K_{180}$.

Perennial bluegrass yields were accounted by continuous plot harvesting and trial sheaf selection. Two mowings per year were performed (the first mowing from June 1 to June 10, the second mowing in the period from August 23 to September 1).

^{137}Cs specific radioactivity level in the plant samples studied was determined using an universal spectrometric complex UKS Gamma Plus (NPP "Dose", Russia), the instrumental measurement error did not exceed 30 %. The specific activity of milk and meat production was calculated as the product of the daily feed intake (green mass of 50 kg), feed specific activity and equilibrium factor of radionuclide transfer in animal husbandry products; internal doses due to milk and meat were determined according to the methodological guidelines [31]. Consumption of milk and dairy products as milk per year was taken equal to 200.8 liters, meat consumption was taken equal to 31.4 kg (according to the law of the Bryansk region of 08.06.2001 № 45-Z, as amended on 10/12/2001 "On the consumer basket in the Bryansk Province").

Experiments were conducted in three replicates. The data were subjected to analysis of variance and correlation analysis using Microsoft Excel 7.0 and Statistica 7.0 software (StatSoft, Inc., USA).

Results. Natural lands play an essential role in fodder production. Natural and seeded grasslands provide cheap and high-grade fodder. The productivity of these lands is increased mainly due to nitrogen fertilization.

Under the conditions of the experiment conducted, the yield of seeded bluegrass mix green mass when no mineral fertilizers were used varied depending on the experiment timing and was 5.8-6.5 t/ha for the first mowing and 2.5-2.8 t/ha for the second moving (Table 1).

From 2000 to 2014, we used two schemes of fertilizer application different both in the amounts of essential nutrients and in their ratios. Increasing the amount of phosphorus-potassium fertilizers for the first mowing from $P_{90}K_{60}$ to $P_{120}K_{90}$ resulted in a significant 1.8-fold increase in the yields versus control, while no significant difference in the yields between the two embodiments of fertilizer application was found. Similar data were obtained with increasing doses from $P_{60}K_{45}$ to $P_{60}K_{60}$. Application of only potassium fertilizers for the second mowing at increasing doses (from K_{60} to K_{90}) resulted in a significant 3-fold increase in the yields versus control, reduction of the doses of potassium fertilizers from K_{60} to K_{45} did not result in statistically significant yield increases.

K_{60} application over the background of $N_{60}P_{90}$ nitrogen-phosphorus fertilizers increased the yield significantly by 5.3 times versus control and 3-fold compared to the embodiment of phosphorus-potassium fertilizers. A further increase in potassium fertilizer doses up to K_{120} resulted in a significant decrease in the yield. Increasing potassium doses (from K_{90} to K_{180}) at $N_{90}P_{120}$ nitrogen-phosphorus fertilizers caused a significant increase in the yield versus control and phosphorus-potassium fertilizers.

Potassium doses increasing from K_{45} to K_{75} over the $N_{45}P_{60}$ background led to a significant increase in the yield versus control (by 3.6 times) and phosphorus-potassium fertilizers (by 1.8 times). At the same time, no statistically significant differences were observed between the $N_{45}P_{60}K_{45}$ and $N_{45}P_{60}K_{75}$. A similar tendency was observed with increasing potassium doses from K_{60} to K_{90} at $N_{60}P_{60}$ application.

Increasing the amount of potassium introduced from K_{60} to K_{90} along with N_{60} nitrogen fertilizers caused a significant yield increase versus control and the parameter for only potassium fertilizers. However, application of $N_{60}K_{90}$ did

not contribute to a significant increase in the yield compared to N₆₀K₆₀. Similar observations were made with increasing potassium doses from K₉₀ to K₁₂₀ at N₉₀; from K₄₅ to K₇₅ at N₄₅ and from K₆₀ to K₉₀ at N₉₀.

With radioactive contamination of the area, fodder specific activity is its most important parameter. Veterinary and sanitary requirements determine the need for the measures to obtain green mass with the maximum ¹³⁷Cs permissible fodder contamination of 100 Bq/kg [32].

1. Productivity of perennial bluegrasses and migration of ¹³⁷Cs in the food chain in the natural grassland in various periods, depending on the doses of mineral fertilizers (Novozybkov district, Bryansk Province)

Doses	Crop yield, t/ha	SA _{fodder}	SA _{milk}	SA _{meat}	IED
Average of the years of 2000-2008					
<i>First mowing</i>					
Control	5.8	942	471	1884	1999
P ₉₀ K ₆₀	10.3	92	46	184	195
P ₁₂₀ K ₉₀	11.1	31	16	62	66
N ₆₀ P ₉₀ K ₆₀	30.9	326	163	652	692
N ₆₀ P ₉₀ K ₉₀	24.6	87	44	174	185
N ₆₀ P ₉₀ K ₁₂₀	23.5	50	25	100	106
N ₉₀ P ₁₂₀ K ₉₀	33.7	103	52	206	219
N ₉₀ P ₁₂₀ K ₁₃₅	29.1	37	19	74	78
N ₉₀ P ₁₂₀ K ₁₈₀	30.0	17	9	34	36
LSD ₀₅	3.9	65	—	—	—
<i>Second mowing</i>					
Control	2.8	960	480	1920	2037
K ₆₀	8.3	108	54	216	229
K ₉₀	9.3	34	17	68	72
N ₆₀ K ₆₀	16.0	390	195	780	827
N ₆₀ K ₉₀	16.7	106	53	212	225
N ₆₀ K ₁₂₀	17.5	58	29	116	123
N ₉₀ K ₉₀	18.7	125	63	250	265
N ₉₀ K ₁₃₅	17.0	41	21	82	87
N ₉₀ K ₁₈₀	16.8	19	10	38	40
LSD ₀₅	2.4	66	—	—	—
Average of the years of 2009-2014					
<i>First mowing</i>					
Control	6.5	887	444	1774	1882
P ₆₀ K ₄₅	13.3	126	63	252	267
P ₆₀ K ₆₀	14.3	84	42	168	178
N ₄₅ P ₆₀ K ₄₅	23.6	273	137	546	579
N ₄₅ P ₆₀ K ₆₀	24.9	146	73	292	310
N ₄₅ P ₆₀ K ₇₅	27.9	96	48	192	204
N ₆₀ P ₆₀ K ₆₀	28.1	121	61	242	257
N ₆₀ P ₆₀ K ₇₅	30.0	82	41	164	174
N ₆₀ P ₆₀ K ₉₀	31.7	58	29	116	123
LSD ₀₅	6.2	108	—	—	—
<i>Second mowing</i>					
Control	2.5	807	404	1614	1712
K ₄₅	5.6	106	53	212	225
K ₆₀	6.5	89	45	178	189
N ₄₅ K ₄₅	11.2	271	136	542	575
N ₄₅ K ₆₀	11.8	164	82	328	348
N ₄₅ K ₇₅	12.8	103	52	206	219
N ₆₀ K ₆₀	14.3	126	63	252	267
N ₆₀ K ₇₅	15.0	83	42	166	176
N ₆₀ K ₉₀	15.7	57	29	114	121
LSD ₀₅	4.7	136	—	—	—

Note. SA_{fodder} — fodder specific activity, Bq/kg; SA_{milk} — milk specific activity, Bq/kg; SA_{meat} — meat specific activity, Bq/kg; IED — internal exposure dose, mSv. Dashes mean that the least significant difference has not been calculated.

With no fertilizer, specific activity of the green mass mix, depending on the experiment timing, exceeded the permissible threshold by 8.9-9.4 times for the first mowing and by 8.1-9.6 times for the second one (Table 1). Application of phosphorus-potassium fertilizers for the first mowing at the doses from P₉₀K₆₀ to P₁₂₀K₉₀ decreased this parameter significantly. We found a significant decrease in fodder specific activity with increased application of fertilizers

at the doses from $P_{60}K_{45}$ to $P_{60}K_{60}$ (findings of 2009-2014). However, the $P_{60}K_{60}$ dose only made it possible to obtain the fodder that met the standard requirements. Application of increasing doses of potassium fertilizers for the second mowing — from K_{60} to K_{90} and from K_{45} to K_{60} — reduces the excessive allowable values as well, and with the doses of K_{90} in 2000-2008 and K_{60} in 2009-2014, the fodder meeting the standard requirements was obtained.

Application of nitrogen fertilizers in combination with phosphorus-potassium or potassium fertilizers increased the green mass specific activity. Application of increasing doses of potassium fertilizers made it possible to decrease the excess over this parameter permissible threshold. Thus, application of K_{90} over the $N_{60}P_{90}$ background, K_{135} at $N_{90}P_{120}$, K_{75} at $N_{45}P_{60}$ and $N_{60}P_{60}$, K_{120} at N_{60} , K_{135} at N_{90} , K_{75} over the N_{60} background guaranteed obtaining of green fodder meeting the veterinary and sanitary requirements.

Analyzing ^{137}Cs transition from green mass to animal husbandry products, we found that to obtain meat that meets the requirements of SanPin 2.3.2.1078-01 (160 Bq/kg) (RF State Standards) [33], the applied doses should be not less than K_{90} for potassium fertilizers, not less than $P_{120}K_{90}$ for phosphorus-potassium fertilizers, not less than $N_{60}K_{90}$ for nitrogen-potassium fertilizers, and not less than $N_{60}P_{90}K_{120}$, $N_{90}P_{120}K_{135}$ and $N_{60}P_{60}K_{90}$ for NPK-compounds. Thus, for milk of the appropriate veterinary and sanitary quality (up to 100 Bq/kg), we recommend to apply at pastures mineral fertilizers at the doses studied, except $N_{60}P_{90}K_{60}$, $N_{45}P_{90}K_{45}$, $N_{60}K_{60}$, and $N_{45}K_{45}$.

According to the Radiation Safety Standards (NRB-99/2009), the total dose of external and internal (due to intakes of radionuclides in the body) public exposure should not exceed 1000 mSv/year [34]. In cases where exposure exceeds the permissible limits, it is very important to assess the dose load structure, that is to determine the contributions of the individual components to the overall load. In this study, we estimated the contributions of milk and meat to the internal dose for the cattle pastured. We also studied the effects of mineral fertilizers on the limitation of ^{137}Cs transition in the soil-fodder-animal husbandry products-human chain. The dose of internal exposure from milk and meat was shown not to exceed 1 mSv/year only when perennial herbage green mass grown with mineral fertilizer treatment was used for cattle fodder (see Table 1).

2. Correlation between the yield of perennial bluegrasses and fodder specific activity under the treatment of natural grassland with mineral fertilizers (Novozybkov district, Bryansk Province, 2000-2014)

Fertilizer N:K ratio	Correlation coefficient, r		Coefficient of determination, d_{yx}		n
	first mowing	second mowing	first mowing	second mowing	
Control (no fertilizers)	0.17	0.29	0.03	0.08	15
1:1	-0.17	-0.18	0.03	0.03	30
1:1.5	-0.34	0.03	0.12	0.001	24

Note. n — number of independent paired observations.

Under the conditions of the south-west of the Bryansk region, the yields of seeded bluegrass mixes without the use of mineral fertilizers remain low and is comparable to the yield of natural grass without improving measures [35-37]. Only the use of fertilizers, mostly nitrogen ones, results in a significant increase in the yields by several times. However, application of nitrogen increases not only the yields, but also the green mass specific activity. It should be noted that the yield is an integral parameter of providing everything required for the growth and development of plants. We found that with no fertilizer used, the correlation between the yield and green mass specific activity was weak and positive; application of fertilizers at the N:K ratio of 1:1 changed the correlation to weak, but negative. A further increase in potassium fraction strengthened the correlation

(Table 2). High correlation was found between the application of potassium fertilizers and the green mass specific activity (Fig.).

^{137}Cs specific activity in perennial bluegrass mix depending on the increasing doses of potassium fertilizers at the first (on the left) and the second (on the right) movements over various backgrounds: A – $\text{N}_{60}\text{P}_{90}$, B – $\text{N}_{90}\text{P}_{120}$, C – $\text{N}_{45}\text{P}_{60}$, D – $\text{N}_{60}\text{P}_{60}$, E – N_{60} , F – N_{90} , G – N_{45} , H – N_{60} (n – number of independent paired observations; Novozybkov district, Bryansk Province).

Thus, the use of mineral fertilizers proved to be the main way to improve the productivity of perennial bluegrasses at radioactively contaminated floodplain feeding grounds under the Bryansk region conditions. Our findings of the decrease in green fodder ^{137}Cs specific activity confirm that potassium fertilizers are most effective for these purposes. Potassium fertilizers limited ^{137}Cs transition from soil to plants and further in the food chain thus lowering ^{137}Cs specific radioactivity in animal husbandry products and corresponding internal exposure

doses in human. At the same time, application of potassium fertilizers did not provide stable high green mass yields, while combined application of NPK at the correct ratio of mineral nutrients (N:K of 1:1.5) contributed to the formation of high yields and prevented the excess of sanitary radiation safety standards.

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