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M. M. Lazarev[1], Y. V. Khomutinin[2,*], O. V. Kosarchuk[2], V. V. Illienko[1], V. V. Pavliuchenko[2], D. M. Lazarev[1], A. V. Klepko[1], T. R. Andriichuk[3]

[1] *National University of Life and Environmental Sciences of Ukraine, Kyiv, Ukraine*
[2] *Ukrainian Research Institute of Agricultural Radiology, Chabany, Kyiv region, Ukraine*
[3] *Taras Shevchenko National University of Kyiv, Kyiv, Ukraine*

*Corresponding author: khomutinin@gmail.com

THE CURRENT RADIOLOGICAL STATE OF NATURAL MEADOWS IN THE ZONE OF UNCONDITIONAL (MANDATORY) RESETTLEMENT OF THE NARODYCHI UNITED TERRITORIAL COMMUNITY OF THE ZHYTOMYR REGION AND THE PROSPECTS FOR THEIR USE AS A FODDER BASE FOR LIVESTOCK

A radiological survey of natural meadows in the vicinity of the settlements of the Narodychi united territorial community, which were contaminated with radionuclides as a consequence of the Chornobyl accident, was conducted, and the feasibility of reclaiming them for economic use was evaluated. The content of ^{137}Cs and ^{90}Sr radionuclides (median, geometric standard deviation, upper limit for P = 0.9) in milk and cattle muscles was predicted using the method of probabilistic modelling. Furthermore, the risks of exceeding the requirements established by the Ukraine state hygiene standards (PL-2006) for the content of radionuclides in these products were assessed. The potential for utilizing hayfields and pastures for the production of milk and cattle meat was demonstrated. These findings serve as the foundation for recommendations and decision-making concerning the return of these lands to economic use.

Keywords: radioactive contamination, activity concentration, pastures, hayfields, milk, meat, return to agricultural use.

1. Introduction

The assessment of the actual radiological situation on the lands that have been withdrawn from use due to contamination with radionuclides in the zone of unconditional (mandatory) resettlement, and solution to the problem of their return to use are becoming increasingly relevant due to the temporary loss of extensive agricultural land in the eastern and southern regions of Ukraine. The situation regarding radionuclide-contaminated natural meadows in the Ukrainian Polissya region represents a distinct issue within the field of agricultural radiology. In the early 1990s, it was established that natural meadows represent a critical link in the trophic chain of radionuclide intake into food, particularly milk and meat of animal origin. Notwithstanding the existence of state programmes designed to enhance natural forage lands, no comprehensive measures have been implemented in the radionuclide-contaminated region. Consequently, to date, there are still over ten settlements where cow milk from private farms fails to meet the requisite state hygiene standards for ^{137}Cs content. It is known that only two settlements have implemented countermeasures in accordance with the recommendations of the Institute of Agricultural Radiology. These are the village of Prylissne in the Volyn Oblast and the village of Velyki Ozera in the Rivne Oblast. The status of these settlements changed at the time that the countermeasures were implemented. For objective reasons, primarily the agrochemical state of soils, natural lands are and will remain a source of additional intake of radionuclides into the human body with food of animal origin. The problem of their return to economic circulation has become particularly relevant in connection with military actions but is subjectively complicated by bureaucratic procedures for reviewing the status of radioactive contaminated lands. In order to ascertain the feasibility of returning radionuclide-contaminated land to economic circulation, the density of radioactive contamination of soil mustn't exceed the relevant values established by the Law of Ukraine "On the Legal Regime of the Territory Affected by Radioactive Contamination as a Result of the Chornobyl Disaster". The principal criterion for ensuring radiation safety for the population residing in an area contaminated with radionuclides is the value of additional individual doses [1]. The permitted levels of radionuclide activity concentrations in milk and meat are derived from this dose and are set out in PL-2006 [2]. These levels should not exceed the following values:

$$C^0_{^{137}\mathrm{Cs}\,\mathrm{milk}} = 100\ \mathrm{Bq/l}\ \text{and}\ C^0_{^{90}\mathrm{Sr}\,\mathrm{milk}} = 20\ \mathrm{Bq/l};$$

$$C^0_{^{137}\mathrm{Cs}\,\mathrm{muscle}} = 200\ \mathrm{Bq/kg}\ \text{and}\ C^0_{^{90}\mathrm{Sr}\,\mathrm{muscle}} = 20\ \mathrm{Bq/kg}$$

furthermore, the ratio must be met:

$$^{137}\mathrm{Cs}/C^{0}_{137_{\mathrm{Cs}}} + {}^{90}\mathrm{Sr}/C^{0}_{90_{\mathrm{Sr}}} < 1, \qquad (1)$$

where ^{137}Cs (^{90}Sr) is the activity concentration of ^{137}Cs (^{90}Sr) in the observed product, Bq/kg (Bq/l); $C^{0}_{137_{Cs}}\left(C^{0}_{90_{\mathrm{Sr}}}\right)$ – permissible level of ^{137}Cs (^{90}Sr) activity concentration in the product, Bq/kg (Bq/l).

According to many studies, radioactive milk and meat form the main share (up to 80 %) of this additional dose [3, 4].

This paper considers natural lands as a cattle fodder base for milk and meat production in private subsidiary plots and farms. The daily diet of cattle is comprised of meadow grasses during the grazing period and hay during the stall period. The activity concentrations of ^{137}Cs and ^{90}Sr in milk and meat are dependent on the content of these elements in the components of the daily diet of cattle. Meadow grass and hay represent a significant source of ^{137}Cs and ^{90}Sr intake for animals.

Following an evaluation of the actual radionuclide contamination levels in pastures and a comparison of the data obtained with the requirements of Ukrainian legislation, a decision can be made regarding the potential for returning natural lands for economic use. The return of radionuclide-contaminated land (pasture) to economic use is possible in either an unrestricted or conditional manner. The most favourable option is to return the areas of natural lands to economic use without restrictions on the radiation factor. Nevertheless, there are instances when this is not feasible. A realistic assessment of radionuclide content in the harvest of meadow herbage plants will allow the conclusion to be drawn that meadows can be returned to economic use both without restrictions, that is to say without the application of counter-radiation measures, and with the application of a set of organisational and special measures that will ensure the obtaining of final products with radionuclide content in accordance with the PL-2006.

The question of returning a particular pasture to economic circulation to produce milk and meat products was explored through the use of statistical modelling in an experimental manner [5]. This paper considers the aforementioned issue in a general formulation applicable to a wide range of natural forage lands utilized as a cattle feed base for milk and meat production in private subsidiary and farm settings.

2. Objects, main provisions, initial data and forecasting methods

In order to make an informed decision regarding the return of pastures and hayfields that have been contaminated with radionuclides and are no longer economically viable, it is essential to ascertain the extent of contamination with radionuclides, particularly ^{137}Cs and ^{90}Sr. This paper considers the territory that has been contaminated with radionuclides as a result of the Chornobyl accident, which is currently under the administrative control of the Narodychi (Narodychi, Selets and Buliv) united territorial community (Figs. 1 and 2).

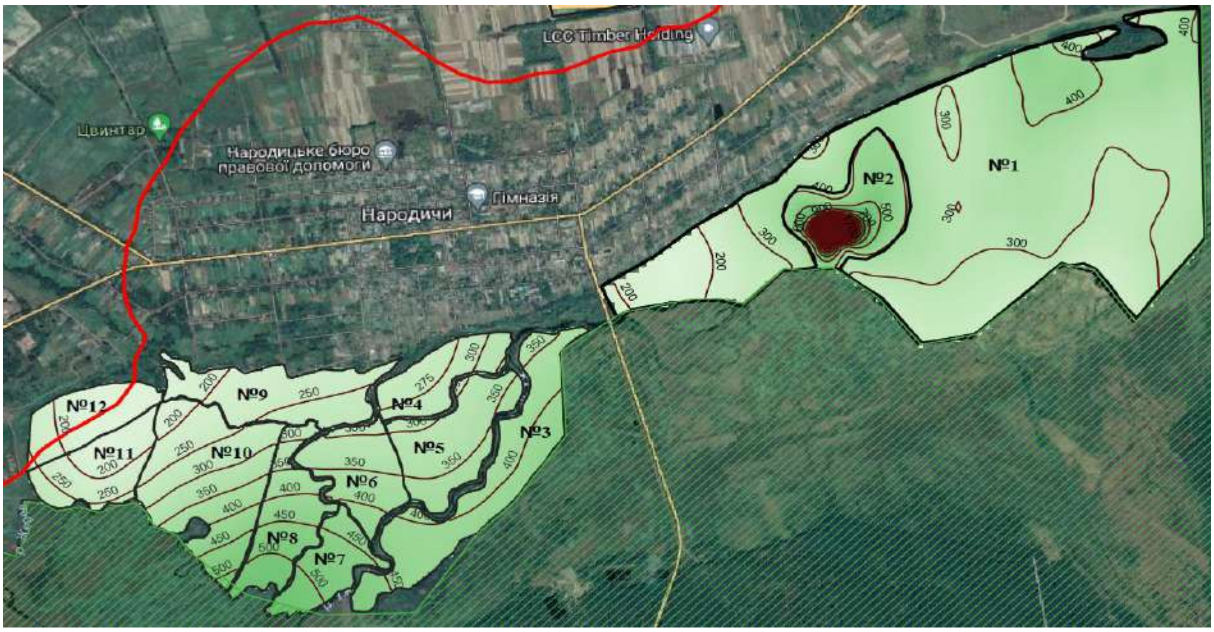

Fig. 1. Density of ^{137}Cs contamination of meadows and pastures near the village of Narodychi as of 2025: – boundary of the zone with caesium isotope contamination density of 555 kBq/m^2 (15 Ci/km^2) and above as of May 1986; – isolines, kBq/m^2. (See color Figure on the journal website.)

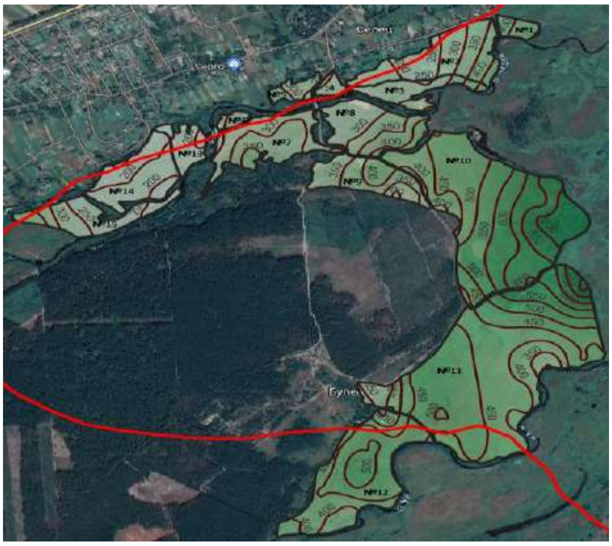

Fig. 2. Density of ^{137}Cs contamination of meadows and pastures near the villages of Selets and Buliv as of 2025: – boundary of the zone with caesium isotope contamination density of 555 kBq/m^2 (15 Ci/km^2) and above as of May 1986; – isolines, kBq/m^2. (See color Figure on the journal website.)

The total area of the 27 conventional pastures and hayfields is 718 ha. This Figure is based on a breakdown of the land area, which corresponds to a modern satellite map. The map includes water bodies, forest belts and the road network. The maps of soil contamination density of pastures and hayfields with ^{137}Cs and ^{90}Sr are consistent with those presented in Figs. 1 and 2 of [6], which also provide a comprehensive account of their characteristics. These lands were previously classified as an unconditional (mandatory) resettlement zone and withdrawn from economic use.

In the course of the radiological surveys of pastures and hayfields, the ambient equivalent dose rate was determined by employing a Stora-TU radiometer-dosimeter. Concurrently, soil and meadow grass samples were collected and analysed for the content of ^{137}Cs using a gamma spectrometer with a semiconductor detector manufactured from high-purity germanium (GEM-30185; EG & ORTEC, USA). Following the radiochemical separation of ^{90}Sr in the soil samples, its content was determined using a method that is generally accepted in the field [7]. This involved measuring the activity of its daughter radionuclide, ^{90}Y, on a beta spectrometer, SEB-01-70 (AKP, Ukraine). A detailed description of this can be found in references [5, 8]. The results of the measurements were used to estimate the actual transfer coefficients (TC) of ^{137}Cs to meadow grasses for the analysed lands.

The results presented in Figs. 1 and 2 demonstrate that the primary area of natural lands situated in the floodplain of the Uzh River in the vicinity of the village of Narodychi exhibits a ^{137}Cs contamination density that falls below the threshold for categorisation as Zone 2, the zone of unconditional (mandatory) resettlement. Consequently, it can be hypothesised that these lands may be returned for economic utilisation. A single site, designated as field No. 2 in Fig. 1, comprising an area of approximately 30 ha, exhibits contamination density that approaches the threshold for classification as Zone 2.

The territory of natural lands situated on the left bank of the Zherev River in the vicinity of the village of Selets is characterised by contamination levels of ^{137}Cs that align with the criteria for the third zone of radioactive contamination. The meadowlands situated in close proximity to the evacuated village of Buliv exhibit an elevated level of radioactive contamination, aligning with the upper threshold of Zone 3 classification (555 kBq/m^2). However, only a portion of fields No. 10 and No. 11 in Fig. 2 displays soil contamination densities exceeding the lower boundary of Zone 2 designation.

The results of scientific studies presented in the literature and our previously obtained data demonstrated that the values of soil contamination with radionuclides, plants, and accumulation (transfer) coefficients at a specific point on the land should be regarded as random variables. This is attributable to the local unevenness of radionuclide deposition and subsequent migration, as well as potential sampling and activity measurement errors. This is clearly illustrated in references [5, 7, 9 - 11], where it is proposed that the results obtained can be well described in the first approximation by the corresponding lognormal probability distribution laws:

$$f(X) = \frac{1}{\sqrt{2\pi} \cdot X \cdot s} e^{-\frac{1}{2}\left(\frac{\ln(X)-\mu}{s}\right)^2}, \qquad (2)$$

where X is the value of the characteristic of radioactive soil contamination at a point; μ and s are the mean value and standard deviation of the logarithm of the value of X. The geometric mean (GM) of the value of X (median) is equal to $\mathrm{GM} = \exp(\mu)$, and the standard deviation is $\mathrm{GSD} = \exp(s)$.

In the context of milk and meat production, contaminated natural land is regarded as a unified entity, exhibiting uneven contamination with radionuclides. In the initial approximation, the density of contamination with radionuclides can be regarded as a random variable with a lognormal probability distribution law. The statistical characteristics of the density of ^{137}Cs and ^{90}Sr contamination of the respective meadows and pastures are presented in Tables 1 and 2, together with additional analysis, in Ref. [6]. These values were determined by combining data from direct and indirect measurements, which provide varying degrees of characterisation of the land's radionuclide contamination density. A detailed description of this methodology can be found in [12 - 14].

Table 1. **Estimates of the characteristics of radioactive contamination of meadows and pastures in the vicinity of Narodychi village as of 2025**

No. of the site	Area, ha	^{137}Cs			^{90}Sr		
		GM, kBq/m^2	GSD	$A_{0.9}$, kBq/m^2	GM, kBq/m^2	GSD	$A_{0.9}$, kBq/m^2
1(H-1)	268.3	311	1.49	520	3.78	1.91	8.7
2(H-2)	28.5	556	1.86	1229	8.33	2.23	23.3
3(H-3)	40.2	403	1.43	640	3.90	1.87	8.7
4(H-4)	17.0	282	1.43	445	2.66	1.87	5.9
5(H-5)	26.8	334	1.43	529	3.19	1.87	7.1
6(H-6)	20.8	351	1.45	563	3.35	1.88	7.5
7(H-7)	15.2	478	1.43	758	4.66	1.36	6.92
8(H-8)	21.9	428	1.48	708	4.14	1.42	6.47
9(H-9)	28.2	230	1.45	372	2.16	1.39	3.28
10(H-10)	46.1	305	1.56	539	2.92	1.51	4.93
11(H-11)	20.0	209	1.47	343	1.95	1.41	3.04
12(H-12)	17.5	181	1.46	295	1.70	1.40	2.61

Table 2. **Estimates of the characteristics of radioactive contamination of meadows and pastures in the vicinity of Selets and Buliv villages as of 2025**

No. of the site	Area, ha	^{137}Cs			^{90}Sr		
		GM, kBq/m^2	GSD	$A_{0.9}$, kBq/m^2	GM, kBq/m^2	GM, kBq/m^2	GSD
1(C-1)	1.4	412	1.43	651.3	3.6	1.87	8.0
2(C-2)	10.7	290	1.48	479.2	2.0	1.90	4.6
3(C-3)	5.7	293	1.46	474.5	2.1	1.89	4.7
4(C-4)	1.1	270	1.43	425.9	2.0	1.86	4.5
5(C-5)	1.8	376	1.62	698.6	2.6	2.02	6.4
6(C-6)	0.8	260	1.43	410.4	2.0	1.86	4.5
7(C-7)	9.2	302	1.44	481.5	2.5	1.87	5.5
8(C-8)	8.8	324	1.47	529.3	2.5	1.89	5.7
9(C-9)	7.2	361	1.44	578.4	3.0	1.87	6.6
10(C-10)	35.9	545	1.48	899.8	5.1	1.90	11.6
11(C-11)	48.6	459	1.47	751.1	3.5	1.89	7.9
12(C-12)	18.2	450	1.44	718.4	3.5	1.87	7.9
13(C-13)	3.1	206	1.43	325.1	1.3	1.86	2.9
14(C-14)	8.5	196	1.44	313.2	1.3	1.87	2.8
15(C-15)	6.4	252	1.50	424.1	2.0	1.92	4.5

The Monte Carlo method was employed for the statistical modelling of the contamination of milk and meat by ^{137}Cs and ^{90}Sr [15]. A comprehensive account of this can be found in reference [5]. In this Section, we will provide a concise overview of the primary provisions and initial data.

The mathematical model of ^{137}Cs and ^{90}Sr intake from soil into cattle milk (muscles) comprises two parts: the transfer of ^{137}Cs and ^{90}Sr to components of the daily diet of cattle; and the transfer of these radionuclides from the daily diet to milk (muscles). The activity concentrations of ^{137}Cs and ^{90}Sr in cattle milk and muscle (C_{milk}; C_{muscle}) are contingent upon the conditions of animal husbandry, specifically whether the animal is pasture-fed or stall-fed. In this study, simplified daily rations for cattle on private subsidiary farms were established (Table 3), based on reference materials and taking into account the seasonal availability of forage.

Table 3. **Daily rations for cattle**

Dietary ingredients	Grazing period		Stall period	
	Milk production	Meat production	Milk production	Meat production
Water, litres	60 ± 10	50 ± 5	60 ± 10	50 ± 5
Grass and hay (air-dry weight), kg	50 ± 8 (12 ± 2)	40 ± 4 (10 ± 1)	12 ± 2	10 ± 1
Compound feed, kg	1 ± 0.2	2 ± 0.2	2 ± 0.2	3 ± 0.2
Soil, kg	0.8 ± 0.1	0.8 ± 0.1	–	–
Potatoes (natural moisture content), kg	–	–	5 ± 1	5 ± 1

During the summer, the cattle were allowed pasture, while during the winter, they were confined to stalls. The rations were based on the consumption of meadow grass during the summer and hay during the winter [16].

Furthermore, it is assumed that during grazing, a dairy cow ingests 50 kg of grass (12 kg of air-dry weight), while a beef cow ingests 40 kg of grass, along with soil [17, 18]. In this study, a model was constructed to simulate the specific activity of ^{137}Cs (^{90}Sr) in cattle milk (muscles). The daily intake of soil via oral intake with grass was assumed to be 0.8 kg.

As stated in [19], the transfer of ^{90}Sr from the soil to the gastric and intestinal juices occurs between 2.0 and 7.4 % of the total activity in the solid phase, with the remaining 1.3 - 3.7 % of ^{137}Cs transferred in a similar manner. In this study, for the purpose of modelling the activity concentration of ^{137}Cs (^{90}Sr) in cattle milk (muscles), it was assumed that up to 3 % of ^{137}Cs and up to 8 % of ^{90}Sr transfer from soil to gastrointestinal juices.

Furthermore, water is regarded as a constituent of the cattle diet. In order to obtain conservative estimates of the activity concentration of ^{137}Cs and ^{90}Sr in milk and meat, it was assumed, as in [5], that the animals consume water from the Uzh River throughout the year. In statistical modelling of the activity concentration of ^{137}Cs (^{90}Sr) in the daily diet, the conservative estimates of the activity concentration of ^{137}Cs and ^{90}Sr in the water of the Uzh River were taken from [20] and recalculated for 2025. The resulting estimates are as follows: the GM of ^{137}Cs in the water of the Uzh River was found to be 0.0048 Bq/l, with a geometric standard deviation (GSD) of 1.35. The GM of ^{90}Sr in the river water was determined to be 0.0126 Bq/l, with a GSD of 1.57.

The content of radionuclides in plants is a dynamic process, dependent on the time (*t*) that has elapsed since contamination of the territory. This is due to the fact that the surface density of deposition and TC are subject to change: $C_{\text{plant}}(t) = \text{TC}(1986+t) \times A(1986+t)$. The dynamics of ^{137}Cs and ^{90}Sr content in plant crops are described in detail in the recommendations [19]. The dynamic model for ^{137}Cs TC proposed in these recommendations is a decreasing asymptotic function that approximates the values of the TC observed in the initial period after the accident and until 2010. Thereafter, the model reaches a plateau for each crop. A similar pattern is observed in the dynamic model for the ^{90}Sr TC. Accordingly, to forecast the radionuclide content of the cattle plant diet components for the period subsequent to 2020, the following ratio was employed in this study:

$$C_{\text{plant}} = \text{TC} \cdot A_s, \quad (3)$$

where the TC of ^{137}Cs (^{90}Sr) to plants (or their parts) is defined as the ratio of the activity concentration of ^{137}Cs (^{90}Sr) in air-dry mass or natural humidity to the activity concentration of ^{137}Cs (^{90}Sr) in soil (Bq/kg)/(kBq/m²). A_s is a density of ^{137}Cs (^{90}Sr) contamination of soil, (kBq/m^2).

The lognormal distribution of TC and A_s, in conjunction with the aforementioned relation (3), also permits the description of the distribution of potential values of the activity concentration of ^{137}Cs (^{90}Sr) C_{plant} for plant components of the daily animal diet, which is also characterised by the lognormal law.

In the case of herbs, the aforementioned relationship (3) was employed in order to ascertain the activity concentration of ^{137}Cs (^{90}Sr). To estimate the ^{137}Cs activity concentration in the air-dry mass of meadow grass (hay), the averaged values of the activity concentration obtained by the National University of Life and Environmental Sciences of Ukraine staff based on the results of ^{137}Cs measurements in soil and plant samples taken in the meadows and pastures under consideration, as illustrated in Figs. 1 and 2, during the 2022 - 2023 period, were employed. In instances where additional data were required, literature sources were consulted. These estimates were extended to 2025, with consideration given to the asymptotic nature of the dynamic model [21]. In the case of ^{137}Cs in the air-dry mass of meadow grass (hay), the values are equal to: GM = 4.72 (Bq/kg)/(kBq/m^2), GSD = 1.9. The ratio between the TC of ^{137}Cs in the hay of natural grasses and the green mass of meadow grass at natural moisture, as reported in [22], is 4.7, while the ratio as reported in [21] is 4.1. In the present study, this ratio was taken to be 4.4. It can therefore be stated that the statistical characteristics of the ^{137}Cs TC for the green mass of meadow grass from natural pastures are equal to: GM = 1.07 (Bq/kg)/(kBq/m^2), GSD = 1.9.

The low content of ^{90}Sr in soil and herbage samples precluded the possibility of obtaining reliable statistical data on the TC of ^{90}Sr in the soil-herbage chain on the surveyed lands. Accordingly, in the present study, the averaged literature values of statistical characteristics of ^{90}Sr TC for forbs in meadows and pastures of Ukraine [23] and Belarus [24] on sod-podzolic sandy loam and sandy soils were employed. All estimates were extended to 2025, with consideration given to the asymptotic nature of the dynamic model [21]. The respective estimates are as follows: for hay from natural pastures, GM = 16.98 (Bq/kg)/(kBq/m^2), GSD = 1.45; for the green mass of grass from natural pastures, GM = 3.93 (Bq/kg)/(kBq/m^2), GSD = 1.49.

The statistical characteristics of the activity concentration of ^{137}Cs (^{90}Sr) in potatoes and fodder (locally produced grain) were taken as averages based on the results of [23] for arable land near the village of Narodychi. The mean value for grain was for ^{137}Cs – GM = 10.0 Bq/kg, GSD = 1.78; for ^{90}Sr – GM = 4.4 Bq/kg, GSD = 1.95; the mean value for potatoes was for ^{137}Cs – GM = 6.0 Bq/kg, GSD = 2.0; ^{90}Sr – GM = 1.0 Bq/kg, GSD = 2.2.

The soil is ingested by cattle as part of their diet, particularly grass from the surface soil layer. In this study, the specified layer is the 0 - 5 cm layer. The specific activity of ^{137}Cs (^{90}Sr) in the surface soil layer for each land type was estimated as follows:

$$A_{5\,\mathrm{cm}} = d \cdot A_s / 0.05 \cdot \rho, \tag{4}$$

In the following equation, d represents the fraction of activity in the surface 5 cm soil layer, and A_s is the density of ^{137}Cs (^{90}Sr) contamination of soil, as presented in Tables 1 and 2 (kBq/m^2). In accordance with [24], the mean value for sod-podzolic soils in 2020 is as follows: for ^{137}Cs, d = 68.8 % of the total activity; for ^{90}Sr, d = 43.5 % of the total activity. The density of air-dry soil mass, ρ = 150 kg/m^3, is taken in accordance with [25] as an average value for soil samples taken in meadows and pastures (see Figs. 1 and 2).

In general, the activity concentration of radionuclides in milk and meat of cows is a dynamic process that can be conditionally described by a model under a fixed diet:

$$C_{\mathrm{milk}}(t) = F_{\mathrm{milk}} \cdot \sum_{j=1} m_j \cdot C_j(t);$$

$$C_{\mathrm{muscle}}(t) = F_{\mathrm{muscle}} \cdot \sum_{j=1} m_j \cdot C_j(t). \tag{5}$$

In this study, we assume that the specific content of radionuclides in the components of the daily diet remains constant over time and can be considered a random variable. In this case, the activity concentration of ^{137}Cs (^{90}Sr) in the milk (muscles) of cows can be calculated as a first approximation by the following formulas:

$$C_{\mathrm{milk}} = F_{\mathrm{milk}} \cdot \sum_{j=1} m_j \cdot C_j;$$

$$C_{\mathrm{muscle}} = F_{\mathrm{muscle}} \cdot \sum_{j=1} m_j \cdot C_j. \tag{6}$$

The primary characteristic of this study is the random nature of the variables involved, including soil contamination with ^{137}Cs and ^{90}Sr, soil-plant TC, diet-milk (F_{milk}) and diet-muscle (F_{muscle}). These variables are distributed according to the laws of the lognormal probability distribution.

The predicted values of the activity concentration of ^{137}Cs and ^{90}Sr in the milk and meat of cattle will be random variables that are functions of other random variables. However, in general, they will not be described by lognormal probability distribution laws, as they are not multiplicative functions of random variables with lognormal probability distribution laws [20]. Consequently, to ascertain the probability distribution of the activity concentration of ^{137}Cs and ^{90}Sr in milk and meat, the statistical modelling method (Monte Carlo) was employed directly in the study [15, 26]. This enabled the estimation of the activity concentration $C_{\mathrm{milk}}(C_{\mathrm{muscle}})$, median $\mathrm{GM}_{\mathrm{milk}}(\mathrm{GM}_{\mathrm{muscle}})$, $\mathrm{GSD}_{\mathrm{milk}}(\mathrm{GSD}_{\mathrm{muscle}})$, and the interval $C^{\min}_{C_{\mathrm{milk(muscle)}}} \le C_{C_{\mathrm{milk(muscle)}}} \le C^{\max}_{C_{\mathrm{milk(muscle)}}}$ in which the true value of $C_{\mathrm{milk}}(C_{\mathrm{muscle}})$ is located with a given probability P. In obtaining these estimates, one of the main parameters is the TC of ^{137}Cs and ^{90}Sr from the daily diet to milk (F_{milk}) and meat (F_{muscle}). In accordance with the findings of reference materials [26, 27], these variables are random and are characterised by lognormal probability distribution laws. The characteristics of these substances in the absence of radionuclide-sorbing impurities are provided in Table 4. The utilisation of fodder mixtures incorporating ferrocin has been demonstrated to reduce the mean value of the TC for ^{137}Cs from the daily diet to milk by a factor of 4.1 and to muscles by a factor of 5 [28]. The intake of ^{90}Sr in animals is not affected by the use of ferrocin.

Table 4. **Average statistical characteristics of ^{137}Cs and ^{90}Sr TC from the daily diet into milk and muscles of cows [21, 28, 29]**

Conversion rate from daily ration	^{137}Cs		^{90}Sr	
	GM	GSD	GM	GSD
in milk F_{milk} during the stall period	0.0071	2.0	0.0015	1.7
in milk F_{milk} during the grazing period	0.0091	2.0	0.0015	1.7
in the muscle F_{muscle}	0.04	2.4	0.001	2.9

An understanding of the laws governing the distribution of potential values for the activity concentration of ^{137}Cs and ^{90}Sr in milk and meat enables the evaluation of the risks (probabilities) q of exceeding the activity concentration of ^{137}Cs and ^{90}Sr in these products in accordance with established standards.

This evaluation is conducted for each radionuclide $q = 1 - F\left((Ln(C^0) - Ln(GM))/Ln(GSD)\right)$ and for their combination $q_{\Sigma} = Ver\left\{\left({}^{137}\mathrm{Cs}/C^0_{^{137}\mathrm{Cs}} + {}^{90}\mathrm{Sr}/C^0_{^{90}\mathrm{Sr}}\right) \geq 1\right\}$, where $F(\ldots)$ is the Gau-s distribution function.

3. Results and discussion

In accordance with the methodology delineated in Section 1, the statistical attributes of the activity concentration of ^{137}Cs and ^{90}Sr in milk and cattle muscles (median, GSD, upper limit C^P_{plant} for $P = 0.9$) were calculated for their production utilising the analysed fields, both in the absence of countermeasures and with the incorporation of a caesium sorbing agent, namely ferrocin, in a mixture with feed. The results of the calculations are presented in the form of bar charts in Figs. 3 - 7 for milk and in Figs. 8 - 12 for muscles. The values C^P_{plant} are plotted in an upward direction.

The results of the ^{137}Cs content prediction in the milk of cows (see Fig. 3), whose diet will consist exclusively of pasture grass of the studied forage lands located near the settlements of Narodychi and Selets, demonstrate that the radioactivity of milk will exceed the requirements of state hygiene standards for both the grazing and stall periods of dairy cattle keeping.

The results presented in Fig. 4 demonstrate that milk contamination levels of ^{90}Sr from cows grazing on pasture within the vicinity of the settlements of Narodychi, Selets and Buliv will be markedly lower than the requirements set forth by state hygiene standards.

The results of the risk calculations for the combination of radioactive isotopes ^{137}Cs and ^{90}Sr in cow milk (PL-2006), presented in Fig. 5, demonstrate that such a risk exists on all studied forage lands, with values ranging from 0.42 to 0.9 (from 42 to 90 %, respectively). With regard to the period spent in stalls, the risk of exceeding the established standards is lower than during pasture periods, provided that each pasture is considered separately. In consideration of the results presented in Fig. 3, it can be concluded that the primary contributor is radioactive caesium.

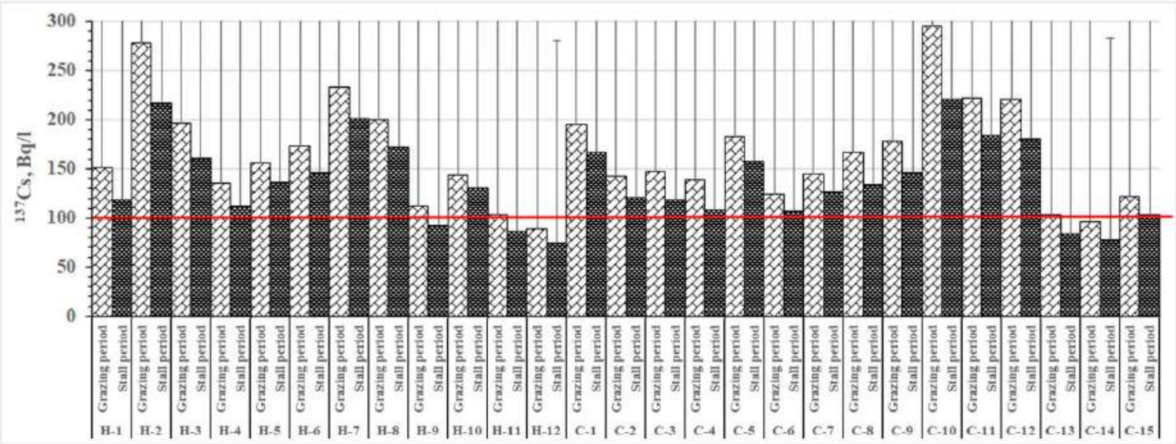

Fig. 3. Predicted ^{137}Cs content in cow milk in 2025 without countermeasures: maximum permissible level (MPL). (See color Figure on the journal website.)

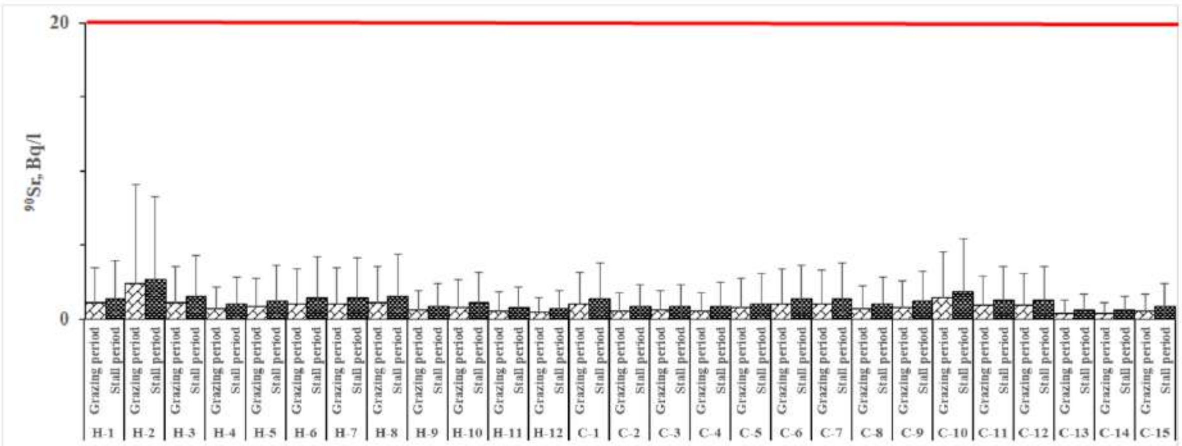

Fig. 4. Predicted ^{90}Sr content in cow milk in 2025 without countermeasures: MPL. (See color Figure on the journal website.)

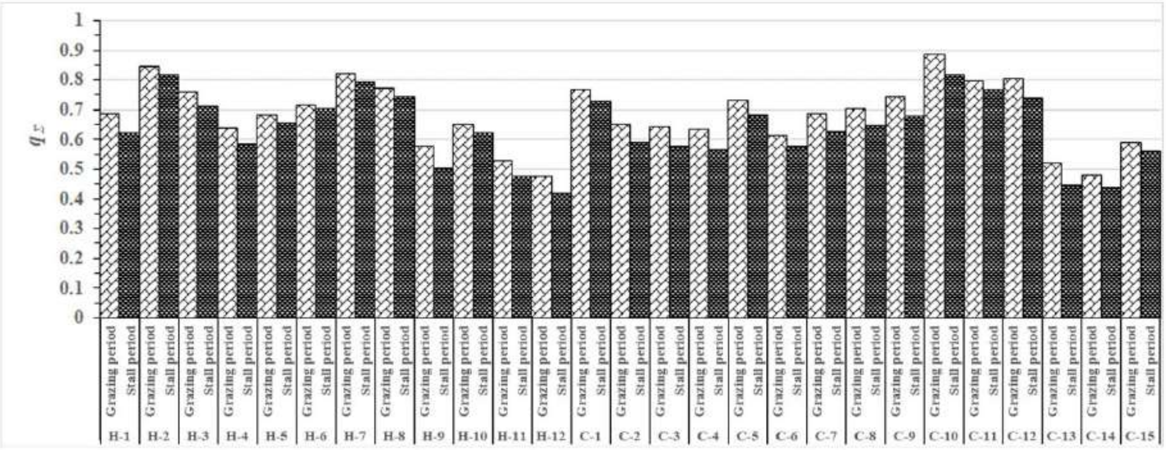

Fig. 5. Risks of exceeding the established standards for ^{137}Cs and ^{90}Sr activity concentration in cow milk in 2025 without the use of countermeasures: $q_\Sigma = Ver\left\{\left({}^{137}Cs / C^0_{137_{Cs}} + {}^{90}Sr / C^0_{90_{Sr}}\right) \geq 1\right\}$.

The data presented in Fig. 6 demonstrate that the issue of exceeding the requirements of state hygiene standards for ^{137}Cs activity concentration in cow milk has been effectively addressed through the utilisation of a selective ^{137}Cs sorbent, namely ferrocin (ferrous hexacyanoferrate or its analogues). The efficacy of this approach was initially evaluated during the acute phase of the Chornobyl accident. Concurrently, alternative strategies for enhancing fodder lands and livestock husbandry in radionuclide-contaminated regions were devised [22, 29].

The data presented in Fig. 7 suggests that, despite the efficacy of caesium-sorbing additives, the probability of exceeding radionuclide content in cow milk remains at the level of 5 to 40 %, contingent on the field utilized for grazing. However, this risk is considerably lower than that depicted in Fig. 5.

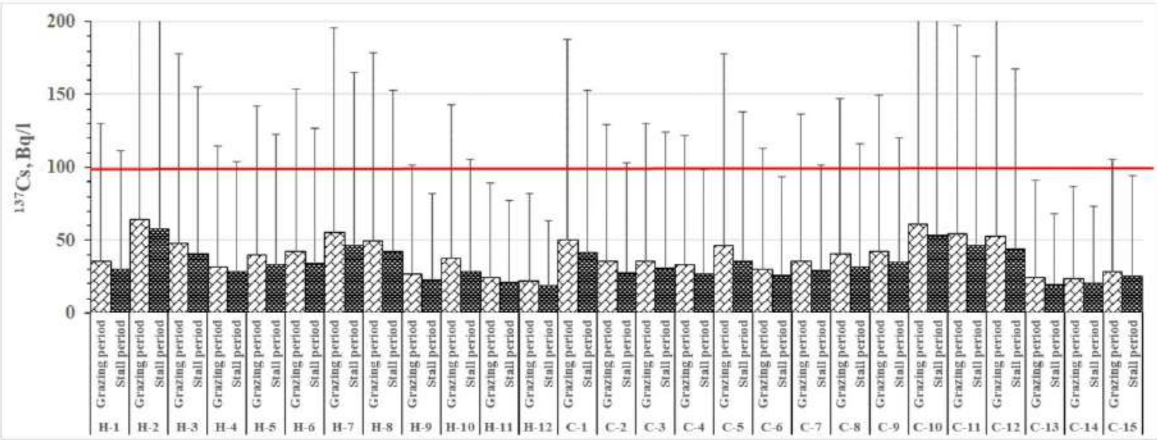

Fig. 6. Predicted ^{137}Cs content in cow milk in 2025 with the use of ferrocin: ▬ MPL.

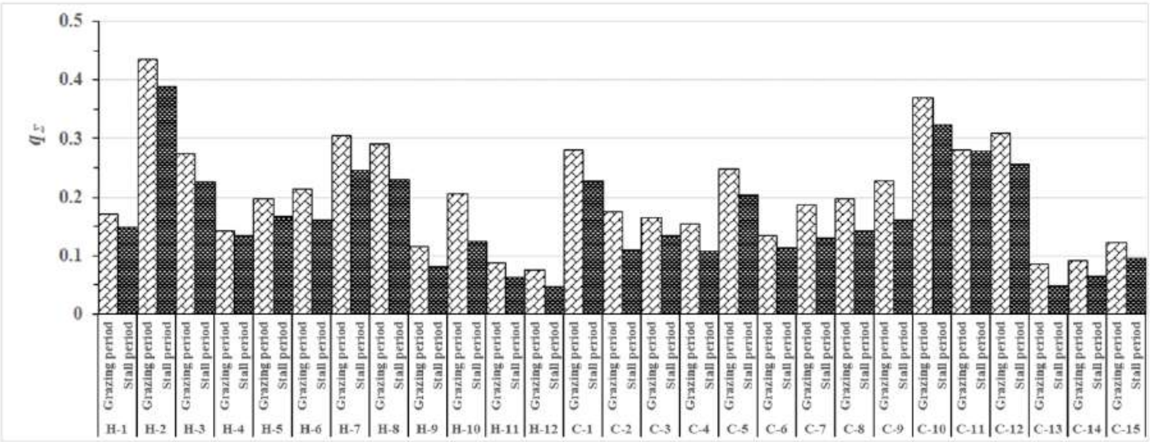

Fig. 7. Risks of exceeding the established standards for ^{137}Cs and ^{90}Sr activity concentration in cow milk in 2025 with the use of ferrocin: $q_\Sigma = Ver\left\{\left({}^{137}Cs / C^0_{137_{Cs}} + {}^{90}Sr / C^0_{90_{Sr}}\right) \geq 1\right\}$.

The TC of radioactive caesium (^{137}Cs) to the muscle tissue of cattle are four times higher than for milk [29]. Consequently, beef production under the same conditions of cattle keeping is accompanied by a higher probability of exceeding the PL-2006 limits, as illustrated in Fig. 8.

The low level of ^{90}Sr contamination of the soils of the studied lands, coupled with the low TC of this isotope to muscle tissue on all studied lands, ensures that beef will meet the requirements of the PL-2006 (see Fig. 9).

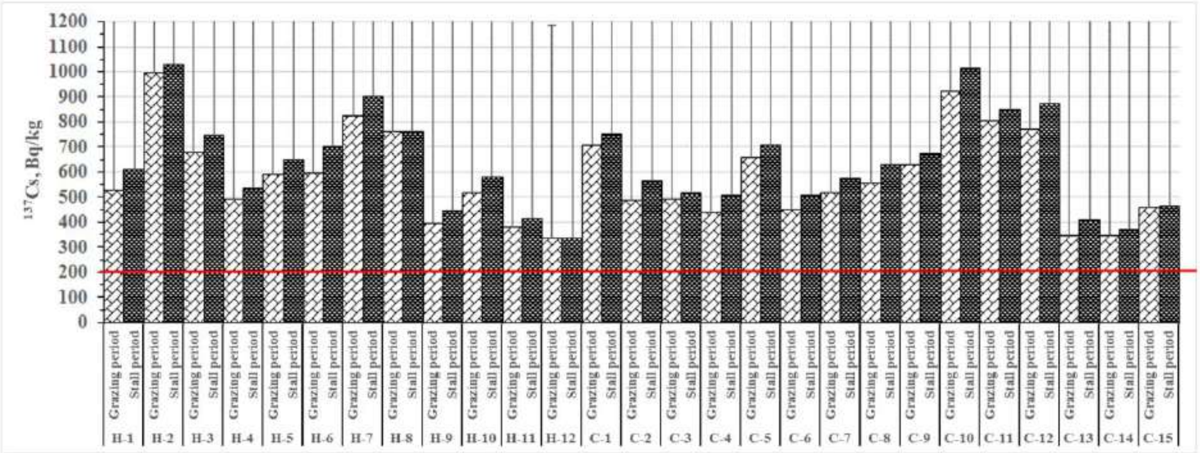

Fig. 8. Predicted ^{137}Cs content in cow muscles in 2025 without countermeasures: ▬▬ MPL.
(See color Figure on the journal website.)

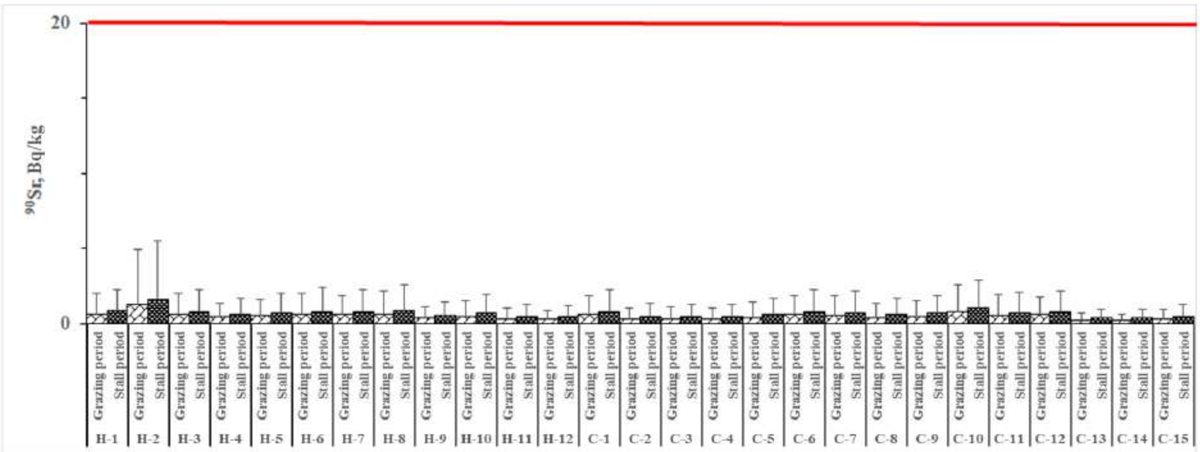

Fig. 9. Predicted ^{90}Sr content in cow muscles in 2025 without countermeasures: ▬▬ MPL.
(See color Figure on the journal website.)

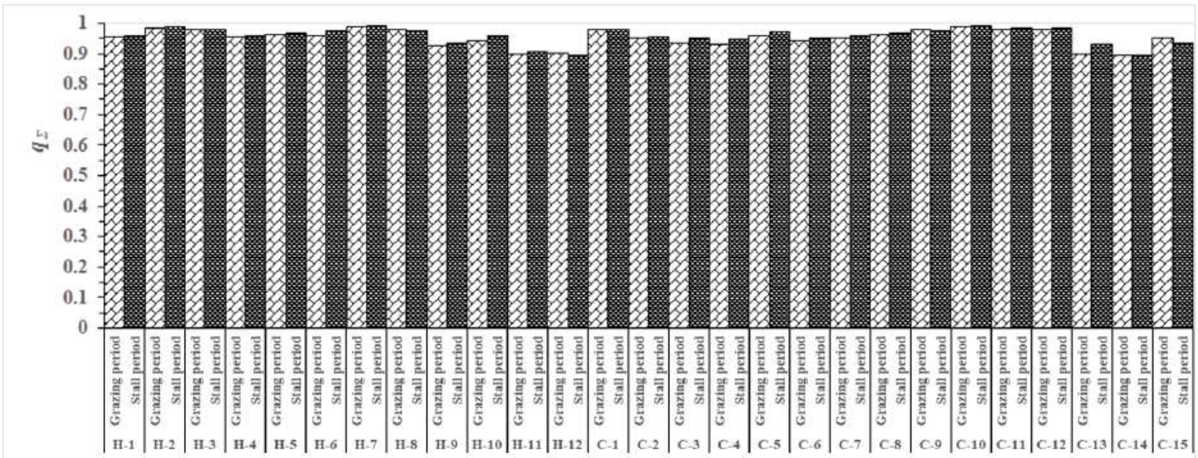

Fig. 10. Risks of exceeding the established standards for ^{137}Cs and ^{90}Sr activity concentration in cow muscles in 2025 without countermeasures: $q_\Sigma = Ver\left\{\left({}^{137}Cs / C^0_{137_{Cs}} + {}^{90}Sr / C^0_{90_{Sr}}\right) \ge 1\right\}$.

The results of the risk calculations for exceeding the established standards for the total content of ^{137}Cs and ^{90}Sr in cow muscles, as illustrated in Fig. 10, underscore the critical nature of this product type that can be obtained using these feedlands. This issue can be partially addressed through the incorporation of caesium-sorbing additives into the diet of adult cattle, akin to milk production (see Fig. 11). However, for the production of beef, there are avenues for the implementation of organisational, agrotechnical and zootechnical measures that will facilitate the attainment of premium meat products on these lands.

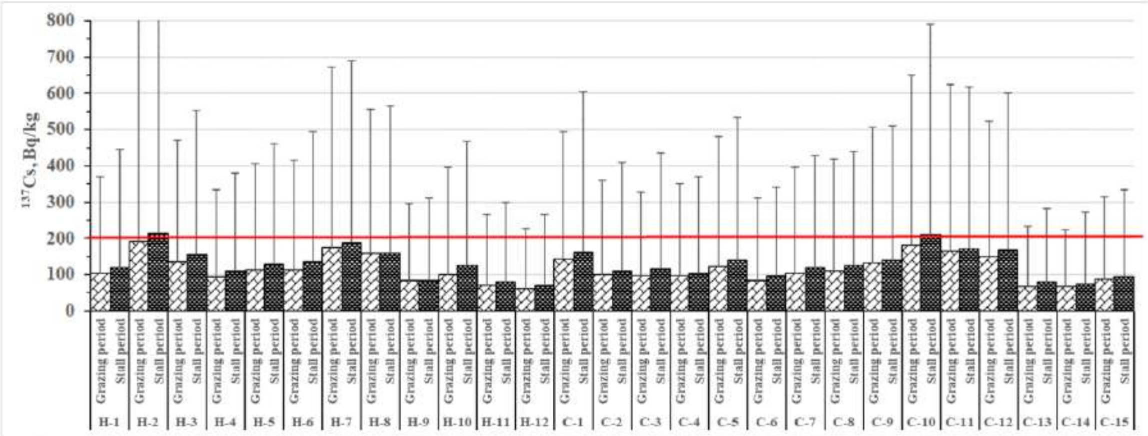

Fig. 11. Predicted ^{137}Cs content in cow muscles in 2025 with the use of ferrocin: MPL.
(See color Figure on the journal website.)

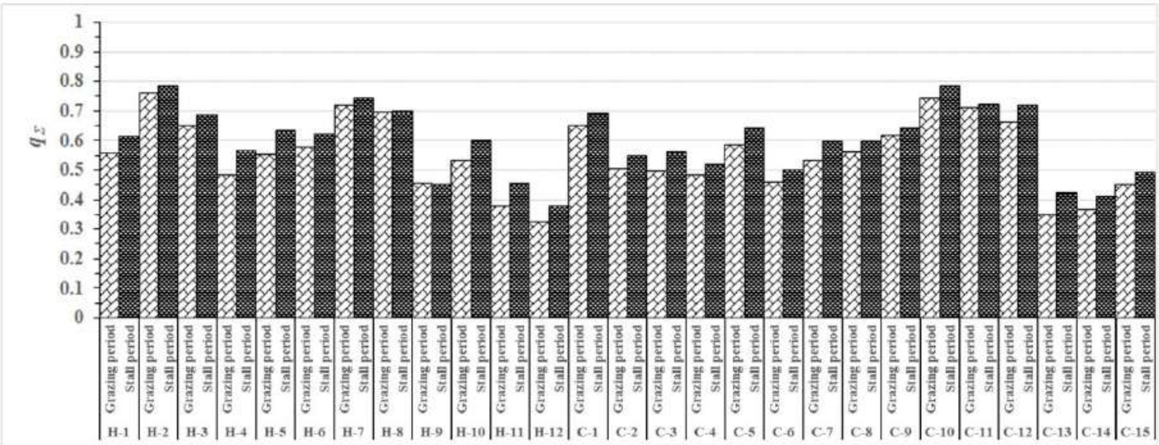

Fig. 12. Risks of exceeding the established standards for ^{137}Cs and ^{90}Sr activity concentration in cow muscles in 2025 with the use of ferrocin: $q_\Sigma = Ver\left\{\left({}^{137}Cs / C^0_{137_{Cs}} + {}^{90}Sr / C^0_{90_{Sr}}\right) \geq 1\right\}$.

The data presented in Fig. 12 indicates that despite the efficacy of caesium-sorbing additives, the probability of exceeding the permissible levels of radionuclides in cow muscles remains at the range of 35 to 80 %, contingent on the field utilized for grazing. However, this risk is significantly lower than that depicted in Fig. 10. Consequently, when utilising specific pastures, it may be imperative to implement supplementary organisational, agrotechnical and zootechnical measures to diminish the activity concentration of radionuclides in cow muscles and guarantee adherence to hygiene standards (PL-2006).

4. Conclusions

The radiation situation in natural meadows situated in the floodplains of the Uzh and Zherev rivers was examined, the density of radioactive contamination of the soil in these areas was determined, and statistical modelling of livestock production was conducted to ascertain the compliance of radioactive contamination of these products with the requirements of the PL-2006.

1. The results of the statistical modelling demonstrated that ^{137}Cs are the primary radioactive contaminant in the meadows and pastures under study. It can be reasonably deduced that if 25 % of the pastures and hayfields in question are utilised, the average ^{137}Cs content in milk samples from 2025 onwards will not exceed the established standards in the absence of any countermeasures. Nevertheless, the projected overall risk of exceeding ^{137}Cs and ^{90}Sr remains considerable (exceeding 40 %). The application of ferrocin as a countermeasure will ensure

that the average ^{137}Cs content in milk samples from 2025 onwards will meet the established standards for all sites under consideration. The predicted overall risk of exceeding the ^{137}Cs and ^{90}Sr content of the established standards is, on average, approximately ≈ 20 %.

2. The findings of the statistical modelling indicated that, in the absence of countermeasures, the utilisation of natural lands would result in an average ^{137}Cs content in cow muscles that exceeds the established standards. The projected risk of exceeding the ^{137}Cs and ^{90}Sr content is exceedingly high (exceeding 90 %). The utilisation of ferrocin as a countermeasure will ensure that the average ^{137}Cs content in cow muscle is in accordance with the established standards for all considered lands. The predicted overall risk of exceeding the established standards for ^{137}Cs and ^{90}Sr is, on average, less than ≈ 5 %.

3. It should be noted that the most conservative approach was employed in the statistical modelling, given that the diet primarily comprises pasture grass during the summer months and hay is also harvested from these lands during the winter. In practice, the situation appears more favourable, as in the private sector, owners provide their dairy cattle with grain meal or herbs from their gardens, and hay can be harvested from arable land, where the TC is considerably lower than in natural habitats.

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М. М. Лазарєв[1], Ю. В. Хомутінін[2,*], О. В. Косарчук[2], В. В. Іллєнко[1], В. В. Павлюченко[2], Д. М. Лазарєв[1], А. В. Клепко[1], Т. Р. Андрійчук[3]

[1] *Національний університет біоресурсів і природокористування України, Київ, Україна*
[2] *Український науково-дослідний інститут сільськогосподарської радіології, Чабани, Київська область, Україна*
[3] *Київський національний університет імені Тараса Шевченка, Київ, Україна*

*Відповідальний автор: khomutinin@gmail.com

СУЧАСНИЙ РАДІОЛОГІЧНИЙ СТАН ПРИРОДНИХ ЛУКІВ ЗОНИ БЕЗУМОВНОГО (ОБОВ’ЯЗКОВОГО) ВІДСЕЛЕННЯ НАРОДИЦЬКОЇ ОБ’ЄДНАНОЇ ТЕРИТОРІАЛЬНОЇ ГРОМАДИ ЖИТОМИРСЬКОЇ ОБЛАСТІ І ПЕРСПЕКТИВИ ЇХНЬОГО ВИКОРИСТАННЯ У ЯКОСТІ КОРМОВОЇ БАЗИ ХУДОБИ

Проведено радіологічне обстеження природних луків навколо населених пунктів Народицької об’єднаної територіальної громади, забруднених радіонуклідами внаслідок аварії на ЧАЕС, і оцінено можливість повернення їх у господарський обіг. За допомогою методу ймовірнісного моделювання зроблено прогноз вмісту радіонуклідів ^{137}Cs і ^{90}Sr (медіана, геометричне стандартне відхилення, верхня межа для $P = 0,9$) у молоці та м’язах великої рогатої худоби та оцінено ризики перевищення вимог встановлених державними гігієнічними нормативами (ДР-2006) щодо вмісту радіонуклідів у цій продукції. Показано можливість використання сіножатей і пасовищ для виробництва молока і м’яса великої рогатої худоби. Ці результати є основою рекомендацій і прийняття рішень щодо повернення цих угідь у господарське використання.

Ключові слова: радіоактивне забруднення, питома активність, пасовища, сіножаті, молоко, м’ясо, повернення до сільськогосподарського обігу.

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