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RADIOLOGICAL EFFICIENCY OF AGRICULTURAL COUNTERMEASURES APPLIED IN RADIOCONTAMINATED FIELDS

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Abstract. Implementation of agricultural countermeasures is one of the principal methods that allow to decrease irradiation doses. Summarizing available information about countermeasures and taking into account the experience in the elimination of the nuclear accident consequences, it is demonstrated that the most widespread countermeasures after the Chernobyl accident were soil ameliorations. These methods are simple, inexpensive and effective in reducing radionuclide transfer from the soil to agricultural crops. Among the above mentioned methods, agrotechnical countermeasures were the most applicable, decreasing the contamination of plant products up to 20 times. Radical and surface improvements of natural and semi-natural meadows were carried out on a large scale on contaminated lands. The biggest decrease of vegetation contamination was observed after the radical improvement of meadows, with and without drainage, 43 and 16 times, respectively. Other effective measures are agrochemical methods. In fact the application of various fertilizers permitted to decrease the radioactive contamination of production averagely 2–3 times. Potassium fertilizers were the most effective for the decrease of ^{137}Cs transfer to harvested crops. Application of sorbing minerals decreased ^{137}Cs transfer to crops from a peaty soil up to 11 times, and from a sod-podzolic soil up to 3 times. Moreover, these countermeasures increased the yield and improved the quality of products.

Keywords: radioactive contamination, ^{137}Cs, ^{90}Sr, agricultural crops, countermeasures, efficiency.

1. Introduction

As a result of the Chernobyl accident a large territory of the Ukraine was exposed to radioactive contamination. 42 000 km^2 have been contaminated by ^{137}Cs with the density above 37 kBq/m^2, and 28 000 km^2 – by ^{90}Sr with the density above 5,55 kBq/m^2 [1].

Reduction of the internal doses of human irradiation is the main purpose of restoration actions in contaminated areas. The implementation of countermeasures is important, and sometimes it is the principal method that permits to decrease the doses, because limiting the consumption of local products is not always a practical and feasible requirement.

The main problems that had to be solved after the Chernobyl accident were optimization of countermeasure application and elaboration of rehabilitation strategy on contaminated lands in different periods after the accident. Urgency of the problem was predetermined by the large scale of environmental pollution and the necessity of application of protective measures in vast areas during a long period, which, therefore, required significant financial support. The solution of this problem involved various factors. The principal ones are as follows: assessment of contamination of arable lands and products; the characteristic of soils in the polluted area; zonal peculiarities of agricultural farming (land-use, orientation of industry, technologies of crops production), efficiency of countermeasures on various land types; changes of countermeasure efficiency in time [2, 3].

Many authors assessed the role of species and varieties characteristics in pollutant accumulation [4–6].

The most significant decrease of radionuclide transfer to the agricultural crop yield was observed after the fertilization of poor soils with a light granulometric composition [7–9]. At the same time, the effect of fertilization on fertile soils was very low [10, 11]. Application of enhanced doses of phosphorous fertilizers decreases ^{137}Cs transfer to crops from sod-podzolic sandy-loamy and sandy soils 2–2,5 times, and ^{90}Sr transfer – up to 8 times [12]. Organic fertilizers decrease ^{137}Cs transfer to crop yield 1,5–3 times, the biggest effect was observed on light soils [13–15].

Some of these protection measures can be applied with restriction, others are applied widely. Generalizing available information on countermeasures and considering the experience in nuclear accident elimination, we can conclude that for minimization of the accidental consequences, it is necessary to apply all acceptable measures. However, at present the general strategy of countermeasure implementation leads to the reduction of the internal doses of human irradiation from the consumption of food stuffs containing radionuclides. The value of population dose, averted by the countermeasure implementation, should be regarded as the first criterion for the evaluation of countermeasure efficiency. The next criterion should be the cost of a unit of averted population dose and the total financial investments for the implementation of countermeasures [16].

Publications of the International Commission of Radiation Protection and Standards of Radiation Safety in the Ukraine [17] state that the implementation of countermeasures (or intervention) should be based on the following two general principles:

– justification: countermeasure shall be justified when the produced sufficient benefit to exposed individuals or to society offsets the radiation detriment it causes;

– optimization: countermeasure shall be optimal when the difference between the total benefit and total detriment is maximal.

Important condition of countermeasure application, in a long-term period, is to guarantee maximal effect and minimal expenses. Reducing internal irradiation is more reliable and cost-effective than reducing external irradiation. Also, exclusion from the diet of agricultural food products with radionuclide content above permissible levels is very important both in social and psychological aspects and will help to prevent the spread of radiophobia among the population. Therefore, we need to evaluate the efficiency of the wide range of protective measures developed during the 20-year period after the Chernobyl accident. The above mentioned approaches to the analysis of countermeasures efficacy are adduced in the present work.

2. Materials and methods

The studies were carried out in long-term field experiments on the radioactively-polluted lands of Polessje and Chernozem zone of the Ukraine in the most contaminated regions: Chernigov, Kiev, Zhitomyr, Rovno and Volyn. Deposition of ^{137}Cs in the soil varies from 34 to 25 000 kBq/m^2 and that of ^{90}Sr – 5–140 kBq/m^2. Sod-podsolic, grey forest and peaty soils are the dominant types of soil in Polessje. The soils of Chernozem zone are represented by chernozems. Table 1 shows the agrochemical properties of the investigated soils. Soil properties widely varied, and that allowed to evaluate the efficiency of countermeasures under different conditions. Influence of agrotechnical and agrochemical countermeasures reducing yield contamination was studied in field experiments on meadows and arable lands radiocontaminated due to the Chernobyl accident. Cultivation and amelioration of fields were carried out according to the local agrotechnical and agronomic practices.

Samples of plants were taken in the stage of production ripeness during harvesting. Soil samples were taken at the same time from the upper 20 cm plough-layer on arable lands, and at 10 cm depth on meadows.

Table 1. Agrochemical properties of investigated soils

Type of soil	Texture		Content of physical clay, %	Bulk density of soil, mg/cm^3	Acidity, pH_{KCl}	Humus, %	Exchangeable calcium (Ca^{2+}), cmol/kg	Exchangeable magnesium (Mg^{2+}), cmol/kg	Extractable potassium (K^+), cmol/kg	Extractable phosphorus (P), mg/kg	CEC, cmol/kg
	Name	n									
Sod-podzolic	Medium loam	204	–	1,3–1,4	6,8–7,4	0,9–1,6	2,4–5,48	0,12–0,58	0,02–0,26	12,4–46,3	2,81–6,46
Sod-podzolic	Loamy sand	948	–	1,2–1,48	4,2–6,8	0,7–2,4	0,7–4,6	0,16–1,7	0,095–0,77	34,9–156	3–45
Sod-podzolic	Sandy	24	–	1,3	4,9	1,2	0,6	0,25	0,21	101	13,5
Sod-podzolic mid-gley	Medium loam	36	20,1–23,1	1,2–1,3	4,8–5,8	1,6–1,7	3,2–4,5	0,7–1,2	0,17–0,28	69–195	6,9–9,4
Sod-podzolic mid-gley	Loamy sand	79	10,5–16,5	1,3–1,4	5,3–5,9	1,3–2,4	3,4–5,5	0,3–1,3	0,15–0,33	100–221	4,9–7,4
Sod-podzolic mid-gley	Sandy	186	5,1–7,9	1,3–1,5	5,3–5,8	1,6–2,4	3,2–5,5	0,3-–0,6	0,1–0,17	140–294	5,9–8,0
Chernozem typical	Medium loam	185	33,5–35,5	1,2	4,7–5,9	5,9–7,0	20,1–26,5	2,1–3,8	0,27–0,43	89–157	22,2–35,4
Grey forest	Medium loam	42	33,6	1,2	4,8	2,4	6,7	1,4	0,28	80	12,3
Soddy strongly gley	Loamy sand	10	12,1	1,0	4,8	4,5	4	0,8	0,13	33	17,1
Peaty	–	48	–	0,1–0,3	4,7–6,5	–	2,3–3,7	0,43	0,18–0,61	44–370	5–83

^{137}Cs content was detected in 100 g of samples by the gamma-spectrometry method using low-background high resolution gamma-spectrometers, with passive shielding: a semi-conducting detector of pure germanium GEM-30185, and a Ge(Li) detector of GMX-series ("EG&G ORTEC"), with multichannel analyzers (ADCAM-300; IN-1200). ^{90}Sr was determined by the radiochemical method. Agrochemical analysis of soils was carried out by standard techniques. Absorption capacity (T) was calculated by the addition of the sum of exchangeable bases (S) to hydrolytic acidity (H_H): $T=S+H_H$. pH of the salt extract was detected potentiometrically. Exchangeable calcium was also determined potentiometrically. Humus was determined by the Turine technique, based on the organic matter oxidation with chromic acid till the carbon dioxide formation. Determination of mobile phosphorus was carried out by the Kirsanov technique. Exchangeable potassium was determined by the method of Maslova. Statistic processing of the data was performed by Statistica 6.0 and S-Plus 6 programs [18].

For the estimation of countermeasure efficiency, a specific data base (DB) "Countermeasures" was developed that consists of two separate sub-DBs: "Plant production" and "Meadow ecosystems". The sequential system of differentiated application of countermeasures for the restriction of radionuclide transfer from the soil to foodstuffs served as a basis of the conceptual structure of the DB. The analysis of countermeasure efficiency is based on the following criteria: a) radiological evaluation expressed by the *reduction factor* of a radionuclide content in a product as a result of countermeasure application, and b) productivity evaluation expressed by the *increase factor* of a yield as a result of countermeasure application.

The reduction factor of radionuclide content in products is the main criterion in estimating the possibility to produce foodstuffs within local standards and determining the time period for application of countermeasures in zones with various levels of radioactive contamination. Productivity evaluation is an additional criterion for the estimation of countermeasure efficiency.

These two criteria are used in the two sub-DBs "Plant production" and "Meadow ecosystems". Sub-DB "Plant production" includes 1328 experiments of countermeasure application on arable lands (Table 2). The influence of countermeasures on ^{137}Cs and ^{90}Sr accumulation in plant products are described in 1240 and 88 cases, respectively. Typical agricultural crops for Polessje and Chernozem zone of the Ukraine were studied and described in this DB.

The countermeasures that include application of agrochemical means and change of species and varieties are the most common in agricultural practices, and they were most widely used after the Chernobyl accident (Table 3).

The sub-DB "Meadow ecosystems" includes 541 records of application of countermeasures in a radioactively-contaminated territory (Table 4). The amount of data for sod-podsolic and peaty soils totals 1825 and 683 records, respectively. The countermeasures were taken on dry-land meadows in 778 experiments, and on low-land meadows in 442 experiments.

Table 2. Number of data by studied plant species, in sub-DB "Plant production"

Crop	Total number of data
Barley spring	20
Bean forage	4
Beet root (food)	4
Beet root (forage)	74
Beet-sugar	2
Buckwheat	4
Cabbage white head	16
Carrot	2
Clover	32
Corn	160
Flax	4
Lupine	242
Millet	4
Oats	516
Peas	4
Peas-oat mixture	16
Potatoes	64
Radish	2
Radish oil-bearing	10
Rye winter	4
Timothy meadow	30
Tomato	4
Winter wheat	110

Table 3. Number of data by type and subtype of applied countermeasures

Countermeasure classification		Total No.
Type	Subtype	
Agrochemistry	Clay minerals	121
	Liming	63
	Mineral fertilizers	10
	Organic fertilizers	131
	Complex application	186
Change of crops	Selection of crop species	12
	Selection of crop varieties	8
Soil cultivation	Ploughing and cultivation	30

Table 4. Total number of data by type of countermeasures in sub-BD "Meadow ecosystems"

Type of countermeasures	Total No.
Complex application with soil cultivation (radical improvement)	491
Complex application	29
Soil cultivation	3
Complex application with soil cultivation (surface improvement)	9
Complex application	9
Mineral fertilizers	29

3. Results and discussion

The general strategy of countermeasure application is aimed at decreasing human irradiation doses formed due to the consumption of contaminated foodstuffs. The value of collective dose averted by the implemented countermeasures, cost of the averted dose and total costs of countermeasure implementation are considered as the criteria of protective measure efficiency [2, 16, 17].

Soil countermeasures are the mostly applied ones at the present time. These countermeasures are aimed at decreasing ^{137}Cs and ^{90}Sr migration through human trophic chains.

Soil amelioration is a simple, inexpensive and effective method to decrease radionuclide transfer from the soil to crops. These countermeasures were applied intensively after the great radiation accident at the industrial association "Majak" (Chelyabinsk, 1957). The most simple and widely spread complete countermeasures are radical and surface improvement of meadows. These protective measures are implemented on the meadows polluted with Chernobyl radionuclides. Soil amelioration is represented by agrotechnical and agrochemical countermeasures.

3.1. Agrotechnical measures

Agrotechnical countermeasures are the most available ones which can be taken urgently on radioactively contaminated lands. After the accident, the most widely used agrotechnical measures were as follows: various types of soil treatment, growing of crop species and varieties with the lowest accumulation of ^{137}Cs and reclamation of abandoned lands. However, the most efficient measures were the removal of the upper soil layer and deep ploughing.

3.1.1. Removal of soil

The analysis of our own data and the data of other authors [7, 11–15] allowed to estimate the efficiency of the main agrotechnical countermeasures that can be used after radiation accidents (Fig 1). This figure shows that the removal of the upper layer of the soil reduces the radiocontamination of fields more than 120 times.

3.1.2. Deep ploughing

One of the effective agrotechnical countermeasures, which can be used on radiocontaminated agricultural lands, is a burial of the upper layer of the soil by deep ploughing (up to 50–70 cm) with the turnover of the layer, which permits to decrease the contamination of the crop yield 5–40 times (Figs 1, 2). This measure is recommended for soils with the depth of a fertile layer of more than 50 cm. Deep ploughing can lead to possible breakdown of the drainage; it is non-effective for sandy soils with a thin humus horizon. This measure was not widely used after the Chernobyl accident because the depth of the upper fertile layer of most soils was shallow (below 20 cm), and soils with the powerful fertile layer were ploughed without any control.

3.2. Agrochemical measures

Agrochemical countermeasures, i.e. ameliorative procedures, were accompanied by the changes of agrochemical properties of the soil (acidity, absorption capacity of soil-absorbing complex (SAC), content of nutrients, and content of ions competing with radionuclides in mineral nutrition of plants). The efficiency of agrochemical countermeasures significantly depends on the soil properties. Therefore, it should be higher for light low-fertile acidic soils than for fertile, clayey neutral soils.

The usual methods of farming aimed at saving and increasing the soil fertility, growth of yield, improvement of plant production quality, as a rule lead to the decrease of radioactive substance transfer to plants.

The used agrochemical countermeasures can be divided into the following groups, taking into account the main principles of their action:

- liming of acidic soils;
- liberal application of mineral fertilizers;
- application of organic fertilizers;
- application of microfertilizers;
- application of adsorbing minerals.

3.2.1. Liming of acidic soils

Lime increases the capacity of cation exchange of acidic soils due to pH decrease, so the migration mobility of radionuclides in the soil-plant system decreases. On the contrary, physiologically acid fertilizers decrease the capacity of cation exchange and increase radionuclide transfer to plants.

Application of calcium to the soil decreases Sr availability due to the decrease of Sr^{2+}/Ca^{2+} ratio in soil solution. Therefore, the best results are obtained in soils with a low concentration of exchangeable calcium (<10 mg-eq. Ca^{2+}/100 g of soil) and with a relatively low saturation in SAC. Liming is useful for soils with calcium content below 10 mg-eq./100 g of soil. It is especially valid for mineral soils where the rate of Sr^{2+} absorption is higher than Ca^{2+}. In soils with a high content of organic matter, where $Ca^{2+}$is well absorbed, lime can force strontium out into the soil solution (low probability). Lime application for the neutralization of acidic soils in Ukrainian Polessje is the traditional method for supporting soil fertility. Achieving high yields of most agricultural crops requires a neutral soil solution. Permanent ploughing of sod-podzolic and peaty soils leads to their acidification because of the acidic layer lifting to the soil surface. Lime ($CaCO_3$), dolomite flour, lime-tufa, lake lime, marl and peaty-tufa were used as lime ameliorants.

The results of our investigation show that radionuclide accumulation in the yield, depending on pH of salt extract and the type of soil, varies: for ^{137}Cs up to 17,5 times, and for ^{90}Sr up to 28 times (Table 5).

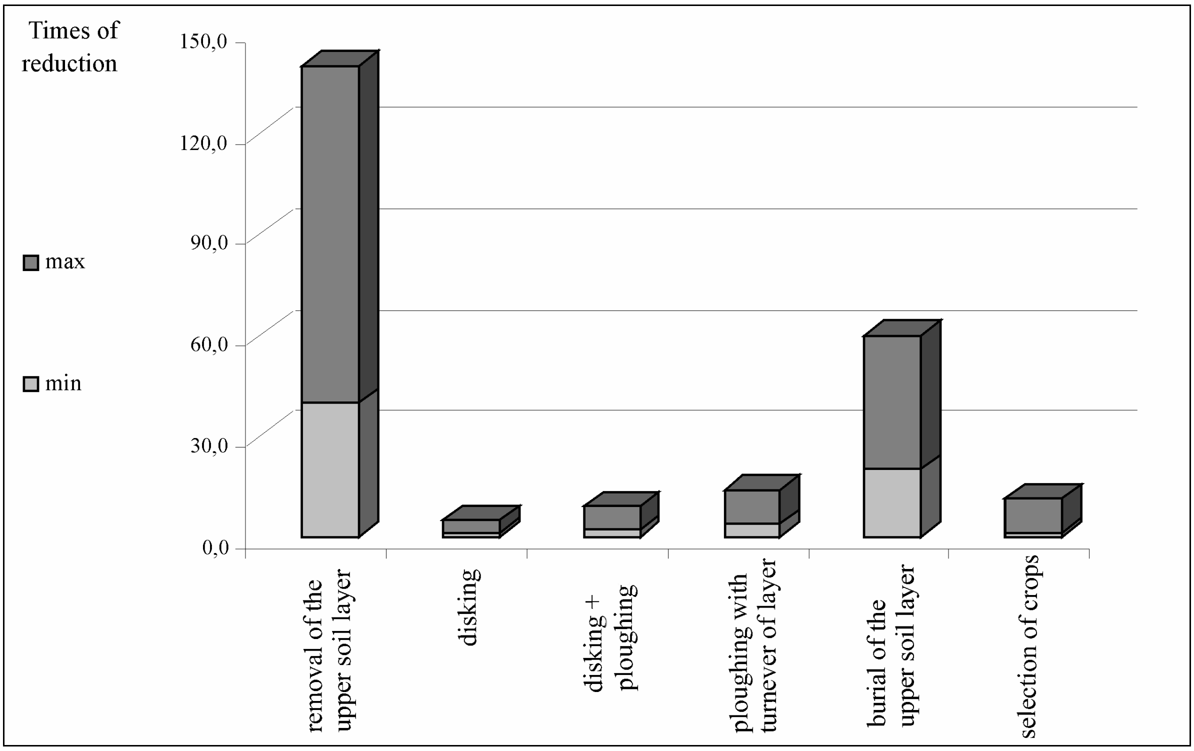

Fig 1. Radiological efficiency of agrotechnical countermeasures

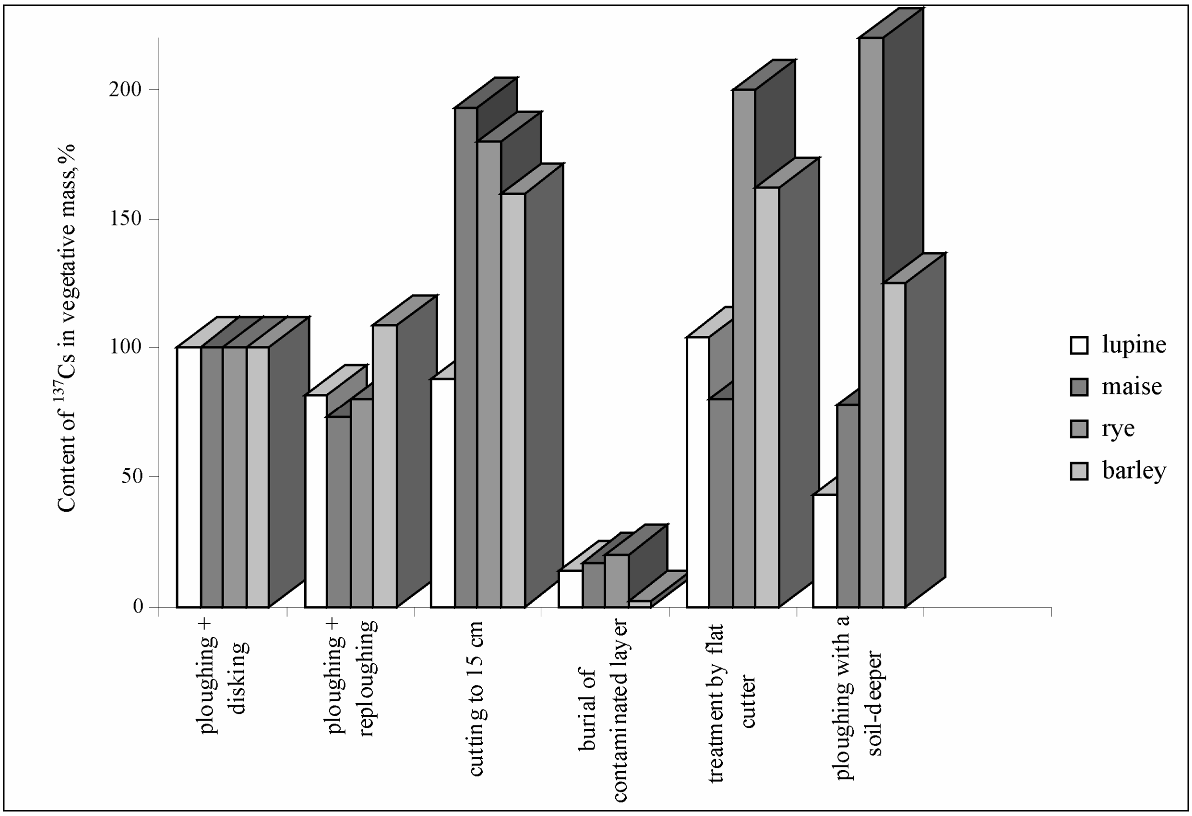

Fig 2. Influence of soil treatment on ^{137}Cs transfer from sod-podzolic sandy soil to agricultural crops

Table 5. Influence of the type of soil and pH of salt extract on radionuclide accumulation in the yield of agricultural crops

Crops*	Accumulation of radionuclides, relative units, according to the type of soil						
	Peaty-bog, pH = 4,0–5,0	Sod-podzolic, pH = 4,5–5,5		Grey forest, pH = 5,6–6,5		Chernozem, pH = 6,6–7,5	
	^{137}Cs	^{137}Cs	^{90}Sr	^{137}Cs	^{90}Sr	^{137}Cs	^{90}Sr
Beet root	–	12,5	31	5,5	6,5	1,5	4,5
Winter rye	15,5	9,5	155	3,5	21	-	5,5
Winter wheat	–	5,5	205	2,5	25	<0,5	16,5
Winter barley	14	6	190	2	25,5	<0,5	10
Cabbage	–	12,5	27	2,5	4	1	1
Potato	17,5	7	26	4	20	1	3,5
Cucumbers	–	5,5	5	1,5	6	1,5	1
Tomatoes		1	10,5	1	4,5	1	1

*moisture at harvesting

Table 6. Influence of countermeasures on ^{137}Cs transfer from peaty soil to meadow herbage

Countermeasure	Concentration of ^{137}Cs in grass, %
Meadow, without countermeasure	100
Disking + plaguing (control)	24,6
Control + N_{60}	55,1
Control +P_{90}	42,8
Control +K_{120}	7,1
Control + Manure 50 t/ha	18,5
Control +Lime 1,5 Hh*	16,5
Control +N_{60} P_{90} K_{120}	19,4
Control +N_{60} P_{90} K_{120} + Lime 1,5 Hh*	6,1
Radical improvement (with drainage)	2,3

Liming of acidic soils decreases the transfer to plants of both radionuclides and microelements. Liming of acidic soils decreases plants contamination in all cases, but the highest effect was observed in the combination of liming with fertilization (Table 6). The biggest effect on natural and semi-natural meadows was found after their radical improvement, including the destruction of the old sod and creation of a new one, applying lime and fertilizers. The efficiency of this measure was reduction 16,4 times without drainage, and 43,5 times with drainage.

3.2.2. Application of mineral fertilizers

Radionuclide transfer from the soil to plants can be decreased or increased after the application of fertilizers. The efficiency of mineral fertilizers depends on their type.

According to our data, the most effective for sod-podsolic sandy loam soils was the use of fertilizers that neutralize the soil solution (Fig 3).

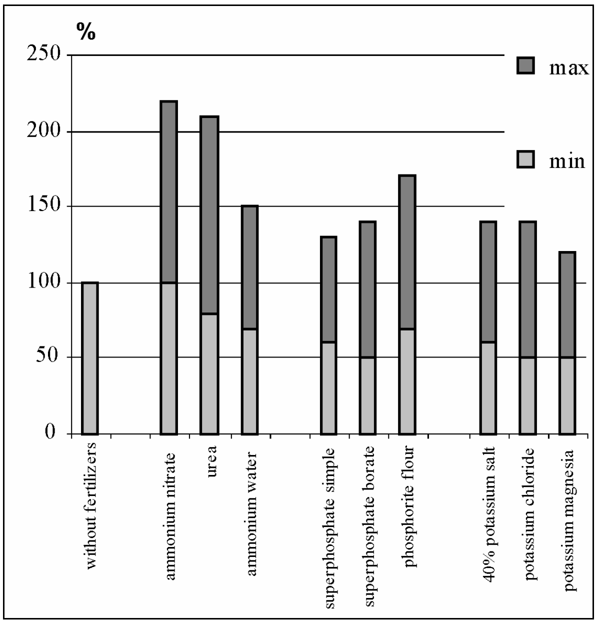

Fig 3. Influence of mineral fertilizers (nitric, phosphorous, potassium) on ^{137}Cs transfer from sod-podzolic sandy soil to the yield of agricultural crops

The addition of fertilizers in the ratio of nutrients is a common local farming practice and is sufficient to decrease radionuclide uptake from poor soils in many cases. However, application of high doses of fertilizers, including nitric ones, leads to the increase of radionuclide transfer to the crop yield (Fig 4). The biggest effect of fertilizers for the decrease of ^{137}Cs uptake was observed at the ratio of nutrients N:P:K = 1:1,5:2. Application of potassium fertilizers decreases radiocaesium transfer to crops due to the decrease of Cs/K ratio in the soil solution because potassium is a chemical analogue of caesium, and the elements are competing in the root uptake. The best results were obtained for a soil with a very low content of available potassium (<8–10 mg/100 g of soil). Application of potassium as potassium-magnesia was the most effective in our studies. But application of increased doses of potassium fertilizers can lead to the displacement of ^{137}Cs by potassium ions from ion-exchangeable zones, and increase of root uptake. Therefore, application of potassium in doses exceeding 200 kg of an active substance for 1 ha per year is not recommended.

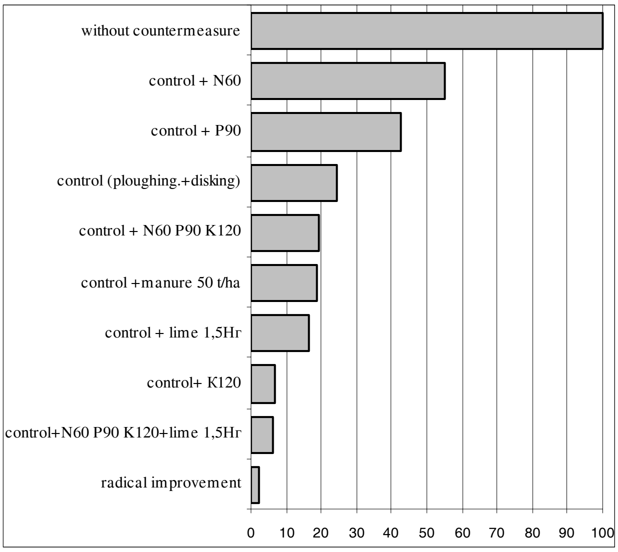

Fig 4. Influence of countermeasures on ^{137}Cs transfer from peaty-gleic soil to meadow herbage

The efficiency of nitric fertilizers depends on their chemical form. Application of ammonia salts leads to the increase of ^{137}Cs mobility and its accumulation in crops [19–20]. Increase of ^{137}Cs availability in the soil after the application of nitric fertilizers in the form of ammonia is connected with similar radii of hydrated NH_4^+ and Cs^+ ions. NH_4^+ can substitute Cs^+ on high absorbing sites of SAC and displace $^{137}Cs^+$ into the soil solution, increasing the availability of radionuclides to roots. Hence, it is mainly recommended to apply nitric fertilizers as nitrates in optimum doses, before sowing.

The biggest effect was obtained after applying phosphorous in the form of phosphate flour (Fig 3). Application of phosphorous fertilizers for peaty soils increased ^{137}Cs uptake by 18 % (Fig 4).

3.2.3. Application of organic fertilizers

Organic fertilizers, such as manure, peaty compost and sapropel, are often used for melioration of radioactively-contaminated lands. A high efficiency of organic fertilizers was observed in light mineral soils; organic fertilizers lead to the increase of absorption capacity of soils, decrease of their acidity, and promote the formation of organo-mineral complexes with radionuclides, where radionuclide forms are unavailable. However, the fraction composition of humus is very important. Humic and fulvic acids promote the formation of soluble substances with univalent ions that results in anomalous high ^{137}Cs transfer from peaty soils to crops.

It should be noted that 137Cs transfer from fresh manure is higher by 1–2 orders of magnitude than its transfer from the soil; therefore, it is expedient to apply manure as humus (fall manure). The results of our study show that the biggest effect (2–3-fold decrease of 137Cs transfer to agricultural crops) was obtained after application of 50 t of manure to a sod-podsolic sandy-loam soil, together with complete fertilizer and lime (Fig 5).

Applying 50 t/ha of sapropel together with the complete fertilizer for the same soils was optimum for these soils, and a 2-fold decrease of ^{137}Cs transfer to agricultural crops was observed [21]. We have estimated that sapropel is active during 3 years. On the 2nd year after sapropel application in a rate of 50 t/ha, ^{137}Cs transfer to maize, beet and lupine decreased 1,9, 3,1 and 1,4 times, respectively. On the 3rd year ^{137}Cs transfer to maize decreased 1,7 time.

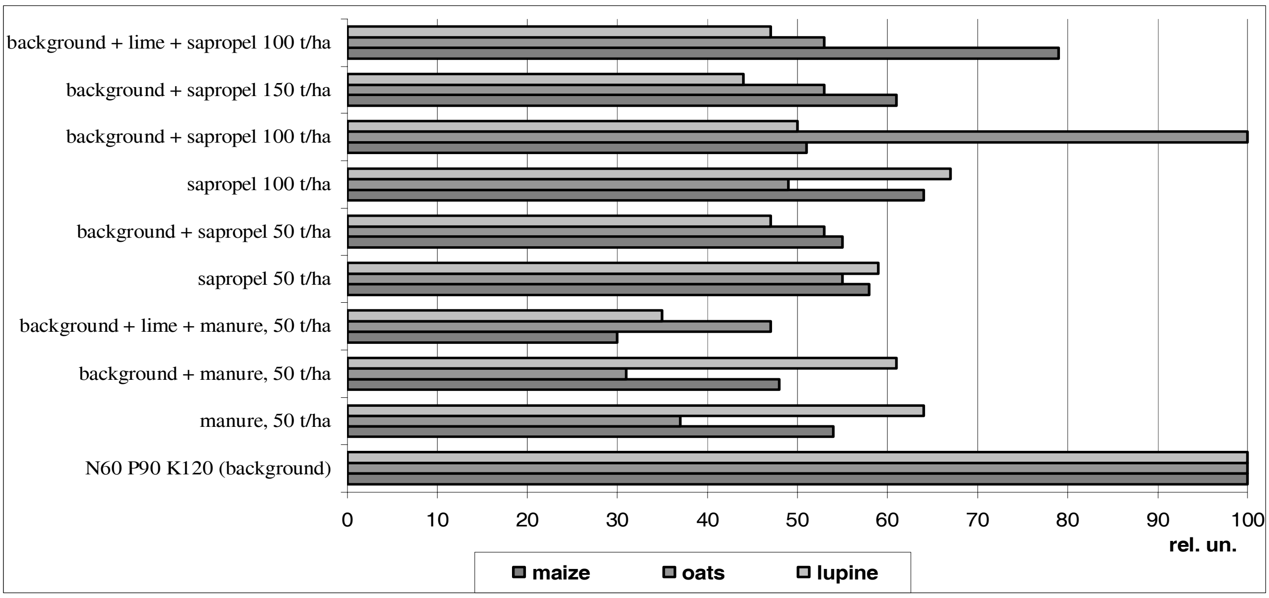

Fig 5. Influence of organic fertilizers on ^{137}Cs transfer from sod-podzolic sandy-loam soil to green mass of agricultural crops

3.2.4. Application of microfertilizers

The province of the Ukrainian Polessje is geochemicaly characterized by a low content of microelements (B, Cu, Co, Mo, Zn, Mn etc.), and liming makes the situation more complicated. Application of microfertilizers in the zone of radioactive contamination was performed in order to measure the improvement of product quality. Moreover, we studied the microelement influence on^{137}Cs migration in soil-plant systems. The results have shown that most of the tested microelements decreased weakly ^{137}Cs transfer to plants, and in some cases a tendency to increase radionuclide content in the yield was observed (Mn for pea and Cu for oats) (Fig 6).

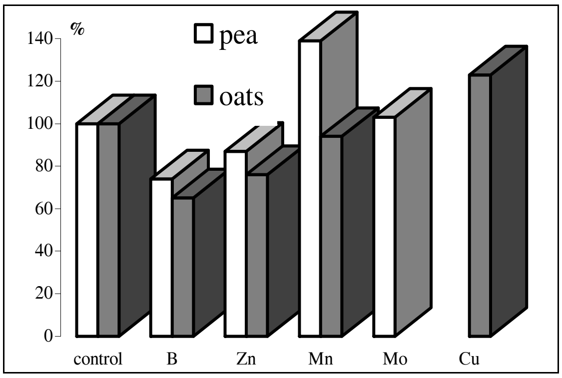

Fig 6. Influence of microelements on ^{137}Cs accumulation in vegetative mass of peas and oats from sod-podzolic sandy-loam soil

3.2.5. Application of adsorbing minerals

This countermeasure includes the application to a soil of clay minerals with a high sorbing capacity. The use of immo bilising substances is based on the transformation of the available radionuclide species into unavailable substances. Application of clay minerals, aluminosilicates of alkaline and alkaline-earth metals with a big sorbing surface, increases the absorbing capacity of soils. Various ions, including ions of radioactive elements, are absorbed by the soil in exchangeable and non-exchangeable forms. At the same time calcium and potassium ions move out from minerals to the soil solution and compete with ^{90}Sr and ^{137}Cs ions in root uptake.

Long-term studies of the influence of various sorbing minerals on ^{137}Cs transfer to agricultural crop yield were carried out. As it is seen from Table 7, the efficiency of amelioration of a peaty gleic soil is higher than that of a sod-podsolic soil. The maximum decrease of ^{137}Cs uptake due to the ameliorant application for a peaty soil reached 11 times, however, the rate of decrease for a sod-podsolic soil did not exceed 2,8 times (Table 7).

The long-term results on the efficiency of different ameliorative measures are summarized in Table 8.

All these countermeasures were applied in farms during the first post-accidental period after the Chernobyl accident. At the present time the implementation of countermeasures is largely confined. The dynamics of countermeasure implementation after the Chernobyl accident is characterized by the increase of volume of lime and fertilizer applications and radical improvement until 1992, when countermeasures were applied on 120 thousand hectares. Since 1993 the financing of the countermeasure implementation had been reduced, and by 2000 amelioration of radioactively-contaminated lands had been practically stopped.

Table 7. Efficiency of adsorbing mineral application

Adsorbing minerals and ameliorants	Rate of decrease of ^{137}Cs transfer to crop yield	
	Peaty gleic soil	Sod-podzolic soil
Sandy soil, 200 t/ha	1,3–5,2	–
Chernozem, 100 t/ha	0,9–11,0	0,9–1,1
Caoline clay, 200 t/ha	1,7-5,9	2,0–2,3
Zeolite, 20 t/ha	1,5–2,5	1,5–2,5
Saponite, 20 t/ha	–	1,7–2,3
Glaukonite, 20 t/ha	–	1,8–2,3
Bentonite, 20 t/ha	2,7–6,4	1,5–2,8
Vermiculite, 5 t/ha	1,7–2,9	1,6–2,5

Table 8. Average efficiency of countermeasure application in farming

Countermeasures	Durability of action, years	Decrease of ^{137}Cs transfer to crops from soil, times	
		sody-podzolic soil	Peaty soil
Radical improvement of meadows	7–10	6	16
Radical improvement of meadows with drainage	7–10	15	43
Liming	3	3	2
Complete mineral fertilizer	1	2	1,3
Potassium fertilizer	1	2	3
Organic fertilizer	2–3	2	1,5
Mineral and organic fertilizer mix	2–3	2	2
Adsorbing minerals	7–10	2	4

4. Conclusion

The most widespread countermeasures used after the Chernobyl accident were soil ameliorations, i.e. simple, inexpensive and effective methods reducing radionuclide transfer from the soil to crops. Among them the most applicable ones were agrotechnical countermeasures, decreasing the plant production contamination about 20 times. The most effective and widely used agrochemical measures after the accident were the application of various fertilizers that permitted to decrease the radioactive contamination of production averagely 2–3-times. Potassium fertilizers were the most effective for the decrease of ^{137}Cs transfer to the crop yield. Application of sorbing minerals decreased ^{137}Cs transfer to crops from a peaty soil up to 11 times, and from a sod-podsolic soil up to 3 times. These countermeasures increased the yield and improved the quality of products. However, the efficiency of soil-based countermeasures varies for separate sites. Considering the soil properties and agricultural practice before application is of great importance.

Radical and surface improvements of natural and semi-natural meadows were carried out on a large scale. The biggest decrease of vegetation contamination was observed after the radical improvement of meadows: 16 times without drainage and 43 times with drainage.

Under the conditions of Polessye zone which has been exposed to radioactive contamination and where locally-produced milk is consumed, the main countermeasure, used in the long-term period after the accident for the decrease of an effective dose, should be the radical improvement of meadows. Recommendations on the countermeasure application should be distributed to the farmers and authorities in radiocontaminated regions.

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AGROKULTŪRINIŲ ATSAKOMŲJŲ PRIEMONIŲ TAIKYMO RADIOAKTYVIĄJA TARŠA UŽTERŠTUOSE LAUKUOSE RADIOLOGINIS EFEKTYVUMAS

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Santrauka

Agrokultūrinių atsakomųjų priemonių įgyvendinimas yra vienas iš pagrindinių metodų, leidžiančių sumažinti spinduliavimo dozes. Apibendrinus informaciją apie atsakomąsias priemones ir įvertinus turimą branduolinių nelaimių padarinių šalinimo patirtį, parodoma, kad po Černobylio avarijos plačiausiai taikomos atsakomosios priemonės buvo dirvožemio gerinimas. Šie metodai, padedantys sumažinti radionuklidų pernašą iš dirvožemio į pasėlius, yra paprasti, nebrangūs ir efektyvūs. Agrotechninės atsakomosios priemonės buvo tinkamiausios siekiant sumažinti augalinės produkcijos užterštumą iki 20 kartų. Natūralių ir pusiau natūralių pievų šakninių ir paviršinių dalių pagerinimas buvo atliekamas plačiu mastu užterštose dirvose. Didžiausias augalijos užterštumo sumažėjimas buvo nustatytas pagerinus pievą su ir be drenažo (atitinkamai 43 ir 16 kartų). Kitos efektyvios priemonės yra agrocheminiai metodai. Naudojant įvairias trąšas galima sumažinti produkcijos užterštumą radioaktyviosiomis medžiagomis vidutiniškai 2–3 kartus. Kalio trąšos buvo efektyviausios mažinant ^{137}C pernašą į javų derlių. Naudojant sorbcinius mineralus ^{137}C pernaša į javus iš durpingos dirvos sumažėjo 11 kartų, o iš velėninio dirvožemio – iki 3 kartų. Be to, šios atsakomosios priemonės padidino derlių ir pagerino produktų kokybę.

Reikšminiai žodžiai: radioaktyvusis užterštumas, ^{137}C, ^{90}Sr, pasėliai, atsakomosios priemonės, efektyvumas.

РАДИОЭКОЛОГИЧЕСКАЯ ЭФФЕКТИВНОСТЬ КОНТРМЕР, ПРИМЕНЯЕМЫХ НА РАДИОАКТИВНО ЗАГРЯЗНЕННЫХ ТЕРРИТОРИЯХ

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Резюме

Применение контрмер в сельском хозяйстве является одним из основных методов, позволяющих снизить дозу облучения населения на радиоактивно загрязненных территориях. Обобщив накопленную информацию о контрмерах и учтя опыт ликвидации последствий ядерных аварий, можно заключить, что наиболее широко применяются почвенные мелиорации. Эти методы достаточно просты, дешевы и эффективны в снижении перехода радионуклидов из почвы в сельскохозяйственные растения. Наиболее доступными являются агротехнические меры, снижающие загрязнение растительной продукции до 20 раз. Корневое и поверхностное улучшение природных и полуприродных лугов было проведено на огромной территории, загрязненной после Чернобыльской аварии. Наибольшее уменьшение загрязнения вегетационной массы лугов и пастбищ наблюдалось после корневого улучшения: в 43 раза с осушением и 16 раз без него. Эффективны также агрохимические меры. Применение различных удобрений позволяет снизить загрязнение продукции в среднем в 2–3 раза. Калийные удобрения наиболее эффективны для снижения перехода ^{137}Cs в урожай культур. Применение сорбирующих минералов также снижает переход ^{137}Cs из торфяных почв до 11 раз и из дерново-подзолистых почв – до 3 раз. Более того, эти контрмеры повышают урожай и улучшают его качество.

Ключевые слова: радиоактивное загрязнение, ^{137}Cs, ^{90}Sr, сельскохозяйственные культуры, контрмеры, эффективность.

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