Soil fertility influence on ^{137}Cs and ^{90}Sr transfer to the crops

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Abstract. The radionuclide uptake by crops strongly depends on soil fertility and biological features of plants. The soil reaction, humus content, calcium, magnesium and potassium status are the most important soil properties, which determine radionuclide transfer to plants. The evaluation of separate soil property influence on the radionuclide uptake by plants is a complex task. It was found that ^{137}Cs and ^{90}Sr transfer to plants are reduced by a factor 1.5 to 3.0 as a result of the change of sod-podzolic soil reaction from acid (pH_{KCl} 4,5-5,0) to neutral range (pH_{KCl} 6,5-7,0), of humus content from 1.0 up to 3.5% and of exchangeable potassium content from low (< 80 mg K_2O/kg of soil) up to high range (200-350 mg/kg). The lowest transferring of radionuclides to plants was observed at the optimal range of soil fertility parameters. On the basis of compilation and processing of experimental data the transfer factors of ^{137}Cs and ^{90}Sr from soil to crop had been differentiated according to soil fertility parameters for prediction of radionuclide accumulation in plant production. The soil fertility has to be improved in such a way that proposes the significant increase of crop yields with decreasing of the risk of people internal irradiation.

1. INTRODUCTION

The Chernobyl accident has resulted in Belarus with the radioactive contamination covering 23% of territory then populated by 2.2 million people. Agricultural production is conducted on 1,3 million hectares of contaminated land with ^{137}Cs deposition 37-1480 kBq.m^{-2}. Some part of this land, 0,46 million hectares, is simultaneously contaminated with ^{90}Sr as well (6 -111 kBq/m²). There are difficulties to produce the foodstuff corresponding to national permissible levels of ^{137}Cs and ^{90}Sr concentration at some areas.

Radionuclides in the topsoil are potentially available for uptake by plant roots for long time period. The availability of ^{137}Cs to plants is significantly declining in the post accidental period due to the process of "ageing" and its fixation in soil. The share of mobile ^{137}Cs decreased in different soils on an average more than 3 times. Presently the share of ^{137}Cs fixed fraction makes up 87-98 % of the total content. For ^{90}Sr, vice versa, a characteristic feature is the prevailing forms easily accessible for plants up to 87% of the total content with a trend to increase on time. Therefore, the radionuclide soil-to-plant transfer coefficients have to be updated periodically to provide the credible forecast of contamination level of agricultural products. The monitoring of soil fertility and radiation status, as well as recommendations for the efficient countermeasures are the responsibility of the State Agrochemical Service and combined research team from institutes and universities under the coordination management of the Belorussian Research Institute for Soil Science and Agrochemistry (BRISSA).

Raising and maintaining the level of soil fertility is of primary importance. This is mainly because of nature of soil-forming processes, which have led to the development of predominantly low-yield sod-podzolic and peat soils. The level of contamination of agricultural products depends on several factors, including the radionuclide deposition, soil types, texture and chemical properties, biological characteristics of plants etc [1, 2]. The design of economically sound countermeasures is of paramount importance to reduce the radionuclide transfer to crops.

The main aim of our work was to determine parameters of radionuclide transfer from soil to plants depending on soil fertility status. These parameters are the basis for development of protective measures in the long-term post accidental period to decrease the transfer of ^{137}Cs and ^{90}Sr in food chain with minimal expenses. In relatively favorable climatic conditions, the level of soil fertility is the most important factor limiting the growth of crop yields with permissible levels of radionuclides.

The studies of soil fertility status influence on ^{137}Cs and ^{90}Sr transfer to plants were carried out by method of randomized plots with size 1 m^2 on crop fields of Gomel and Mogilev regions. The efficiency of agrochemical countermeasures on sod-podzolic loamy sand was studied in field stationary experiments at the farm "Strelichevo" of Khoiniki district, Gomel region under conventional agricultural conditions.

2. INFLUENCE OF SOIL FERTILITY ON RADIONUCLIDE TRANSFER TO CROPS

Nuclides are in solubility equilibrium between dissolution in water and solid forms. Uptake by plant roots depends on the amount of nuclides dissolved in water. Therefore, soil humidity as well as other solubility-controlling parameters such as the soil acidity (pH) influence the availability for plant uptake directly and indirectly through increased relocation by diffusive or advective nuclide transport. The degree of soil humidity has the most important influence on these processes. It was proved that semi-natural meadow ecosystems are the most important contributors to irradiation of population living on radioactive contaminated territory [2]. The BRISSA experiments showed that ^{137}Cs contamination of perennial grasses on automorphic soils with a normal degree of rainfall humidity was by 10-27 times lower than that on gley soils with a permanently high degree of humidity. The transfer coefficients of ^{90}Sr were also lower in normally humid soils than in the excessive humid ones, although the difference was less important - up to 2 times.

Soil components like clay or humus adsorb nuclides, especially caesium. According to our experiments, the transfer factors of radionuclides to the plants growing on sod-podzolic loamy soils are by 1.5-3.0 times lower than the same coefficients for sod-podzolic sandy soils. The increase of humus content in sod-podzolic loamy sand soils from 1 to 3 % has resulted in the reduction of the level of ^{137}Cs accumulation in perennial grass by 1.7 times, and accumulation of ^{90}Sr -- by 1.9 times. The priority in countermeasure strategy has been addressed recently at the chemical amendments, trying to reduce the level of radionuclides in soil solution by increasing the concentration of competitive species, as Ca and K [3].

2.1. Influence of soil acidity on radionuclide accumulation in crops

The soil acidity influences the availability of dissolved nuclides and their uptake in plants. Our investigation on typical farmers fields showed that liming changed the reaction of sod-podzolic soils from pH (KCl) 5.0 to pH 6.5-7.0, and reduced the ^{137}Cs accumulation in perennial grass up to 2 times (Fig. 1). It is known, that in case of highly acidic soils (pH = 4.0-4.5), liming may reduce radionuclide transfer by up to 3 and more times.

Fig. 1. Influence of the soil reaction pH (1M KCl) on the uptake of ^{137}Cs ($Bg.kg^{-1}$) by perennial grass hay from

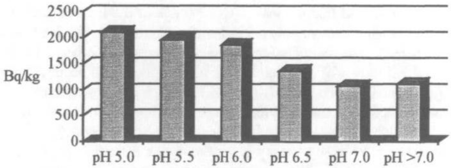

Fig. 1. Influence of the soil reaction pH (1M KCl) on the uptake of ^{137}Cs ($Bg.kg^{-1}$) by perennial grass hay from sod-podzolic loamy sand soil related to a deposition of ^{137}Cs 370 $kBq.m^{-2}$

The acidity and soil saturation with exchangeable forms of calcium and magnesium have essential influence on ^{90}Sr transfer to crops. It was found that ^{90}Sr accumulation in perennial grass was closer negatively correlated with the exchangeable Ca content in soil ($R^2 = 0.78$) than with reaction of soil solution or value of pH (R^2 = 0.59) (Fig.2). But for practical use both indices are similarly valuable. It should be taken in consideration that soil test for pH (KCl) is simpler than test for exchangeable Ca and Mg content. The similar relations had been established for other crops. The reduction factors of ^{137}Cs and ^{90}Sr accumulation in plants due to different soil reaction pH (KCl) varied from 1.5 to 3.0 times.

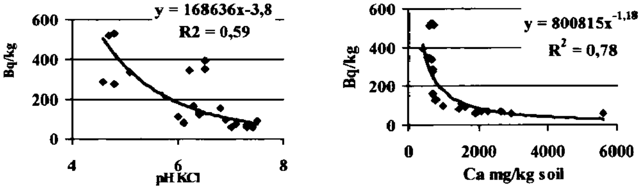

Fig 2. : The ^{90}Sr accumulation in hay of perennial grass in dependence on acidity and exchangeable Ca content of loamy sand gley soil related to ^{90}Sr deposition – 37 kBq.m^{-2}, Bragin, Gomel region (1999)

It was found in the field experiments that lowest accumulation of ^{137}Cs and ^{90}Sr in all tested crops were at the same pH (KCl) range 6.5-7.0. But pH values for maximum yield of growing plants on sod-podzolic loamy sand soil were different: 6.7 for barley, 5.9 for potatoes and 4.9 for lupine. The optimization of soil reaction has to be done with consideration for achievement both final results – low radionuclide concentration and high extra yield. The selection of agricultural countermeasures is needed from point of view of reducing cost of 1 man-Sv of averted dose of irradiation in a long-term period after Chernobyl accident [4]. The priority criteria for the choice of the countermeasure treatments has to be based not only on reduction factor for radionuclides transfer to plants, but also on the value of extra yield obtained. An example of combined economical and radiological justification the optimal liming treatment for potato plants is presented in tables 1, 2. Economic efficiency parameters of fertilizer application in this paper were calculated using the crop response data of field experiments and current prices of fertilizers and crop production. The prices are given in US dollars according to official transfer rate of National Bank of Belarus.

Table 1. Influence of fertilizers and liming on productivity of potato on sod-podzolic soil (Deposition of ^{137}Cs – 370 and ^{90}Sr - 37kBq.m^{-2}, P_2O_5 150 mg.kg^{-1}, K_2O 180 mg.kg^{-1}, humus 2.0 % - Gomel, Khoiniki, 1996)

Treatments	Yield of potato		Net profit, \$/ha	Profitability, %
	t/ha	Increase factor		
Control (pH 4.9)	16.2	1.0	-	-
Dolomite 6 t (pH 5.9)	17.6	1.1	74	194
Dolomite 18 t (pH 6.7)	15.4	0.9	-106	-253
N70P60K160 (pH 4.9)	24.3	1.5	448	224
N70P60K160 (pH 5.9)	26.4	1.6	566	226
N70P60K160 (pH 6.7)	23.1	1.4	331	150
LSD_{05}	1.4			

It was found that the highest yield of potato tubers in experiment, 26.4 tons per ha, has been achieved on 6 tons dolomite + N70P60K160 (pH 5.9) treatment. The treatment resulted in net profit 566 USD per hectare with the highest rate of profitability – 226 % of invested sum in countermeasure. The reduction of ^{137}Cs accumulation in tubers by factor 2.1 and ^{90}Sr accumulation by factor1.5 made this treatment acceptable.

The liming with high rate of dolomite (18 t.ha^{-1}) on unfertilized plots provided some decrease of yield and the net economic loss 106 USD/ha has been calculated. The ^{137}Cs accumulation in potato tubers in this treatment has reduced in 1.7 times, and collective dose of internal irradiation of man reduced by factor 1.8 as compared with control treatment (Tab. 2). This treatment is not acceptable economically because the cost of 1 man-Sv of averted collective dose reaches 104 thousands USD.

Application of dolomite 18 t.ha^{-1} on fertilizer background was profitable and it reduced activity of tubers by factor 2.3 for ^{137}Cs and by factor 1.7 for ^{90}Sr in comparison with control treatment. The reduction of collective doses was less appreciable, correspondingly 1.6 times for ^{137}Cs and 1.2 times for ^{90}Sr. We may conclude that optimal rate of dolomite on fertilizer background is 6 t.ha^{-1} which allows to raise the value of acid loamy sand soil to pH (KCl) 5.9, to achieve the highest potato yield and profit and decrease ^{137}Cs accumulation in tubers by factor 2.1. On soil contaminated with ^{90}Sr there is preferable higher rate of dolomite - up to 18 t.ha^{-1}.

Table 2. The irradiation dose reduction dependence on fertilizers and liming of sod-podzolic soil at the growing potatoes.

Treatment	Activity of potato		Collective dose	
	Bq.kg^{-1}	Reduction factor	mSv.ha^{-1}	Reduction factor
		^{137}Cs		
Control (pH 4.9)	10.2	1.0	2.3	1.0
Dolomite 6 t (pH 5.9)	6.2	1.6	1.5	1.5
Dolomite 18 t (pH 6.7)	6.0	1.7	1.3	1.8
N70P60K160 (pH 4.9)	5.8	1.8	2.0	1.2
N70P60K160 (pH 5.9)	4.9	2.1	1.8	1.3
N70P60K160 (pH 6.7)	4.5	2.3	1.5	1.6
LSD_{05}	0.9			
		^{90}Sr		
Control (pH 4.9)	11.2	1.0	4.3	1.0
N70P60K160 (pH 4.9)	9.0	1.2	5.2	0.8
N70P60K160 (pH 5.9)	7.4	1.5	4.7	0.9
N70P60K160 (pH 6.7)	6.5	1.7	3.6	1.2
LSD_{05}	0.9			

The minimal radionuclides accumulation in the plant-growing products has been related to optimal ranges of pH (KCl) indices for texture groups of sod-podzolic soils: clay and loamy – 6.0-6.7; loamy sand – 5.8-6.2; sandy – 5.6-5.8; on peat-boggy soils of meadows and pastures – 5.0-5.3. The lime rates were differentiated according to the soil types, texture, initial degree of acidity and level of radionuclide deposition [5]. It is important also to considerate different lime requirements of crop rotations: (1) with lupine, flax and potato and (2) with corn, sugar beet, wheat and barley. Light textured soils of Belarus had a very poor content of magnesium that seriously limited crop yields twenty years before. Using the cheapest source of Mg - finely grounded dolomite for liming, the exchangeable magnesium content of soils has been significantly increased. It was proved that application of conventional rates of dolomite (6-12 t/ha) ensure a good supply of Mg for plants for several years without detrimental effect.

2.2. The influence of soil K-supply and K-fertilizer on the crop uptake of radionuclides

It is well known that potassium, as a chemical analogue of caesium, could effectively inhibit the transfer of radiocaesium from soil to plants. However, the inhibitory effect is strongly dependent of potassium concentration in soil solution, which will determine the effect of K fertilization as countermeasure to reduce the Cs contamination of crop production [3]. Our investigation aimed for obtaining the experimental background of K-fertilizer application efficiency in dependence on radionuclide deposition, soil agrochemical status and biological features of crops. The genotypic differences in ^{137}Cs uptake between the various crops are very important, however these also depend on exchangeable potassium content in soil [6]. Our experiments were carried out on soils characterized by different levels of K supply. Increasing doses of potassium fertilizers were applied on each level of K supply.

The reliable close correlation between ^{137}Cs activity of crop yield and exchangeable K content in soil were found for the most important agricultural crops. The close reverse correlation was observed between ^{137}Cs accumulation in the yield of clover hay and exchangeable K content in soil (Fig. 3). It can be seen that significant decrease of hay activity has been found in the range of K content 50-250 mg.kg^{-1} of soil.

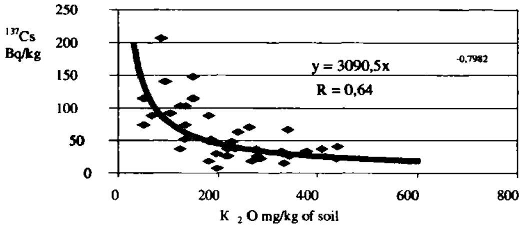

Fig. 3. : ^{137}Cs accumulation by clover hay depending on K- supply of sod podzolic loamy sand soils at deposition of 370 $kBq.m^{-2}$ (Khoiniki, 1998-2000)

The differences of ^{137}Cs accumulation in oat grain depending of differently textured soils were found. The most evident differences were observed on soils with poor potassium supply less than 80 mg kg^{-1} where the ^{137}Cs activity of oat that was grown on sandy soil had been twice higher than activity of oat on loam soil. The differences between of ^{137}Cs accumulation in oat grain on sand and loam soils became insufficient on high level of K supply of tested soils.

The radionuclide transfer from soil to plant in dependence on increasing K-fertilizer doses was studied in field experiment. There were prepared three different levels of exchangeable potassium supply of sod- podzolic loamy sand soil: 150, 250 and 350-mg kg^{-1} (Tab. 3.).

Table 3. Productivity of spring wheat and ^{137}Cs irradiation dose reduction depending of rates of K fertilizer and soil K status on sod-podzolic soil (^{137}Cs deposition 370 $kBq.m^{-2}$, pH 5.9, P_2O_5 180 $mg.kg^{-1}$, humus 2.1 % - Gomel, Khoiniki, 1995).

Treatment	Yield of grain, t/ha	Net profit, $/ha	^{137}Cs activity of grain, Bq/kg	Reduction factor	Collective dose		Cost of 1 man-Sv of averted dose, 1000 $
					mSv per ha	Reduction factor	
150 mg K_2O $.kg^{-1}$							
Control	3.24	-	10.2	1.0	4.6	1.0	
N70P60K80	4.58	56	8.9	1.1	5.7	0.8	
N70P60K160	4.79	61	6.4	1.6	4.3	1.1	-
N70P60K240	4.90	57	5.1	2.0	3.5	1.3	-
250 mg K_2O $.kg^{-1}$							
N70P60K80	4.90	7	5.1	2.0	3.5	1.3	-
N70P60K160	4.90	-5	3.8	2.7	2.6	1.8	2.6
N70P60K240	5.00	-9	3.6	2.8	2.6	1.8	4.5
350 mg K_2O $.kg^{-1}$							
N70P60K80	5.00	-15	3.8	2.7	2.7	1.7	7.8
N70P60K160	5.13	-17	3.6	2.8	2.6	1.8	8.5
N70P60K240	5.21	-23	3.5	2.9	2.6	1.8	11.2
LSD_{05}	0.22		1.4				

It was established that ^{137}Cs accumulation in grain was decreased in 2.0 times at the increasing K-fertilizer rates from 80 to 240 kg K_2O per hectare on first level of potassium content in soil. All tested fertilizer rates were profitable with net return 56-61 USD per hectare. The collective dose reduced by factor 1.3 in comparison with control. On the second level of soil K supply 250 $mg.kg^{-1}$ the ^{137}Cs accumulation in grain reduced by factor 2.8 and the collective dose of irradiation reduced by factor 1.8. Only low fertilizer rate K80 had been profitable. The medium rate K160 may be also acceptable as it provides relatively low cost of averted dose.

Experimental data indicate that threshold of optimal potassium content in sod-podzolic loamy sand soil is about K_2O 250-mg kg^{-1} for the most field crops. Further increase of exchangeable potassium content in soil did not provide the significant reduction of radionuclide accumulation in plants but strongly increased the expenses. Only moderate potash fertilizer rates are needed for rich K-supplied soils (K_2O 250-mg kg^{-1} and more) to replace of the crop K-removal. The K-fertilization efficiency was found to be increasing after liming if soil acidity was reduced.

Conclusions

1. The level of soil fertility is the most important factor limiting the growth of crop yields with permissible levels of radionuclides. The priority criteria for the choice of the countermeasure treatments has to be based on reduction factor for radionuclides transfer to plants, as well as on the value of extra yield obtained for profitable or self-sufficient production.
2. Fertilization based on balanced rates of nutrients according the soil tests, combined with liming of acid soils with consideration to different crop requirements, provides the most effective countermeasure for reducing ^{137}Cs and ^{90}Sr accumulation in crop products.
3. The lowest accumulation of ^{137}Cs and ^{90}Sr in all tested crops was at the same pH (KCl) range 6.5-7.0. But pH values for maximum yield of growing plants on sod-podzolic loamy sand soil were different: 6.7 for barley, 5.9 for potatoes and 4.9 for lupine. The optimization of soil reaction has to be done with consideration for achievement both final results – low radionuclide concentration and high extra yield.
4. High K-fertilizer rates up to 160 - 240 kg K_2O per hectare are effective for cereals and potato on sod-podzolic loamy sand soils with poor K supply that is lower than threshold about K_2O 250-mg kg^{-1}. Only moderate potash fertilizer rates are needed for rich K-supplied soils (K_2O 250-mg kg^{-1} and more) to replace of the crop K-removal.

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