Radioprotection, vol. **44**, n° 5 (2009) 77–82

DOI: 10.1051/radiopro/20095020

^{137}Cs and heavy metals accumulation by crops and modifying effects of biologically active substances on the root uptake of radioactive and non-radioactive contaminants

L. Ulyanenko, S. Kruglov, A. Filipas, N. Loi and N. Stepanchikova

Russian Institute of Agricultural Radiology and Agroecology, 249032 Obninsk, Russia

Abstract. Soil contamination with Co and Cd at concentration 20–25 times exceeding the Maximum Permisible Level for sod-podzolic light loam soil produced not only negative effects on the spring barley productivity formation, but also decreasing of ^{137}Cs root uptake. Effects of Co on the barley development and ^{137}Cs accumulation in plants was more pronounced than Cd influence. The ^{137}Cs activity decrease in barley biomass and harvest amounted to 2.5 and 1.6 times on Cd and Co contaminated soil, respectively. The mechanisms regulating root uptake of K by barley plants in dependence of the kind of soil contamination were discussed. Seed incrustation with Zircon and Epin did not produce significant influence on Co and Cd phytotoxicity, however the use of this plant growth regulators resulted in different in direction and value effects on Co, Cd and ^{137}Cs accumulation in barley plants at various stages of its development. The experimental data do not make it possible to link directly the effect of biologically active substances on ^{137}Cs uptake with their influence on heavy metals toxicity, which was estimated on the base of morphological and physiological parameters of plants.

1. INTRODUCTION

Improvements are required in the state of knowledge regarding processes and parameters affecting the transfer of radionuclides from soil to plant in order to provide guidelines for dealing with future nuclear accidents. Root uptake of radionuclide by plants is complex, involving processes in the soil and the plant. In the soil, any factors that alter the distribution of radionuclides between solid and liquid phases may be of significance. These factors include the chemistry of the radionuclide, soil properties, and the presence and concentrations of elements – chemical analogues. In the plant, root uptake of the radionuclide from soil solution also depends on its chemistry and the concentration of competing ions. However, the nature of the plant and its physiological characteristics are also important.

The obtaining of agricultural products with the permissible content of dangerous or toxic substances becomes a more and more urgent problem. Among the factors that aggravate the ecological situation in agriculture is land contamination with anthropogenic radionuclides and heavy metals (HM), both considered as dangerous environmental pollutants, and one cannot exclude the situation when radioactive and non-radioactive contaminants present in the soil simultaneously. In the latter case, HM in large amounts may be expected to influence the risk of plant contamination with radioactive substances [1]. The minimization of hazardous and toxic substances accumulation in farm products based on the consideration of migration peculiarities of radionuclides and HM in agrolandscapes and assessment of the importance of factors influencing the behavior of pollutants in the soil-plant system is of great significance. Though, there is little information concerning HM effects on the radionuclide soil-to-plant transfer.

Besides soil fertilizers application, in modern agricultural practices is widely adopted other chemicals affecting plant metabolic processes and to improve crop productivity and resistance to disease. The increased use of these chemicals has led to major changes in production technologies and input requirements resulting in improved resistance to biotic and abiotic factors, leading to increased crop productivity and yields [2]. Unlike fertilisers the effect of pesticides and plant growth regulators on radionuclide behaviour in agricultural ecosystems has not been extensively investigated and is not well understood.

Article published by EDP Sciences and available at http://www.radioprotection.org
or http://dx.doi.org/10.1051/radiopro/20095020

It has been shown earlier that the application of chemicals and plant growth regulators (PGR) in radioactively contaminated areas can alter not only the productivity of farm crops but also radiocesium and radiostrontium accumulation in the useful part of plants [3, 4].

The objectives of our work were: (i) to study effects of HM (Co and Cd) at elevated concentrations on the ^{137}Cs root uptake by spring barley at different stages of its development, and (ii) to consider modifying effects of plant growth regulators, Zircon and Epin, on the accumulation of radioactive and non-radioactive contaminants in barley.

2. MATERIALS

A greenhouse experiment was undertaken with barley (*Hordeum vulgare L*, c.v. Elf) grown on soddy-podzolic light loam soil. Soil taken from the arable horizon of agricultural lands (Kaluga region of Russian Federation) was air dried and ground to pass 2 mm sieve. A ^{137}Cs solution was added to obtain radioactivity of 50 kBq kg^{-1} dry soil, and the soil was thoroughly mixed. The uniformity of ^{137}Cs distribution within soil was estimated based on the results from gamma-spectrometric analysis of samples collected before sowing. The analysis revealed a satisfactory uniformity in ^{137}Cs distribution in the experimental soil. The relative deviation of measurements from the experimental mean did not exceed 10–12%.

The radioactively contaminated soil was fertilizers at a rate (g kg-1 soil) of 0.2 N, 0.14 P_2O_5, 0.14 K_2O and again manually mixed. The amended bulk soil mass was divided then into sub-samples which received Cd (50 mg/kg), Co (100 mg/kg) and their combination (50 mg Cd/kg + 100 mg Co/kg) in the form of aqueous solutions of metal nitrates. Immediately after mixing, soils were introduced into 5 l plastic pots and incubated at ambient temperature for 14 days. Four replications were prepared for each soil (each variant and two controls).

Fifteen barley seedlings were transplanted per pot. Soil moisture was brought to 60% of the soil water-holding capacity and maintained by daily adjustment with deionized water. In respective trials, barley seeds before sowing were treated with Epin and Zircon (treatments E and Z). Epin is antistress adaptogen, immuno-stimulator, inducer of plant resistance to fungal and bacterial infections. Active substance is 24R–brassinolide. Zircon – chemical based on a new class of chemical compounds, in particular 2,3-bis(3-(3,4-dihydroxyphenyl)-1-oxo-2-propenyl)-oxybutadiene acid. One of the active substance is chicory acid with an antioxidant activity. The symbol of a chemical element in a treatment's labeling indicates which metal was applied to soil simultaneously with ^{137}Cs. The PGRs were applied at doses recommended for cereal crops: Epin – 2×10^{-1} ml kg^{-1} seeds and Zircon – 2×10^{-3} ml kg^{-1}.

The barley plants were harvested in maturity, but during the whole growing season plants development was monitored. To evaluate dynamics of the radionuclide and HM uptake, plant samples were taken also at the following stages: late tillering – early shooting (30 d), earring (60 d) and complete ripeness (100 d after sowing). The following parameters have been measured: plant height (from the root to the end of upper leaf), leaf area index (LAI – the ratio of the total leaf area to the number of leaves), fresh mass and air-dried mass.

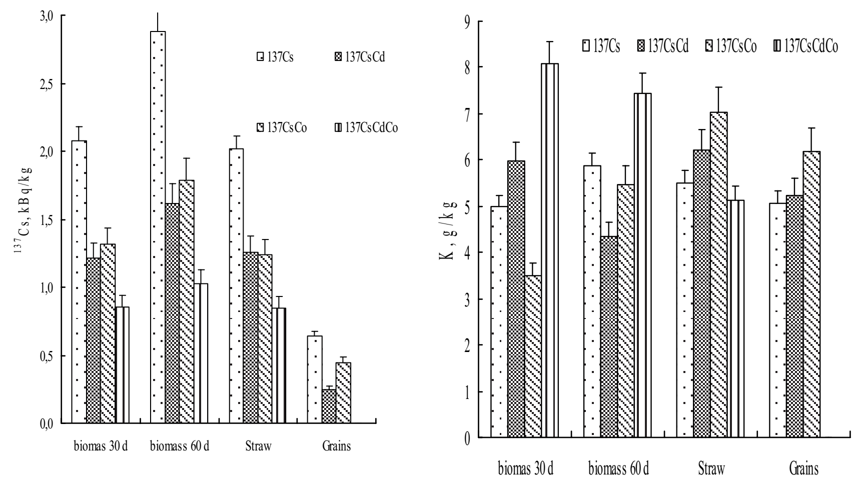
Activity of ^{137}Cs in soil and plants was assayed by gamma-spectrometry, metal concentration – by atomic absorption.

The significance of differences between the treatments evaluated on the basis of a pair two-side t-test for averages.

3. RESULTS

3.1 ^{137}Cs and K accumulation

Maximal rate of the radionuclide uptake was noted in the period of active plants growth (Fig. 1a), probably because of general similarity between the ^{137}Cs and nutrient element K behavior in the soil-plant system. Higher radionuclide content in plants was observed on the tillering-shooting phase (60 d after sowing), in the same period when an intensive biomass production has been registered. A decrease in ^{137}Cs specific activity in the barley yield (straw, grain) may be caused either by reduced uptake rate or by high rate of biomass gain and, consequently, biological dilution of radionuclide concentration. Thus, an increased ^{137}Cs uptake is observed during accelerated plants development and intensification of the key metabolic reactions. At later stages (formation of generative organs) ^{137}Cs accumulation was dropped.



a) b)

Figure 1. ^{137}Cs (a) and K (b) accumulation in spring barley plants in ontogenesis (no grain was obtained in variant^{137}CsCdCo).

An effect of Co and Cd on ^{137}Cs soil-to-plant transfer is also given in Fig. 1a. It is clearly evident that soil contamination with Co and Cd at concentration 20 and 25 times exceeding the Maximum Permisible Level (MPL) for soddy-podzolic soil not only produced negative effects on the spring barley productivity formation, but also resulted in decreasing of ^{137}Cs root uptake. There might be two possible reasons for changes in the rate of ^{137}Cs accumulation by plants at different stages of the development caused by the presence of large amounts of Cd^{2+} and Co^{2+} ions in the soil: 1) added Co and Cd decrease the ^{137}Cs proportion which will be readily available to plants or subjected to leaching, and 2) because of their toxicity, heavy metals influence the metabolic processes in plants and thus change radionuclide accumulation.

It is well known that the most important soil constituents responsible for ^{137}Cs retention are the clay minerals. Some HM [5] also can fix as a result of physical entrapment in clay lattice wedge zones and/or strongly adsorbed at the exchange sites.

The general rules of the radionuclide uptake in ontogenesis being observed, application of metals to the soil inhibited ^{137}Cs uptake by barley plants and yield on average 1.4–2.9 times compared to the control. It has been shown that the dynamic of K concentration of barley plant in ontogenesis were similar to ^{137}Cs dynamic in whole (Fig. 1b). Cd resulted in more K accumulation in barley plant on early stage (30 days after sowing). On the contrary, Co increased K in straw and grain. The highest K concentration in biomass of 30–60 days plant was noted in variant with Cd and Co soil contamination.

3.2 PGR influence

PGR are physiologically active and are responsible for controlling various metabolic processes in plants. A secondary effect of their application might be modification of the radionuclide uptake and distribution between different parts of plant. The application of PGR may increase or decrease radionuclide concentrations in crops as a result of processes that occur both in the soil and the plant. It has been shown also that the biologically active substances influence on the accumulation of such HM as cadmium and lead in barley straw and grain [6, 7].

Seed incrustation with Zircon and Epin did not produce significant influence on Co and Cd phytotoxicity, however the use of these chemicals resulted in different in direction and value effects on ^{137}Cs accumulation in barley plants at various stages of its development. The pre-sowing seed treatment by PGR produced the decreasing of ^{137}Cs accumulation in 30 days plant cultivated in uncontaminated soil. The increasing of radionuclide transport was observed for barley grown on the contaminated soil, beginning from the tillering stage and up to maturity (Fig. 2a). Application of biologically active substances promoted increase of the K contents in plants at all stages of their development (Fig. 2b).

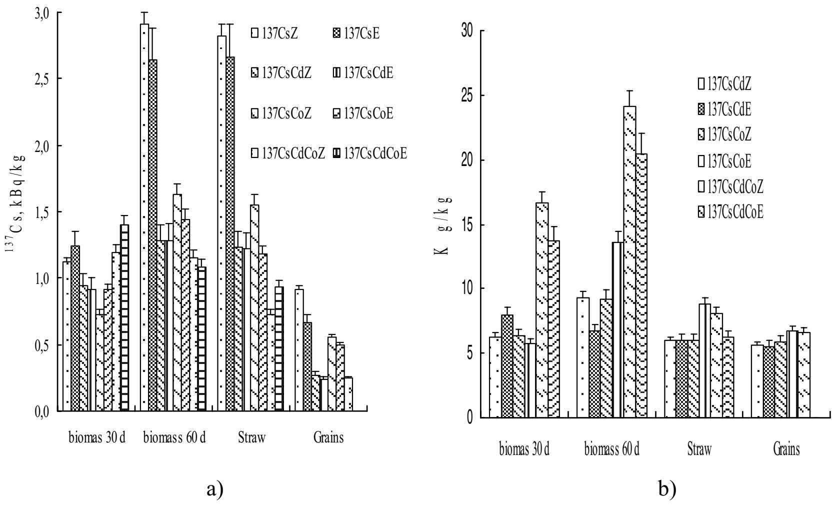


Figure 2. Effects of pre-sowing seeds treatment by Epin and Zircon on the ^{137}Cs (a) and K (b) accumulation in spring barley.

The decreasing of ^{137}Cs activity, in general, was accompanied by growth of K concentration in a biomass and a yield. The effect of Cd and/or Co soil contamination on ^{137}Cs in the plants was more significant, than influence of Zircon and Epin. The experimental data, however, do not make it possible to link directly the effect of biologically active substances on ^{137}Cs uptake with their influence on HM toxicity, which was determined through the morphological and physiological parameters of plants.

3.3 Cd and Co phytotoxicity

As previously established [4], ^{137}Cs at applied to soil activity produced no negative effect on the plants development. Higher Co concentrations produced a more negative effect on the productivity formation in spring barley than these of Cd (Table 1), though in terms of the MPL exceeding both the Co and Cd contents were quite similar. The inhibition of plants growth due to separate and combined Cd and Co soil contamination was most evident in changes of the parameters such as plant height (by 5–20, 20–30 and 30–40% respectively for Cd, Co and in the case of multielements pollution), leaf area index (8–23; 19–34 and 37–44% in the same variant) and barley biomass in different ontogenesis stages. In plants grown on Co contaminated soil, the absence of productive undergrowth and 50% reduction in the main ear productivity were reported.

Soil contamination with Cd at toxic concentrations reduced photosynthetic processes as well as total crop productivity [4, 8].

Table 1. Co and Cd effects on barley development (complete ripeness stage).

Treatment	Number of productive stems	Plant height, cm	Main shoot			Subsidiary ears	
			Ear length, cm	Number of grains grains	Grain, g	Number of grains	Grain, g
^{137}Cs	$1,8 \pm 0,2$	$67,8 \pm 1,1$	$7,4 \pm 0,2$	$17,8 \pm 0,8$	$0,7 \pm 0$	$7,8 \pm 1,4$	$0,3 \pm 0,1$
^{137}Cs Cd	$1,0 \pm 0^*$	$64,4 \pm 1,1$	$6,4 \pm 0,2^*$	$16,4 \pm 1,9$	$0,7 \pm 0,1$	$0,4 \pm 0,2^*$	$0,01 \pm 0^*$
^{137}CsCo	$0,9 \pm 0^*$	$48,6 \pm 1,6^*$	$6,2 \pm 0,1^*$	15,7±1,6	$0,4 \pm 0,1^*$	0	0
^{137}CsCdCo	0	$42,9 \pm 0,9^*$	$1,5 \pm 1,0^*$	0	0	0	0

* - Significant difference at <0,05 to ^{137}Cs treatment; 0 – no grain.

In Cd treatment (50 mg/kg), ^{137}Cs decrease in biomass of 60-day plants and barley yield was 1.8 times; in the presence of Co (100 mg/kg) – 1.6 times. The most significant decrease in ^{137}Cs specific activity (2.4–2.9 times) was reported in biomass of 30- and 60-day plants and yield in mixed soil pollution with the two metals.

Considering that in combined Cd and Co treatments a reduction was observed in parameters of barley growth and development such as plant height, LAI, dry biomass of 30 and 60 d plants, number of productive stems, straw and grain mass of a whole plant, mass of 1000 grains, it may be assumed that radionuclide uptake reduction was caused largely by the phytotoxic effect of the metals. Pre-sowing seeds incrustation with Zircon and Epin did not reduced significantly accumulation of heavy metals and their phytotoxicity.

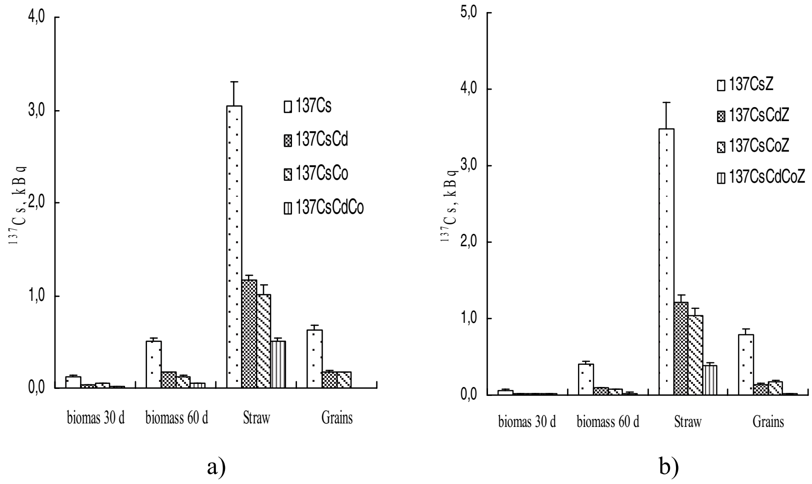


Figure 3. ^{137}Cs removal from soil with spring barley plants in ontogenesis (a-without application by PGR, b-after seed treatment with Zircon).

3.4 ^{137}Cs removal

Elements removal with biomass may be considered as an integral function of the rate of growth and intensity of metabolic processes in different phases of plant development. In the early period (30 days), ^{137}Cs removal with barley biomass, calculated per 1 plant, dropped significantly when plants were grown on soil with increased HM concentrations compared to the background content of elements in the soil (Fig. 3).

This trend persisted during the ontogenesis. Thus, in spite of the fact that the absolute values for ^{137}Cs transfer with the biomass of 60 d plants and vegetative mass (straw) grew, increased Cd content in the soil caused a significant (80-90%) reduction in ^{137}Cs removal.

4. CONCLUSION

It has been concluded that regulation of ^{137}Cs transport from soil to plants due to the interlocking mechanisms of the radionuclide uptake by the root system or change in the metabolic processes under the action of HM in toxic concentrations was more significant than the influence on the same processes of biologically active substances.

The present findings are to be taken into account when developing technologies for rehabilitation of radioactively contaminated lands located near large industrial centers and introducing large amounts of ameliorants with elevated HM content.

References

[1] Sviridenko D.G., *PhD Thesis. Obninsk* (2006) pp. 1-28.

[2] Uri N.D., *Sci. Total Environ*. **204** (1997) 57-74.

[3] Ulyanenko L.N., Filipas A.S. Diachenko I.V. and Alexakhin R.M., *Doklady RASHN* **5** (1993) 17-19.

[4] Ulyanenko L.N., Krouglov S.V., Filipas A.S. and Alexakhin R.M., *Agrohimiya* **3** (2002) 75-81.

[5] Oulianenko L.N., Filipas A.S., Diachenko I.V. and Stepanchikova N.S. "To the problem of chemical toxicants and radionuclides accumulation in plant production", Chemical problems of ecology, Proc. V Mendeleyev' Congress on total and applied chemistry, Byelarus, Minsk (1993) 304-305.

[6] M.R. Reddy, H.F. Perkins, *Soil Science Society of American* **38** (1974) 229-230.

[7] Ulyanenko L.N., Filipas A.S., Diachenko I.V., Stepanchikova N.S. and Vakulenko V.V., *Radiation Biology. Radioecology* **36** (1996) 241-248.

[8] Oulianenko L.N., Filipas A.S., Diachenko I.V. and Stepanchikova N.S., "ome aspects of the rehabilitation of agricultural lands contaminated with radionuclides and heavy metal", International Conference on Nuclear Waste Management and Environmental Remediation, New York (1995) 1491-1493.