

TOWARD A THEORY OF THE EFFECT OF INHIBITION OF THE TRANSFER OF RADIONUCLIDES AND HEAVY METALS FROM SOIL TO PLANTS BY AMELIORANTS. 1. FORMULATION OF THE PROBLEM

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The effect of an ameliorant on soil and plants is characterized. A model of convective diffusion transfer of nutrition elements from the soil to plants is substantiated. Experimental results that determine a decrease in the ion diffusion coefficients in soil after the application of an ameliorant are presented.

The present work deals with the problem of production of radionuclide-free agricultural products in radionuclide or heavy metal-contaminated lands.

The method of production of such products is based on the application of quicklime and phosphogypsum to the soil. Development of the method was started in 1981, when for the first time we found a substantial increase in the filtration coefficient of heavy soils modified with calcium oxide.

Studies conducted for many years have shown that the effect of application of an ameliorant consists in an increase in the filtration coefficients of heavy soils (dermo-podzolic, composed of heavy loamy soils, clays, and solonets soils) of up to 50 times and an increase in the drainage effluent modulus of up to 2 times; intensification of the uptake of salt from saline solonets soils of up to 10 times; development of a favorable microbiological regime in the soil; protection of soils irrigated by slightly mineralized water from magnesium and sodium solonetzification; an increase in the productivity of cereal crops of up to 20% and of green material of up to 60%; and decreases in plant cesium-137 concentrations (depending on the properties of soils and plant species) of 2–8 times, strontium-90 concentrations of 3–7 times, and cadmium concentrations of up to 2 times.

Explanation of the effect of the substantial decrease in the radionuclide and heavy metal contents in agricultural products requires theoretical calculations.

At present it is recognized that the rate of ion uptake by plants is determined by the number of ions coming in contact with the absorbing surface of the root per unit time. This number depends on the intensity of the three processes:

- 1) growth of the roots that results in the fact that roots penetrating to new soil areas come in contact with a larger number of ions;
- 2) convective transfer of ions to the surface of the roots by the flow of moisture that results from imbibition of water by roots;
- 3) diffusion of ions to or from the surface of the roots.

Experimental studies carried out to determine the contribution of each of the three processes to absorption of the various elements by the plants have shown that most of the important nutrition elements such as phosphorus or potassium are brought to plants by diffusion.

This finding has allowed some researchers to suggest models of absorption of the elements by plants, where roots were assumed to be drain pipes to which the elements diffuse. In principle, the use of mathematical models for quantitative description of such a complicated process as absorption of nutrients from the soil by roots is highly promising since these models can be used to express the whole diversity of the conditions of the growth and development of plants in terms of a limited number of parameters. However, though these models are simple and give fair agreement with experimental data on phosphate absorption, they can be used in a limited number of cases,

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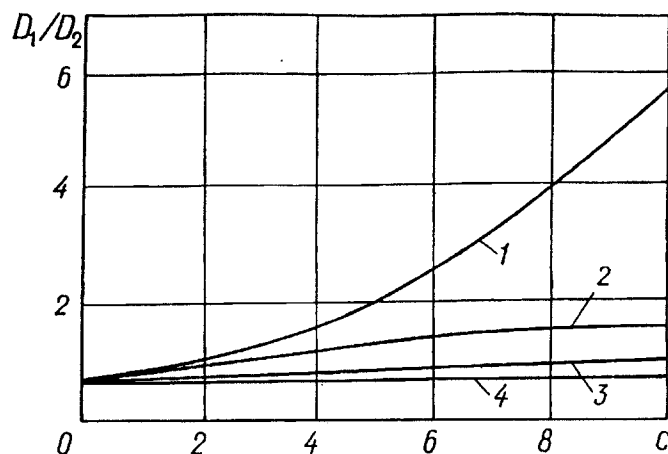


Fig. 1. Plot of relative diffusion coefficients of cadmium (1), strontium (2), cesium (3), and lead (4) ions in solutions filtering through loamy soil modified with 5 t/ha of quicklime and 5 t/ha of phosphogypsum. c , mg/liter.

since they neglect the other processes, namely, the growth of roots and convective transfer that provide many important elements to plants.

The model suggested by Nai and Spacer, who assumed root absorption to be a result of simultaneous convective transfer and diffusion, is more complete than pure diffusion models. This model is based on the following assumptions: the concentration of the absorbed element in the soil solution is a linear function of the total concentration of the solution in the soil; the absorbing surface of the roots has a cylindrical shape; the rate of absorption of the element by the root surface is directly proportional to the concentration of the element in the soil solution and the surface.

Drawbacks of this model are a poorly justified transition from a steady-state solution to an unsteady-state solution and use of such an ambiguous quantity as the root radius.

Even in the same plant, roots that are able to absorb ions have different dimensions (the thickness of the roots proper is many times larger than the thickness of root hairs). Since both roots and root hairs participate in absorption of ions, some authors include roots with two different diameters in their models, using the ratio of the total lengths of the roots with these two dimensions. This, however, restricts the applicability of the model to other plant species with different dimensions of the roots and a different ratio of their total lengths.

In [1, 2] an attempt was made to describe absorption of ions caused by all three processes by considering a linear convective-diffusive ion flow to the absorbing surface, whose surface area changes in time.

The model was developed for the case of absorption of radionuclides, which are products of nuclear fission, by plants. An expression was obtained for the radionuclide absorption rate per unit surface area

$$i = \frac{aV}{2} \left[\frac{2k - V}{V} \exp \frac{(k - V) kt}{D} \operatorname{erfc} \left(\frac{2k - V}{2} \sqrt{t/D} \right) + \operatorname{erf} \left(\frac{V}{2} \sqrt{t/D} + 1 \right) \right],$$

where a is the radionuclide concentration in the soil; V is the linear velocity of motion of a radionuclide in the soil as a result of moisture flow to the root; k is the linear velocity of motion of a radionuclide during its absorption by the surface of the root; D is the ionic diffusion coefficient in the soil; t is the time of the process. We will use this equation in further calculations. It should be assumed that upon application of an ameliorant all the three parameters (V , k , and D) will change. Here we will dwell on experimental estimation of the change in the ionic diffusion coefficient in the soil. The experiments were carried out in loamy and sandy loamy soils, and solutions of cesium, strontium, cadmium, and lead salts were used as filtering solutions.

Dynamic experiments were conducted to determine these parameters. Soil with a disturbed structure was placed in a glass column 20 mm in diameter and 30 cm in length. The thickness of the layer of a pre-packed soil was 1–1.5 cm. Before the experiment, the samples were washed with distilled water and then solutions of cesium, strontium, lead, and cadmium with concentrations of 10.0, 5.0, and 0.5 mg/liter were passed through them.

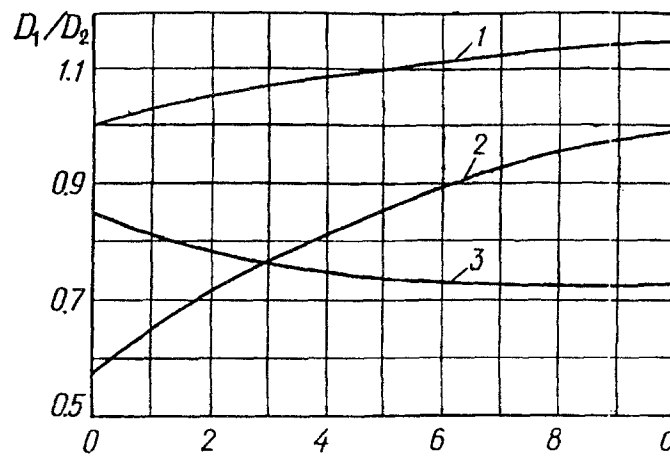


Fig. 2. Plot of relative diffusion coefficients of cesium ions in solutions filtering through loamy and sandy loamy soils modified with powdered dolomite at a dose of 5 t/ha (1), through sandy loamy soil modified with 5 t/ha of quicklime and 5 t/ha of phosphogypsum (2), through loamy soil modified as in the previous case (3).

In the course of the experiment the filtrates were collected in small batches (10 ml) at the column outlet at the initial moment of the filtration cycle and at certain intervals.

The obtained solutions were filtered and analyzed to determine the contents of cesium, strontium, cadmium, and lead in them.

In experiments with ameliorant-modified soils, quicklime (CaO) and phosphogypsum were introduced at a dose of 5 t/ha of each chemical ameliorant component (the suggested experimental variant) and 5 t/ha of powdered dolomite (a conventional experiment).

In the experiments the following parameters of the yield curve were recorded: the filtrate volume, the time of filtrate yield, and the ion concentrations in the filtrate. The relative ion concentration in the filtrate $\bar{c} = c/c_0$ and the parameter

$$\Sigma = \sqrt{t} \operatorname{arccerfc}(1 - 2\bar{c}) = \frac{x}{2\sqrt{Dt/n}} - \frac{V_f n}{\sqrt{Dt/n}},$$

were calculated from these data. In these expression V_f is the filtration rate, x is the filtration path length, n is the porosity of the soil, c is the instantaneous ion concentration in the filtrate, c_0 is the initial ion concentration in the solution, t is the filtration time, and D is the ionic diffusion coefficient in the soil.

The calculated parameters were used for determination of the ionic diffusion coefficient, the ion distribution in the soil, and the effective porosity.

In Fig. 1 one can see the relative diffusion coefficients D_1/D_2 of cadmium, strontium, cesium, and lead ions in solutions with various concentration filtering through a soil modified by 5 t/ha of quicklime and 5 t/ha of phosphogypsum (D_1 is the ionic diffusion coefficient in the ameliorant-modified soil and D_2 is the ionic diffusion coefficient in the control soil (without the ameliorant)).

Two important conclusions follow from Fig. 1: 1) when the concentration of the filtering solution $c \rightarrow 0$, which corresponds to the real concentration of cesium-137, strontium-90, cadmium, and lead, the ionic diffusion coefficients decrease under the action of the ameliorant; 2) at $c \rightarrow 0$ the relative diffusion coefficients D_1/D_2 are independent of the properties of the ion but are determined totally by the properties of the soil (the theory of this mechanism will be presented in a subsequent publication).

In Fig. 2 one can see a plot of relative diffusion coefficients of the cesium ion in solutions filtering through loamy and sandy loamy soils modified by quicklime and phosphogypsum and separately by powdered dolomite. The following conclusions can be made from the figure: 1) the powdered dolomite has no effect on the ionic diffusion coefficients in soil with neutral pH; 2) in the transition from heavy soils to light soils modified by quicklime and

phosphogypsum, D_1/D_2 increases but remains less than 1 (the theory of this mechanism will be presented in a subsequent publication).

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