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INVESTIGATION OF MECHANISMS OF POTASSIUM AND CESIUM-137 UPTAKE BY PLANTS WITH OPTICAL AND GAMMA SPECTROMETRIES IN THE FIELD UNDER WATER-STRESSED CONDITIONS

Channels of the ^{137}Cs and potassium transfer from soil to plants in the field under water-stressed conditions are investigated. Different rapidly maturing plants were grown and selected simultaneously several times during the 2012 and 2013 seasons at the same experimental sites with different soil types under natural conditions at the Chornobyl 10-km Exclusion Zone. After each selection, the contents of ^{137}Cs and K in the plants and extracted soil solutions were measured. Potassium and cesium entered plant roots, as a rule, through transporters with low selectivity, when the concentration of dissolved potassium (C_{K}) in soil was greater than 2 μg/cm^3. In this case, the selectivity of the plant uptake for ^{137}Cs versus potassium r was near 1. However, when C_{K} was between 0.5 and 2 μg/cm^3, potassium also appeared to enter plant roots through highly selective potassium transporters, while cesium entered roots only through the transporters with low selectivity. In this case, the value of r was much less than 1. When C_{K} was less than 0.5 μg/cm^3, cesium and potassium appeared to enter roots through a complement of transporters with greater selectivity for cesium than for potassium. The value of r in this case could exceed 1.

Keywords: cesium, ion channel, potassium, root, soil humidity, soil solution.

1. Introduction

There is always the possibility of an accident “a la Chornobyl” or “a la Fukusima” for all countries with nuclear power stations. Moreover, soil may be polluted with radionuclides from other sources. So, the problem of the prediction of the ^{137}Cs concentration in plants from contaminated land with certain type of soil is actual for any country and, to a greater extent, for those with a significant agrarian part in the economy.

Cesium, which is not required by plants, is taken up from the soil solution by various cation transporters in the plasma membrane of root cells [1–3]. By contrast, potassium is an essential plant nutrient. The nonselective cation channels (NSCCs) generally show a low selectivity between Cs and K. It has been demonstrated that NSCCs mediate most of the cesium uptake by root cells in potassium-replete plants, but that K/H-symporters mediate most of the cesium uptake by root cells in potassium-deficient plants [4–7]. Nonselective cation channels in plants are described in Ref. [8].

The inward-rectified K-channel (KIRC) as a low-affinity transport system generally has a high selectivity for K versus Cs and contributes little to the cesium uptake by root cells under typical soil conditions [1, 3, 4]. A high-affinity system catalyzes most of the potassium uptake in potassium-deficient plants and at submillimolar potassium concentrations in the rhizosphere solution [9, 10].

The NSCC (passive) is dominant at millimolar potassium external concentrations, and the high-affinity system is dominant at micromolar potassium external concentrations [11, 12]. The cross-over point defining the potassium external concentration either side of which one of the systems assumes dominance has been shown to be in the range from 0.3 to 1 mM [1].

It was concluded in Refs. [6, 13] after investigations of *Arabidopsis* that Cs is transferred to the plant via voltage-nonsensitive cation channels at a potassium depletion. If there is a potassium starvation of the plant, the essential part of the Cs transfer to the plant is via K^+/H^+ transporters.

It was affirmed in Ref. [2] that the Cs transfer to plants occurs only via the potassium transport system, i.e., the K^+/H^+ transporter and potassium channels. There is a slight discrimination against Cs if the external potassium concentration is less than 0.3 mM, and there is a strong discrimination against Cs if the external potassium concentration is more (potassium channels are prevailing).

The above-mentioned investigations were performed under artificial conditions. These results could be not applicable to the plants grown under native conditions.

A theoretical model of the effect of potassium on the uptake of radiocesium by rice was proposed in Ref. [14] after pot and field experiments.

It was suggested in Refs. [15, 16] after the experiment under field conditions that the dissolved potassium per unit of soil volume (C_K) as the amount of potassium available to a plant determines the selectivity of ^{137}Cs and potassium accumulation by plants in the field, rather than potassium concentration in the soil solution. In those studies, C_K was always above 0.5 μg/cm^3. However, no experiments were done for less C_K, which is usually an attribute of water-stress conditions. In this work, the use of ion channels by plants under different field conditions including the hard deficit of the dissolved potassium in soil (C_K is below 0.5 μg/cm^3) is investigated.

2. Experiment

We studied the growth of different plants at three experimental field sites with different types of soil in the 10-km Exclusion Zone of the Chernobyl Nuclear Power Plant: i) site B (51°22′33.6″N, 29°54′5.1″ E) with a sandy-loam soil, the pollution by Cs-137 was about 1.7×10^4 Bq/kg, gamma background was 380 μRh/h, and soil density was 1.41 g/cm^3; ii) site B2 (51°22′29.5″N, 29°54′6.3″ E) with a sandy soil, the pollution by Cs-137 was about 1.1×10^4 Bq/kg, gamma background was 350 μRh/h, and soil density was 1.42 g/cm^3; and iii) site D (51°22′29.2″ N, 29°54′0.1″ E) with a peaty soil, the pollution by Cs-137 was about 1.5×10^4 Bq/kg, gamma background was 200 μRh/h, and soil density was 0.85 g/cm^3.

Rapidly maturing plants distinguishable one from another as possible were mixed together and sowed at the sites B, B2, D. These were radish (*Raphanus sativus*), mustard (*Sinapis sp.*), lettuce (*Lactuca sativa*), spinach (*Spinacia oleracea*), beet (*Beta vulgaris*), coriander (*Coriandrum sativum*), watercress (*Lepidium sativum*), and valerianella locusta (*Valerianella locusta*).

The plants were sowed (and then harvested) simultaneously at each experimental site several times during each season. No artificial moisturizing of soils at the sites was done in the experiment. We selected the samples several times each season as in Refs. [16,17]. Every time, we harvested samples of the soils, sowed plants if they had grown, as well as some kinds of wild plants grown within the site areas. These were couch grass (*Elytrigia repens*), lady's-thumb (*Persicaria maculosa*), berteroa (*Berteroa incana* L.), bunias (*Bunias orientalis* L.), ground-ivy (*Glecoma hederacea*), pansy (*Viola tricolor*), common sorrel (*Rumex acetosa*), st. John's wort (*Hypericum*), common orach (*Atriplex patula*), evening primrose (*Oenothera rubricaulis*), bindweed (*Convolvulus*), and yellow-foxtail grass (*Setaria glauca*). As a rule, we selected whole plants. We harvested all the grown plants at each experimental site at each sample selection. But we did not harvest sprouts of plants, so they could continue to grow. The mass of each kind of selected plants was within 5–500 g. The plants were sampled before blossoming and were washed and dried. Soil solutions were extracted from soil by an OS-6M centrifuge (USSR) with a frequency of 6000 rpm for 15 min. The soil solution was extracted immediately if the humidity was enough. If the sample of soil was too dry for the extraction, we added distilled water to the sample and centrifuged 12 hours later. It was shown [18] that the addition of even a low amount of water to some soils significantly changes

Table 1. **Parameters of plant and soil samples for site D (peaty soil)**

h	Date	Sample	K, mg/g	^{137}Cs, Bq/kg	$(^{137}\mathrm{Cs/K})_p/(^{137}\mathrm{Cs/K})_{ss}$	C_{K}, mg/cm^3
0.139	28.05.2012	Soil solution	0.0084	8.52		0.99
		Raphanus sativus	31.2	4108	0.130	
0.208	25.06.2012	Soil solution	9.1	6.01		1.61
		Elytrigia repens	21.26	1690	0.120	
		Sinapis sp.	42.52	7251	0.259	
		Persicaria maculosa	38.39	2752	0.109	
		Raphanus sativus	32.12	11446	0.539	
		Lactuca sativa	69.6	3400	0.073	
		Spinacia oleracea	66	270	0.006	
		Beta vulgaris	52.9	11000	0.315	
		Coriandrum sativum	48.5	1700	0.053	
0.358	18.09.2012	Soil solution	0.0075	5.21		2.28
		Raphanus sativus	42.6	13870	0.470	
		Berteroa incana L.	28	7156	0.369	
		Glecoma hederacea	27.3	6188	0.326	
		Persicaria maculosa	30.8	2560	0.120	
0.252	15.05.2013	Soil solution	0.004	2.32		0.856
		Viola tricolor	31.76	3514	0.191	
		Elytrigia repens	18.38	1957	0.184	
		Rumex acetosa	37.79	4500	0.205	
		Hypericum	16.31	865	0.091	
0.345	04.06.2013	Soil solution	0.0094	2.64		2.75
		Raphanus sativus	31.84	12047	1.347	
		Lepidium sativum	42.81	6130	0.510	
0.173	26.06.2013	Soil solution	8	4.89		1.176
		Coriandrum sativum	20.71	2851	0.225	
		Persicaria maculosa	21.81	15347	1.151	
		Beta vulgaris	41.91	33366	1.302	
		Atriplex patula	52.72	10888	0.338	
		Raphanus sativus	26.23	17893	1.116	
0.0772	09.07.2013	Soil solution	0.0075	1.85		0.492
		Raphanus sativus	26.86	29383	4.435	
		Beta vulgaris	32.87	40829	5.036	
		Lactuca sativa	21.8	13662	2.541	
		Atriplex patula	54.35	12454	0.929	
		Coriandrum sativum	17.15	3994	0.944	
		Lepidium sativum	26.1	26000	4.038	
0.0718	20.08.2013	Soil solution	0.0049	2.52		0.297
		Atriplex patula	30.5	15255	0.965	
		Valerianella locusta	11.9	11663	1.890	
		Raphanus sativus	7.38	32222	8.420	
		Coriandrum sativum	7.31	4409	1.163	
		Oenothera rubricaulis	10.25	12063	2.270	

the content of ^{137}Cs in a soil solution. We selected the sites with soils, for which the ^{137}Cs concentration in their solutions was not changed with the addition of a little of water. As a rule, we obtained near 200 ml of a soil solution at each extraction. Extracted soil solutions were filtered, first through a filter pa-

Table 2. **Parameters of plant and soil samples for site B (sandy-loam soil)**

h	Date	Sample	K, mg/g	^{137}Cs, Bq/kg	$(^{137}\mathrm{Cs}/\mathrm{K})_p/(^{137}\mathrm{Cs}/\mathrm{K})_{ss}$	C_{K}, mg/cm^3
0.0579	25.06.2012	Soil solution	0.0108	4.4		0.882
		Raphanus sativus	36.94	1729	0.115	
		Sinapis sp.	37.91	1904	0.122	
		Rumex acetosa	36.17	1513	0.103	
0.0081	01.08.2012	Soil solution	0.0198	14.41		0.226
		Raphanus sativus	45.37	2918	0.0879	
		Rumex acetosa	30.26	2510	0.114	
		Sinapis sp.	22.44	2840	0.174	
0.050	18.09.2012	Soil solution	0.0079	7.6		0.557
		Raphanus sativus	45.8	4069	0.0925	
		Rumex acetosa	46.2	4839	0.109	
0.0716	15.05.2013	Soil solution	0.0072	5.11		0.725
		Rumex acetosa	25.46	8341	0.460	
		Elytrigia repens	12.53	4556	0.511	
0.111	04.06.2013	Soil solution	0.011	9.15		1.73
		Raphanus sativus	45.45	10763	0.285	
0.0178	26.06.2013	Soil solution	0.0208	14.32		0.522
		Elytrigia repens	22.39	3012	0.195	
		Lepidium sativum	31.85	19082	0.870	
		Rumex acetosa	23.38	7846	0.487	
		Convolvulus	23.59	1595	0.0982	
		Raphanus sativus	29.32	12212	0.605	
0.0111	09.07.2013	Soil solution	0.020	10.62		0.31
		Setaria glauca	26.26	6944	0.498	
		Coriandrum sativum	14.7	4311	0.552	
		Raphanus sativus	38.16	25099	1.239	
0.0070	20.08.2013	Soil solution	0.0105	7.43		0.1036
		Setaria glauca	19.01	2636	0.196	
		Convolvulus	26.88	2263	0.119	
		Oenothera rubricaulis	25.42	14577	0.810	
		Raphanus sativus	21.64	30145	1.969	

per with a pore near 1–3 μm in diameter and then through a membrane filter with a pore 0.1 μm in diameter (Melior XXI Ltd., Russia). The soil solutions after the filtration were clear (colorless). To conserve the obtained soil solutions, we added nitric acid to them a in a proportion of 1 ml of concentrated nitric acid per 500 ml of the solution and heated it to boiling.

The soil humidity "in situ" h was found with experimental error of 10%, by using a gravimetric technique as a ratio of water mass in the soil sample to the mass of the dried soil. The soil samples were dried in a drying oven at 100 °C. The content of ^{137}Cs in the samples of plants and soil solutions was monitored through the activity concentration, which was obtained, by using a HPGe ORTEC GMX40P4-83-RB POPTOP sn.48-TN22465A gamma-spectrometer (AMETEK, USA) with a semiconductor detector. The experimental error, as a rule, did not exceed 10%. The minimal detectable activity for ^{137}Cs was of 0.1 Bq per a sample for the measuring time of 10^4 s, the average error was 20% ($p = 0.95$). The concentrations of potassium in the samples of plants and soil solutions were measured by the atom-absorption technique, by using a S-115-M1 spectrophotometer at a wavelength of 766.5 nm with an error of 5%. The method was described in more details in Ref. [19].

Table 3. **Parameters of plant and soil samples for site B2 (sandy soil)**

h	Date	Sample	K, mg/g	^{137}Cs, Bq/kg	$(^{137}\mathrm{Cs/K})_p/(^{137}\mathrm{Cs/K})_{ss}$	C_K, mg/cm^3
0.0744	04.06.2013	Soil solution	0.0131	19.1		1.38
		Lepidium sativum	39.55	5046	0.088	
		Raphanus sativus	39.27	20525	0.358	
0.0119	26.06.2013	Soil solution	0.0218	16.95		0.368
		Lepidium sativum	21.74	5055	0.299	
		Atriplex patula	49.03	6690	0.175	
		Raphanus sativus	117.61	6380	0.070	
		Setaria glauca	31.33	4990	0.205	
0.0042	09.07.2013	Soil solution	0.0168	7.31		0.0954
		Setaria glauca	26.26	4196	0.367	
		Atriplex patula	53.25	7907	0.343	
		Raphanus sativus	34.96	8491	0.562	
0.0061	20.08.2013	Soil solution	0.0139	3.92		0.1204
		Setaria glauca	23.62	2577	0.387	
		Oenothera rubricaulis	25.57	4850	0.673	
		Raphanus sativus	22.76	9947	1.550	
		Atriplex patula	42.59	3189	0.266	

3. Results

The obtained data for the sites B, B2, and D are represented in the Tables 1–3. We can see the humidity h (ratio of the water mass in the sample to the mass of dried soil), date of sample selection, kind of species, concentrations of potassium and ^{137}Cs in the plants and the corresponding soil solution, selectivity of plant uptake for ^{137}Cs versus potassium $r = (^{137}\mathrm{Cs/K})_p/(^{137}\mathrm{Cs/K})_{ss}$, were $(^{137}\mathrm{Cs/K})_p$ and $(^{137}\mathrm{Cs/K})_{ss}$ – the ratios of concentration ^{137}Cs and K in the plant and corresponding soil solution, respectively, and the concentration of dissolved potassium in soil (product of the potassium concentration in a soil solution and the content of the soil solution in a unit volume of soil) C_K. We can see that r is also the ratio of the concentration coefficients plant/soil solution for ^{137}Cs and K in the investigated samples. The experimental error for all data does not exceed 10%.

One can see for site D (Table 1) with peaty soil that r was close to 1, when $C_\mathrm{K} = 2.75\ \mu\mathrm{g/cm}^3$ (the highest value). In the cases where $0.5\ \mu\mathrm{g/cm}^3 < C_\mathrm{K} < 2\ \mu\mathrm{g/cm}^3$, r was much less than 1 for most of the plants. For the selection dates of 09.07.2013 and 20.08.2013, when C_K was below 0.5, r was much higher than 1 for most of the plants.

For sites B and B2 with, respectively, sandy-loam and sandy soils (see Tables 2 and 3), C_K did not exceed 2 μg/cm^3 in each case. When C_K was below 0.5 μg/cm^3, r was higher than that in the cases where C_K was above 0.5 μg/cm^3. This is especially evident for the selection dates of 09.07.2013 and 20.08.2013.

4. Discussion

So, the concentration coefficients plant/soil solution are approximately equal (r is close to 1) at higher concentrations of dissolved potassium in soil ($C_\mathrm{K} > 2\ \mu\mathrm{g/cm}^3$). This implies that the potassium and cesium uptake to the plants occurs by the NSCCs. These data confirm the conclusions of Refs. [15, 16].

As C_K decreases into the range from 0.5 to 2 μg/cm^3 (potassium deficit), r becomes much less than 1 for all the sites, i.e., the concentration coefficient plant/soil solution for potassium is much higher than that for cesium, whose concentration in plants becomes much times less. The cesium uptake in plants remains approximately proportional to the concentration of cesium dissolved in the soil. Potassium transfers to plant also use a highly selective channel (KIRC). This is also in accordance with the data of Refs. [15, 16].

One can see in the tables that r is high and can significantly exceed 1 at $C_\mathrm{K} < 0.5\ \mu\mathrm{g/cm}^3$. The cesium content in the plants becomes much greater than that in the previous case. We believe that, as C_K falls below 0.5 μg/cm^3, plants begin to use one highly selective channel more. This is a K/H-symporter. The cesium uptake to plants through this channel exceeds that for potassium. Therefore, the ^{137}Cs content in plant increases.

5. Conclusion

While the concentration of dissolved potassium C_K in soil exceeds 2 μg/cm^3, the potassium and cesium uptakes occur through mainly low-selectivity potassium channels (NSCC). The selectivity of the plant uptake for ^{137}Cs versus potassium r is herewith close to 1. As the concentration of dissolved potassium becomes below 2 μg/cm^3 but above 0.5 μg/cm^3, potassium transfers to plants also through a high-selective channel (KIRC). In this case, cesium transfers to plants through the low-selective channel only. Herewith, r is much less than 1. When $C_K < 0.5$ μg/cm^3, plants use one highly selective potassium channel more (K/H-symporter). The cesium uptake to plants through this channel is rather significant. In this case, r can exceed 1.

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ОПТИЧНІ ТА ГАММА-СПЕКТРОМЕТРИЧНІ ДОСЛІДЖЕННЯ МЕХАНІЗМУ НАДХОДЖЕННЯ КАЛІЮ ТА ЦЕЗІЮ-137 У РОСЛИНИ В ПОЛЬОВИХ УМОВАХ ПРИ НЕСТАЧІ ВОДИ

Резюме

Канали надходження ^{137}Cs та калію з ґрунту в рослини при нестачі води досліджено в польових умовах. Різноманітні рослини швидкого визрівання одночасно вирощувалися і збиралися кілька разів протягом двох сезонів 2012–2013 рр. на одних і тих самих експериментальних ділянках і з різними типами ґрунтів при одних і тих самих природних умовах у 10-кілометровій Чорнобильській Зоні Відчуження. Після кожного відбору вимірювався вміст ^{137}Cs та K в рослинах та екстрагованих ґрунтових розчинах. Калій та цезій надходили до коренів рослин, як правило, через низькоселективні канали, коли концентрація розчиненого калію (C_{K}) у ґрунті перевищувала 2 мкг/см^3. В цьому випадку селективність надходження в рослину для ^{137}Cs відносно калію r була близька до 1. Однак коли C_{K} була в інтервалі від 0,5 до 2 мкг/см^3, калій, як виявилося, також надходив до коренів рослин через високоселективні калієві канали, тоді як цезій надходив до коренів лише через низькоселективні канали. В цьому випадку величина r була набагато меншою від 1. Коли ж C_{K} була нижчою за 0,5 мкг/см^3, цезій та калій надходили до коренів через конкуруючі канали з більшою селективністю для цезію, ніж для калію. Значення r у цьому випадку могло перевищувати 1.