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Resistance of heather plants (*Calluna vulgaris* L.) to cesium toxicity

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Abstract Experiments were carried out to determine uptake and distribution of ^{137}Cs, and total isotopes of Cs and K in plants of heather (*Calluna vulgaris*) growing at two levels of CsCl: 0.03 and 0.3 mM. Levels of Cs and K were determined in soil and in parts of plants: roots, stem, leaves and flowers. Also calculated were: (i) transfer factor of Cs and K from soil to parts of plant and (ii) discrimination of K by Cs during the transport of Cs from roots to aboveground parts of plants, expressed as K/Cs discrimination factor. The results confirmed that heather plants are hyper-accumulators of cesium, because the accumulation of Cs in shoot was much greater than in roots. The K level in heather did not change at Cs concentrations as high as 8-fold Cs level in this plant. Heather plants seem to be relatively resistant to cesium toxicity at 0.3 mM of CsCl; the effect of exposure to CsCl at this concentration was exerted only on roots, without affecting leaves and flowers. These results supply new information on the interactions between Cs and K nutrition in plants; they also point to a possible role of heather in redistribution of the radiocesium pollution in the forest ecosystem.

Key words radiocesium • cesium toxicity • heather plants • K/Cs discrimination • potassium transport • potassium uptake

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Introduction

Natural soil Cs concentration is low and non-toxic to plants. The stable isotope ^{133}Cs is present at concentrations close to 25 μg per g of dry soil [23] and only specially Cs-rich pollucite might cause environmental toxicity of Cs, as in areas of Manitoba [20]. Additionally, two radioisotopes of Cs, ^{134}Cs and ^{137}Cs, originating from industry, testing of thermonuclear weapons and from radiation accidents in nuclear power plants, such as that of Chernobyl, might be toxic and dangerous for plant organisms. Both these radionuclides, beta emitters with gamma component, are biologically important due to their energy levels, long half-life, ubiquitous production during the fission processes, and their tendency to follow the potassium cycle in nature.

The influence of radiocesium and stable cesium on potassium uptake, transport and metabolism may be especially dangerous for plants because K is an essential macronutrient.

The Cs^+ ion shows nearly identical chemical properties as K^+ and competes with K^+ for cation binding sites in proteins [1]; this feature is important for K^+ transport *via* carriers. Cs^+ may inhibit K^+ channels in the plasma membranes [23] and thus, it may induce K starvation in plants. The variation of ^{137}Cs concentrations in plants among various soils is related to differences in ^{137}Cs and K concentrations in soil solution, consistent with previous observations in hydroponic and pot trials [22]. The soil chemistry of cesium is more complex. As elucidated by Ehlken and Kirchner [10], the fate of radiocesium in soils is dominated by ion exchange to a small number of sites located in hydrated mica which are accessible only to poorly hydrated cations and show high selectivity for Cs^+ over K^+ and NH_4^+.

The growth and metabolism of many plants as *Lepidium sativum* [6], *Zea mays* [5], onion [7] and barley [17] is inhibited by Cs^+ concentrations in the rhizosphere close to 0.3 mM. The first reaction of plants under influence of such ^{137}Cs + ^{133}Cs concentrations was closing of stomata and decrease in transpiration processes, as well as decreasing hydration level in plant tissues [4, 6]. This is consistent with the hypothesis that Cs is toxic, because it interferes with K uptake and/or K biochemistry [8, 12].

The measure of plant resistance to cesium toxicity seems to be the lack of discrimination of K by Cs in uptake and transport processes of potassium in plants under the influence of cesium concentrations. We want to investigate the influence of 0.3 mM, a generally toxic cesium concentration in soil in comparison with that of 0.03 mM on K uptake and transport from soils to roots and aboveground parts of a selected plant species. We selected heather (*Calluna vulgaris* L.) because it is Cs-hyper-accumulator, evergreen, and an important part of the trophic chain.

Heather plants

Heather (*Calluna vulgaris* L.) is a popular species in Poland growing in the vicinity of forests and in many coniferous forests on poor, sandy and acidic soils. Plant species growing under acidic pH often show an increased transfer of radiocesium from the soil to the plants [6, 22]. Heather takes up high amounts of radioactive cesium compared with other plant species growing in the same ecosystem [13] on acidic pH and peat soils. Usually, acidic pH of soil increases the uptake of cesium [6, 7, 21].

Among the plants belonging to the *Ericaceae*, heather has been shown to concentrate ^{134}Cs and ^{137}Cs to a higher degree than most other plants [18]. Heather provides an important part of diet of bees and hence, eventually is part of human diet as heather honey in which many laboratories estimated the level of radiocesium [2]. All Scottish heather honey samples contained radiocesium, with activity concentration ranging from 43 to 680 $Bq \cdot kg^{-1}$, consistent with Chernobyl deposition [11].

Radiocesium activity concentrations in wild birds reflected those in their diet and it is suggested that sampling of birds such as red grouse shot for sport could form an efficient means of monitoring radiocesium levels in heather-dominant uplands in the UK [15].

Heather is a background of diet of sheep [16] and ^{137}Cs can be concentrated in the meat of these animals and available for transfer to the human body, similarly as in the case of honey. Heather also is a potential plant for radionuclide phytoremediation because it is associated with mycorrhizal fungi. Clint and Dighton [9] showed that the final shoot:root Cs ratio was higher in mycorrhizal than in non-mycorrhizal heather plants. Despite their lower overall accumulation during the first 3 h, a higher proportion of the Cs taken up is translocated to the shoot. An increase of 100-fold in the total external Cs concentration (from 5 to 500 μM) gave between 35-fold to 96-fold increase in the initial influx of Cs. In most treatments with ^{134}Cs, heather plants with mycorrhiza exhibited a significantly higher transfer of ^{134}Cs to the shoots than heather plants without mycorrhiza [19].

In the evergreen plant *Calluna vulgaris* which was contaminated superficially by the Chernobyl fallout, the concentrations of K and ^{137}Cs were rather constant during total 1987 (leaves about 10,000; stems about 5000 $Bq \cdot kg^{-1}$ dry weight), even though radiocesium was taken up by the leaves and transported within the plant [3]. In contrast, for such two grasses as *Trichophorum caespitosum* and *Molinia coerulea*, the concentration of ^{137}Cs decreased considerably during the growing season (1800–240, 4000–320 $Bq \cdot kg^{-1}$ dry weight, respectively). A remarkably similar behavior was observed for the seasonal variability of K and radiocesium in two grass species, which resulted in a nearly constant ratio of ^{137}Cs:K during the year [3].

Killham [14] presumed that heather will take up cesium-137 in the same manner as potassium. There is no data about the discrimination of potassium by cesium in heather plants.

Materials and methods

Heather plants were obtained from a Polish supplier (Gospodarstwo Ogrodnicze RIM Kowalczyk S.J., Warsaw, Poland). The plants cultivated in plastic pots were contaminated by addition of 0.03 mM or 0.3 mM CsCl (10 kBq or 17.5 kBq, respectively) to soil, four pots for each concentration. After 36 days of incubation polluted plants were taken out, divided in parts: roots, stalk, leaves and flowers, dried at 105°C until total dehydratation, homogenized and portioned. Level of radiocesium was determined by means of scintillator analyzer (InterPOLON Sp. z o.o. Warszawa). Measurement duration was set for 6000 s for all samples. There were two measurements of each sample. Then, samples were mineralized and analyzed in atomic emission flame spectrometer (AES) in order to determine cesium and potassium concentrations.

The ^{137}Cs transfer factor was defined as follows:

$$\mathrm{TF} = \frac{\mathrm{A}\ {}^{137}\mathrm{Cs\ in\ plant}}{\mathrm{A}\ {}^{137}\mathrm{Cs\ in\ soil}}$$

where A symbolizes activity.

The K/Cs discrimination factor was defined as follows:

$$\mathrm{DF} = \frac{[\mathrm{K}]/[\mathrm{Cs}]\ \text{in shoot}}{[\mathrm{K}]/[\mathrm{Cs}]\ \text{in root}}.$$

Results

Under the influence of CsCl 0.03 and 0.3 mM concentrations traced with ^{137}Cs, the uptake of ^{137}Cs from soil

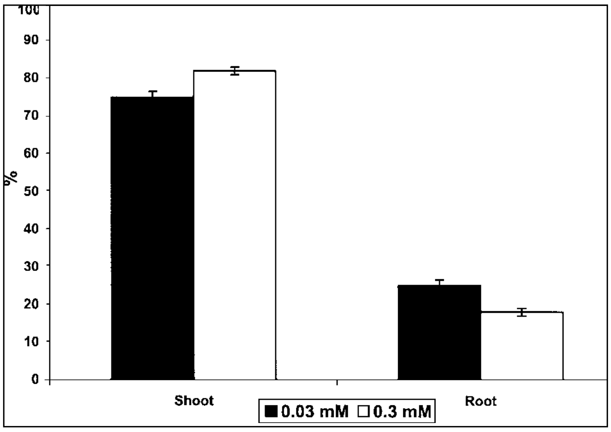

Fig. 1. Cesium distribution in heather plants exposed to two concentrations of cesium. Standard deviation indicated.

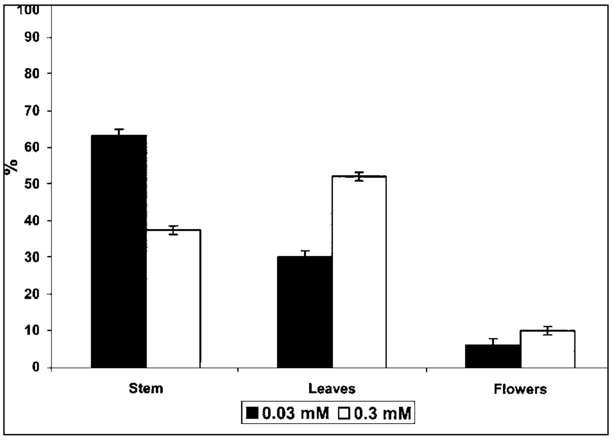

Fig. 2. Cesium distribution in parts of the shoot of heather plants exposed to two concentrations of cesium. Standard deviation indicated.

to plant increased 3-fold, whereas TF increased nearly 3-fold (Table1). The levels of Cs and K, calculated for one plant, were increased for Cs – nearly 10-fold, and for K – nearly 1.5-fold under these conditions (Table 2). The distribution of all isotopes of Cs between shoot and root depended on CsCl concentration (Fig. 1). Their relative content was much higher for shoots than for roots (Fig. 1). We observed differences between the distribution of Cs in organs of shoot depending on CsCl concentration (Fig. 2). Increased CsCl concentration reduced the percentage of Cs in stem, and increased it in leaves and flowers (Fig. 2). The concentration of CsCl affected the level of Cs (10-fold greater in 0.3 mM), whereas it did not affect the level of K (Table 3). Cs transfer factor plant/soil was near 2-fold greater, and K transfer factor – near 1.5 as related to CsCl concentration (Table 4).

The data on the effect of CsCl concentrations on discrimination factor K/Cs in heather plants are presented in Table 5. DF K/Cs root/soil was only 0.8 at 0.3 mM CsCl. We also observed diminishing values

Table 1. The coefficient of ^{137}Cs uptake (TF) from soil to plant.

Concentration of CsCl traced with ^{137}Cs (mM)	TF ^{137}Cs	Uptake of ^{137}Cs from soil (%)
0.03	0.17 (±0.06)	7.80 (±0.40)
0.3	0.48 (±0.11)	20.02 (±0.50)

Table 2. The level of cesium and potassium calculated for 1 plant.

CsCl concentration (mM)	Cs (mg)	K (mg)
0.03	0.035 (±0.01)	53.90 (±1.64)
0.3	0.33 (±0.02)	81.21 (±0.97)

Table 3. Concentrations of Cs and K in soil and in heather plants.

CsCl concentration (mM)	Cs concentration (mg·g^{-1} dry weight)		K concentration (mg·g^{-1} dry weight)	
	in soil	in plant	in soil	in plant
0.03	0.012 (±0.001)	0.004 (±0.001)	1.69 (±0.21)	6.22 (±0.33)
0.3	0.053 (±0.004)	0.032 (±0.003)	1.43 (±0.17)	7.75 (±0.20)

Table 4. Cs transfer factor and K transfer factor (TF) for heather plants exposed to CsCl concentration indicated.

CsCl concentration (mM)	TF$_{Cs}$ plant/soil	TF$_{K}$ plant/soil
0.03	0.33	3.68
0.3	0.60	5.42

Table 5. K/Cs discrimination factor (DF) for heather plants exposed to CsCl concentrations indicated.

K/Cs DF	CsCl concentration (mM)	
	0.03	0.3
root/soil	1.7	0.8
stem/soil	8.8	1.1
leaves/soil	21.6	1.6
flowers/soil	46.1	7.5
stem/root	5.1	7.4
leaves/root	12.5	11.0
flowers/root	26.6	49.4

of DF K/Cs for stem/soil, leaves/soil, and flowers/soil, but under these conditions the DF values were above 1 (Table 5). The K/Cs discrimination factor for the above-ground parts of plant in relation to roots was generally greater under the influence of increasing CsCl concentrations (Table 5). It was increased for stem/roots, unchanged for leaves/roots, and two-fold increased for flowers/roots.

Discussion and conclusions

The obtained results confirmed that heather plants are hyper-accumulators of cesium, because the accumulation of Cs in shoot was much greater than in roots (Fig. 1). Transfer factor was lower than one, which might be explained by short period of cultivation of plants with Cs (Tables 1 and 4). The results were in agreement with those obtained by Harrison *et al.* [13] and Strandberg [18]. The K level at increasing Cs concentrations was unchanged in heather plants whereas of Cs level increased 8-fold (Table 3). These data indicate the lack of effect of high Cs concentrations on K uptake by the plant (Table 3). TF for all isotopes of cesium and potassium was 2-fold greater in relation to CsCl concentrations (Table 4). Heather plants seem to be relatively resistant to cesium toxicity at when exposed to 0.3 mM CsCl because the effect was exerted only on roots (Table 5). The same effect (described as toxic) was observed in *Arabidopsis* at the same Cs concentration [12]. The results reported above brought new information concerning the interactions between Cs and K nutrition. K/Cs discrimination factor applied in this work seems to be a proper indicator of cesium toxicity. Cs did not affect the potassium transport from roots to leaves and flowers; so, the results point to resistance of leaves and flowers to the effect of exposure to 0.3 mM CsCl. This seems to be very important, because leaves and flowers provide food for sheep and bees, and the reported observations should be taken into account in food examination procedures.

The report also points to a possible role of heather in redistribution of the radiocesium pollution in the forest ecosystem.

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