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RESEARCH ARTICLE

Uptake and translocation of ^{134}Cs by maize roots as affected by heterogeneous distribution of ^{134}Cs

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Abstract Structure-induced non-uniform water flow induces a heterogeneous distribution of surface-applied radionuclides in the soil profile. This study was conducted to assess the amount of ^{134}Cs which can be taken up by a single root growing in an area enriched in ^{134}Cs relative to the total amount of ^{134}Cs that can be taken up by the whole root system growing in an area homogeneously contaminated with ^{134}Cs. A split-root experiment was used to simulate the heterogeneous distribution of ^{134}Cs and roots. Seedlings of maize (*Zea mays* L. cv Corso) were grown for 14 days in solution culture and then transferred to a two-compartment pot system, where a single root was grown in a ^{134}Cs contaminated compartment while the rest of the root system was grown in an uncontaminated compartment. Plants with the whole root system growing in a solution contaminated with ^{134}Cs were used as control. We tested the effect of the competition between Cs and K on the uptake and translocation of ^{134}Cs by using two K concentrations, 0.2 and 1.05 mM. At the K concentration of the nutrient solution of 0.2 mM the single root representing 21% of the total root weight was able to take up 47% of the ^{134}Cs taken up by the entire root system, while at 1.05 mM the single root, representing 15% of the total root weight, took up 15% of the ^{134}Cs taken up by the entire root system. The translocation of ^{134}Cs from the root to the shoots did not depend on the external K concentration in the nutrient solution, but it was lower in the split root treatment than in the control treatment at both K concentrations.

Keywords ^{134}Cs uptake · Maize · Potassium · Root system · Shoot to root transfer · Split-root system

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Introduction

Soils are characterized by a heterogeneous structure caused by the presence of macropores, earthworm burrows, cracks, and pores left by decaying roots which can affect both the displacement of surface-applied nutrients and contaminants and the distribution and growth of new plant roots (Stewart et al. 1999; Bundt et al. 2000). It has been shown that, due to structure-induced non-uniform water flow in soils, highly sorbing solutes such as selected radionuclides (Albrecht et al. 2002; Bundt et al. 2000) and pesticides (Flury 1996) distribute heterogeneously

in the soil profile, accumulating within and around macroporous preferential flow pathways.

Centofanti et al. (2005) showed that the amount of ^{134}Cs recovered in the aerial parts of maize grown in an untilled agricultural soil, where surface-applied radionuclides accumulated within and near the structure-induced water flow paths, was 10 times higher than the amount of ^{134}Cs recovered in the aerial parts of maize grown in a glasshouse in the same soil that had been sieved and homogeneously labelled before being repacked in pots. The author suggested that plants grown under field conditions had obtained a substantial amount of their ^{134}Cs from roots that were growing within enriched areas, although only 12.5% ± 2.5 of the roots were located within these areas of radionuclide enrichment.

The response of roots to the heterogeneous or patchy distribution of nutrients (as N and P) has been analysed in many studies, some of which have employed the split-root system technique in solution (Drew et al. 1984) while others have used banded fertilization as a temporary concentrated source (Caldwell et al. 1991; Hodge 2003). Some of these studies have demonstrated that plant roots respond to these nutrient-patches displaying morphological (flexibility in architectural patterns) and/or physiological plasticity (altered nutrient uptake capacity and increased ion affinity) (Hodge 2004). Robinson et al. (1991) in an experiment with wheat plants harvested at six steps from 13 to 97 days after germination estimated that the mean fraction of the root system likely to have been involved in nitrate uptake were 11 and 3.5% of the total root length in a treatment without N and in a treatment with 200 kg N ha^{-1}, respectively. However, whether the activity of a small fraction of the root system could account for the total uptake of a trace element that is heterogeneously distributed in the soil profile as ^{134}Cs is not yet known.

The aim of this study was to assess to what extent a small fraction of the root system, growing in areas of ^{134}Cs enrichment, may contribute to the total uptake and translocation of ^{134}Cs in relation to its uptake and translocation by the whole root system growing in a homogeneously contaminated medium. A split-root experiment, carried out in hydroponic system, was used to simulate the heterogeneous distribution of ^{134}Cs and root. A single root was allowed to grow in a ^{134}Cs contaminated compartment, while the rest of the root system grew in an uncontaminated compartment. Plants with the whole root system growing in a nutrient solution contaminated with ^{134}Cs were used as control. As Cs uptake is known to be related to that of K (Shaw and Bell 1991; Sacchi et al. 1997; Zhu et al. 2000) the split root and the control experiment were conducted using two K concentrations: 0.2 and 1.05 mM in order to understand how different K concentrations could affect the uptake of ^{134}Cs by a small fraction of the root system and its further translocation in the plant.

Materials and methods

Hydroponic system

Maize (*Zea mays* cv. Corso) seeds of 0.28–0.30 g were selected, put in a substrate composed of 2/3 soil, which was obtained from a previous field experiment (Centofanti et al. 2005), and 1/3 sand (0.7 mm), and incubated at 28°C for 3 days. Germinated seeds were transferred in a climate chamber for 2 days under the following conditions: a day/night cycle of 16 h with 25/20°C, 70% relative humidity, and a light intensity of 300–400 μmol s^{-1} m^{-2}. Seedlings, homogenous in growth, were chosen to be transferred to 10 l plastic (PVC) barrels (25 cm × 12 cm and 22 cm deep) containing a continuously aerated nutrient solution. The chemical composition of the nutrient solution is listed in Table 1. Two K concentrations were tested: (a) the K1 treatment at 0.2 mM; and (b) the K2 treatment at 1.05 mM. The seedlings were placed into 2 cm diameter holes drilled into 22 cm × 12 cm plastic plates which were put on the top of the barrels. Through the holes roots gained access to the nutrient solution. The individual plants were vertically held by supporting their collar with cotton wool. Four plants were arranged in the holes of each barrel. The nutrient solution was constantly aerated. The water level and pH (6.0–6.5) were kept constant throughout the growing period by changing the solution every 2 days. Plants grew in

Table 1 Composition of the nutrient solution differing in the K concentration

Salt	Concentration in nutrient solution (mM)	
	K1 treatment (0.2 mM)	K2 treatment (1.05 mM)
$Ca(NO_3)_2$	5	5
KH_2PO_4	0.15	0.15
KNO_3	–	0.85
$CaHPO_4$	0.2	0.2
$MgSO_4$	2	2
Fe-EDTA	0.1	0.1
KCl	0.05	0.05
H_3BO_3	0.025	0.025
$MnSO_4$	0.002	0.002
$ZnSO_4$	0.002	0.002
$CuSO_4$	0.0005	0.0005
Na_2MoO_4	0.0005	0.0005

the greenhouse under the following conditions: 16 h photoperiod, day/night temperatures 27/20°C, 40–50% relative humidity of ambient air, and 300 μmol photons m^{-2} s^{-1} minimum light intensity (provided as artificial light by 400 W DL/BH Lamps, Eye, Japan).

Split-root experiment

Plants were grown in hydroponic culture as described above. On the 15th day of growth half of the plants were transferred to two-compartment barrels while the other half of the plants were left in the original one-compartment barrels. The two-compartment barrels were made out of 10 l barrels divided into two equal compartments with a plastic (PVC) panel fixed in the middle of the barrel's short side. Silicone gel was used to fix the vertical panel and to create an impermeable barrier between the two compartments. Both compartments were filled with either the K1 or the K2 nutrient solution. On the same day, a ^{134}Cs activity of 9.2 kBq in chloride form and diluted in a 1:100 water solution of 0.1 M HCl (Specific Activity of 37 MBq mg^{-1}, purchased at Amersham®) was added to one of the two compartments (referred to as contaminated compartment) and to the single-compartment barrels (referred to as control). One seminal root of each seedling was placed in the contaminated compartment and the rest of the root system was placed in the uncontaminated compartment, whereas the whole root system was placed in the single-compartment barrels (control).

Twelve barrels per K treatment were prepared, with 48 seedlings and two seedlings per barrel, for the control and for the split-root experiment, respectively. Growing conditions in the greenhouse were as described above. The experiment lasted for 5 days during which the nutrient solution was not changed but the water level was kept constant by adding deionized water (from 25 to 30 ml day^{-1} $compartment^{-1}$).

Plant harvest

Plants were harvested at 12, 24, 48, 72, 96 and 120 h after the addition of ^{134}Cs in the nutrient solution. At each harvest occasion 4 replicates per treatment were harvested: 4 of the control experiment and 4 of split-root experiment for the K1 and K2 treatments (Fig. 1). Shoots were cut with a sharp knife 0.5 cm above the plastic panel covering the barrels. Shoots, roots and the single root from the split-root experiment were kept separated. Root samples were first washed with a solution of 10 ml HCl (0.1 M) diluted in 100 ml of water over a period of 2 min to remove the surface film of radio-labelled solution and then were blotted dry on a paper towel. All samples were weighed, oven-dried at 60°C for 3 days, weighed again and milled to powder. Part of each sample was put in plastic tubes calibrated for the γ-spectrometry measurements, while the rest was used for measurements of K concentration. After harvest, aliquots (5 and 1 ml) of the nutrient solution were sampled from each barrel of the control experiment and from both compartments of the split-root experiment. The 5 ml samples were used to measure the K concentration in the nutrient solution, while the 1 ml samples were used for the ^{134}Cs analysis.

^{134}Cs measurement

The concentration of ^{134}Cs (half-life $t_{1/2}$=2.07 years, 475.34 keV) was measured at the γ-spectrometry laboratory of EAWAG (Swiss Federal Institute for Environmental Science and Technology,

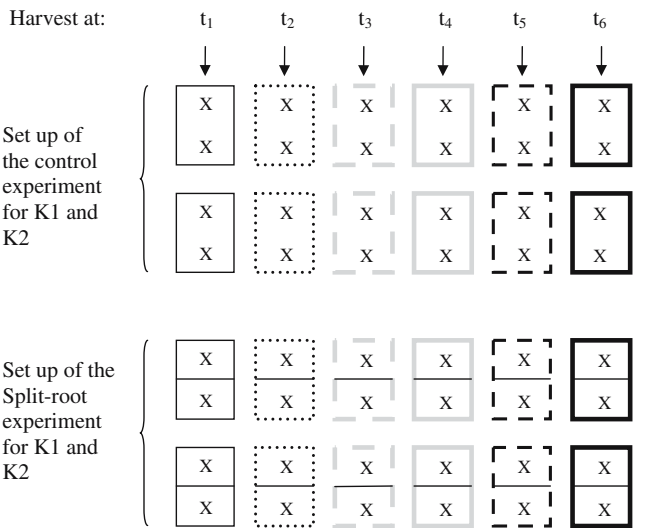

Fig. 1 Design of the set up of the control and split-root experiment. Rectangles=barrels; X=plants; t1, t2, t3, t4, t5, t6 = 12, 24, 48, 72, 96, and 120 h after the addition of ^{134}Cs in the nutrient solution. Four plants harvested at each time and for each experiment are considered replicates

Dübendorf, Switzerland) on high purity Ge detectors. Plant, roots, and nutrient solution were measured with flat crystals. Radionuclide activities were determined in Bq g^{-1} (dry weight) for solid samples and in Bq mL^{-1} for the solution samples. The activities were decay corrected to the common date of May 14, 2003, 12:00 h. Measurements error was 5–10%. Geometry correction and calibration are based on standard solutions.

K measurements

Ground samples (0.25 g) of shoots, roots, and seeds were weighed in plastic tubes and 2 ml of nanopure water was added. To obtain a complete wetting of the dry material samples were put in an ultrasonic bath (Bandelin, SONOREX Super, RK 510, Switzerland) for 10 s and then 4 ml of HNO_3 (65%, Suprapure, Merck) and 2 ml of H_2O_2 were added. After 30 min the samples were digested in the microwave oven (MLS mega 1200, Germany) using the following programme: 5 min, at 269 W and 180°C, 8 min at 600 W and 185°C, and 7 min at 350 W and 180°C. After digestion, samples were diluted to 50 ml with nanopure water and filtered under vacuum through a 0.45 μm Millipore membrane. K concentration of the seed, plant, root, and nutrient solution was measured by ICP-MS (Agilent, 7500 C). The concentration of K in the seeds was about 3.5 mg g^{-1} with a standard variation of 0.8. This K content has been partitioned between shoot and root according to their K content relative to the total K content of the plant. These values were withdrawn from the K content measured in the shoot and root.

Calculation of shoot:root ratio

The shoot:root ratio of ^{134}Cs was calculated as: Bq (g $shoot^{-1}$)/Bq (g $root^{-1}$), and the shoot:root ratio of K as: mg (g $shoot^{-1}$)/mg (g $root^{-1}$), as proposed by Staunton et al. (2003).

Statistical analysis

Statistical analysis was carried out with Statgraphics version 3.1 (Manugistics 1997). Mean values for plant dry matter production, ^{134}Cs and K uptake, and ^{134}Cs and K concentration in the nutrient solution between the control and the split-root experiment at each harvest occasion were compared using paired Student *t* test. Dry matter production, ^{134}Cs and K uptake, and ^{134}Cs and K concentration in the nutrient solution were tested by three-way ANOVA with the factors K supply, time and experiment (control/split-root) followed by Tukey's multiple comparison test. All tests were conducted at the 5% significance level.

Results

Dry matter production

The shoots of the control and of the split-root experiment are referred to *control shoot* and *split-root shoot*, respectively, whereas root of the control and of the split-root experiment are referred to as *control root* and *split-root*, respectively; the one root grown in the contaminated compartment of the split-root experiment is referred to as *single root*.

Differences in dry matter production between *control shoot* and *split-root shoot* were significant at 12 and 96 h in K1 and at 72 h in K2 (Fig. 2). No significant differences were observed between *control root* and *split root* in both K treatments except at 72 h in K2; whereas significant differences were observed between *control root* and *single root* (Fig. 2).

Plant dry matter production increased significantly with time, except for the single root at both K treatments (Fig. 2). No significant difference in shoot dry matter production was observed

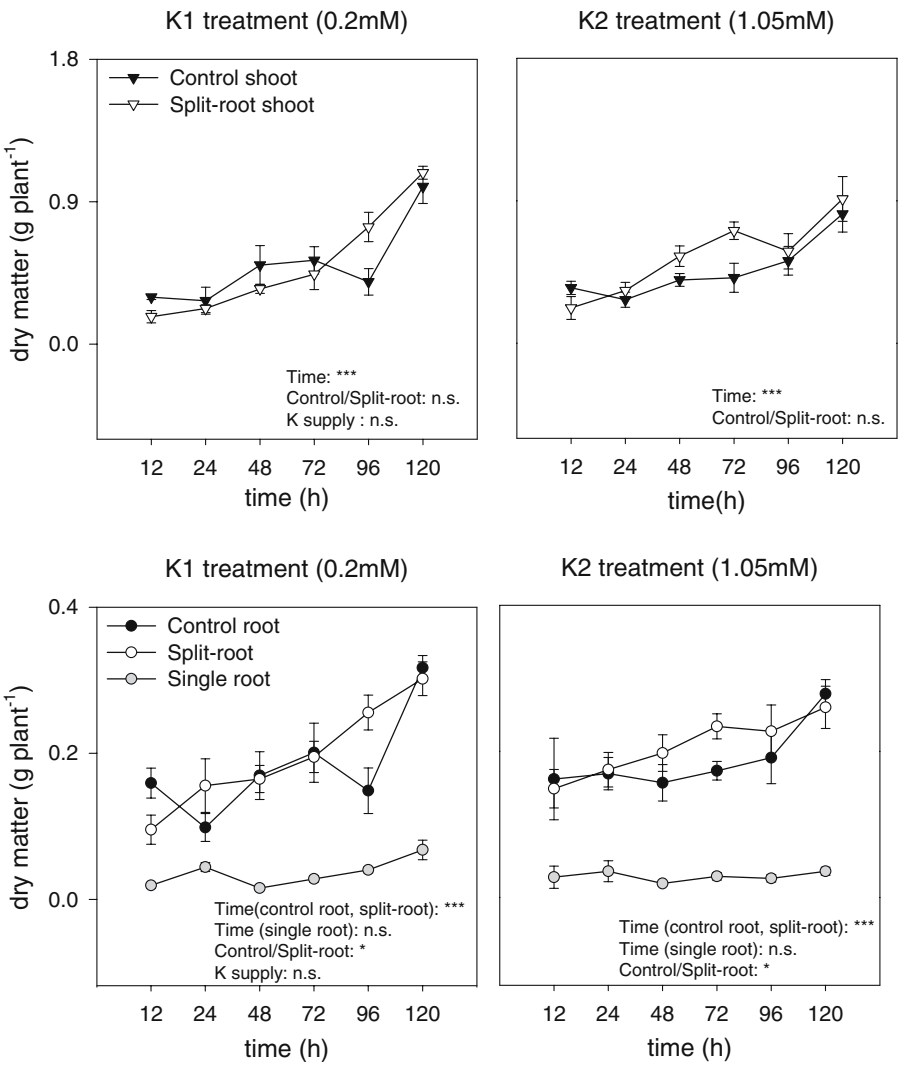

Fig. 2 Plant dry matter production of maize seedlings of the control and split-root experiments grown in solution culture with two K concentrations. Vertical bars indicate standard errors calculated from four replicates. The significance of the effect of the factors time, experiment (control/split-root), and K supply is given at $*P \leq 0.05$, $**P \leq 0.01$, $***P \leq 0.001$, n.s. not significant

between the control and split-root experiment while a slightly significantly higher root dry matter production was observed in the control experiment.

Plant dry matter production did not differ between the K1 and K2 treatments indicating that the K concentration of the nutrient solution in the K1 treatment was not limiting for plant growth and that the extra source of nitrogen added in the K2 treatment had no effect on plant growth. At the end of the experiment the dry matter of the *single root* represented 21% and 15% of the dry matter of the *control root* grown in the K1 and K2 treatment, respectively.

^{134}Cs uptake

The variations in ^{134}Cs uptake during the experiment (Fig. 3) are due to the variations in dry matter production of the plants at each harvest occasion. Uptake of ^{134}Cs increased significantly with time in the shoot of both experiments, in the control root at both K treatments, and in the single root at K1 treatment. In the control experiment ^{134}Cs uptake was significantly higher than in the split-root experiment; only at 24 and 96 h in K1 the differences between the *control shoot* and *split-root shoot* were not significant. In the split-root experiment at the last harvest and in both K treatments a small concentration of ^{134}Cs was

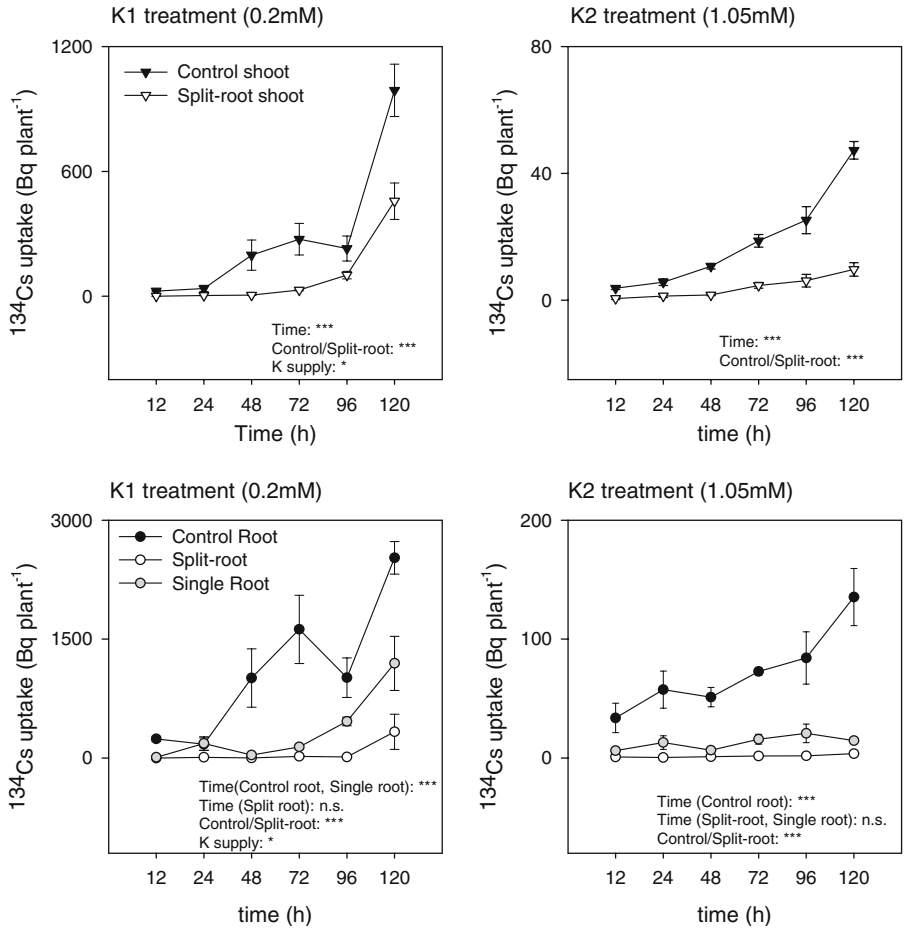

Fig. 3 Dynamic of ^{134}Cs uptake measured at the end of each harvest in the shoot and root. Vertical bars indicate standard errors calculated from four replicates. The significance of the effect of the factors time, experiment (control/split-root), and K supply is given at $*P \leq 0.05$, $**P \leq 0.01$, $***P \leq 0.001$, n.s. not significant

measured in the roots grown in the uncontaminated compartment (Fig. 3), showing no significant difference between the two K treatments. Significantly higher ^{134}Cs uptake was observed in the K1 treatment in comparison to K2 treatment for both control and split-root experiment.

No ^{134}Cs was found in the uncontaminated compartment of the split-root experiment (split-root solution, Fig. 4) in both K treatments. In K1 the concentration of ^{134}Cs in the nutrient solution of the control and split-root experiment (Fig. 4) decreased significantly with time, whereas there was no effect of time in the K2 treatment. The ^{134}Cs concentration in solution was significantly lower in the control experiment than in the split-root experiment in both K treatments. The ^{134}Cs concentration was lower in the K1 treatment than in the K2 treatment.

In the K1 treatment the uptake of ^{134}Cs by the whole plant of the control experiment and by the whole plant of the split-root experiment represented 38% and 21% of the ^{134}Cs applied, respectively. Six days after adding ^{134}Cs to the solution the *single root* took up 47% of the ^{134}Cs taken up by the *control root*. In the K2 treatment, the uptake of ^{134}Cs by the whole plant of the control experiment and by the whole plant of the split-root experiment was 2% and 0.3% of the ^{134}Cs applied, respectively. The *single root* took up 15% of the amount of ^{134}Cs taken up by the *control root*.

K uptake

The variations in K uptake during the experiment were due to the variation in the biomass production of the analyzed plant parts (Fig. 5). A significant increase of K uptake with time was observed in the shoot in both K treatments and in the *control root* and s*plit-root* in the K2 treatment. K uptake by the *control shoot* and *split-root shoot* showed no significant differences between the two experiments except at 12 h in K1. Differences in K uptake between *control root* and *single root* were significant in both K treatments, while no significant differences were observed between *control root* and *split root*, except at 12 h in K1. K uptake was significantly higher in K2.

In the control solution in K1 the K concentration dropped quickly within the first 12 h, while the K concentration in the split-root solution (uncontaminated compartment) reached similar low values only at 48 h (Fig. 6). In K1, the decrease of K concentration in the single root solution (contaminated compartment) appeared after 48 h when solution K in the uncontaminated compartment was depleted. In K2 the concentration of K decreased slightly with time in the control solution and split-root solution but remained stable with time and at higher level in the single root solution (contaminated compartment).

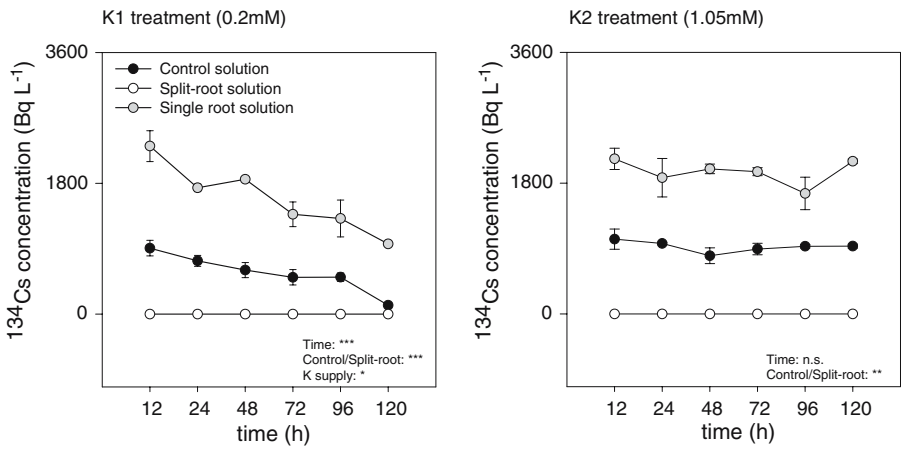

Fig. 4 Concentration of ^{134}Cs in the nutrient solution measured at the end of each harvest. Vertical bars indicate standard errors calculated from four replicates. The significance of the effect of the factors time, experiment (control/split-root), and K supply is given at $*P \leq 0.05$, $**P \leq 0.01$, $***P \leq 0.001$, n.s. not significant

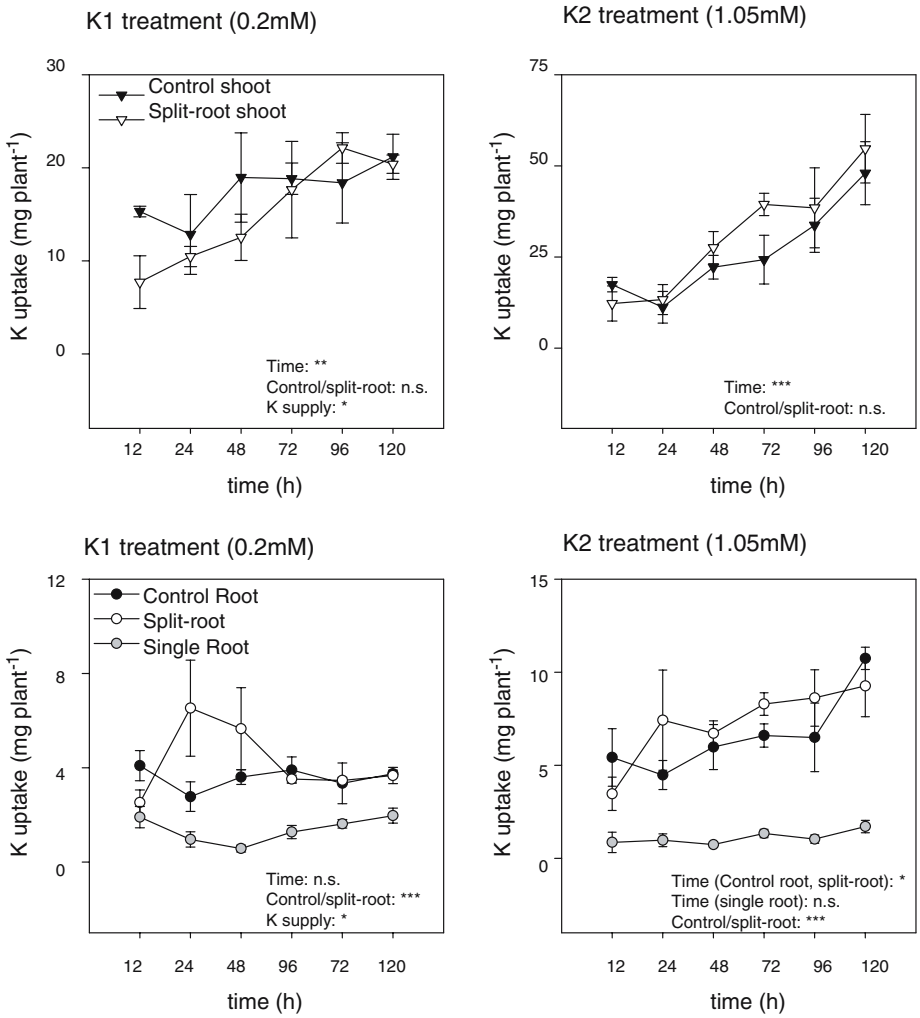

Fig. 5 Dynamic of K uptake measured at the end of each harvest. Vertical bars indicate standard errors calculated from four replicates. The significance of the effect of the factors time, experiment (control/split-root), and K supply is given at $*P \leq 0.05$, $**P \leq 0.01$, $***P \leq 0.001$, n.s. not significant

Shoot:root transfer of ^{134}Cs and K

The shoot:root concentration ratio of ^{134}Cs and K did not depend on the K concentration in the solution. In both the control and the split-root experiments, the translocation of ^{134}Cs to the shoot started within the first 12 h after adding ^{134}Cs into the solution and was faster in the control experiment (Fig. 7).

The shoot:root ratio of K showed no significant variation with time (Fig. 8). For both ^{134}Cs and K the concentration ratio between shoot and root was significantly higher in the control experiment then in the split-root experiment. In addition, for ^{134}Cs the concentration ratio showed a significantly increasing trend with time in both experiments and in both K treatments ($R^2 = 0.75$ and P value=0.0002 for the control experiment and $R^2 = 0.71$ P value=0.0006 for the split-root experiment).

Discussion

The results of the split-root experiment show that in the presence of a low K concentration a

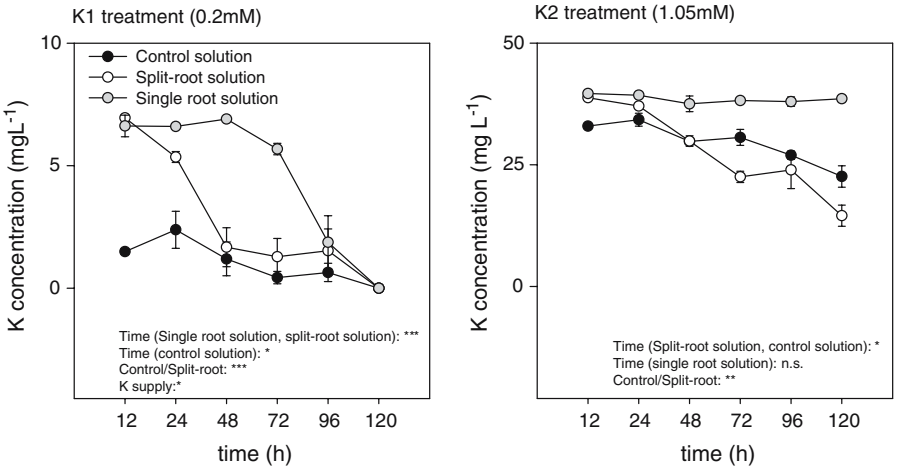

Fig. 6 Concentration of K meas ured in the nutrient solution at the end of each harvest. Vertical bars indicate standard errors calculated from four replicates. The significance of the effect of the factors time, experiment (control/split-root), and K supply is given at $*P \leq 0.05$, $**P \leq 0.01$, $***P \leq 0.001$, n.s. not significant

single root growing in a compartment enriched with ^{134}Cs is able to take up a significant amount of ^{134}Cs relative to the uptake by the whole root system. On the opposite at a higher K concentration the contribution of the single root was proportional to its biomass. The contribution of the single root relative to the total ^{134}Cs uptake was five times higher at low (0.2 mM) K concentration in the nutrient solution than at K concentrations higher than 1 mM. In the split-root experiment plants grown at lower external K concentration depleted the solution from its K after 5 days causing a higher ^{134}Cs uptake compared to the plants grown at higher external K concentration. In our experiment, in both the K1 and K2 treatments, plants of the control and of the split-root experiment continued to translocate increasing amounts of ^{134}Cs to their shoots with time. Our results indicate that within 6 days after adding ^{134}Cs into solution the distribution of ^{134}Cs from the root to the shoot did not attain equilibrium. This increasing trend was not observed for K. In the case of K plants were given the same pre-treatment and thus were brought to equilibrium with the external solution, whereas to

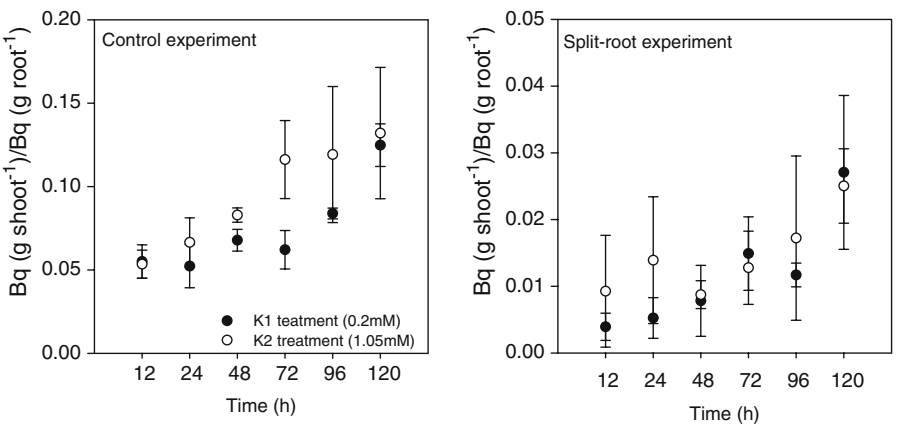

Fig. 7 Ratio of concentration of ^{134}Cs measured in shoot and root. Vertical bars indicate standard errors calculated from four replicates

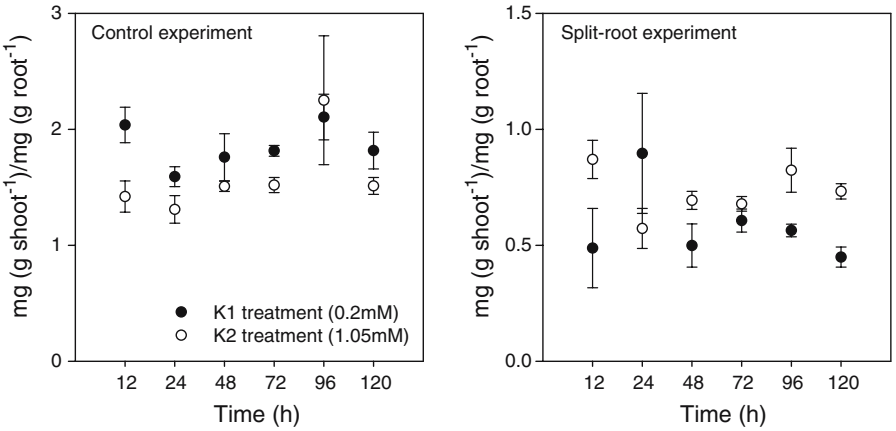

Fig. 8 Ratio of concentration of ^{134}Cs measured in shoot and root. Vertical bars indicate standard errors calculated from four replicates

simulate accidental release of ^{134}Cs, ^{134}Cs was added as a pulse without pre-treating the plants. The transfer of ^{134}Cs to the split root located in the uncontaminated compartment can be explained by the transfer of ^{134}Cs through phloem. Feller et al. (2000) have shown that, in steam-girdling experiments where the transfer of ^{134}Cs with the xylem sap of detached wheat shoots was stopped, ^{134}Cs was loaded into the phloem during acropetal transport. This suggests that in our experiment the adsorbed ^{134}Cs was translocated to the stem and leaf and it was then redistributed to the other part of the root system via phloem transport.

In contrast to the uptake of ^{134}Cs by the roots, the ^{134}Cs in the shoot: ^{134}Cs in the root ratio was independent from the external K concentration. This observation is in agreement with the data of Staunton et al. (2003) who found no significant effect of K supply on the ^{137}Cs in the shoot: ^{137}Cs in the root ratio of various plant species. Contrarily, Buysse et al. (1996) found that at K solution concentration of 0.25 mM the ^{137}Cs concentration ratio between shoot and root of sunflower was lower than that at higher (>1.0 mM) K concentration, indicating an increase of the proportion of Cs retained by the roots at low external K concentration. They found no effect of external K concentration on the concentration of K in the shoots.

Finally, in our experiment the shoot:root ratio of K was higher than that of ^{134}Cs suggesting that the transport and redistribution processes of K within the plant selectively discriminate against Cs.

Conclusions

Our results show that a single root had the capacity of taking up a high proportion of ^{134}Cs relative to the uptake by the whole root system when grown in a medium presenting a high ^{134}Cs concentration and a low K concentration. Under a high solution K concentration the single root has taken up an amount of ^{134}Cs proportional to its biomass. Furthermore, an increasing fraction of the absorbed ^{134}Cs was continuously translocated to the shoots, independently of the external K concentration.

Although these results should not be used to explain field data since under field conditions other complex interactions occurring at the soil–solution–root interface also affect the transfer of ^{134}Cs from the soil to the plant, they give hints to conduct further research to better understand the importance of fractions of the root system in the uptake of heterogeneously distributed non essential trace elements in the soil.

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