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Changes in radiocaesium uptake and distribution in wheat during plant development: a solution culture study

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Abstract

Spring wheat plants were grown in a ^{137}Cs labelled nutrient solution, either in the presence or absence of NH_4 as a secondary N source. Between 11 and 64 days after sowing (DAS), plants were harvested on nine occasions. The plants supplied with NH_4 and NO_3 had lower root ^{137}Cs Activity Concentrations (AC) than those supplied with NO_3 only. Shoot AC were equal in both nutrition treatments. Shoot and root ^{137}Cs AC (dry weight basis) showed the same trends with plant age in both nutrition treatments. Shoot AC almost doubled between 11 and 28 DAS after which they gradually decreased concomitant with a similar decrease in K concentrations. Root AC were always higher than shoot AC and increased to a maximum at 35 DAS after which they fluctuated. Expressed on a tissue water basis, the ^{137}Cs AC varied less during plant age than did dry weight based AC. Furthermore, root and shoot AC expressed on a tissue water basis were almost equal. It is shown that the initial increase in ^{137}Cs AC in both root and shoot can largely be explained by the initial dilution of absorbed ^{137}Cs in the unlabelled seedling tissues. No correlation was found between K and ^{137}Cs distribution among ears, leaves, stems and roots in 64 old wheat plants. NH_4 as a secondary N source in a nitrate nutrient solution marginally affected ^{137}Cs distribution.

Abbreviations: AC-activity concentrations, DAS-days after sowing.

Introduction

^{137}Cs is one of the major long living fission products ($t_{1/2}$=30.2 y). Soil-plant transfer of this element is an important step which adds to the radiation dose to man after a nuclear accident. For this reason, considerably attention has been paid to the bioavailability of this radionuclide in soil.

The transfer of ^{137}Cs uptake from soil to plant can only be fully evaluated if both the soil- and plant processes are known. In the past four decades, research on the plant factors controlling ^{137}Cs uptake in higher plants has mainly focused on interionic effects (Cline and Hungate, 1960; Shaw et al., 1992). Generally in such work, uptake is compared in plants of equal age; the effect of the growth stage on the ^{137}Cs uptake capacity of the plant and the ^{137}Cs distribution within the plant is generally not investigated. Distinct changes in ^{137}Cs AC in soil grown plants parts are, however, apparent during plant development (e.g. Nishita et al., 1958). Previous lysimeter experiments with spring wheat showed a strong time-dependency of the ^{137}Cs AC in the shoots during plant development: soil-to-plant transfer factors (the ratio of the AC in plant to that in soil) varied by 3 orders of magnitude in a single growing season (Shaw, unpubl. results). Without knowledge of the plant growth stage effect, it cannot be calculated to what extent such changes are due to changes in the ionic environment of the plant roots. For this reason, the ontogenetic change in the uptake and distribution characteristics of the plant can only be studied if the root ionic environment is controlled, a prerequisite achieved in solution culture. A number of solution culture experiments have been published on the distribution of ^{137}Cs in plants at one growth

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stage (e.g. Cline and Hungate, 1960). Growth stage effects on ^{137}Cs uptake in kale have been investigated in solution culture (Weaver et al., 1981). Their results are however intricate to interpret: ^{137}Cs AC in plants continuously exposed to ^{137}Cs in solution increases about threefold during plant development between 2 and 9 weeks whereas accumulation of ^{137}Cs in plants exposed for 48 h to ^{137}Cs in solution decreases threefold over the same period.

In this paper, the results of a solution culture experiment with spring wheat are reported. Wheat plants were grown up to an age of 64 days and the ^{137}Cs AC in the plants was measured at regular intervals. The distribution of ^{137}Cs among stems, leaves, ears and roots was quantified and compared with the K distribution, the plant nutrient most closely related in charge and ionic radius to Cs. If the distributions of both elements in the plants are similar, predictions of ^{137}Cs distributions in other nutritional conditions or in other plants could be based on known effects on K distribution. This was partly verifed in the experiments reported here by varying the type of inorganic N-source (NH_4 or NO_3) in solution which has consequences on K distribution (Van Beusichem et al., 1988). ^{137}Cs uptake and distribution was quantified in wheat plants either supplied with NO_3 only or with NH_4 and NO_3 in the nutrient solution.

Materials and methods

Rinsed seeds of spring wheat (*Triticum aestivum* cv. Tonic) were germinated in moist perlite for 7 days. Seedlings were subsequently transferred to 160 L tanks containing continuously aerated nutrient solution (49 seedlings per tank). Six similar tanks were installed in one line in a shaded greenhouse without climate control. The experiment was carried out during May and June in 1993. Three tanks contained the solution with NO_3 as the single nitrogen source, three tanks contained the solutions with both NH_4 and NO_3 as N-sources. Both solutions were of equal anionic composition but the NH_4 ions in the latter solution replaced K, Ca and Mg salts of the nitrate solution. The nitrate solution was formulated to contain: $Ca(NO_3)_2$,2.49 m*M*; KNO_3, 0.94 m*M*; KCl, 0.5 m*M*; KH_2PO_4, 0.5 m*M*; K_2SO_4, 0.72 m*M*; $MgSO_4$ 1.01 m*M* and KOH 0.09 m*M*. The solution with both NH_4 and NO_3 as N-sources contained: NH_4NO_3,4.24 m*M*; KNO_3, 0.14 m*M*; $CaCl_2$, 0.25 m*M*;$Ca(NO_3)_2$,0.77 m*M*; KH_2PO_4, 0.5 m*M*; K_2SO_4, 1.27 m*M* $MgSO_4$ 0.46 m*M* and KOH 0.09 m*M*. Fe and trace elements were added to both solutions at the following rate: FeNaEDTA, 0.08 m*M*; $ZnSO_4$. 1.8 μM; $CuSO_4$, 0.3μM; $(NH_4)_6Mo_7O_{24}$, 0.07 μM; $MnSO_4$, 12 μM and H_3BO_3, 43 μM. The initial pH of both solutions was between 6.0 and 6.2. Carrier free ^{137}Cs was added to the solutions at an AC of 5 Bq mL^{-1}. During plant growth, ^{137}Cs activity in solution was controlled at regular intervals and analyses showed that the AC did not decrease below 90% of the initial AC. Solution pH was controlled with H_2SO_4 (NO_3 solution) and KOH (NH_4NO_3 solution). The lowest pH value was 4.7 (NH_4NO_3 solution) and the highest was 7.0 (NO_3 solution). We expect, however, little effect of this high pH variance since solution culture work with lettuce showed no pH effect on ^{137}Cs solution to plant transfer ratio for ^{137}Cs between pH 4.5 and 7.5 (Lembrechts, pers. commun.). Depletion of nutrients was controlled in the following way: solutions were completely replaced at 32 DAS; at 42 DAS, 20% of all nutrients (except Fe and trace elements) were added using concentrated stock solutions and at 53 DAS another 10% was added to the nitrate solutions. The nutrients were added to overcome a K and N depletion brought about through plant uptake which was calculated based on the dry matter production and normal K and N concentrations in plant tissue. The water level in the tanks were adjusted regularly using deionised water.

Thirty seedlings were harvested at the day of transplanting (7 DAS) and per container 10 plants were harvested at 11 DAS, 8 at 15 DAS, 8 at 21 DAS, 6 at 28 DAS, 4 at 35 DAS, 4 at 42 DAS, 4 at 49 DAS, 3 at 56 DAS and 2 at 64 DAS. All plants were divided into shoot and roots. Roots were rinsed in deionised water and blotted dry on a paper towel. The shoots harvested on the two last occasions (at 56 and 64 DAS) were furthermore divided into ears, leaves (peeled from the stem as far as possible) and stems. Individual fresh weight was recorded per plant part and pooled samples (containing the parts of plants grown on the same container) were dried at 70°C for at least 3 days and reweighed.

Ground plant samples were assayed for ^{137}Cs activity in a well type NaI(Tl) detector (Compugamma 1282', LKB Wallac, Finland). K in the plant tissue was analysed in a $H_2SO_4/HNO_3/HClO_4$ digest by atomic absorption spectrophotometry. The data on K distribution within ears, leaves, stems and roots were obtained by neutron activation analysis using an 8 hour irradiation in the Imperial College reactor (neutron flux about 10^{12} n cm^{-2} s^{-1}) followed by a one day 'cool-

Table 1. Shoot and root dry weight (g) of the wheat plants grown in the NO_3 (Treatment 1) and the NH_4NO_3 solution (Treatment 2). Standard deviations are given in brackets

Plant age (DAS)	Treatment 1		Treatment 2	
	Shoot	Root	Shoot	Root
7	0.008(0.001)	0.007(0.002)	0.008(0.001)	0.007(0.002)
11	0.022(0.005)	0.012(0.003)	0.025(0.005)	0.013(0.003)
15	0.047(0.008)	0.022(0.005)	0.052(0.010)	0.023(0.005)
21	0.171(0.029)	0.067(0.011)	0.174(0.034)	0.066(0.012)
28	0.399(0.088)	0.136(0.037)	0.364(0.051)	0.128(0.020)
35	1.063(0.343)	0.242(0.086)	1.058(0.326)	0.219(0.081)
42	2.680(0.815)	0.496(0.208)	2.687(0.671)	0.384(0.113)
49	6.740(2.275)	0.929(0.399)	6.619(1.836)	0.873(0.376)
56	11.79(2.74)	1.793(0.259)	14.67(4.96)	1.939(0.838)
64	19.00(2.19)	2.756(1.021)	26.93(3.7)	3.539(0.942)

ing' period and a one hour count on a high resolution γ spectrometry (Ge-Li) system.

Results and discussion

Plant growth

The shoot and root dry weights at both nutrition treatments are given in Table 1. Total plant dry weight (shoot + root) was not signifcantly ($p<0.05$) affected by the nutrition treatments unless at 64 DAS. The tillering stage (stage 21 on the decimal code of Zadocks et al., 1974) started at about 18 DAS and stem formation (stage 31) at about 31 DAS. The first ears were visible from 50 DAS (stage 50). At the last harvest (64 DAS), plants were in the flowering stage (stage 60). The number of ears per plant then varied between 3 and 7 and the number of tillers between 17 and 45. The average shoot-root dry weight ratio increased in both treatments from about 2.2 at 15 DAS to 7.7 at 64 DAS.

^{137}Cs uptake and distribution

^{137}Cs AC in shoot and root tissues of both treatments are shown in Figures 1a and b. In both treatments, the same tendency during development can be found. Shoot AC initially increase until 28 DAS after which they slowly decrease. In the root tissue, the increase of the ^{137}Cs AC is more pronounced than in the shoot and continues up to 35 DAS after which it fluctuates. The AC in the shoot are almost equal in both treatments. The AC in the root are always higher than in the shoot and are slightly lower in the NO_3 treatment which is consistent with previous results for 19 day old wheat plants (cf. corresponding treatments 7 and 8 in Smolders et al., 1993). Dividing these data by the ^{137}Cs AC in solution (5 Bq mL^{-1}) yields ^{137}Cs transfer factors of 30 to 60 mL g^{-1} for the shoot and 60 to 140 mL g^{-1} for the roots. Ontogenetic changes in shoot AC are much lower here than those found in a lysimeter study (Shaw, unpublished results) which indicates that soil related factors are probably responsible for that variance. The changes during development are even more reduced if the AC are expressed on a tissue water basis (Figs. 2a and b). Since tissue water represents the physiological 'pool' for caesium, it has previously been suggested (Nimis et al., 1991) to use it as the basis on which to express ^{137}Cs AC in plants. In addition, Leigh and Storey (1991) have shown that K concentrations in the tissue water of cereals remain almost constant throughout the growing season. The shoot AC, expressed on a tissue water basis alleviate the decrease in shoot AC on a dry weight basis at subsequent growth stages (Fig.1). This is most clear in the data of the plants grown on the NO_3 solution where shoot AC seem to reach an equilibrium value after an initial increase. Expressed on a tissue water basis, shoot and root AC are about equal except for the latter growth stages at which ^{137}Cs AC in the shoot are higher than in the root. The shoot and root AC expressed on a tissue water basis are always higher (five- to tenfold) than in the solution. Due to the chemical characteristics of caesium, this increase in ^{137}Cs AC during transport from solution to the plant must be

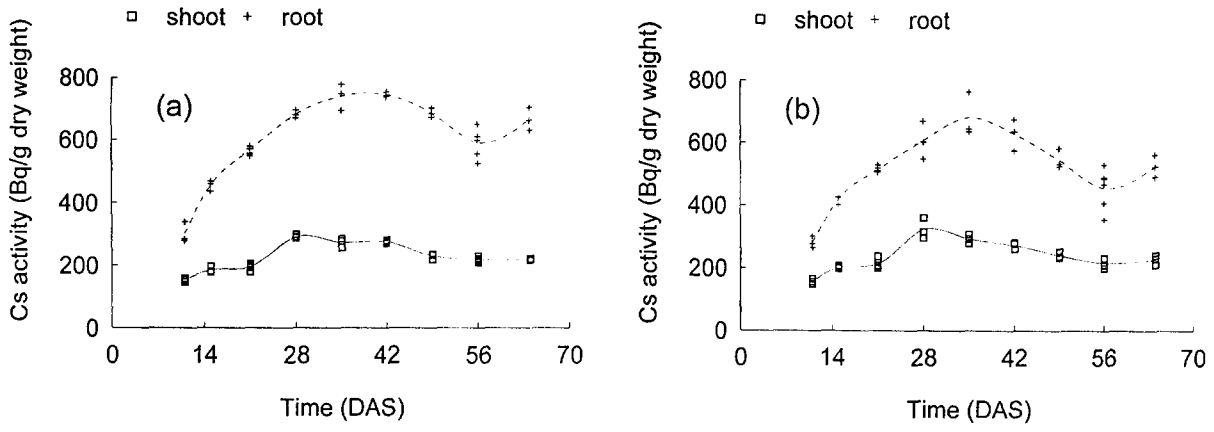

Fig. 1. ^{137}Cs AC, expressed on a dry weight basis, in shoots and roots of wheat plants grown in the NO_3 nutrient solution (**a**) and in the NH_4NO_3 nutrient solution (**b**).

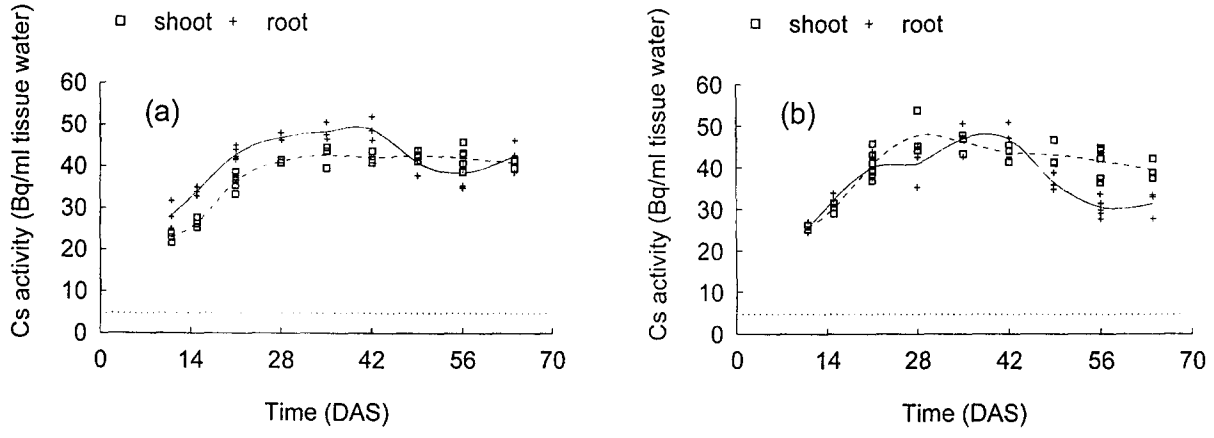

Fig. 2. ^{137}Cs AC, expressed on a tissue water basis, in shoots and roots of wheat plants grown in the NO_3 nutrient solution (**a**) and in the NH_4NO_3 nutrient solution (**b**). Tissue water is defined as the difference between fresh and dry weight. The dashed straight line represents the ^{137}Cs activity in the external medium showing that ^{137}Cs is concentrated in the plant compared to the external solution.

due to active uptake rather than to specific binding of ^{137}Cs to organic ligands within the plant.

The initial rise in ^{137}Cs AC can be explained by the dilution of ^{137}Cs in the unlabelled tissue of the seedling. If it is assumed that uptake of ^{137}Cs is coupled to the plant growth rate, ^{137}Cs AC are initially reduced compared to later growth stages by a factor equal to the ratio of the weight of plant tissue formed since the labeling of the plant and the total plant weight. This assumption was tested for the total plant AC on a tissue water basis (weighed average of shoot and root AC). To calculate the rise in AC in young plants, it was assumed that the tissue which is formed after the transfer of the seedlings to the active solution has the equilibrium ^{137}Cs AC observed in the plants at later growth stages (NO_3 treatments: 42.7 Bq mL^{-1}) or the maximum level observed in plants at later growth stages (NH_4NO_3 treatment, 45.6 Bq mL^{-1} figures not shown). In this way, AC in the plants are predicted (NO_3 treatment) to increase from 26 Bq mL^{-1} to 40.1 Bq mL^{-1} between 11 DAS and 21 DAS whereas they are found to increase from 24 Bq mL^{-1} to 38 Bq mL^{-1} in this period. For the same period, AC in the plants of the NH_4NO_3 treatment are predicted to increase from 27 Bq mL^{-1} to 42 Bq mL^{-1} and observations show an increase from 26 Bq mL^{-1} to 43 Bq mL^{-1}.

In a separate experiment which ran consecutively with the experiment described above, ^{137}Cs was added to the nitrate nutrient solution at an intermediate growth stage of the plant (29 DAS). The rise of AC in the shoot and root tissue was followed over the next 20 days and compared with control plants (continu-

Table 2. ^{137}Cs AC (Bq g^{-1} dry weight) and K concentrations (mmol g^{-1} dry weight) in four different tissues of 64 day old wheat plants grown in the NO_3 or the NH_4NO_3 solution. Averages and standard deviations (in brackets of three independent observations

Tissue	NO_3 solution		NH_4NO_3 solution	
	^{137}Cs	K	^{137}Cs	K
Leaves	336(13)	1.14(.03)	324(19)	1.30(.09)
Stem	127(2)	1.41(.08)	133(13)	1.45(.14)
Ears	179(4)	0.42(.02)	181(9)	0.47(.06)
Roots	665(36)	1.34(.07)	526(35)	1.18(.15)

ously exposed plants). Again, as found for the plants between 11 DAS and 21 DAS, the AC in the shoot increased as predicted based on growth dilution principles (details not given). However, the AC in the root tissue increased more quickly than expected based on growth dilution principles. In any case, it can be concluded that that the rise in AC in the shoot after labeling can be described by a constant net translocation to the shoot per unit shoot biomass produced. A close correlation between shoot growth rate and net translocation rate has also been shown for the plant nutrients N, K and Ca (Engels and Marschner, 1992).

An initial increase in K concentrations was not seen, as it was for the ^{137}Cs AC. Young seedlings contain K and no ^{137}Cs from their seed resources and this discrepancy can be explained by growth dilution effects on ^{137}Cs AC as described above. A linear regression was made of the K concentrations, on dry weight basis, on the plant age. K concentrations in roots decreased signifcantly ($p< 0.05$) in both treatments but decreased only significantly in the shoot tissue at the NO_3 treatment. The regression lines predict that at 25 DAS, the K concentration in the shoot was 1.48 mmol g^{-1} (NO_3 treatment) and 1.36 mmol g^{-1} (NH_4NO_3 treatment), decreasing to 1.29 mmol g^{-1} (NO_3 treatment) and 1.30 mmol g^{-1} (NH_4NO_3 treatment) at 60 DAS. The predicted K concentration in the root was 1.50 mmol g^{-1} (NO_3 treatment) and 1.47 mmol g^{-1} (NH_4NO_3 treatment) at 25 DAS decreasing to 1.39 mmol g^{-1} (NO_3 treatment) and 1.20 mmol g^{-1} (NH_4NO_3 treatment) at 60 DAS. Broadly speaking, corresponding ^{137}Cs AC decrease by the same (small) degree of magnitude as K concentrations in that time interval (see Figs. 1a and b).

The concentrations of ^{137}Cs and K in stems, ears, leaves and roots of 64 old wheat plants are given in Table 2. Neither K nor ^{137}Cs distribution are significantly affected by the nutrition treatment. The K concentration in roots is lower (although not significantly) in the NH_4NO_3 treatment than in roots of the NO_3 treatment and vice versa for the leaves. This is in line with the well known effects of the inorganic N-source on K distribution (e.g. Van Beusichem et al., 1988). The nutrition effect on K distribution may perhaps be only small because NH_4 was not the single inorganic N-source in that solution. ^{137}Cs AC are all significantly different between the different tissues, the sequence of the AC being roots > leaves > ears > stems. Significant differences are also found between K concentrations. However, the sequence is different: stems > root $\approx$ leaves > ears. K concentrations are considerably lower in the ears than in the roots, leaves and stems but this is not found for ^{137}Cs AC. Hence, these results show that K and ^{137}Cs are differently distributed within the plants. This may be the result of Cs/K discrimination for every membrane transfer involved in the internal distribution. In an experiment using spinach in a vegetative phase, the recirculation of K and ^{137}Cs within the plants was measured indirectly after a resupply of K to previously K stressed plants (Buysse et al., 1995). At all occasion after the K resupply, it was shown that the retranslocation (the flow from shoot to the root) was considerably higher for ^{137}Cs than for K. This also shows that ^{137}Cs cannot be used as a K analogue in the plant, resulting in a different distribution of the two ions.

In conclusion, our results show that growth stage effects on ^{137}Cs uptake are correlated with growth stage effects on K uptake. Based on the initial increase in ^{137}Cs AC after the start of labelling the nutrient solution, a direct relationship between shoot growth rate and the net ^{137}Cs translocation rate can be shown. The distribution of ^{137}Cs within the plant is however much different from that of K.

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