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^{137}Cs uptake in spring wheat *(Triticum aestivum* L. cv. Tonic) at varying K supply

II. A potted soil experiment

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Abstract

Spring wheat (Triticum aestivum L. cv. Tonic) was grown for 16 days in a sandy loam soil which was contaminated with ^{137}Cs. The soil was fertilised with K at three rates (0,1 and 2 mmol K per 950 g dry soil) and with NO_3^--N at two rates (0 and 2 mmol per 950 g dry soil) in a factorial design. The ^{137}Cs Activity Concentration (AC) in the shoot tissue significantly reduced 8.2-fold (nil N treatment, $p<0.001$) and 9.3-fold (highest N dose, $p<0.001$) with increasing K supply. In contrast, the K application increased the ^{137}Cs AC in soil solution 1.7 fold (nil N treatment) or had no significant effect (highest N dose). At similar K application, the application of N increased the ^{137}Cs AC in the shoot compared to the control. This effect is most probably due to the increased NH_4^+ concentration in soil solution which increased the ^{137}Cs AC in soil solution. The soil solution composition (^{137}Cs and K concentration) in the rhizosphere was estimated from the average soil solution composition at day 16 and solute transport calculations. The ^{137}Cs AC in the shoot tissue was predicted from the estimated soil solution composition in the rhizosphere and the relationship between K concentration and ^{137}Cs uptake derived from a nutrient solution experiment. The predictions of ^{137}Cs AC's in the shoot are qualitatively correct for the fertiliser effects but underestimate the observations between 1.4 and 9.9 fold.

Introduction

Potassium fertilisation has been shown to be efficient in reducing ^{137}Cs availability to crops growing in contaminated soils. In comparative studies on countermeasures, K fertilisation is generally more efficient than liming (e.g. Lönsjö et al., 1990; Mitchell et al., 1990; Rosén, 1992) and has a more immediate effect than application of zeolites which are used to immobilise radiocaesium (Jones et al.,1994). A large number of field experiments on the effect of K fertilisation have been carried out in the area affected by the Chernobyl accident of 1986 such as Ukraine (Prister et al.,1993), Sweden (Lönsjö et al., 1990; Rosén,1992) and the upland areas of the UK (Jackson and Nisbet,1990; Jones et al., 1994; Mitchell et al., 1990). The reduction factors (ratio of ^{137}Cs activity concentration in plants of untreated versus treated plots) vary widely with the type of soil and crop used. In peat soils or peat bogs, reduction factors for grasslands vary from 1.1 (Mitchell et al., 1990) to over 12 (treatments up to 200 kg K ha^{-1}, Lönsjö et al., 1990). Potassium fertilisation can also reduce ^{137}Cs transfer from peat soils to barley (Rosén, 1992). In mineral soils, reduction factors vary from almost unity in leek and carrots grown on a silt loam soil to over 5 in barley grown in a sandy loam (Rosén, 1992). Larger reduction factors of over 30 have been found in long-term studies (1961-1981) with oats, peas and white mustard grown in mineral soils (Lönsjö et al., 1990). These factors may perhaps not reflect common agricultural conditions as the control plots were probably strongly depleted in nutrients.

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The reduction in ^{137}Cs availability by increased K supply has also been found in a number of pot trials (Belli et al., 1995; Fawaris and Johanson, 1994; Fowler and Christenson, 1959; Grauby et al., 1990; Jackson et al.,1965; Nishita et al.,1960, 1962). It is generally found in these studies that enhanced K supply reduces ^{137}Cs uptake substantially at low K availability in soil and reduction factors up to 100 have been demonstrated (Grauby et al.,1990). At high K availability in soil however, enhanced K supply has only little effect or even stimulates ^{137}Cs uptake (Fowler and Christenson, 1959; Grauby et al.,1990; Nishita et al.,1960).

Net ^{137}Cs uptake from soil results from a combination of the effects of the added cations on maintaining ^{137}Cs in (soil) solution and on inhibition of uptake and transport processes (Jackson et al., 1965). The two processes act in an opposite way. No attempt has yet been made to separate the effect of K supply on ^{137}Cs desorption from soil and its effect on the root uptake process. In mineral soils, increased K in solution increases the ^{137}Cs activity in solution. This has been quantified in the radiocaesium interception potential theory which state that the ^{137}Cs solid/liquid distribution constant K_D equals

$$K_D = \frac{RIP}{m_{\mathrm{K}} + 5m_{\mathrm{NH_4}}} \qquad (1)$$

(De Preter, 1990) in which m_{K} and $m_{\mathrm{NH_4}}$ represent the K and NH_4^+ concentrations in solution and RIP is the radiocaesium interception potential, a soil characteristic which can be measured experimentally (Sweeck et al.,1990). If NH_4^+ concentration in soil is low, K additions to a soil will result in a proportional increase in both K and ^{137}Cs concentration in soil solution. In organic soils (e.g. peat soils) a considerable fraction of ^{137}Cs is adsorbed to organic matter. In these soils, the effect of K addition on the ^{137}Cs activity in solution varies from almost absent to a significant increase. This increase is however less than proportional to the K concentration increase (Nisbet et al.,1994).

Solution culture studies showed that increasing K concentrations in solution decrease ^{137}Cs uptake sharply at micromolar concentrations of K (Shaw et al.,1992). Previously, we demonstrated that between 50 and 250 μM K, ^{137}Cs uptake was more than proportionally affected by $1/m_{\mathrm{K}}$ (Smolders et al., 1996). From this observation it follows that, even if ^{137}Cs levels in soil solution rise along with increasing K concentration, a reduction in net uptake by increased K supply could be possible because of the larger effect on the uptake process.

In this paper, we present results of a potted soil experiment in which the effect of increased K supply on (a) ^{137}Cs uptake in wheat and on (b) soil solution ^{137}Cs activity was measured. It is assessed whether the effect can be predicted based on the solution culture observations (Smolders et al., 1996) and soil solution composition (^{137}Cs and K concentrations). The potted soil experiment was carried out at similar environmental conditions as the solution culture experiment. The soil solution composition at the soil/root interface is approximated from the average soil solution composition with a solute transport calculation. The experiment was set-up in a factorial design with three rates of K and two rates of N (added as NO_3^-). The NO_3^- application was included to assess the effect of an increased plant growth rate independent of K nutrition.

Materials and methods

Soil sampling and treatments

A silt-loam soil (USDA) was sampled from the E horizon of a luvisol (FAO,1990). This mineral soil was collected in a forest and was selected for its low K availability at which the effect of added K on ^{137}Cs availability can be large. The soil was sieved (3 mm) and amended with lime (10 mmol $Ca(OH)_2$ per kg dry soil) and phosphorous (1. 05 mmol $CaHPO_4$ kg^{-1} dry soil). Treatments were three rates of K (0,1 and 2 mmol K 950 g^{-1} dry soil, the quantity of soil to fill one pot) and two rates of NO_3^- -N (0 and 2 mmol NO_3^- /pot) in a factorial design with 5 fold replication. K was added as a Cl salt at the nil N treatment and as a NO_3^- salt in the 2 mmol N treatment. NO_3^- was added as a mixture of Ca and K salts depending on the K application rate. Selected characteristics of the amended soil at the nil K and N treatment are given in Table 1. The soil amendments (application of lime, P, N and K),^{137}Cs contamination and moistening to 21% (g g^{-1} oven dry soil, 86% of water holding capacity) were carried out by mixing 5.5 kg soil with appropriate volumes of stock solutions (N, K, and ^{137}Cs), amount of dry salts (lime and P) and volumes of distilled water. Mixing was made using a conventional kitchen mixer. Application of carrier-free ^{137}Cs was about 1 MBq per pot, added through a 10 mL solution per 5.5 kg soil. Per treatment, another 10 uncontaminated replicates were prepared. These replicates (further denoted as 'unlabelled') were used to quantify shoot and root growth rate at the different treatments. These biome-

Table 1. Selected characteristics of the silt loam soil after liming and P application at zero N and K application

pH(KCl)	4.7
% Clay	9
% Silt	61
% Sand	30
C(%)	1.1
Macronutrients(cmol kg^{-1})	
P	0.064
K[a]	0.17
Mg[a]	0.04
Ca[a]	1.2
Na[a]	0.034
NH_4^+[b]	0.029
NO_3^-[b]	0.016
CEC[c] (cmol$^+$kg^{-1})	6.5

[a] In 0.1 *M* ammoniumlactate extract (1:20) and measured colorimetrically by ammonium vanadate (P) or by atomic absorption spectophotometry (K, Mg, Ca, Na).
[b] In 1 *N* KCl extract and measured colorimetrically using sulfanylamide and N-(1-naftyl)ethylenediaminedihydrochloride (NO_3) or indophenylblue method (NH_4).
[c] Ammoniumacetate method.

tric data are essential for the solute transport calculation (see below).

All potted soils were installed in a growth cabinet at 25 °C, 40% relative humidity and high light intensity (650 μmol photons m^{-2} s^{-1}). Soils were allowed to dry in these condition for 4 days, remoistened to 24% and redried for 3 days. Soils were then finally remoistened to 21 % after which they were covered and incubated for 4 days in darkness at 18.5 °C prior to seed transplanting.

Plant growth

Seeds of spring wheat (*Triticum aestivum* L., cv. Tonic) were soaked in water and germinated on moist tissue paper in a plastic bag at 25 °C. One day later, germinated seeds were transplanted to the pots (two per pot). The soil surface was covered with polythene beads to reduce surface evaporation. Plants were grown in a growth cabinet (Weiss, 18'SP/+5Ju-Pa) with a 12h/12h day/night cycle. Air temperature was 18.5 °C during the day and 14.5 °C during the night. Relative humidity was 75% throughout. Light intensity at canopy height was 650 (±30) μmol photons m^{-2} s^{-1}. Daily water loss from the pots was recorded by weighing and adjusted with deionised water. At day 7 (day 0 is day of germination), plants were thinned to one per pot.

Harvest

Unlabelled plants were harvested at day 13 and day 17, removing 5 replicates at each occasion. Labelled plants (shoots only) were harvested at day 16. The shoot fresh weight of the labelled plants was recorded, transferred into 5 mL counting vials and their gamma activity measured (Minaxi, 5530 auto-γ,1 h per sample). ^{137}Cs activities ranged between 18 cpm and 632 cpm per plant. Plants were subsequently dried at 65 °C and reweighed. The shoots of the unlabelled plants were harvested and their roots were isolated (two replicates per treatment only). Roots were isolated by gently washing the soil from roots over a 2 mm sieve. Roots were further cleaned from soil and debris in a $Na_2P_2O_7$ solution and subsequently weighed. Root fresh weight was recorded. A subsample of about 0.2 g fresh weight (15 to 50% of the root sample) was coloured with safranine, cut to 1-2 cm pieces and root length was measured with the line intersection method on a 0.5 cm grid (Tennant, 1975). Root diameter was measured on 20 roots per sample. The subsample was then combined with the remaining root sample. All plant tissues were dried (65 °C) and reweighed.

Soil solution isolation

Soil solution was sampled from all labelled replicates at harvest. Per pot, the majority of the roots were removed by hand-picking and the soil was homogenised. A syringe from which the plunger was removed was filled with glass wool and 50 g soil. A holder with a 0.22 μm membrane filter (Millipore) was connected to the syringe outlet. The syringe was transferred to a centrifuge tube and centrifuged for 1 h at about 1100 RCF. For each pot, two soil samples were centrifuged and the collected solutions (about 2.5 mL each) were combined. The ^{137}Cs activities in the combined solutions were counted for 1 h and varied from 12 to 78 cpm per sample.

Chemical analyses

The soil solution was analysed for K, Ca and Mg by Atomic Absorption Spectrophotometry (AAS), for

NH_4^+ by colorimetry (indophenol-blue method) and for Cl^-, NO_3^- and SO_4^{2-} by Ion Chromatography (Dionex, AS4A column). The plant tissues (all replicates for the labelled plants, and two plants per harvest and treatment for unlabelled plants) were digested in HNO_3 and K in the digest was measured by AAS. No clear digest was obtained of the root tissues of the unlabelled replicates. K concentrations in these digests were low and irreproducible, hence no K content of the roots could be obtained.

Data analysis and soil solute transport calculation

Data were subjected to a two way ANOVA for the effect of K and N fertilisation and their interaction.

The soil solution composition (K and ^{137}Cs concentration) at the root surface was calculated from the average soil solution composition and soil and plant parameters. The approach of estimating rhizosphere composition by calculation is similar to that used by Rengel and Robinson (1990). The approximation of Baldwin et al. (1973) was used to calculate the steady-state concentration profile around the root.

For a randomly dispersed root at constant root density in a finite volume of soil, assuming only radial transport in the solution phase by diffusion and mass flow, the concentration of solute X at the root surface, $m_{X,a}$, is given by Baldwin et al. (1973) as:

$$m_{X,a} = m_X\left[\frac{\alpha}{\nu} + \left(1-\frac{\alpha}{\nu}\right)\left(\frac{2}{2-\frac{a\nu}{Db}}\right)\frac{\left(\left(\frac{x}{a}\right)^{2-a\nu/Db}-1\right)}{\left(\left(\frac{x}{a}\right)^{2}-1\right)}\right] \qquad (2)$$

m_X is the average concentration in soil solution, α is the root absorption power (solute uptake rate on a root area basis divided by solute concentration, m day^{-1}), ν is the water flux at the root surface (m day^{-1}), a is the root radius (m), D is the effective diffusion coefficient of the solute in the soil (m^2 day^{-1}), b is the buffer power (see below) and x is the radius of the soil cylinder that can be exploited by the root. The radius x is calculated as

$$x = \frac{1}{\sqrt{\Pi L}} \qquad (3)$$

L is the root density (root length/soil volume, m m^{-3}).

Whereas in the solute transport model of Baldwin and co-workers the root absorption power is an input parameter derived from solution culture studies (e.g. Bhat et al.,1979a and b) it was derived here from the *observed* uptake rate in this soil experiment. This method corresponds to that used by Rengel and Robinson (1990). For this purpose, Equation (2) was modified by replacing α by U_a/m_{xa} in which U_a is the solute uptake rate per unit root surface. This modified equation was solved for $m_{X,a}$ In this way, the steady-state concentration profiles of K and ^{137}Cs in soil solution around the root were calculated from their average concentrations in soil solution and the observed uptake rates. The input parameters were found as follows:

m_x: the average of the soil solution concentrations of K and ^{137}Cs respectively at day 16.

U_a: for both K and ^{137}Cs, U_a at day 16 was calculated from the ratio of the uptake rate per unit root dry weight (average for each treatment) and the average root area per root dry weight (average of all treatments and harvests). For K, the uptake rate was calculated from the difference in K content (mmol plant $^{-1}$) between the successive harvests of unlabelled replicates. As mentioned in previous section, K analysis on roots failed, and, based on the solution culture experiment (Smolders et al., 1996), an average content of 1.4 mmol g^{-1} dry weight root tissue was assumed. The uptake rate per root weight was derived by dividing the uptake rate by the average root weight of successive harvests. This implies that root growth rate is assumed to be linear between the two harvests. The average root surface area per unit root dry weight was calculated from the average root radius of each subsample and its total root length per root dry weight. From all samples (all treatments and harvests), an average of 0.150 (±0.034) m^2 g^{-1} dry weight was derived. The ^{137}Cs uptake rate was calculated from the shoot and root growth rate of the unlabelled replicates (averages per treatment) and, for the shoot, a ^{137}Cs AC equal to that observed at day 16 (averages per treatment). Solution culture studies showed that in wheat, concentration changes with growth stage were small (Smolders and Shaw,1995). Root concentrations of ^{137}Cs were not measured as it was anticipated that contamination of roots by soil particles would make root activities difficult to interpret. Therefore, it was assumed that ^{137}Cs concentration in the root tissue is 5 fold higher than the shoot concentration, corresponding to solution culture observations at 250 μM K (Smolders et al., 1996). This value was found to increase at lower K concentrations, but it affects our calculation results slightly in only one treatment (see Results). ^{137}Cs uptake rate per root area was calculated from ^{137}Cs uptake rate as for K.

v : The net daily water uptake in the plant was measured from the difference in daily water loss between planted pots and the initial daily water loss when plants were small. The cumulative net water uptake of each plant was plotted to the shoot biomass and a linear regression was made. The slope of the line was 190 mL g^{-1} dry weight(±50). This value was converted to average water intake per unit root area, *v*, using the shoot relative growth rate (average per treatment), the shoot:root dry weight ratio (average per treatment of second harvest), and the root area per root dry weight (average of all samples).

a : an average root radius of 0.17 mm (±0.03) was derived from all treatments and harvests.

Db : the product Db equals $D_l \Theta f_l$ (Baldwin et al., 1973) in which D_l is the diffusion coefficient in water, θ is the volumetric moisture content and f_l is the tortuosity factor. D_l of ^{137}Cs was assumed equal to that of K as 1.74 10^{-5} cm^2 s^{-1} (Robinson and Stokes,1965). At the volumetric soil moisture content of 0.22, a tortuosity factor of 0.18 was selected for the silt-loam soil (Barraclough and Tinker, 1981).

x : The root length per soil volume (900 mL pot^{-1}) was averaged for each treatment at each harvest of the unlabelled plants. The root density at day 16 was then estimated from the regression line of the root densities at day 13 and 17. The value of x was then derived according to Equation 3 and varied between 5 and 6 mm according to the treatment.

In our calculations, we assume that the concentration profile around the roots is in a steady-state. It can be demonstrated that the concentration profile readily reaches a steady-state if the value of the ratio $\alpha a/Db$ is small. Solute uptake calculated from the steady state concentration profile in a stepwise manner (i.e. by adjusting the concentration profile in each step to account for the amount of solute absorbed by the root) has been compared to numerical non-steady state calculations. Good correspondence between both methods was found when the ratio $\alpha a/Db$ is below 5.0 (Baldwin, 1973). Using our parameter values, the ratio for K and ^{137}Cs was maximum 0.004. Hence, the use of the steady-state approximation is justified to calculate the K and ^{137}Cs concentration gradients for our conditions.

Results

Shoot growth was significantly enhanced by the N application whereas the K application only slightly enhanced growth at the nil N treatment (Table 2). Root biomass in contrast was unaffected by the fertiliser treatments (Table 3, unlabelled replicates). Root length per plant was not significantly affected by fertilisation although a decreasing trend with increasing K application was found at the 2N treatment. The root:shoot weight ratio was always highest at the nil N treatment compared to the N treatment. The data of the specific root length (length per root dry weight) and the root radius were subjected to a statistical analysis. No treatment effects (p>0.05) were found on both parameters except for a significant N-K interaction on specific root length at the first harvest: at increasing K supply, specific root length decreased at the 2N treatment only (details not shown).

Increasing K supply increased the K concentration in soil solution about fourfold (Table 2). A similar increase was found for the NH_4^+ concentration at the nil N treatment. In the NO_3^- supplied soil, NH_4^+ concentrations (over 1 m*M*) were high and increased slightly with K application. Ca and Mg concentrations in soil solution also increased by K application (figures not shown). The high NH_4^+ concentration at the 2N treatment were rather unexpected as N was given as NO_3^- only. Inhibition of nitrification of mineralised N by high NO_3^- concentrations and low soil pH values may explain this result.

The ^{137}Cs AC in the shoot decreased sharply by increasing K application rate (Fig. 1). Application of NO_3^- -N enhanced the ^{137}Cs AC. The reduction factors at a K application of 2 mmol pot^{-1} were 8.2 at the nil N treatment and 9.3 at the 2 N treatment compared to the nil K treatment. In contrast, ^{137}Cs AC's in soil solution either increased 1.7 fold (nil N treatment) or was unaffected (2 N treatment) by the K application (Fig. 2). According to Equation 1 and soil solution composition, the ^{137}Cs AC in soil solution is expected to increase 3.8-fold (nil N treatment) and 1.3-fold (2 N treatment) following K application. ^{137}Cs AC's were higher in the N supplied soils than at no N application. Equation 1 predicts a 3.3 fold increase of the ^{137}Cs AC in solution by the N application at no K gift whereas a 2 fold increase is observed. Hence, in a quantitative way, the effects of K and NH_4^+ on the ^{137}Cs activity in soil solution did not fully obey Equation 1. It has however been found that the product $K_D(m_K + 5m_{NH_4})$ Is slightly increased in the micromolar range of K and NH_4^+ (Wauters,1994).

Solute transport calculations reveal a considerable K depletion at the root surface compared to the bulk soil solution at the 0K treatments (Table 4). At the

Table 2. Shoot dry weight, shoot K content (mmol g^{-1} dry weight) and the K and NH_4^+ concentrations in isolated soil solution at the various K and N application rates (in mmol pot^{-1}). Averages and standard deviations(between brackets) of the 5 replicates observed at day 16. Treatment effects (including the N-K interaction) are assessed by two way ANOVA

N-K application (mmol pot^{-1}	Shoot dry weight(g)	K shoot(mmol g^{-1} dry weight)	K soil solution (mmol L^{-1})	NH_4^+ soil solution(mmol L^{-1})
0-0	0.032(0.006)	1.05(0.14)	0.17(0.02)	0.32(0.11)
0-1	0.036(0.005)	1.04(0.13)	0.42(0.07)	0.80(0.28)
0-2	0.041(0.009)	1.13(0.19)	0.81(0.11)	1.18(0.21)
2-0	0.048(0.007)	0.97(0.07)	0.21(0.03)	1.13(0.21)
2-1	0.051(0.004)	1.00(0.02)	0.46(0.05)	1.20(0.34)
2-2	0.045(0.013)	0.90(0.19)	0.94(0.05)	1.32(0.23)
Treatment effect^{a}				
N	***	ns	**	***
K	ns	ns	***	***
N-K	ns	***	ns	*

^{a}*,**,*** Significant at the 0.05, 0.01 or 0.001 level respectively; ns, not significant at the 0.05 level.

Table 3. Root dry weight, the root to shoot dry weight ratio and the root length of 13 and 17 days old wheat plants grown at the various K and N application rates (in mmol pot^{-1}). Averages and standard deviations (between brackets) of 2 replicates. Treatment effects (including the N-K interaction) are assessed by two way ANOVA

N-K application (mmol pot^{-1})	Root dry weight(g)		Root:shoot dry weight ratio		Root length per plant(m)	
	Day 13	Day 17	Day 13	Day 17	Day 13	Day 17
0-0	0.053(0.005)	0.074(0.015)	1.95(0.44)	2.04(0.62)	6.5(0.7)	13.5(4.3)
0-1	0.060(0.008)	0.066(0.011)	1.49(0.01)	1.62(0.31)	8.7(0.7)	12.0(3.7)
0-2	0.070(0.005)	0.082(0.014)	1.82(0.22)	1.91(0.14)	7.2(0.7)	13.2(1.8)
2-0	0.048(0.010)	0.098(0.023)	1.31(0.23)	1.28(0.10)	7.5(2.1)	13.4(2.8)
2-1	0.058(0.018)	0.074(0.058)	1.25(0.11)	1.04(0.41)	7.6(2.3)	11.7(8.4)
2-2	0.054(0.017)	0.065(0.013)	1.48(0.18)	1.25(0.23)	4.4(0.8)	8.4(0.8)
Treatment effect^{a}						
N	ns	ns	*	*	ns	ns
K	ns	ns	ns	ns	ns	ns
N-K	ns	ns	ns	ns	ns	ns

^{a} Significant at the 0.05 level; ns not significant at the 0.05 level.

other treatments, K was not so strongly depleted from the bulk solution because a K concentration gradient ($m_K - m_{K,a}$, below 100 μM K was sufficient to match the observed K uptake rate. This concentration gradient is relatively small compared to the bulk solution concentration. The calculated ^{137}Cs AC's at the root surface were not lower than 50% of the bulk soil solution AC's (Table 4). A parameter sensitivity analysis showed that the K concentrations at the root surface in the nil K treatment are most sensitive to changing input parameters (details not shown). The fact that potassium is more readily depleted around roots than ^{137}Cs is related to the higher value of α for K than for ^{137}Cs. This is confirmed by the observation that in solution culture, K is more efficiently absorbed by plant roots than ^{137}Cs (see e.g. Smolders et al., 1996).

The solution composition at the root surface was used to compare the results of the potted soil experiments with those of a solution culture experiment (Smolders et al., 1996). In the solution culture

Table 4. Predicted and observed ^{137}Cs activity in wheat shoots grown at different N-K application rates. The predictions are based on the K and ^{137}Cs concentrations in soil solution at the root surface and ^{137}Cs uptake characteristics measured in solution culture. The soil solution composition at the root surface is calculated with a solute transport model

N-K application	Average soil solution		Soil solution at root surface		^{137}Cs activity in shoot(cpm g^{-1} dry weight)	
(mmol pot^{-1})	K(μM)	^{137}Cs (cpm mL^{-1})	K(μM)	^{137}Cs (cpm mL^{-1})	Predicted	Observed
0-0	170	4.7	44	2.8	4444	6191
0-1	420	5.7	354	5.2	278	2765
0-2	810	7.8	776	7.7	249	755
2-0	210	9.2	49	4.5	5665	11831
2-1	460	9.8	403	9.4	451	3219
2-2	940	9.5	918	9.5	285	1267

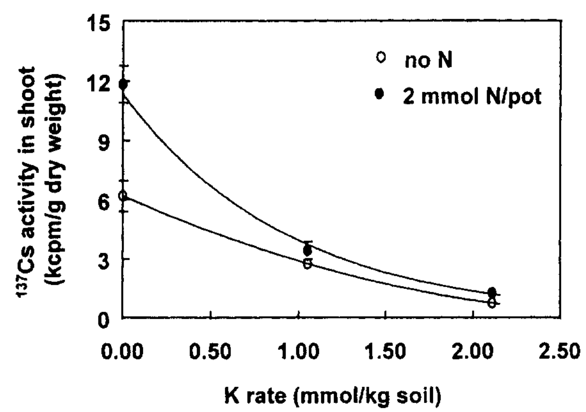

Figure 1. ^{137}Cs activity (kcpm g^{-1}) in the shoot of 16 day old wheat plants grown at varied K and NO_3^--N application rates. Data points represent averages and standard deviations (error bars) of 5 replicates. Error bars are not visible when standard deviations are smaller than the symbol size.

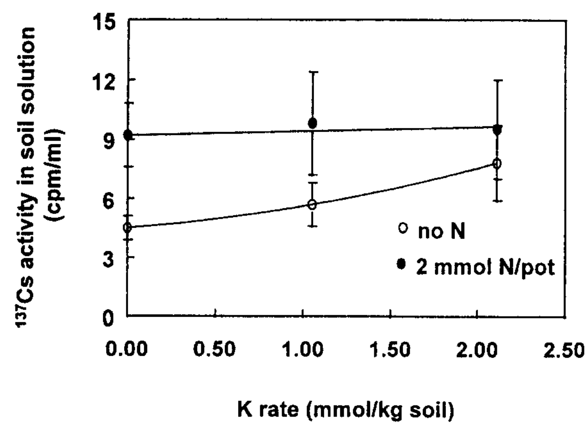

Figure 2. ^{137}Cs activity concentration in soil solution (cpm mL^{-1}) at the different K and NO_3^--N application rates. Averages and standard deviations (error bars) of 5 replicates.

experiment, ^{137}Cs Transfer Factor (TF, the ratio of the ^{137}Cs AC in the tissue to that in solution) was measured in wheat plants grown at K concentrations varying between 25 μM K and 1000 μM K. The shoot ^{137}Cs transfer factor was regressed to m_K (a non-linear regression of the form $\log TF = (A - Bm_K)/(C + m_K)$ in which A, B and C are regression parameters). This curve, combined with the K and ^{137}Cs concentration at the root surface, was used to predict ^{137}Cs AC's in shoots (Table 4).

The calculations predict a decrease in the ^{137}Cs AC with increasing K application and an increase in the ^{137}Cs AC in the plants with N supply at corresponding K application. The calculated reduction factors by the K application are however twice as large as observed. The predicted AC's in the plant are always higher than the observed AC's. The continued decrease in ^{137}Cs uptake with increasing K supply above 1 mmol K pot^{-1} could hardly be predicted.

Discussion

As in most other potted soil experiments referred to in the introduction of this paper, a substantial reduction in the ^{137}Cs AC in the plant by K application is found. As demonstrated here, the K application reduces the ^{137}Cs AC in the plant in contrast to the soil solution AC's which are either enhanced or unaffected by the K supply. The reduction in ^{137}Cs availability is most probably related to the sharp reduction in the root ^{137}Cs absorption power at increasing K supply which has been found in solution culture experiments (Shaw et al.,1992; Smolders et al., 1996). Other plant parameters such as root length per plant or root area per plant influence ^{137}Cs uptake from soil but are not sufficiently affected to explain our results.

The reduction factors found here can be compared to those found in field trials. An application of 2 mmol K pot^{-1} should be compared to an application rate in the field of 204 kg K ha^{-1} if it is assumed that the K dose on 1 ha is spread into 3000 tons of soil (0-25 cm plough layer, ρ=1.2 g cm^{-3}). Such a K dose does not represent an exceptionally high fertiliser rate, yet a strong effect is found on ^{137}Cs transfer. In field trials, reduction factors for pasture grass at 200 kg K ha^{-1} vary between 2 and 12 (Lönsjö et al., 1990; Rosén, 1992). The K content of the unfertilised soils used by Lönsjö et al.(1990) varied between 1.1 and 4.0 μmol g^{-1} soil (peat, sand and loamy sand soils) a range which covers the K content of the soil used here (Table 1).

The increase of ^{137}Cs uptake with N application was rather unexpected as all N was applied as NO_3^-. Reports on the effect of nitrate application in potted soil or fields have not been found. NH_4^+ or urea application is known to increase ^{137}Cs transfer (e.g. Belli et al., 1995; Jackson et al.,1965). The soil solution data of our experiment however showed that NH_4^+ concentrations increased with nitrate application (Table 2). Since NH_4^+ has been shown to have much less competitive effect on ^{137}Cs uptake than does K (Shaw et al.,1992), the increased ^{137}Cs uptake by N supply can be explained by the mobilisation of ^{137}Cs in soil by NH_4^+. This hypothesis is supported by the fact that the ratio of ^{137}Cs AC's in plant to that in soil solution is almost equal at equal K supply in both N treatments.

The calculated soil solution composition at the root surface is most probably a better indicator to compare uptake of elements from soil with uptake from nutrient solution (Nye et al., 1975). Our predictions of ^{137}Cs uptake made in this way are biased to an overestimation of the reduction factors by K application and a general underestimation of the ^{137}Cs transfer (Table 4). A number of assumptions in this calculation can obviously be questioned. The calculated rhizosphere solution composition is only based on soil solution data at the day of plant harvest. The composition could have been different during earlier plant growth stages. The total uptake of K and ^{137}Cs from the pot by the biomass is however very small (respectively maximum 12% of the ion exchangeable K and below 0.1% of the total amount of ^{137}Cs in soil, calculation details not shown). Therefore, uptake of elements by the plant may not have caused a varying composition during plant growth. The ^{137}Cs AC could however have been reduced during plant growth because of a slow fixation in the soil of the freshly added ^{137}Cs. The solute transport calculation (steady-state approximation) can also be questioned. A numerical non-steady state calculation was made (details can be obtained from senior author) and results were compared with those obtained with the approximative method. Between 2 and 5 days after the start of the simulated uptake, concentrations at the root surface reached almost stable values which showed good correspondence with the values given in Table 4. Refining the numerical calculation by including the effect of K concentration on the ^{137}Cs K_d and including a kinetic term for ^{137}Cs desorption would both yield an even lower ^{137}Cs uptake from soil, yet current predictions underestimate the observations. Rhizosphere effects and possible effects of mycorhizza are here not accounted for. Because of a lack of consistent views on to the influence of these on ^{137}Cs availability these are not further discussed here. It may be critical in our calculations to assume that uptake of ^{137}Cs and K is occurring over the whole root system. Confining the uptake of both cations to a fraction of the root length because of root morphology or physiology, root age or partial soil solution/root contact would yield lower calculated element concentration at these active roots. For reasons given above, it is thought that the ^{137}Cs activity depletion is generally lower than the K concentration depletion. As a result, predictions of ^{137}Cs AC's would be higher and the effect of K fertilisation would persist between 1 and 2 mmol K, in line with the observations.

Our current knowledge on interionic effects on ^{137}Cs uptake and behaviour in soil can be used to understand K fertiliser effects on ^{137}Cs availability in field and pot trials. It is generally found that K fertilisation reduces ^{137}Cs availability at low K concentration in soil whereas at high K availability, K fertilisation has little or even a stimulation effect on ^{137}Cs uptake. At low K availability, the ^{137}Cs absorption capacity of the roots can be substantially reduced by increased K supply, even though ion exchange reactions increase ^{137}Cs mobility in soil. At high K availability, increasing K concentrations (above 1 m*M*) have been found to have no effect on ^{137}Cs uptake characteristics of the root (Cline and Hungate,1960) whereas ^{137}Cs mobility can be increased, resulting in an increased ^{137}Cs AC in the crop.

Based on the observations in solution culture (Shaw et al., 1992; Smolders et al., 1996), we think that K fertilisation will reduce ^{137}Cs availability if micromolar K concentrations occur at the root surface. Such concentrations do not only depend on the K intensity in soil solution but also on the K buffering capacity of the soil. Also, the K depletion around root depends on K demand rate of the crop which is correlated with growth rate.

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