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Uptake and distribution of ^{137}Cs and ^{90}Sr in *Salix viminalis* plants

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Abstract

Agricultural areas in middle and northern parts of Sweden were contaminated with radionuclides after the Chernobyl accident in 1986. Alternative crops in these areas are biomass plantations with fast-growing *Salix* clones for energy purposes. The uptake and internal distribution of ^{137}Cs and ^{90}Sr in *Salix viminalis* were studied. Plants were grown in microplots under field conditions. The soils in the experimental site had been contaminated in 1961 with 35.7 and 13.4 MBq m^{-2} of ^{137}Cs and ^{90}Sr, respectively. The experiment was carried out during three years. The plots were fertilised with 60 kg N ha^{-1} and three treatments of K, consisting of 0, 80 and 240 kg K ha^{-1}, during the first two years. The activity concentration of ^{137}Cs in the different plant parts varied between 140 and 20,000 Bq kg^{-1} and was ranked in the following order: lowest in stems < cuttings < leaves < roots. The fine roots (0–1 mm) had the highest ^{137}Cs activity concentration. One-year-old stems had higher ^{137}Cs activity concentrations than two-year-old stems. The activity concentration of ^{137}Cs in the plants was significantly affected by K-supply and was higher in the 0 kg K treatment than in the 80 or 240 kg K treatment. Leaves contained more ^{90}Sr than stems and cuttings.

Keywords: Basket willows; Caesium; Contamination; Energy forestry; Potassium; Radionuclides; Strontium; Transfer factor

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1. Introduction

The accident at the nuclear power plant in Chernobyl in 1986 resulted in deposition of radionuclides in the middle and northern parts of Sweden. Among these, ^{137}Cs (caesium) and ^{90}Sr (strontium) are the most widespread with an estimated fallout of 4.25 PBq ^{137}Cs in Sweden (Edwardsson, 1991). The deposition levels of ^{90}Sr in Sweden have not been established, but are estimated to be about one percent of the ^{137}Cs-fallout (Forsberg, 2000).

It is well-known that the uptake of caesium and strontium from soil to plant depend on a range of different factors and that the soil and plant relationships of radiocaesium and radiostrontium are rather complex. Some studies in Sweden after Chernobyl have dealt with the flow of ^{137}Cs and ^{90}Sr between soil and plants both in boreal forest ecosystems (Johanson, Bergström, von Bothmer, & Kardell, 1991; Melin, Wallberg, & Suomela, 1994; Nylen, 1996) and in an agricultural environment with annual crops (Rosén, 1996a, b; Forsberg, 2000). In general, results have shown that forest plants had higher ^{137}Cs activity concentrations than plants from agricultural areas. It was also shown that uptake and distribution of radionuclides in plants differed depending on soil type, climate, plant species, soil nutrient status and also on agricultural practices.

Potassium (K)-fertilisation has been reported to reduce transfer of radiocaesium from contaminated soils to plants (De Preter, van Loon, Maes, & Cremers, 1991; Rosén, 1991; Smolders, Kiebooms, Buysse, & Merckx, 1996). Rosén (1991) showed that K-fertilisation up to 100 kg ha^{-1} resulted in a decrease of the transfer of ^{137}Cs to the crops grown in different soil types. Adding more K, up to 200 kg ha^{-1}, however, only gave a small additional effect. It was concluded that K could replace ^{137}Cs from exchangeable sites in the soil matrix due to their chemical similarity. Other studies have demonstrated that the behaviour of radiocaesium deviated from K to a certain degree, since the former element was taken up much slower than the latter (Marschner, 1986).

In agricultural areas with very high deposition levels of radionuclides, farmers have problems to find suitable crops since food or fodder is not regarded to be safe from a human health perspective. If the transfer of radionuclides from contaminated soils to *Salix* stem wood used for energy purposes is low, these areas might be suitable for energy plantations with fast-growing *Salix* species (Sennerby-Forsse & Johansson, 1989; Christersson, Sennerby-Forsse, & Zsuffa, 1993). Energy forestry with *Salix* consists of intensively managed fast growing willows that are harvested for biomass in a 3–5 year rotation. Today about 16,000 ha of *Salix* plantations are being grown for biomass production on agricultural land in Sweden (Christersson, 1999). Little is known about uptake and distribution of radiocaesium and radiostrontium in fast-growing *Salix* spp. One study of uptake and distribution of radiocaesium in four months old *Salix* was carried out by Sennerby-Forsse, Melin, Rosén, and Sirén (1993). They showed that the total plant uptake of both ^{134}Cs and ^{137}Cs was about 0.2% of the caesium present in the soil substrate. Almost 90% of the assimilated caesium were found in the roots. The total amount of caesium in the plants increased over time.

In order to gain better understanding of the uptake and internal distribution of caesium and strontium in *Salix* plantations, a K-fertilisation experiment including ^{137}Cs and ^{90}Sr was carried out. The main aim of the study was to assess the uptake of ^{137}Cs and ^{90}Sr from contaminated soil to *Salix* plants and distribution of these radionuclides in *Salix* plants. The following hypotheses were tested: (i) accumulation of ^{137}Cs and ^{90}Sr differs between plant organs, (ii) there is a seasonal variation in uptake and distribution of ^{137}Cs as well as of ^{90}Sr and (iii) the uptake of ^{137}Cs is related to the availability of K.

2. Material and methods

2.1. Experimental layout

The study was carried out at a field experimental station of the Dept. of Radioecology, Swedish University of Agricultural Sciences (SLU) in Uppsala (59°49′ N, 17°40′ E, alt. 5 m), Sweden. Annual mean of air temperature was 6.1°C during the study years (1994–1996) and the mean annual precipitation was 520 mm during the same period (SMHI, 1994–1996).

A microplot technique was applied on the experimental site (Fredriksson, 1962). The microplot size was $0.5 \times 0.5 \times 0.3\,m^3$ with an area of $0.25\,m^2$. Three blocks, each consisting of 16 microplots were included in the experiment (Fig. 1). For practical reasons, the fertilization treatments coincided with blocks and were distributed in blocks with four replicates (Fig. 1). A true block design was not used in this study also because it was feared that growth differences caused by the treatments could create severe problems due to shading. The treatments were thus not randomised within the blocks. The plough layer, 0–23 cm, of the soils consisted of loam (A) and clay loam (B) and the subsoil was loamy sand (Table 1). The topsoil layers were

Soil Nuclide	Block1 0 kgK/ha				Block2 80 kgK/ha				Block3 240 kgK/ha			
A ^{90}Sr	A-Sr	A-Sr	A-Sr	A-Sr	A-Sr	A-Sr	A-Sr	A-Sr	A-Sr	A-Sr	A-Sr	A-Sr
B ^{90}Sr	B-Sr	B-Sr	B-Sr	B-Sr	B-Sr	B-Sr	B-Sr	B-Sr	B-Sr	B-Sr	B-Sr	B-Sr
A ^{137}Cs	A-Cs	A-Cs	A-Cs	A-Cs	A-Cs	A-Cs	A-Cs	A-Cs	A-Cs	A-Cs	A-Cs	A-Cs
B ^{137}Cs	B-Cs	B-Cs	B-Cs	B-Cs	B-Cs	B-Cs	B-Cs	B-Cs	B-Cs	B-Cs	B-Cs	B-Cs

Fig. 1. Experimental layout. The soils consisted of loam (A) and clay loam (B). The topsoil layers were homogeneously contaminated with ^{137}Cs and ^{90}Sr, the deposition levels were 16.68 MBq m^{-2} for ^{137}Cs and 6.04 MBq m^{-2} for ^{90}Sr at the experiment start (1994). Three blocks were fertilised in 1994 and 1995 with 60 g ha^{-1} N and 0 kg ha^{-1}, 80 kg ha^{-1}, 240 kg ha^{-1} K, respectively.

Table 1
Soil characteristics of the topsoil (0–10 cm) and subsoil of the microplots before (1993) and after (1996) the experiment. ($N = 4$–5)

Soil characteristics	Loam (A)			Clay loam (B)			Loamy sand (subsoil)
Bulk density ($g\,cm^{-3}$)	1.4			1.3			1.6
Organic matter (%)	5.4			5.3			—
Particle size							
Sand 2–0.06 mm (%)	38.3			27.9			86.3
Silt 0.06–0.002 mm (%)	44.0			38.8			8.8
Clay <0.002 mm (%)	17.6			33.3			4.9
CEC (meq/100 g)	11.8			15.8			3.8
	Treatment ($kg\,ha^{-1}$)			Treatment ($kg\,ha^{-1}$)			
1993	0	80	240	0	80	240	
PH (H_2O)	5.6	5.6	5.7	6.1	6.1	5.9	
K-HCl ($mg\,(100\,g^{-1})$)	150	150	150	260	260	260	
P-HCl ($mg\,(100\,g^{-1})$)	90	90	90	90	90	100	
N (tot) ($mg\,(100\,g^{-1})$)	180	170	170	190	190	210	
1996							
PH (H_2O)	5.8	6.0	6.0	5.7	5.7	5.9	
K-HCl ($mg\,(100\,g^{-1})$)	100	180	130	110	110	240	
K-AL ($mg\,(100\,g^{-1})$)	8	20	25	12	12	44	

homogeneously contaminated with 35.7 and 13.4 MBq m^{-2} of ^{137}Cs and ^{90}Sr in 1961 (Fredriksson, Lönsjö, & Eriksson, 1969). After 33 years, at the start of the experiment (1994), these activities had decayed to 16.68 and 6.04 MBq m^{-2}, respectively.

2.2. Plant material, cultivation and fertilisation

In the beginning of August 1993, two dormant stem cuttings (12 cm long and 0.6–1.2 cm in top diameter) of *Salix viminalis*, clone 78183, were planted in each of the microplots. Prior to planting, the dormant cuttings were soaked in water for 48 h in order to promote rooting. The cuttings were planted with approximately 2–5 cm of the stem above ground. In order to promote an even plant development during the next growing season, all one-year-old stems were cut in the mid-March 1994, leaving about 5 cm of the stem above ground.

During 1994 and 1995, all blocks were fertilised once per year with 60 kg N ha^{-1}. The treatment in the micro plots consisted of different amounts of K.

Block 1 — 0 kg K ha^{-1}
Block 2 — 80 kg K ha^{-1}
Block 3 — 240 kg K ha^{-1} (Fig. 1).

N was added as a balanced mixture of NH_4^+-N and NO_3^--N and K was added as a mixture of KNO_3 and K_2SO_4.

2.3. Sampling

Before onset and at termination of the experiment, soil samples were taken in order to determine the soil characteristics. Three or four soil cores, 57 mm in diameter were taken to a depth of 10 cm and the core samples were pooled. The samples were air-dried at 30–40°C for one week, weighed, ground, and passed through a 2 mm sieve. Thereafter soil physical and chemical characteristics were determined.

Samples for activity measurements in stems and leaves were taken during the years 1994–1996. Stems were sampled by removing one middle-sized shoot per plot. Leaves representing different ontogenetic stages were pooled to one sample per shoot. Roots and original cuttings of two plants per treatment were harvested in the autumn of 1994. In March 1996, all shoots were harvested. In September the same year the whole plants including roots, cuttings and current shoots were harvested. The roots were washed and separated into coarse roots (> 2 mm) and fine roots (0–1 and 1–2 mm). The plant material was oven-dried at 70°C for 3 days, weighed, ground and stored in plastic containers until the radiometric or chemical analyses were carried out.

2.4. Analysis

2.4.1. Growth measurements

Above-ground growth was measured during the autumns of 1994 and 1995 as shoot height and shoot diameter at 55 cm height for shoots more than 55 cm long. At the same time the number of living shoots per plant was counted.

2.4.2. Soil analysis

The particle-size distributions were analysed by sedimentation, using the hydrometer method according to Day (1965). For bulk density determination, duplicates of cylinders were dried at 105°C. Total content of N was analysed in duplicate on an elemental analyser (Leco), and pH was measured in de-ionised water using the soil-solution ratio 1 : 2.5. Phosphorus (P) and potassium (K) were extracted with ammonium lactate (AL) solution and 2 M HCl, in order to obtain the easily soluble and slightly soluble fractions (Egner, Riehm, & Domingo, 1960).

2.4.3. Chemical analysis of macro-nutrients

Milled tissue samples for analysis of the following macronutrients: N, P, K, Mg and Ca were prepared by digestion in a solution of 10 ml concentrated HNO_3 and 1 ml $HClO_4$. Thereafter, 1 ml of 2 M HNO_3 was added to the digest and the solution was diluted with distilled water to 35 ml. Nitrogen was analysed with an elemental analyser (Elemental analyser NA 1500, Rodano, Italy). The other macronutrients, P, K, Ca and Mg, were analysed by inductively coupled plasma spectrometry (Jobin Yvon JY-70, Longjumeau, France).

2.4.4. Radiometry and calculation of transfer factors

Activity concentrations of ^{137}Cs in plant samples were determined by means of high-purity germanium detector systems housed in a low-background laboratory. The measurement time needed for obtaining acceptably low counting errors, 1–5% (1 sigma), varied from 1 to 48 h. Activity concentrations of ^{90}Sr were measured via its decay product ^{90}Y after separation by means of liquid–liquid extraction. ^{90}Y separation was carried out according to the method described by Suomela, Wallberg, and Melin, 1993. All activity data were measured and corrected back for decay to the date of the experimental start.

Transfer factor, TF_g, $m^2\,kg^{-1}$ d.w., was used to describe the transfer of ^{137}Cs and ^{90}Sr from soil to plants (IAEA, 1987).

$$TF_g = \frac{\text{Plant activity concentration (Bq kg}^{-1}\text{ d.w.)}}{\text{Ground deposition (Bq m}^{-2}\text{)}}$$

The value of ground deposition in this study was used as a constant in the calculations and it was equal to the activities in the soil of the two nuclides at the experiment start (1994).

2.4.5. Statistical analysis

Statistical analyses were performed by Systat for Windows version 8 (Systat, Inc.). Tests of significant differences between K treatments within each sampling occasion were performed in ANOVA/GLM and the pooled variance was later used in Fisher's-LSD tests after a significant *F*-test. The criteria for significant models were set at probability level $p \leqslant 0.05$.

3. Results

3.1. Soil characteristics and plant growth

Results of the soil chemical analysis are shown in Table 1. Between 1993 and 1996, the concentration of slightly soluble potassium, K-HCl, remained relatively stable in block 3 (240 kg K/ha), while it decreased in block 1 (0 kg K ha^{-1}) and block 2 (80 kg K ha^{-1}), especially in clay loam soil. No significant difference in plant growth between the two soils was observed in spite of the fact that they differed in K-HCl and easily soluble potassium K-Al.

Chemical analysis of macronutrients in the stem samples before onset of fertilisation showed the same results in all plants. The levels were: 9.20 to 9.36 mg N, 1.27 to 1.33 mg P, 5.42 to 5.71 mg K, 3.98 to 4.14 mg Ca and 0.77 to 0.80 mg Mg g^{-1}d. w.

Shoot growth usually started in early May and continued until late August. After one growing season (1994), the average shoot height was about 100 cm (Fig. 2A) and shoot diameter at 55-cm height was about 4.5 mm (Fig. 2B). There were, on average, 3–4 shoots per plant. After the second growing season (1995), the shoot height was

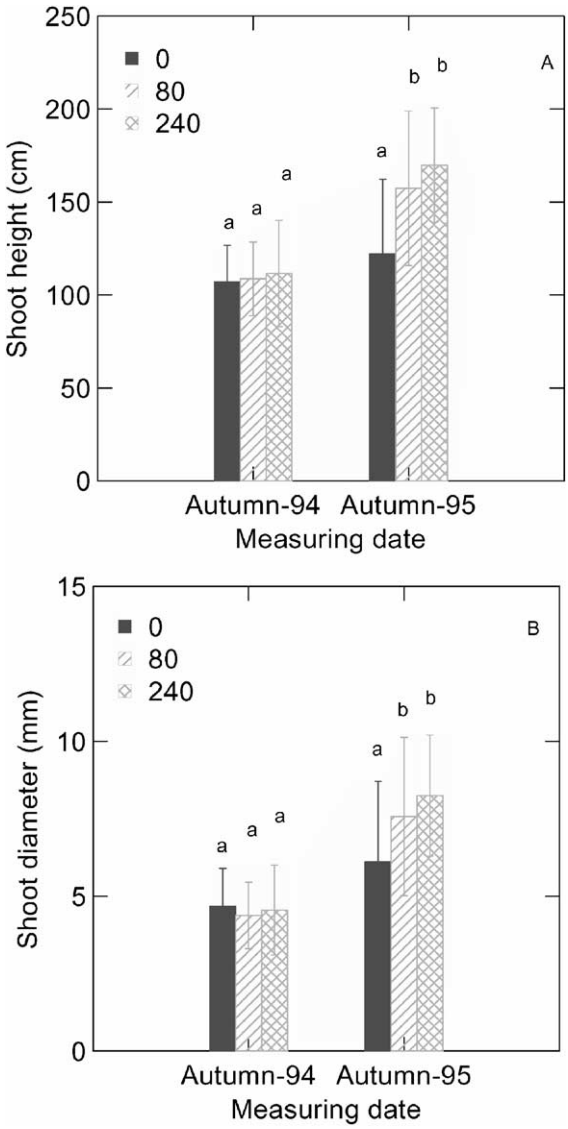

Fig. 2. Mean shoot height (cm) (A) and mean shoot diameter (mm) (B) at 55 cm above ground level measured in the autumn of 1994 and 1995 for three treatmenst (0, 80 and 240 kg K ha^{-1}). Means with the same letter are not significantly different ($p \leqslant 0.05$ $N = 50$).

about 150 cm (Fig. 2A) and shoot diameter at 55-cm height was about 7.5 mm (Fig. 2B). At that stage there were, on average, three shoots per plant. There was a significant difference in plant growth (shoot height and shoot diameter) between the treatments with and without K after the second growing season (Figs. 2A and B). No

significant difference in plant growth was observed between plots supplied with 80 or 240 kg K ha^{-1} (Figs. 2A and B).

3.2. Activity concentrations and distribution of ^{137}Cs and ^{90}Sr in plants

No significant difference in either activity concentration or distribution of ^{137}Cs and ^{90}Sr in plants was observed between the two soils (A and B) (Fig. 1).

During and after the first (1994) and second (1995) growing seasons, concentrations of ^{137}Cs in stem and leaves were significantly affected by K supply, particularly between the treatments with 0 and 240 kg K ha^{-1} (Table 2). However, the fertilisation effects on the activity concentration of ^{137}Cs in cuttings and roots were not obvious (Table 2). In general, the ^{137}Cs activity concentration was higher in the 0 kg K/ha treatment than in the 80 or 240 kg K ha^{-1} treatment (Table 2).

The ^{137}Cs activity concentration in the different plant parts ranked in the following falling order: roots > leaves > cuttings > stems. The highest ^{137}Cs activity concentrations were found in the fine roots (0–1 mm). One-year-old stems had higher ^{137}Cs activity concentrations than two-year-old stems. The ^{137}Cs activity concentration in stems and leaves decreased from summer to autumn. The ^{137}Cs concentration in roots increased considerably with time from the first growing season in 1994, to the third growing season in 1996 (Table 2).

The total uptakes of ^{137}Cs in plants (roots, cuttings and stems) were almost the same in the three treatments at the end of the experiment, although plant sizes in the

Table 2
^{137}Cs activity concentration (mean ± SD, Bq kg^{-1}) in Salix plants grown under different K fertilisation. Means followed by the same letter between fertilisation treatment are not significantly different ($p \leqslant 0.05$). N = number of samples

Plant organ	Sampling date	Treatment (kg K ha^{-1})			N
		0	80	240	
Stems	9408	800 ± 245c	569 ± 276b	368 ± 146a	14
	9410	704 ± 67b	346 ± 96a	308 ± 136a	4
	9508 all	1138 ± 465b	351 ± 123a	382 ± 350a	10
	One-year-old	1969 ± 958b	586 ± 249a	740 ± 679a	5
	Two-years-old	844 ± 305b	278 ± 89a	306 ± 301a	5
	9603	903 ± 513b	478 ± 294a	405 ± 352a	35
Leaves	9408	2938 ± 1313b	2272 ± 1144b	1418 ± 69a	14
	9410	2558 ± 1747b	1373 ± 615a	770 ± 289a	8
	9508	3522 ± 1304b	1334 ± 531a	1279 ± 1058a	5
Cuttings	9410	935 ± 286a	663 ± 281a	532 ± 571	2
	9609	1386 ± 497a	1170 ± 270a	1205 ± 215a	8
Roots	9410	2954 ± 1237a	1858 ± 1040a	3162 ± 1307a	2
	9609 all	4085 ± 1029a	3138 ± 682a	3357 ± 837a	24
	0–1 mm	20536 ± 4878a	20483 ± 3513a	19468 ± 4208a	8
	1–2 mm	4866 ± 1280a	4005 ± 711a	4271 ± 640a	8
	> 2 mm	1750 ± 284a	1622 ± 505a	1866 ± 559a	8

0 K ha^{-1} treatment were slightly smaller (Table 3). The amount of ^{137}Cs in stems was higher in 0 K ha^{-1} treatment, while the amount of ^{137}Cs in coarse roots was higher in 80 and 240 kg K ha^{-1} treatments (Table 3). In percent of total root uptake of ^{137}Cs, fine roots in the 0 kg K ha^{-1} treatment contained the largest fraction, while in the 80 and 240 kg K ha^{-1} treatments fine and coarse roots contained about the same fraction of ^{137}Cs (Table 3).

There was no significant difference in ^{90}Sr activity concentration between the K treatments (data not shown). Leaves contained more ^{90}Sr than the other organs. The ^{90}Sr activity concentration in stems decreased from summer to autumn, while it increased in leaves during the same time period. The ^{90}Sr activity concentration in stem and leaf decreased from the first growing season to the second growing season (Table 4).

3.3. Transfer of ^{137}Cs and ^{90}Sr from soil to plants

The transfer factor, TF_g, of ^{137}Cs varied from 0.02×10^{-3} to 0.1×10^{-3} in stems, 0.05×10^{-3}–0.2×10^{-3}, in leaves, 0.03×10^{-3} to 0.08×10^{-3} in cuttings and 0.1×10^{-3}–1.3×10^{-3} in roots (Table 5). TF_g of ^{90}Sr in stems varied between 2.1×10^{-3}–3.6×10^{-3}, in leaves between 3.9×10^{-3}–7.6×10^{-3}, in cuttings it was 3.1×10^{-3} and in roots 2.8×10^{-3} (Table 5). The TF_g of ^{90}Sr was much higher than of ^{137}Cs.

Table 3
The total amount of ^{137}Cs (mean ± SD, Bq kg^{-1} in different parts of *Salix* plants grown under different K-fertilisation. Means followed by the same letter within each row are not significantly different ($p \leqslant 0.05$ $N = 8$)

Plant organ	Sampling date	Treatment (kg K ha^{-1})		
		0	80	240
Stems	9603	71.75 ± 81.5a	51.75 ± 33.9a	51.82 ± 60.0a
Cuttings	9609	23.23 ± 17.2a	27.62 ± 10.4a	26.71 ± 15.6a
Roots	9609			
	0–1 mm	67.48 ± 52.8a	61.71 ± 19.8a	63.44 ± 46.2a
	1–2 mm	10.29 ± 6.7a	13.03 ± 3.3a	12.37 ± 8.2a
	> 2 mm	39.42 ± 21.5a	62.32 ± 29.5a	67.26 ± 49.0a
	Roots total	117.19 ± 76.0a	137.05 ± 48.5a	143.07 ± 100.7a

Table 4
^{90}Sr activity concentration (mean ± SD, Bq kg^{-1}) in *Salix* plants. Date = sampling date, N = number of samples

Date	Stems	N	Leaves	N	Cuttings	N	Roots	N
9408	22030 ± 7883	24	38625 ± 15662	40				
9410	14351 ± 4597	9	45880 ± 12074	24	18567 ± 4971	6	17015 ± 4951	6
9508	12669 ± 7647	24	23466 ± 13640	13				

Table 5
Transfer factor, TF_g (mean ± SD) of ^{137}Cs and ^{90}Sr ($m^2\,kg^{-1}$ d.w. $*10^{-3}$) from soil to *Salix* plants. The numbers of samples are given in Table 2 (for ^{137}Cs) and Table 4 (for ^{90}Sr)

Plant organ	Sampling date	^{137}Cs			^{90}Sr
		0	80	240	
Stems	9408	0.048 ± 0.02	0.034 ± 0.02	0.022 ± 0.01	3.648 ± 1.31
	9410	0.042 ± 0.00	0.021 ± 0.01	0.018 ± 0.01	2.376 ± 0.76
	9508 all	0.068 ± 0.03	0.021 ± 0.01	0.023 ± 0.02	2.097 ± 1.27
	One-year-old	0.118 ± 0.04	0.035 ± 0.02	0.044 ± 0.04	
	Two-years-old	0.051 ± 0.02	0.017 ± 0.01	0.018 ± 0.02	
	9603	0.054 ± 0.03	0.029 ± 0.02	0.024 ± 0.02	
Leaves	9408	0.176 ± 0.08	0.136 ± 0.07	0.085 ± 0.04	6.395 ± 2.60
	9410	0.153 ± 0.05	0.082 ± 0.04	0.046 ± 0.02	7.596 ± 2.00
	9508	0.211 ± 0.08	0.080 ± 0.03	0.077 ± 0.06	3.885 ± 2.26
Cuttings	9410	0.056 ± 0.02	0.040 ± 0.02	0.032 ± 0.00	3.074 ± 0.82
	9609	0.083 ± 0.03	0.070 ± 0.02	0.072 ± 0.01	
Roots	9410	0.177 ± 0.07	0.111 ± 0.06	0.190 ± 0.08	2.817 ± 0.82
	9609 all	0.245 ± 0.06	0.188 ± 0.04	0.201 ± 0.05	
	0–1 mm	1.231 ± 0.29	1.228 ± 0.21	1.167 ± 0.25	
	1–2 mm	0.292 ± 0.08	0.240 ± 0.04	0.256 ± 0.04	
	> 2 mm	0.105 ± 0.02	0.097 ± 0.03	0.112 ± 0.03	

4. Discussion

The macronutrient activity concentrations in stems prior to fertilisation agreed well with results from other studies with *Salix viminalis* (Ericsson, 1994a). This indicates that the soil in this study contained adequate amounts of all essential elements at the start of the experiment. During the experiment, however, the concentration in the soil of slightly soluble potassium, K-HCl, decreased in the $0\,kg\,K\,ha^{-1}$ treatment. The concentration of easily soluble potassium, K-AL, of the $0\,kg\,K\ ha^{-1}$ treatment was 0.07–0.08 $mg\,g^{-1}$ at the end of the experiment, which indicates that K deficiency may have appeared as a result of K depletion. This may partly explain why plants of the $0\,kg\,K\,ha^{-1}$ treatment was smaller than the plants from the K-fertilised treatments. Another factor might be that K-fertilisation had a positive effect on N-uptake and thereby improved growth in plants where K was abundant.

The ^{137}Cs activity concentration in all tissues was generally higher in the $0\,kg\,K\,ha^{-1}$ treatment. This indicates that uptake of ^{137}Cs is negatively correlated with the K-fertilisation. However, the amount of ^{137}Cs taken up was the same in all three treatments despite the fact that the plants in the 0 K treatment were smaller. The distribution of ^{137}Cs in the different plant parts was affected by K-fertilisation. This was shown by the fact that in the absence of K-fertiliser, the content of ^{137}Cs in stems increased, whereas the content of ^{137}Cs in coarse roots was low. In the presence of extra K, the transport of ^{137}Cs from the coarse roots to the shoots was reduced, resulting in lower stem ^{137}Cs levels and high coarse root contents of ^{137}Cs. There were significant differences in both plant growth and ^{137}Cs activity

concentration between treatments with and without K-fertilisation. However, no clear differences in these aspects were observed between the treatments 80 and 240 kg ha^{-1} K. This agrees well with results from Rosén (1996b), where K-fertilisation at the level of 100 kg K ha^{-1} resulted in a large decrease of ^{137}Cs-transfer to grass, but when increasing K-fertilisation to 200 kg/ha the difference in Cs-uptake was less pronounced. Smolders et al. (1996) also found that K-fertilisation reduced ^{137}Cs availability at low K concentration in soil, whereas at high K-availability, K-fertilisation had little effect on ^{137}Cs uptake. One possible explanation was believed to be that at high K-availability, the ^{137}Cs absorption capacity of the roots was substantially reduced and eventually disappeared.

The ^{137}Cs activity concentration was higher in roots than in other plant organs, which agrees well with other studies on *Salix* (Sennerby-Forsse, Melin, Rosén, & Sirén, 1993). This result is different to ^{90}Sr distribution in plants, where most of this nuclide transferred from the soil is accumulated in leaves. The reason could be due to the low Cs uptake capacity of the cellular vacuoles in the shoots (Buysse, Van Den Brande, & Merckx, 1995). This also indicates that the active parts of the root system absorbs and stores most of the ^{137}Cs taken up. The ^{137}Cs activity concentration in fine roots (0–1 mm) was about 2.5 times higher than that of >2 mm roots, although the ^{137}Cs content was almost the same. This may indicate that fine roots play an important role for ^{137}Cs uptake while coarse roots are more important for ^{137}Cs storage. The distribution pattern of caesium within the root system may indicate that ^{137}Cs had been transported from the fine roots to the coarse roots before exudation and other losses occurred. One-year-old stems had higher ^{137}Cs activity concentration than two-year-old stems, possibly indicating that the ^{137}Cs translocated in shoots is very mobile and easily accumulates in new growth.

The ^{137}Cs activity concentration decreased from summer to autumn in the leaves. Similar results have been shown by Peter, Olson, and Anderson (1969) in tulip poplar and by Nylen (1996) in Scots pine. This is probably due to retranslocation of ^{137}Cs from foliage to woody tissue during mature and senescent stages of leaf development and to removal of ^{137}Cs from foliage by rain and dew leaching prior to leaf fall. It may also indicate that the behaviour of ^{137}Cs in physical processes is analogous to K since withdrawal of K from senescing leaves is a normal feature in woody plants (e. g. review by Ericsson, (1994b)).

There was an increase of ^{137}Cs activity concentration in roots and cuttings during the third growing season compared with the previous two years. The increase may be due to the coppicing of shoots carried out in early spring before the growing season started. The resprouting and growth of current shoots became a strong sink for nutrient uptake through a higher rate of tissue turnover, which may have stimulated ^{137}Cs uptake by plant roots. Another reason could be a large root system in combination with reduced sink strength of the shoot, due to stem removal.

The ^{90}Sr activity concentration in leaves increased from summer to autumn. In this respect, strontium showed a trend similar to Ca (calcium) since accumulation of Ca in leaves is a normal feature (Bernier, 1984; Ericssonb, 1994). The ^{90}Sr activity concentration in leaves was higher than in other organs, which agrees well with results reported by Coughtrey and Thorne (1983) who concluded that root-absorbed

strontium accumulates in leaf veins and petioles. This may indicate that strontium, like calcium, is phloem-immobile and cannot be recirculated from leaves to other plant parts.

The ^{90}Sr activity concentration in plants as well as the transfer factor between soil and plants was generally higher than that of ^{137}Cs. Previous studies have shown that after some years of soil contamination, ^{137}Cs become less available for plant uptake than does ^{90}Sr (Krouglov, Filipas, Alexakhin & Arkhipov, 1997; Forsberg, 2000). From the nutrient cycling point of view, it has been reported that the time required to complete a cycle of turnover was rapid in the case of alkali metals, such as caesium and potassium, but slow in the case of alkali earth metals, such as strontium and calcium (Russell, 1966).

5. Conclusions

The main aim of this study was to gain a better understanding of the uptake and internal cycling of caesium and strontium in *Salix* plants and to assess the transfer of ^{137}Cs and ^{90}Sr from contaminated soils to the plants. The results confirmed the hypothesis that accumulation of ^{137}Cs and ^{90}Sr differ between plant organs. There were differences in the distribution pattern between caesium and strontium and the fine roots had the highest ^{137}Cs activity concentration, while ^{90}Sr activity concentration was highest in leaves. The study also showed that there is a seasonal variation in activity concentration of ^{137}Cs and ^{90}Sr in leaves. And the ^{137}Cs activity concentration in leaves decreased from summer to autumn while the ^{90}Sr activity concentration in leaves increased during the same time. Finally, it was evident from the results that the activity concentration of ^{137}Cs was significantly affected by K availability. The ^{137}Cs activity concentration was higher in the 0 kg K treatment than in the 80 or 240 kg K treatment.

Since the low transfer of radiocaesium to the wood, it may be concluded that energy forestry with fast-growing *Salix* species might be an alternative crop suitable for agricultural soils that are contaminated with radiocaesium.

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