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The transfer of ^{137}Cs through the soil-plant-sheep food chain in different pasture ecosystems

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A grazing experiment with sheep was carried out in 1990–1993 on natural, semi-natural and cultivated pasture on clay soil. The pastures were located in Southern Finland and were moderately contaminated with ^{137}Cs by Chernobyl fallout. Natural pasture refers to forest pasture and semi-natural pasture to set-aside field pasture, the latter having been under cultivation about 15 years ago. The transfer of ^{137}Cs to sheep was clearly higher from forest pasture than from the other two pastures and it was lowest from cultivated pasture. The transfer was higher to muscle and kidney than to liver and heart. The transfer of ^{137}Cs to plants and to meat varied with years. Seasonal variation in the plant ^{137}Cs was followed-up on forest and set-aside field pasture; the activity concentration of plants reached a maximum in June, a lesser increase occurred later in the autumn. In 1993, which was considered an average year with respect to ^{137}Cs transfer to plants, the mean soil-plant transfer factors of ^{137}Cs for forest, set-aside field and cultivated pastures were 1.78, 0.36 and 0.09, and soil-meat aggregated transfer factors 11.0, 0.28 and 0.03, respectively.

Key words: radiocesium, Chernobyl, transfer factor, concentration factor, forest, set-aside field, cultivated pasture

Introduction

The ^{137}Cs activity concentration in sheep grazing on natural or semi-natural ecosystems has been elevated since the Chernobyl reactor accident in 1986, and it has decreased more slowly than predicted (Mayes 1988, Salt et al. 1992). Sheep farmers in Great Britain, Norway and Sweden have had problems with the high activity level of radiocesium found in sheep grazing on natural grasslands (Mayes 1988, Hove et al. 1994). It is known that natural or semi-natural pastures of poor vegetation facilitate the long-term transfer of radiocesium from soil via vegetation to sheep (Coughtrey et al. 1989, Howard et al. 1990, Livens et al. 1991, Melin et al. 1994). In Finland, sheep are mainly grazed on cultivat-

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ed pastures in southern areas, where Cs-fixing clay soils dominate. Both the cultivated pasture with high soil K status and the soil clay fraction are considered to contribute to the low transfer of radiocesium to plants. However, interest in the restoration of natural and ecological values in the countryside and, consequently, grazing on natural and semi-natural ecosystems have grown in recent years. Further, the importance of sheep husbandry has increased in eastern and northern parts of the country and especially in areas too sparse for cultivation. The aim of this study was to get more information about the problem of sheep grazing on natural and semi-natural pastures compared to cultivated pastures in case of a severe nuclear fallout.

Table 1. Dominant plant species or genera of grasslands.

Forest pasture	
Agrostis capillaris	*Ranunculus acris*
Deschampsia cespitosa	*Cirsium palustre*
D. flexuosa	*Trifolium repens*
Festuca ovina	*Rubus arcticus*
Achillea spp.	*Anemone nemorosa*
Lathyrus pratensis	*Geranium sylvaticum*
Galium spp.	
Set-aside field pasture	**Cultivated pasture & ley**
Deschampsia cespitosa	*Dactylis glomerata*
Festuca rubra	*Lolium perenne*
F. pratensis	*Phleum pratense*
Agrostis capillaris	*Festuca pratensis*
Phleum pratense	
Meadow-1	**Meadow-2**
Trifolium pratense	*Agrostis capillaris*
Achillea millefolium	*Poa pratensis*
Agrostis capillaris	*Achillea millefolium*
	Anthriscus sylvestris
	Trifolium repens
	Veronica chamaedrys

Material and methods

Grasslands

Natural, semi-natural and cultivated pastures were situated on heavy clay soil in Southern Finland in Jokioinen (60.9 °N, 23.5 °E) belonging to the Chernobyl fallout category 3 with an estimated surface activity of ^{137}Cs of 11–23 kBq m^{-2} in 1987 (Arvela et al. 1987). The area of natural and semi-natural pasture was about 2 hectares. Half of it was forest pasture (natural pasture) with junipers, small birches, herbs and grass and the other half set-aside field pasture (semi-natural pasture) with grass vegetation (Table 1). The latter pasture had been under cultivation about 15 years ago. The area had been used for sheep grazing in the 1980's. Soil and plant samples of these pastures were taken during 1990–1994. Meteorological data are given for this period (Table 2).

Table 2. Meteorological data from Jokioinen in May-September 1990–1994.

Month	Mean temperature [a] (° C)					Precipitation [a] (mm/month)					Evaporation [b] (Class A) (mm/month)				
	1990	1991	1992	1993	1994	1990	1991	1992	1993	1994	1990	1991	1992	1993	1994
May	9.3	7.2	11.4	13.6	7.8	22	29	7	1	34	114	88	141	155	108
June	14.4	12.1	15.7	11.4	12.1	20	69	25	56	66	159	86	178	99	104
July	15.2	16.6	16.0	15.6	19.0	85	55	47	107	1	112	123	146	122	186
Aug	15.0	16.2	14.3	12.9	15.1	90	92	107	136	54	85	81	72	59	93
Sept	8.0	9.1	11.3	5.7	10.0	62	80	59	13	105	31	41	24	35	36

[a] Monthly Reports of Finnish Meteorological Institute.
[b] Hydrological Yearbooks of National Board of Waters and the Environment.

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Table 3. Mean weight, mean growth rate, age and grazing period of sheep grazing on different types of pastures in 1990–1993.

	Combined pasture			Forest pasture	Set-aside field pasture
	1990	1991	1992	1993	
Live weight[1] (kg)	22.1	26.0	22.4	21.5	21.9
Live weight[2] (kg)	40.2	42.7	40.1	33.5	35.5
Carcass weight (kg)	15.7	16.9	15.5	11.5	13.1
Growth rate (g d^{-1})	160	151	145	115	131
Age[1] (d)	71	71	73	70	69
Grazing period (d)	112	109	122	104	104
(Number of sheep)	(10)	(10)	(10)	(6)	(6)
	Cultivated pasture				
	1990	1991	1992	1993	
Live weight[1] (kg)	19.0	28.8	26.2	24.5	
Live weight[2] (kg)	38.8	47.0	58.1	50.2	
Carcass weight (kg)	16.6	19.6	26.2	20.5	
Growth rate (g d^{-1})	180	166	262	247	
Age[1] (d)	63	72	74	66	
Grazing period (d)	112	109	122	104	
(Number of sheep)	(10)	(10)	(10)	(12)	

[1] in the beginning, [2] at the end of grazing period

The cultivated pasture used in 1990 had not been ploughed after the Chernobyl accident and was partly on Carex peat soil and partly on clay soil. Since 1991, the cultivated pasture was moved to a nearby pasture on clay soil ploughed at least twice after the deposition. The pastures were fertilized normally (125 kg N, 50kg K and 25 kg P ha^{-1}) during the growing season.

Soil to plant transfer of ^{137}Cs was studied also on cultivated ley and on two semi-natural meadows in 1990–1992. The ley on Carex peat soil was located near the cultivated pastures in Jokioinen and had been tilled once after the deposition and fertilized and harvested yearly. The two meadows were located in Pälkäne (61.3 °N, 24.2 °E) on fine sand soil. They had not been fertilized for 10–15 years but had been harvested yearly. The area belonged to the ^{137}Cs fallout category 4 (23–45 kBq m^{-2}). During the experiment, no agricultural practices were done on the ley and meadows. Meadow-1 was ploughed in 1991 and the sampling site was moved in 1992 to the nearby similar meadow established after the Chernobyl fallout. The same grass species dominated on ley as on cultivated pasture (Table 1). Only few species grew on meadow-1, while on meadow-2 several species were found.

Animals

Five pure-bred and five cross-bred Finnsheep ewe lambs grazed on the combined forest and set-aside field pasture in 1990–1992 and on cultivated pasture in 1990. Ten ram lambs were kept on the cultivated pasture in 1991–1992 (Table 3). In 1993, after dividing the combined pasture into two parts, six Finnsheep ewe lambs (four pure-bred and two cross-bred) grazed on forest pasture, six ewe lambs on set-aside pasture and 12 ram lambs on cultivated pasture. The lambs were supplemented with barley grain, 0.3 kg per head

Table 4. Grassland soil characteristics. Soil depth 0–10 cm.

Grassland (soil type)	Bulk density ($g\ cm^{-3}$)	Clay (%)	Humus (%)	pH (H_2O)	K	Ca	Mg	P
					(Acid AAc-extractable) (mg l^{-1} of soil)			
Forest pasture (sandy clay)	0.83	52	11.6	5.1	184	700	262	3.3
Set-aside field pasture (heavy clay)	0.92	63	7.6	5.7	292	1970	464	1.2
Cultivated pasture (heavy clay)	1.01	62	7.6	5.8	407	1850	748	1.6
Ley (Carex peat)	0.61		34.9	5.6	152	3190	503	4.2
Meadow-1 (medium sand)	1.12	3	4.8	6.0	88	1020	43	2.0
Meadow-2 (medium sand)	1.12	5	4.0	5.5	165	780	43	3.1

per day during the first ten grazing days. No other supplemental feeds except salt and minerals were given.

Soil and plant sampling

For studying soil to plant transfer of ^{137}Cs four random squares of 0.25 m^2 each were taken. The vegetation was cut at the height of 2 cm. Thereafter four soil samples were taken from each of the squares with the aid of a soil cylinder 10 cm high and 5 cm in diameter. Samples were collected in the beginning of September. For studying the vertical distribution of ^{137}Cs in the soil cores, three of the four soil samples were divided horizontally into seven fractions in 1990; during the subsequent years the soil samples were divided into two fractions (0–5 and 5–10 cm). The fourth sample of a square was kept intact (0–10 cm). In addition, soil samples of unploughed (1990) and ploughed meadow (1992) were taken with a soil cylinder of 18 x 5 cm and divided into seven fractions. For studying the seasonal variation of ^{137}Cs in pasture vegetation four random squares were taken in 1992–1994. For studying the ^{137}Cs level of certain plant species of forest and set-aside field pastures single species were collected at different sites of pastures in July and combined for ^{137}Cs measurement. Moss and lichen samples were taken from forest pasture in 1994.

Sample analysis and measurement of activity

Soil samples were air-dried, ground and passed through a 2-mm sieve. Soil potassium, calcium and magnesium were extracted with acid ammonium acetate (AAc, pH 4.65), pH was determined in soil-water suspension, organic carbon by dry combustion, clay fraction by dry and wet sieving and by the pipette method (Table 4) (MTT 1986). Plant samples were dried at 60° C and milled. The plant activity concentration of ^{40}K was used instead of K. (The amount of ^{40}K in the natural potassium is constant.) Samples of the neck muscle, heart, liver and kidney of the sheep were taken the day after slaughter. Visible fat was removed from the meat samples. Activity measurements were performed using a low-background semiconductor spectrometer with a high purity germanium detector placed in a 13 cm lead background shield. The gamma spectra were analyzed with a computer pro-

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gramme. The ^{137}Cs activity concentrations were decay-corrected to 1990. The plant and soil activity concentrations are presented in dry matter (DM) and that of meat in fresh weight (FW).

Calculation of ^{137}Cs transfer and concentration factors

Transfer factors (TF), aggregated transfer factors (T_{ag}) and concentration factors (CF) of ^{137}Cs were calculated as follows:

TF (soil-plant) = Bq kg^{-1} DM of plant per kBq m^{-2} DM of soil

T_{ag} (soil-meat) = Bq kg^{-1} FW of meat per kBq m^{-2} DM of soil

CF (soil-plant) = Bq kg^{-1} DM of plant per Bq kg^{-1} DM of soil

CF (plant-meat) = Bq kg^{-1} FW of meat per Bq kg^{-1} DM of plant

Soil samples were taken from the depth of 0–10 cm.

TF and T_{ag} values for grasslands ploughed after the fallout might be too high due to the soil sampling depth of 10 cm. In this case, CF values are more reliable provided that ^{137}Cs was distributed rather evenly in the plough layer.

Statistical methods

The effect of year and pasture type on the ^{137}Cs activity concentration of plants was investigated by using the standard two-way analysis of variance. Differences between years were tested by means of trend contrasts. The effect of year on the ^{137}Cs activity concentration of tissues was investigated using the analysis on a univariate repeated measures model similar to the split-plot model (Crowder and Hand 1990) where year was the between subject factor and tissue type was the within subject factor. Differences between muscle and other tissues were tested by contrasts. All the ^{137}Cs activity concentrations were log-transformed. The data were analyzed with the SAS MIXED procedure.

Results

Soil ^{137}Cs

In 1990, the 0–2 cm soil layer of forest pasture and other unploughed grasslands contained 80–90% of ^{137}Cs and that of tilled ley about 50% (Fig. 1 a,b). In unploughed meadow, over 90% and in ploughed meadow, about 35% of ^{137}Cs was found in the soil layer of 0–3 cm (Fig. 1 c,d). The distribution of ^{137}Cs in the undisturbed pasture soils between the layers of 0–5 and 5–10 cm (Table 5) remained rather constant during the experimental years. The $^{134}Cs/^{137}Cs$ ratio of pasture soils, decay-corrected to 1986, was 0.5.

Plant ^{137}Cs

Activity concentration

The ^{137}Cs activity concentration of plants on forest pasture was clearly higher than that on the other pastures, and it fluctuated with years. The plant ^{137}Cs of set-aside field pasture was significantly higher than that of cultivated pasture, and the activity levels differed between years. When investigating the trend of the plant ^{137}Cs for the two pastures over years using orthogonal polynomials the quadratic polynomial proved to be the best approximation to this trend (Table 6). On forest pasture there were differences in the ^{137}Cs concentration between plant species (Table 7). There was no correlation between the plant ^{137}Cs and ^{40}K (Fig. 2). Lichens had much higher and mosses mostly higher ^{137}Cs concentrations than vascular plants. The average ^{137}Cs activity concentration was 180 in the mosses *Aulacomnium palustre* and *Climacium dendroides,* 370 in *Hylocomium splendens* and *Polytrichum* spp., 610 in *Pleurozium Schreberi,* 750

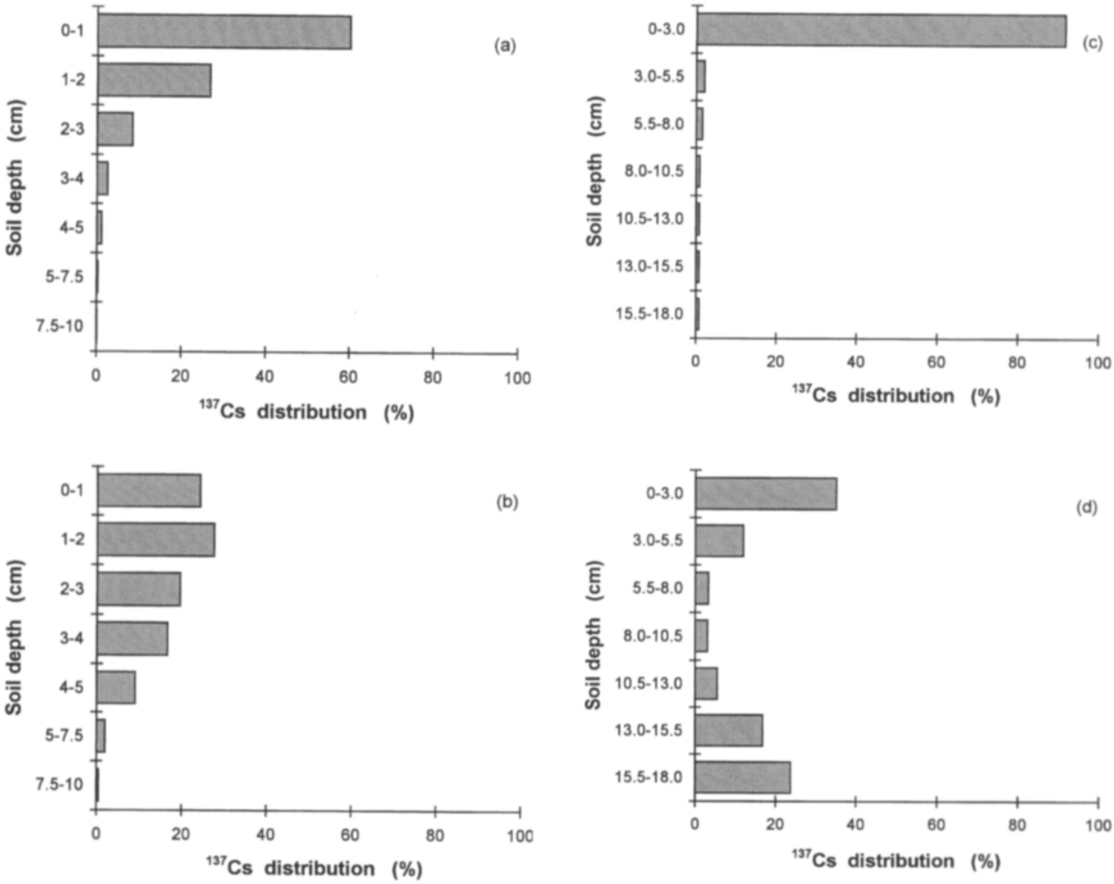

Fig. 1. Vertical distribution of ^{137}Cs in soils of (a) forest pasture, (b) tilled ley, (c) umploughed meadow-1 and (d) ploughed meadow.

in *Sphagnum* spp. and 4880 Bq kg^{-1} in *Grimmia* spp. In the lichen genera *Cladonia* and *Stereocaulon* the activity concentration was 490 and 5360 Bq kg^{-1}, respectively, and in the mushroom *Lactarius torminosus* 2240 Bq kg^{-1}. Sheep were not found to feed on mosses and lichens.

Table 5. Activity concentration of ^{137}Cs of soil layer 0–5 cm as a percentage of that of layer 0–10 cm.

Grassland	^{137}Cs in soil (%)					
	1990	1991	1992	1993	Mean	SD
Forest pasture	96.6	96.7	93.7	95.1	95.5	1.4
Set-aside field pasture	91.3	91.4	90.8	89.6	90.8	0.8
Cultivated pasture*	–	72.2	51.7	77.6	67.2	13.7
Meadow-1	97.3	97.3	(54.5*)		97.3	0
Meadow-2	96.0	95.5	92.7		94.7	1.8
Ley**	74.7	73.9	68.1		72.2	3.6

* = ploughed, ** = tilled, SD = standard deviation

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Table 6. Results of analysis of variance for logarithmic plant activity concentration of ^{137}Cs of set-aside field pasture and cultivated pasture in 1991–1993.

Source of variation	df	F-value	p-value
Pasture	1	6.06	0.02
Year	2	7.66	< 0.005
Linear trend	1	4.31	0.05
Quadratic trend	1	11.02	< 0.005
Pasture x year	2	0.18	0.84

Error mean square = 1.78 (df = 18).

Transfer factor

The behaviour of the soil-plant transfer factors of ^{137}Cs resembled in general those of the plant concentration of ^{137}Cs in regard to pasture type and year (Table 8). The transfer factor of ^{137}Cs for cultivated ley was rather low compared to that for meadows. The soil-plant transfer factor for semi-natural meadows on finesand soil was higher than that for semi-natural (set-aside field) pasture on clay soil. For meadow-1 the transfer factor was higher and soil K lower than those for meadow-2.

Seasonal variation

The ^{137}Cs activity level of vegetation on forest and set-aside field pasture fluctuated during the growing season. The highest activity concentration was found at the time of vigorous growth in the early summer followed by a decrease in the middle of the summer and a slight increase in the autumn (Fig. 3). The second increase in growth was relatively more prominent on set-aside field pasture. Potassium 40 in vegetation decreased during the growing season on both pastures from about 800 to 320 Bq kg^{-1} and plant dry weight (%) on forest pasture increased from 25 to 50% and on set-aside pasture from 30 to 43% (1993).

Table 7. Activity concentration of ^{137}Cs of some plant species or genera of forest pasture (f) and set-aside field pasture (s). Each sample is a mixture of several subsamples.

Species	^{137}Cs in plant (Bq kg^{-1} DM)					
	1990	1991		1993	1994	
	f	f	s	f	f	s
Grasses, sedges						
Festuca ovina	103	321		36		
Phleum pratense		233	3		15	2
Agrostis capillaris					37	6
Poa pratensis		16	4			
Deschampsia cespitosa		24			13	1
D. flexuosa		176		354		
Carex spp.		207		95		
Juncus spp.		19		14		
Herbs						
Anemone nemorosa		113		33	80	
Ranunculus acris		41		12	9	
Filipendula ulmaria	36			11		
Galium spp.	10			4	12	
Anthriscus sylvester	28	165	23	5	7	3
Vicia cracca		145	8		30	3
Lathyrus pratensis		74	9	33	24	1
Achillea millefolium	16				35	4

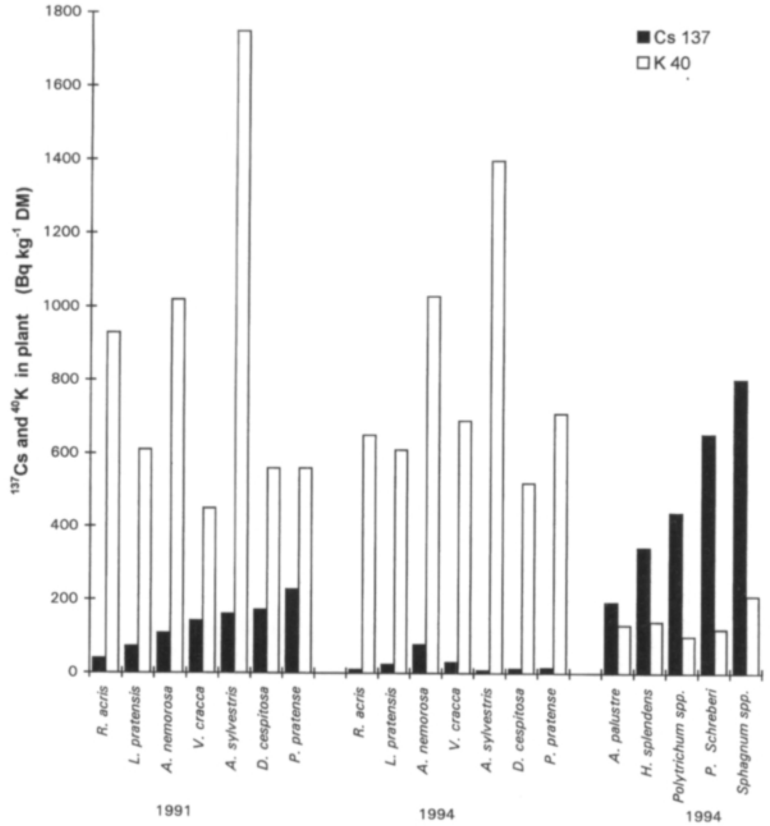

Fig. 2. Activity concentration of ^{137}Cs and ^{40}K of some vascular plant (1991, 1994) and moss species (1994) on forest pasture. Each sample is a mixture of several subsamples.

Sheep ^{137}Cs

Activity concentration

When the ^{137}Cs activity concentration of tissues of sheep on combined pasture in 1991–1992 was tested by the analysis of variance, the effects of year, tissue type and their interaction were highly significant ($p < 0.001$). Practically, the ^{137}Cs activity level between muscle and kidney and between liver and heart was of the same order of magnitude (Table 9). The mean and standard deviation (in parentheses) of ^{137}Cs activity concentration of muscle, kidney, liver and heart of 6 sheep grazing on forest pasture in 1993 was 254 (70), 185 (57), 134 (35) and 126 (47) Bq kg^{-1} and on set-aside field pasture 4.0 (0.9), 2.7 (1.4), 1.3 (1.1) and 1.9 (0.8) Bq kg^{-1}, respectively.

Transfer and concentration factors

The soil-meat aggregated transfer factor of ^{137}Cs for combined and cultivated pasture fluctuated by year and was clearly highest in 1991 (Table 10). The differences between forest, set-aside field and cultivated pasture were obvious (Table 11). The meat/plant concentration factor was not calculated for combined pasture in 1990–1992 due to considerable differences in the plant concentration of ^{137}Cs of the two sampling sites. After dividing the pasture in 1993, the mean and the standard deviation (in parentheses) of the meat/plant concentration factor of ^{137}Cs for for-

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Table 8. Soil-plant transfer and concentration factors of ^{137}Cs for different pastures by years.

Year	^{137}Cs (soil-plant)				
	Transfer factor			Concentration factor	
	Mean	SD	Range	Mean	SD
Forest pasture					
1990	1.83	0.98	0.95–3.20	0.151	0.081
1991	8.24	2.66	5.59–10.62	0.684	0.221
1992	0.87	0.24	0.54–1.04	0.072	0.020
1993	1.78	1.92	0.33–4.56	0.149	0.159
1994	2.72	2.75	0.61–6.74	0.225	0.226
Set-aside field pasture					
1990	0.39	0.14	0.31–0.60	0.036	0.013
1991	0.56	0.34	0.25–1.00	0.052	0.031
1992	0.07	0.06	< 0.01–0.12	0.006	0.005
1993	0.36	0.31	< 0.01–0.66	0.033	0.029
1994	0.18	0.11	0.05–0.28	0.016	0.010
Cultivated pasture*					
1991	0.35	0.21	0.14–0.63	0.036	0.021
1992	0.01	0.01	< 0.01–0.03	0.001	0.001
1993	0.09	0.07	< 0.01–0.15	0.009	0.009
Ley					
1990	0.16	0.16	0.02–0.39	0.010	0.010
1991	0.12	0.10	< 0.01–0.20	0.007	0.006
1992	0.13	0.10	0.02–0.27	0.008	0.006
Meadow-1					
1990	3.28	2.00	0.78–5.40	0.367	0.223
1991	1.95	0.93	0.71–2.77	0.219	0.104
1992*	0.07	0.06	0.02–0.14	0.008	0.006
Meadow-2					
1990	0.72	0.29	0.37–1.03	0.081	0.032
1991	1.20	0.84	0.42–2.35	0.135	0.094
1992	0.17	0.08	0.08–0.24	0.020	0.009

* = ploughed, SD = standard deviation, number of observations = 4.

est, set-aside field and cultivated pasture were 7.44 (2.05), 0.85 (0.19) and 0.31 (0.29), respectively.

Discussion

Soil distribution

The very slow vertical migration of the ^{137}Cs in the undisturbed soil profiles found in this study has been confirmed by several authors. Rogowski and Tamura (1970) found in their 2-year study that most of the ^{137}Cs which was not eroded remained in the 0–3 cm soil layer. According to Fawaris and Johanson (1994), 5 years after the Chernobyl accident about 85% of the ^{137}Cs was found in the 0–5 cm humus layer of forest soil. Similar low cesium transfer has been reported by Colgan et al. (1990) and Livens et al. (1991).

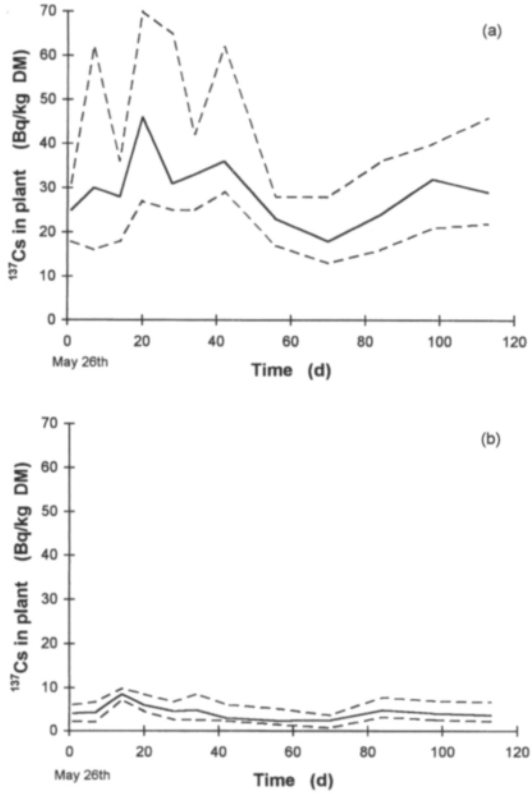

Fig. 3. Seasonal variation of ^{137}Cs activity concentration of vegetation on (a) forest and (b) set- aside field pasture. Medians (—) with lower and upper quartiles (– – –) of three growing seasons (1992–1994) are presented.

Table 9. Activity concentration of ^{137}Cs and logarithmic ^{137}Cs of tissues of sheep grazing on combined pasture in 1991–1992.

Tissue	^{137}Cs in tissues (Bq kg^{-1} FW)			
	Mean	SD	Range	Mean*
1991				
Muscle	32.1	10.6	21.3–57.8	3.43
Kidney	25.7	8.1	17.1–42.3	3.20
Liver	13.3	4.9	7.7–23.3	2.53
Heart	13.1	3.2	9.2–20.3	2.55
1992				
Muscle	9.5	2.0	6.6–12.7	2.24
Kidney	11.4	2.3	6.4–14.2	2.42
Liver	7.3	1.9	4.0–9.9	1.95
Heart	6.1	1.9	2.6–8.6	1.78

SD = standard deviation, *standard error of mean (ln^{137}Cs) = 0.09 (df = 54), number of sheep per year = 10.

Pastures and sheep

The soil-plant-meat transfer of ^{137}Cs of the Swedish mountain pasture was much higher than that of forest pasture in this study, although these areas had been nearly equally affected by fallout (Hove et al. 1994). The sandy and peaty soils of mountain pasture had lower concentrations of soluble potassium and calcium, lower pH and higher organic matter contents than the clay soil

Table 10. Soil-meat aggregated transfer factors and concentration factors of ^{137}Cs for combined (forest and set-aside field) and cultivated pasture by years.

Year	^{137}Cs (soil-meat)				
	Transfer factor$_{(ag)}$			Concentration factor	
	Mean	SD	Range	Mean	SD
Combined pasture					
1990	0.73	0.1	0.57–0.89	0.064	0.013
1991	1.41	0.47	0.93–2.53	0.122	0.041
1992	0.38	0.08	0.26–0.50	0.033	0.007
Cultivated pasture*					
1991	0.18	0.07	0.02–0.25	0.018	0.007
1992	0.02	0.01	< 0.01–0.05	0.002	0.001

* = ploughed, SD = standard deviation, number of observations per row = 10.

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Table 11. Soil-meat aggregated transfer factors and concentration factors of ^{137}Cs for different pastures in 1993.

Pasture type	^{137}Cs (soil-meat)					
	Transfer factor$_{(ag)}$				Concentration factor	
	n	Mean	SD	Range	Mean	SD
Forest pasture	6	10.96	3.01	6.60–14.94	0.910	0.250
Set-aside field pasture	6	0.28	0.06	0.20– 0.38	0.026	0.006
Cultivated pasture*	12	0.03	0.03	< 0.01– 0.08	0.003	0.003

* = ploughed, SD = standard deviation, n = number of observations.

of forest pasture. Acid, coarse-textured soils with poor nutrient status and high humus content are known to increase the ^{137}Cs activity concentration of herbage and grazing sheep, while ^{137}Cs is fixed in the soil unavailable for plant uptake by the clay fraction (Kühn et al. 1984, Frissel et al. 1990, Rosén 1991, van Bergeijk et al. 1992, Thiry and Myttenaere 1993). The variation of the soil-plant and soil-meat transfer factors of ^{137}Cs followed by and large that of plant and meat activity concentrations. The meat/plant concentration factor of ^{137}Cs for forest pasture in 1993 was rather high compared to that for other pastures. In general, the ratio has been reported to be lower than one (Hove et al. 1994). Similarly, the higher ^{137}Cs activity level of plants and sheep of forest pasture than that of other pastures was due to the lower nutrient status of the forest soil and to the humus layer, where ^{137}Cs probably remained readily available for plant uptake (Livens et al.1991). The low ^{137}Cs activity level of cultivated pasture was explained by the clay soil rich in nutrients and without organic matter. The distribution of the ^{137}Cs concentration between the different tissues of sheep agrees well with earlier studies (Andersson and Hansson 1989, Howard et al. 1989, Vandecasteele et al. 1989).

The ^{137}Cs transfer factors for the soil-plant-sheep system in this study are valid for natural and semi-natural pastures on clay soils. Pastures on coarse mineral soils with lower K status are supposed to have higher transfer of ^{137}Cs and, consequently, higher soil to plant and soil to meat transfer factors. The soil-plant transfer factor of this study was higher for semi-natural meadows on medium sand soil than for the semi-natural pasture on clay soil. The difference in the plant activity concentration and the soil to plant transfer factors of ^{137}Cs between the meadows was suggested to account for the differences in their soil K status.

Plant species

The observed differences in the interspecific ^{137}Cs activity concentration of vascular plants were considered mostly to be due to environmental factors like uneven distribution of cesium in the soil, differences in the soil properties of pastures and the yearly variation. High variability in the ^{137}Cs activity level between plant species grown on the same site has been reported by Horrill et al. (1990). Also Nelin and Nylén (1994) found significant differences in the activity concentration of ^{137}Cs between forest plant species. Kirton et al. (1990) observed that after the Chernobyl fallout the ^{137}Cs concentration of indigenous plants varied according to the growth pattern of individual plant species. Further, Salt and Mayes (1991) emphasized the importance of taking into account besides the growth pattern, the stage of development and possibly rooting depth when making interspecific comparisons of the plant ^{137}Cs. According to Guillitte et al. (1994), besides rooting depth, mycorrhizae had an important role determining the interspecific differences of the undercover vegetation of coniferous forests. On the forest pasture of this study, lichens and several mosses had higher ^{137}Cs activity levels than vascular plants, which has been documented by several authors (Paakkola and Miettinen 1963, Häsänen and Miettinen 1966, Jackson and Smith 1989, Horrill et al. 1990, Livens et al. 1991). The highest activity levels were detected in lichen and moss genera grown on rocks. Of the former ones, especially *Stereocaulon* spp. seemed to be able to trap radiocesium abundantly, probably due to the morphology of the thallus.

The plant ^{137}Cs did not correlate with plant ^{40}K, which has been confirmed by Evans and Dekker (1968) in crop plants. According to Andersen (1967), the relative uptake of ^{137}Cs and K by crop plants was more dependent on soil properties, thus affecting the relative availability of the elements, than on plant species. Coughtrey et al. (1990) reported that soil potassium status did not explain all the observed ^{137}Cs activity concentrations of plant species. The ^{137}Cs–K relations of plants in grassland ecosystems have been discussed by Salt and Mayes (1993) concerning the selectivity of K uptake, the discrimination of ^{137}Cs in favour of K and differences in ^{137}Cs uptake by plant groups.

Yearly variation

The plant and sheep ^{137}Cs on forest pasture did not vary with years with the exception of the fluctuations probably caused by weather. The results are confirmed by Beresford et al. (1992) who found that after 4 years the Chernobyl radiocesium in organic soils of natural grasslands was as available as aged radiocesium, present in soil for over 20 years. According to the predictions of Hove and Strand (1990), the Chernobyl cesium will remain available in natural ecosystems for decades. Johanson et al. (1991) reported that the ^{137}Cs activity concentration of moose had not decreased in 4 years after the Chernobyl accident.

The yearly variation of the plant ^{137}Cs has been suggested by several authors to be partly due to weather conditions (Coughtrey et al. 1989, Livens et al. 1991, Fawaris and Johanson 1994). In addition to the direct effect of moisture and temperature on root growth and nutrient uptake by plants, weather conditions may affect the plant uptake of ^{137}Cs also via the biological activity of soil micro-organisms. Guillitte et al. (1994) had estimated that even 40% of the soil ^{137}Cs could be retained in the humus layer by soil microflora. In the field studies (Paasikallio et al. 1994), the low ^{137}Cs level of leaf vegetables was suggested to be due to cold and rainy June. In this study, such weather conditions seemed to have had an opposite effect on the plant ^{137}Cs on forest pasture. In 1991, June was cool and rainy and the plant ^{137}Cs high, whereas in 1992, June was warm and dry and the plant ^{137}Cs low. The variable effect of weather factors on the plant ^{137}Cs level of the forest pasture with the humus layer and on the other hand, on the plant ^{137}Cs of cultivated fields lacking the humus layer might be partly associated with weather-microbe-cesium interactions of the humus layer.

Under certain conditions, fungi were the most important factor causing the yearly variation of ^{137}Cs in ruminants feeding on natural pasture. The ^{137}Cs activity concentration of fungal fruit bodies might be 50–100 times higher than that of herbage on the same site (Hove et al. 1990, Olsen 1994). Because only few fungal fruit bodies were found on forest pasture, fungi were not considered to be an important source of ^{137}Cs in sheep.

Seasonal variation

Seasonal changes in the ^{137}Cs concentration of vegetation are typical of permanent pastures (Jackson and Smith 1989, Salt and Mayes 1991, Rafferty et al. 1994). The second increase in the plant ^{137}Cs level in autumn was probably due to the regrowth of grasses dominating on this pasture. In general, the variation followed the most common seasonal patterns described by Salt and Mayes (1993) with seasonal and annual variations, which the authors suggested to be partly due to fluctuations of the water content of plants. The decrease of the plant ^{40}K on both pastures during the growing season was accounted for the

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increasing dry matter content of plants. The decline of the plant ^{40}K was in accordance with the results of Rafferty et al. (1994) and Bunzl and Kracke (1989).

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SELOSTUS

Radiocesiumin kulkeutuminen eri laidunekosysteemien maa-ruoho-lammas -ravintoketjussa

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Maatalouden tutkimuskeskus

Cesium 137 viipyy kauemmin luonnon kuin maatalouden ravintoketjuissa. Tshernobylin reaktorionnettomuuden jälkeen havaittiin, että cesiumia kulkeutui Iso-Britannian karuilla nummilla ja Norjan ja Ruotsin tunturiniityillä kasveihin ja lampaaseen enemmän kuin oli aikaisemmin otaksuttu, ja että cesiumin määrä väheni niissä hitaammin. Cesiumia on liukoisessa muodossa myös pohjoisten havumetsien humuskerroksessa, josta se vuosittain yhä uudelleen kulkeutuu kasveihin ja niitä ravinnokseen käyttäviin eläimiin. Metsäekosysteemissä ^{137}Cs-määrän katsotaankin vähenevän melkein yksinomaan radioaktiivisen hajoamisen kautta. Luonnontilaisille, karuille kasvupaikoille on usein ominaista korkea humuspitoisuus, alhainen pH, liukoisen kaliumin ja kalsiumin vähäisyys ja saveksen puuttuminen. Näiden maaperän ominaisuuksien on todettu lisäävän juurten kautta kulkeutuvan cesiumin pitoisuutta kasveissa savesta lukuunottamatta, joka estää kulkeutumista. Luonnonlaitumien ja viljelyyn soveltumattomien alueiden käyttö lammaslaitumina on viime vuosina lisääntynyt. Tutkimuksen tarkoituksena oli hankkia lisätietoa ydinlaskeuman lammastaloudelle aiheuttamien ongelmien ratkaisemiseksi.

Radiocesiumin kulkeutumista maa-ruoho-lammas -ravintoketjussa tutkittiin neljänä vuonna metsä-, kesanto- ja viljelylaitumella, jotka sijaitsivat savimaalla. Laidunkausi kesti toukokuun lopusta melkein syyskuun loppuun, jolloin lampaat teurastettiin. Maa- ja kasvinäytteet otettiin laitumilta syyskuun alussa. Metsä- ja kesantolaitumella seurattiin kolmen vuoden ajan kasvillisuuden ^{137}Cs-aktiivisuuspitoisuuden vaihtelua kasvukauden aikana ottamalla kasvinäytteitä kahden viikon välein. Lisäksi tutkittiin cesiumin kulkeutumista maasta kasviin kahdella puoli-luonnonniityllä, jotka sijaitsivat karkealla hietamaalla.

Radiocesiumia kulkeutui ruohoon ja lampaaseen huomattavasti enemmän metsälaitumelta kuin kesantolaitumelta, vähäisintä kulkeutuminen oli viljelylaitumelta. Cesium 137:n keskimääräiset maa-kasvi siirtokertoimet metsä-, kesanto- ja viljelylaitumella viimeisellä laidunkaudella olivat 1,78, 0,36 ja 0,09 ja vastaavat maa-liha siirtokertoimet 11,0, 0,28 ja 0,03. Siirtokertoimissa havaittujen eri laidunten välisten erojen katsottiin johtuvan metsälaidunmaan runsaammasta orgaanisen aineksen määrästä, alemmasta pH:sta, vähäisemmästä liukoisen kaliumin ja kalsiumin määrästä muihin laitumiin verrattuna. Viljelylaidunmaan liukoisen kaliumin pitoisuus oli selvästi muita laidunmaita korkeampi. Säätekijöiden vaikutus näkyi kasvien ja eläinten ^{137}Cs-aktiivisuuspitoisuuden vuosittaisena vaihteluna. Putkilokasvien ^{137}Cs-pitoisuuteen vaikuttivat laiduntyypin ja sääolojen lisäksi kasvien kehitysvaihe ja ^{137}Cs:n epätasainen jakautuminen pintamaassa. Koska putkilokasvilajien väliset erot cesiumpitoisuudessa johtuivat monista tekijöistä, itse kasvilajista mahdollisesti aiheutuneet erot peittyivät muun vaihtelun alle. Sammalien ja jäkälien ^{137}Cs-pitoisuudet olivat useimmiten selvästi putkilokasveja suurempia. Yli 90 % radiocesiumista sijaitsi metsä- ja kesantolaidunmaan pintakerroksessa, 0–5 cm syvyydessä, josta sen ei todettu kulkeutuvan alaspäin 4 tutkimusvuoden aikana.

Tämän tutkimuksen ^{137}Cs- siirtokertoimet maa-ruoho-lammas -ketjussa pätevät savimailla oleviin laitumiin. Karkeilla kivennäismailla, joilla luonnonlaitumet usein sijaitsevat, cesiumin maa-kasvi siirtokertoimet ovat yleensä savimaita korkeampia. Paitsi maalajista tämä johtuu karkeiden kivennäismaiden savimaita pienemmästä kaliumpitoisuudesta. Karkealla hietamaalla sijainneen kahden niityn erot ^{137}Cs:n maa-kasvi siirtokertoimissa katsottiin johtuvan suureksi osaksi niiden maaperän liukoisen kaliumin pitoisuuseroista. Siirtokerroin oli pienempi niityllä, jonka maaperässä oli enemmän liukoista kaliumia.