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-
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.

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 $^{137}\text{Cs}$ 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 1. Dominant plant species or genera of grasslands.

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

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

| Month | Mean temperature $^a$ | Precipitation $^a$ | Evaporation $^b$ |
|-------|----------------------|--------------------|------------------|
|       | (° C) | (mm/month) | (mm/month) | (Class A) |
|       | 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.
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 pasture       |
|------------------|---------------------------|----------------------|-------------------------|
|                  | 1990 | 1991 | 1992 | 1993 | 1993 | 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) |

|                  | 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, 50 kg 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 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...
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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**Table 4. Grassland soil characteristics. Soil depth 0–10 cm.**

| Grassland (soil type)          | Bulk density (g cm$^{-3}$) | Clay (%) | Humus (%) | pH (H$_2$O) | K (Acid AAc-extractable) (mg l$^{-1}$ of soil) | Ca | Mg | P |
|-------------------------------|---------------------------|----------|-----------|------------|-----------------------------------------------|----|----|---|
| 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|
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
Paasikallio, A. & Sormunen-Cristian, R. Transfer of $^{137}$Cs through soil-plant-sheep food chain 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                        | 1990 | 1991 | 1992 | 1993 | Mean | SD  |
|----------------------------------|------|------|------|------|------|-----|
| Forest pasture                   | 96.6 | 97.3 | 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 | 72.2 | 51.7 | 77.6 | 67.2 | 13.7|
| Meadow-1*                        | 97.3 | 97.3 | 97.3 | 97.3 | 97.3 | 0   |
| Meadow-2*                        | 96.0 | 95.5 | 92.7 | 94.7 | 94.7 | 1.8 |
| Meadow-3*                        | 74.7 | 73.9 | 68.1 | 72.2 | 72.2 | 3.6 |

* = ploughed, ** = tilled, SD = standard deviation
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            | 1990 f | 1991 f | 1991 s | 1993 f | 1993 s | 1994 f | 1994 s |
|--------------------|--------|--------|--------|--------|--------|--------|--------|
| Grasses, sedges    |        |        |        |        |        |        |        |
| Festuca ovina      | 103    | 321    | 36     |        |        |        |        |
| Phleum pratense    | 233    | 3      |        | 15     | 2      |        |        |
| Agrostis capillaris|        |        |        | 37     | 6      |        |        |
| Poa pratensis      | 16     | 4      |        | 13     | 1      |        |        |
| Deschampsia cespitosa| 24    |        |        |        |        |        |        |
| 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      |
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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-
Table 8. Soil-plant transfer and concentration factors of $^{137}$Cs for different pastures by years.

| Year | Transfer factor | $^{137}$Cs (soil-plant) | 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.

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).
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 11. Soil-meat aggregated transfer factors and concentration factors of 137Cs for different pastures in 1993.

| Pasture type               | n  | Mean (mg) | SD  | Range | Mean (Bq/kg) | 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 137Cs activity concentration of herbage and grazing sheep, while 137Cs 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 137Cs followed by and large that of plant and meat activity concentrations. The meat/plant concentration factor of 137Cs 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 137Cs 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 137Cs probably remained readily available for plant uptake (Livens et al. 1991). The low 137Cs activity level of cultivated pasture was explained by the clay soil rich in nutrients and without organic matter. The distribution of the 137Cs concentration between the different tissues of sheep agrees well with earlier studies (Andersson and Hansson 1989, Howard et al. 1989, Vandecasteel et al. 1989).

The 137Cs 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 137Cs 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 137Cs between the meadows was suggested to account for the differences in their soil K status.

Plant species

The observed differences in the interspecific 137Cs 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 137Cs 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 137Cs between forest plant species. Kirton et al. (1990) observed that after the Chernobyl fallout the 137Cs 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 137Cs. 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 137Cs ac-
tivity levels than vascular plants, which has been documented by several authors (Paakkola and Miettinen 1963, Hässinen and Miettinen 1966, Jackson and Smith 1989, Horril 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 radioesium abundantly, probably due to the morphology of the thallus.

The plant $^{137}\text{Cs}$ did not correlate with plant $^{40}\text{K}$, which has been confirmed by Evans and Dekker (1968) in crop plants. According to Andersen (1967), the relative uptake of $^{137}\text{Cs}$ 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 $^{137}\text{Cs}$ activity concentrations of plant species. The $^{137}\text{Cs}$--K relations of plants in grassland ecosystems have been discussed by Salt and Mayes (1993) concerning the selectivity of K uptake, the discrimination of $^{137}\text{Cs}$ in favour of K and differences in $^{137}\text{Cs}$ uptake by plant groups.

**Yearly variation**

The plant and sheep $^{137}\text{Cs}$ 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 radioesium in organic soils of natural grasslands was as available as aged radioesium, 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 $^{137}\text{Cs}$ activity concentration of moose had not decreased in 4 years after the Chernobyl accident.

The yearly variation of the plant $^{137}\text{Cs}$ 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 $^{137}\text{Cs}$ also via the biological activity of soil micro-organisms. Guillitte et al. (1994) had estimated that even 40% of the soil $^{137}\text{Cs}$ could be retained in the humus layer by soil microflora. In the field studies (Paaskallio et al. 1994), the low $^{137}\text{Cs}$ 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 $^{137}\text{Cs}$ on forest pasture. In 1991, June was cool and rainy and the plant $^{137}\text{Cs}$ high, whereas in 1992, June was warm and dry and the plant $^{137}\text{Cs}$ low. The variable effect of weather factors on the plant $^{137}\text{Cs}$ level of the forest pasture with the humus layer and on the other hand, on the plant $^{137}\text{Cs}$ 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 $^{137}\text{Cs}$ in ruminants feeding on natural pasture. The $^{137}\text{Cs}$ 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 $^{137}\text{Cs}$ in sheep.

**Seasonal variation**

Seasonal changes in the $^{137}\text{Cs}$ 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 $^{137}\text{Cs}$ 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 $^{40}\text{K}$ on both pastures during the growing season was accounted for the
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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Cesium 137 viipyy kauemmin luonnon kuin maatalouden ravintoketjussa. Tshernobylin reaktorionnettomuuden jälkeen tuli selvästi, että cesiumia kulkeutui Iso-Britannian karuilla muillakin maaseudun puoliväliin, Norjan ja Ruotsin tunturimaitoilla kasveihin ja lampaaseen enemmän kuin oli aikaisemmin otettu huomioon. Toistaan on kuitenkin esitetty, että cesiumin määärä vähenee niissä hitaammin. Cesiumia on liukoisessa muiden puolijalan kasvien kanssa myös pohjoisten havumetsien himmukerrostossa, josta se vuosittain yhä uudelleen kulkeutuu kasveihin ja niitä ravinnokseen käyttäviin eläimiin. Metsäekosysteemissä ^137Cs-määärän kasvattaa vähenevän melkein kaksikertainen yksinomaan yksikirjoituksen hajoamisen kautta. Luonnontilaisille, karuille kasvupäikoille on usein ominaisia karkeita humuspitoisuuksia, pH, liukouden kaliumin ja kalsiumin vähäisyys ja saveksen puuttuminen. Näiden maaperän ominaisuuksien on todettu lisäävän juurten kautta kulkeuttavan cesiumin pitoisuutta kasveissa savesta lukuun ottamatta, joka estää kulkeutumista. Luonnontilaisista ja viljelyyn soveltumattomien alueiden käyttö lammaslaitumina on viime vuosina lisääntynyt. Tutkimuksen tarkoituksena on hankkia lisätietoa ydinlaskeuman lammaslautaralle aiheuttamien ongelmien ratkaisemiseksi.

Radiocesiumin kulkeutumista maa-ruoho-lammas -ravintoketjussa tutkittiin neljänä vuonna Metsä-, kesiato- ja viljelykylälaitumella, jotka sijaitisivat savimailla. Laidunkaudella kesti toukokuun lopusta melkein syyskuun loppuun, jolloin lampaat teurastettiin. Maa- ja kasvinäytteet otettiin laitumilta syyskuun alussa. Metsä- ja kesiataloudelaitumilla seurattiin kolmen vuoden ajan kasvillisuuden ^137Cs-aktivisuuspitoisuuden vaihtelua kasvukauden aikana ottamalla kasvinäytteitä kahden viikon välein. Lisäksi tutkittiin cesiumin kulkeutumista maan kasvien kahdella puoli-luonnontilayhteisöllä, jotka sijaitisivat karekalla hietamaalla.

Radiocesiumia kulkeutui ruohon ja lampaaseen huomattavasti enemmän metsälaitumelta kuin kesan- tolaan. Cesium 137:n keskimääräiset maa- ja siirtokertoimet metsä-, kesiato- ja viljelylaitumilla viimeisellä laidunkaudella olivat 1,78, 0,36 ja 0,09 ja vastaavat maa-liha siirtokertoimet 11,0, 0,28 ja 0,03. Siirtokertoimissa havaittujen erojen katsottu johtuvan metsälaidunmäen runsaamasta organaasen aineen määrästä, alemmasta pH:sta, vähäisemmästä liukouden kaliumin ja kalsiumin määrästä muihin laitumien verrattuna. Viljelylaidunmäen liukouden kaliumin pitoisuus oli selvästi muita laitumaita korkeampi. Sääteiköiden vaikutus näki kasvien ja eläinten ^137Cs-aktivisuuspitoisuuden vuosittaisena vaihteluna. Putkilokasvien ^137Cs-pitoisuuteen vaikuttiin laiduntyyppin ja sääolojen lisäksi kasvien kehitysvaiheja ja ^137Cs:n epätasainen jakautuminen pintamaassa. Koska putkilokasvivalojen väliset erot cesiumpitoisuudessa johtuvat monista tekijöistä, itse kasvilajista mahdollisesti aiheutuneet erot peittivät muun vaikutelmaan alle. Sammalen ja jääkäsen ^137Cs-pitoisuudet olivat useimmiten selvästi putkilokasveja suurempia. Yli 90 % radiocesiumista sijaitsee metsä- ja kesiatalaidunmäen pintakerroksessa, 0–5 cm syvyydessä, josta sen ei todettu kulkeutuvan alaspäin 4 tutkimusvuoden aikana.

Tämän tutkimuksen ^137Cs-siirtokertoimen maa-ruoho-lammas -ketjussa pätivät savimailla oleviin laitumiin. Karkeilla kivennäismailolla, joilla luonnollaiset laitumet usein sijaitsevat, cesiumin maa- ja siirtokertoimet ovat yleensä savimaita korkeampia. Paitsi maalaajista tämä johtuu karkeiden kivennäismaiden savimaita pienemmästä kalsiumpitoisuudesta. Karkealla hietamaalla sijainneen kahden niityn erot ^137Cs:n maa-kaasvi siirtokertoimissa katsottiin johtuvan sen suureksi osaksi niiden maaperän liukouden kaliumin pitoisuuseroista. Siirtokerroin oli pienempi niittyllä, jonka maaperässä oli enemmän liukosta kalmiumia.