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EcoDoses
Improving radiological assessment of doses to man from terrestrial ecosystems

Edited by:
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NRPA, Norway

July 2005

Abstract

The NKS B-programme EcoDoses project started in 2003 as a collaboration between all the Nordic countries. The aim of the project is to improve the radiological assessments of doses to man from terrestrial ecosystems. The present report sums up the work performed in the second phase of the project. The main topics in 2004 have been: (i) A continuation of previous work with a better approach for estimating global fallout on a regional or national scale, based on a correlation between precipitation and deposition rates. (ii) Further extension of the EcoDoses milk database. Estimation of effective ecological half lives of ^{137}Cs in cow's milk focussing on suitable post-Chernobyl time-series. Modelling integrated transfer of ^{137}Cs to cow's milk from Nordic countries. (iii) Determination of effective ecological half lives for fresh water fish from Nordic lakes. (iv) Investigate radioecological sensitivity for Nordic populations. (v) Food-chain modelling using the Ecosys-model, which is the underlying food- and dose-module in several computerised decision-making systems.

Key words

Nuclear weapons fallout, deposition modelling, food-chain modelling, ecological half-lives in milk and freshwater fish, radioecological sensitivity for Nordic populations

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A status report for the NKS-B project 2004

Edited by Tone D. Bergan, Ali Hosseini, Astrid Liland, Øyvind G. Selnæs, and Håvard Thørring

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Table of content

1 Introduction

The NKS B-programme EcoDoses project started in 2003 as a collaboration between all the Nordic countries. The aim of the project is to improve the radiological assessments of doses to man from terrestrial ecosystems.

The first part of EcoDoses focused on an extensive collation and review of both published and unpublished data from all the Nordic countries for the nuclear weapons fallout period and the post-Chernobyl period. This included data on radionuclides in air filters, precipitation, soil samples, milk and reindeer. Based on this, an improved model for estimating radioactive fallout based on precipitation data during the nuclear weapons fallout period was developed. Effective ecological half- lives for ^{137}Cs and ^{90}Sr in milk were calculated for the nuclear weapons fallout period. The data were also used to compare modelling results with observed concentrations.

The present report sums up the work performed in the year 2004. In this second phase the main topics have been:

- A continuation of previous work with a better approach for estimating global fallout on a regional or national scale, based on a correlation between precipitation and deposition rates.
- Further extension of the EcoDoses milk database. Estimation of effective ecological half lives of ^{137}Cs in cow's milk focussing on suitable post-Chernobyl time-series. Modelling integrated transfer of ^{137}Cs to cow's milk from Nordic countries.
- Determination of effective ecological half lives for fresh water fish from Nordic lakes.
- Investigate radioecological sensitivity for Nordic populations.
- Food-chain modelling using the radioecological food-and dose module in the ARGOS decision support system.

2 Deposition of radioactive global fallout in Norway from nuclear weapons tests

Tone D. Bergan & Øyvind Gjølme Selnæs, Norwegian Radiation Protection Authority, Norway

2.1 Introduction

The deposition of radioactive global fallout from the nuclear weapons test in the Nordic countries in the 1950s and 1960s have been notably larger than global models have predicted, especially in the years 1957 and 1958. Previously unpublished measurements of radioactivity in air and rainwater at different Norwegian stations have been collated and based on these data we have established the dependence of the deposition on precipitation and air concentration of radioactive debris. Monitoring data show that not only the air concentration is relatively uniform over large areas, but also the concentration in precipitation (e.g. Bq/litre) is relatively uniform over the same areas. The global deposition model used by UNSCEAR reproduces the deposited fallout on a global scale, but looking at the deposition of fallout in the Scandinavian countries, the amount of precipitation must be taken into account.

Of special interest for Norway, are the nuclear tests conducted on Novaya Zemlya. Updated information on the number of nuclear tests performed (UNSCEAR 2000 and Minatom, 1996) show that a total of 85 atmospheric, 3 surface water and 3 underwater were performed on Novaya Zemlya or in the adjacent sea.

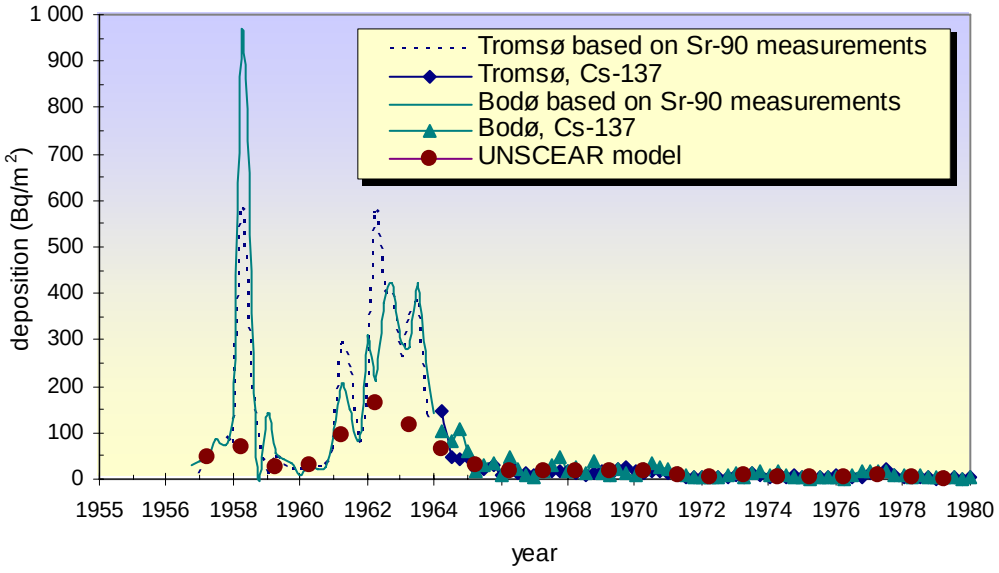


Figure 1. *Deposition of ^{137}Cs at Bodø and Tromsø, compared with UNSCEAR global fallout model. (The UNSCEAR model was based on deposition input from the same monitoring network)(From Bergan & Liland, 2004).*

There have been speculations whether Norway received local fallout from any of the tests performed on Novaya Zemlya, especially in connection with the lower level tests during the period 1955 to 1962.

It has previously been shown that monitoring data from Norway show higher deposition of ^{137}Cs and ^{90}Sr than the global UNSCEAR model predicts.

2.2 Methods

There are seasonal and latitudinal variations in the concentration of debris in ground-level air and in the rate of deposition. These variations can mostly be explained by spatial and temporal differences in precipitation by a simplified fallout model, where the removal of debris from the troposphere is proportional to precipitation and tropospheric concentration. The correlations may appear only in average values over reasonably wide areas and long periods.
Dust injected into the lower polar stratosphere by Russian thermonuclear explosions had a mean residence time of less than 6 months, whereas in tropical latitudes the residence time was longer at 2 to 3 years in the middle stratosphere and 5 to 10 years if injected at 100 km or more above ground. In the troposphere, fallout had a mean residence time of 20-40 days (UNSCEAR, 1962).

The ratio between ^{137}Cs and other main isotopes in the fallout contributing to total beta, allows us to estimate the time between detonation and deposition. This is a rough method, as the yields of different radioisotopes differ between different detonations, but will still give an indication of the age of fallout (Bjurman et al., 1990, Asikainen & Blomqvist, 1970, Cambray et al., 1978).
The age of fallout, t, was calculated based on the ratio between total beta in air (Bq/m^3) and ^{137}Cs in air (Bq/m^3) and the half-lives of the 11 radionuclides (^{95}Zr, ^{95}Nb, ^{140}Ba, ^{131}I, ^{141}Ce, ^{144}Ce, ^{90}Sr, ^{103}Ru, ^{106}Ru, ^{125}Sb and ^{89}Sr) considered to be the most dominating radionuclides contributing to total beta in fallout, according to:

$$\frac{Total\ beta}{^{137}Cs} = \sum_{n=1}^{n=11} k_n \exp\left(\frac{-\ln 2 \cdot t}{T_{1/2n}}\right) \qquad (1)$$

where $T_{1/2n}$ is the physical half-life for nuclide number n and k_n is the ratio between the originally released activity of nuclide n and ^{137}Cs.

The method is described in more detail in Bergan, 2000. The last months in 1957, 1960 and 1961 all stand out as bringing fresh radioactivity to Norwegian territory and motivates closer analysis of these periods.

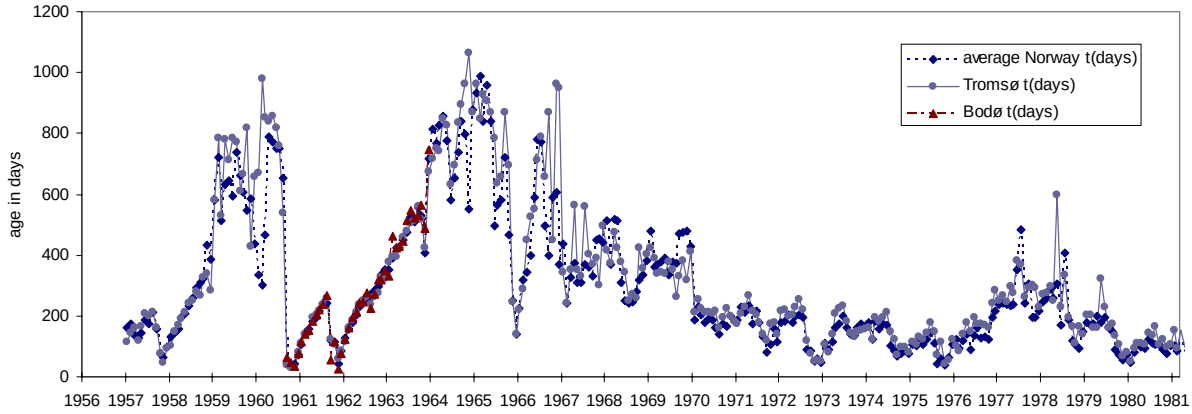


***Figure 2**. Calculated average age of fallout, in days from detonation*

2.3 Reconstruction of ^{131}I in ground air

United Nations Scientific Committee on the Effects of Atomic Radiation, UNSCEAR-2000 gives an update of exposures to the public from man-made sources of radiation. New information on the yields of individual tests, providing more reliable basic input data, has allowed more detailed calculations of the dispersal of radionuclides throughout the world following the injection of debris into the atmosphere.
Iodine-131 is a volatile radionuclide with half-life of only 8.1 days, and the concentration in ground air is thus very dependent on the age of fallout. In reconstructing the input of ^{131}I to ground air, we have combined the UNSCEAR estimates of annual deposition of ^{131}I, derived from the annual measured concentration of ^{90}Sr in air and deposition, with the calculations of ^{131}I from each individual test. As a general assumption, 5500 TBq ^{131}I is produced per kiloton fission yield. Only estimated fission yields to the troposphere have been considered to be of importance, due to ^{131}I's short half-life of 8.1 days.

The calculated age (in days from detonation) of radioactivity in ground air measured at the different stations in Norway has been used to reconstruct the concentration of ^{131}I in air. The relative proportion of ^{131}I to total beta activity from fission products can be calculated after the initial in-growth period (fallout older than 15 days) according to:

$$\frac{^{131}I}{total\ beta} = 13.161 \cdot e^{-0.043 \cdot t}$$

where t is time after detonation in days.

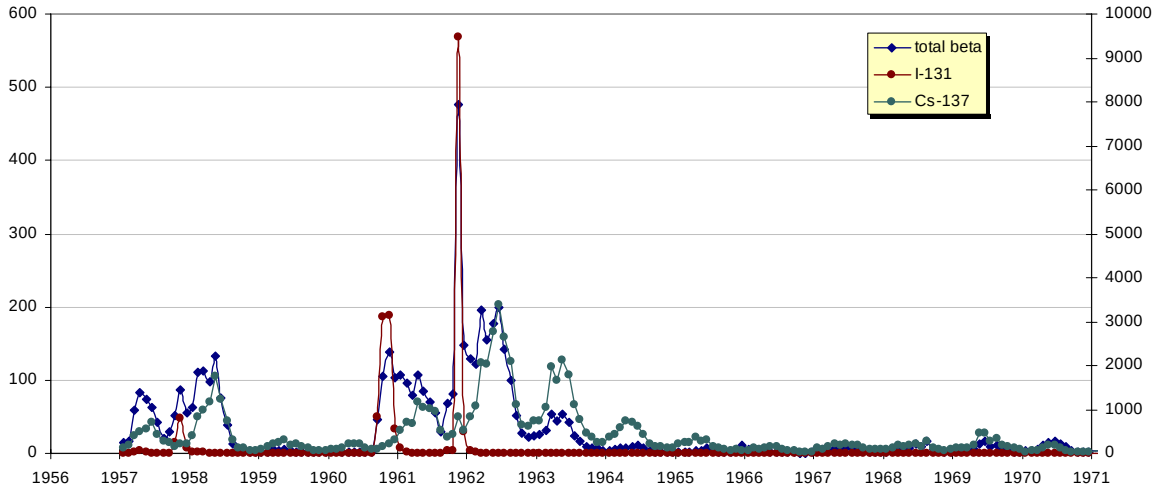


Figure 3. *Calculated ^{131}I in ground air, based on the calculated age of fallout and the measured concentrations of total beta and ^{137}Cs in air. Total beta in air is denoted on the primary y-axis as mBq/m^3, while ^{131}I and ^{137}Cs is denoted on the secondary y-axis as microBq/m^3.*

2.4 Results

Measurements at Kjeller (average annual precipitation of 867 mm), show that precipitation accounts for more than 85% of the fallout deposition, but in areas with little precipitation the percentage of dry fallout is assumed to be greater (Small, 1960). Larger particles were found in precipitation samples compared to air samples. A substantial part of the radioactivity occurred on particles in the size region for which dry collection efficiency is low (< 0.05 μm radius), again indicating that dry deposition is of minor importance. All available data on ^{137}Cs in air and precipitation has been collated.

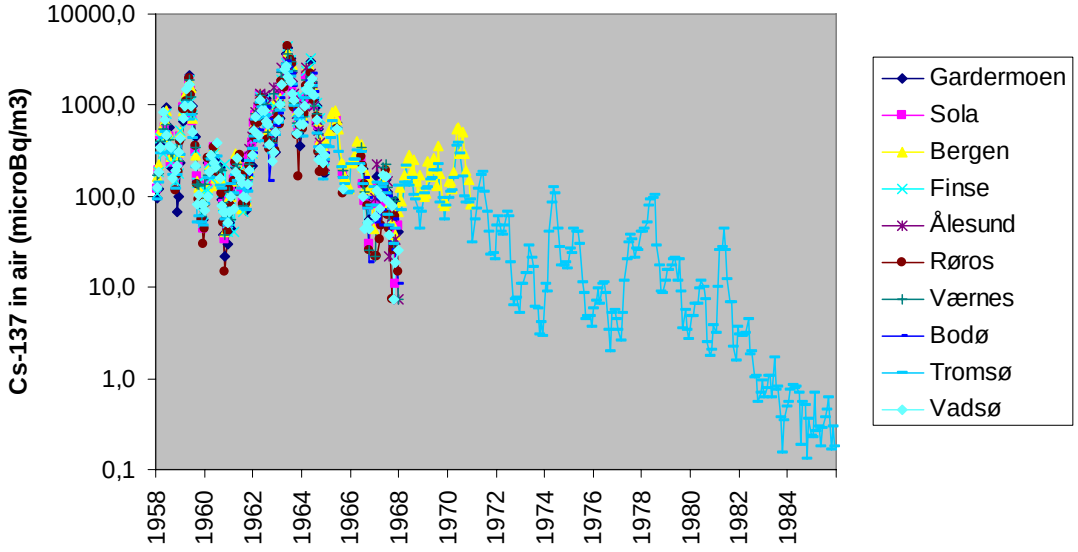


Figure 4. *Measurements of monthly averages of ^{137}Cs in air. After 1970 only Tromsø/Skibotn has been analysed for ^{137}Cs.*

Measurements from several stations in the period 1958-1968 indicates that the spatial variation in air concentration is not large. However, a closer look at the data show that there are significant differences between coastal and inland stations, and southern and northern stations.

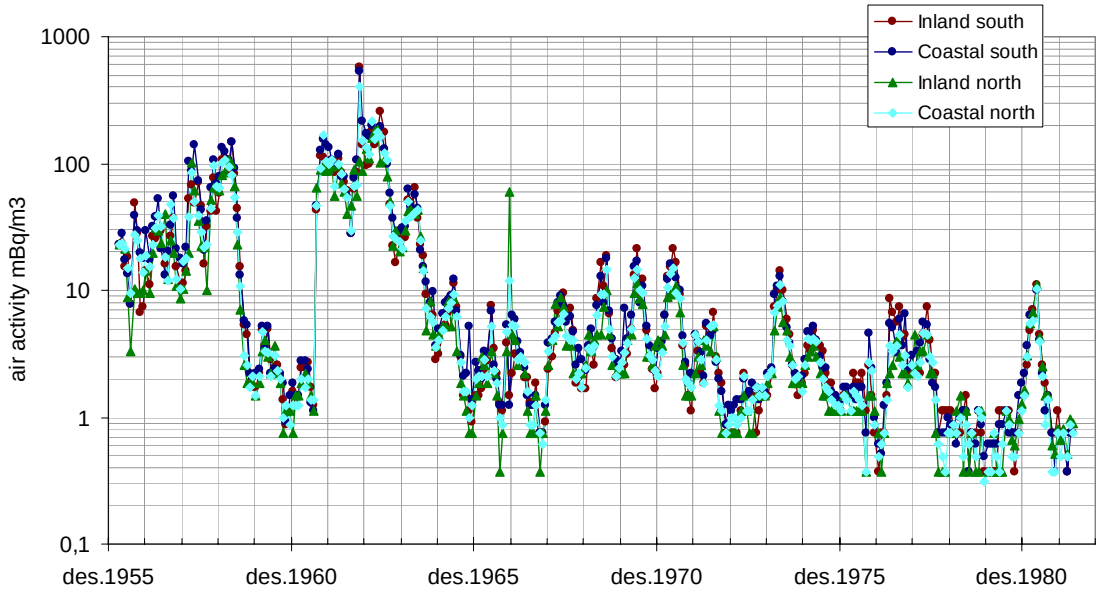
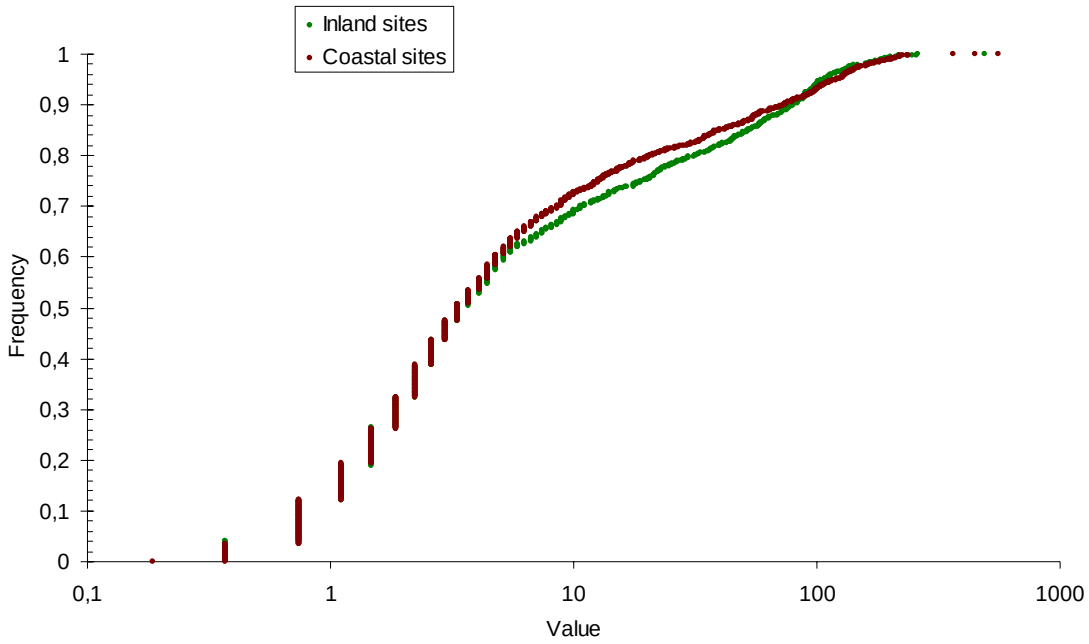


Figure 5. *Grouping data on total beta in air for the four categories "inland south", "coastal south", "inland north" and "coastal north".*



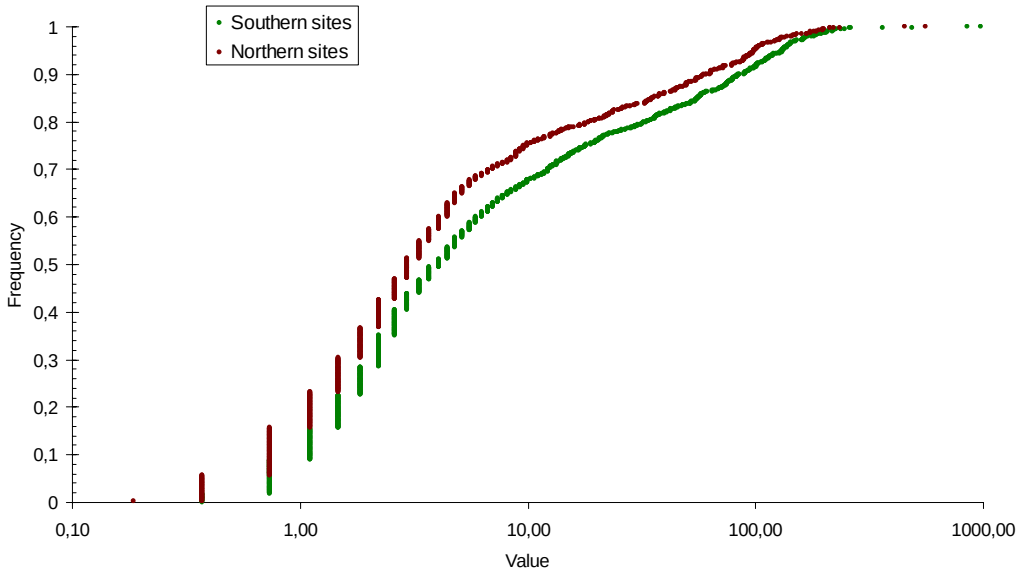


***Figure 6A & 6B**. Cumulative probability analysis of inland sites versus coastal sites and northern sites versus southern sites show that air concentrations are slightly higher in coastal sites compared to inland sites, and higher in southern sites compared to northern sites. These analyses are performed on monthly averages of total beta in air, because of a more complete data set being available for the whole period (1958 to 1982).*

Sigurður Emil Palssón has already shown that the concentration in precipitation is close to uniform, looking at smaller areas or regions.

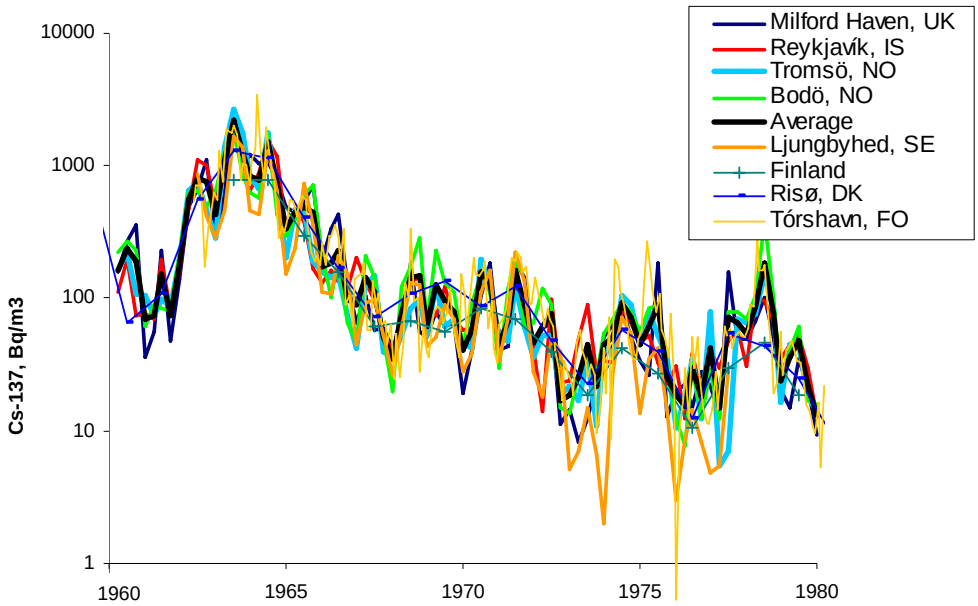


Figure 7. *^{137}Cs concentrations in rain water, decay corrected to 01.01.1965. Monitoring data from the AERE-network, data from UK, IS, NO, SE, DK, FIN, and FO. Work by S.E. Pálsson presented in previous EcoDoses-project.*

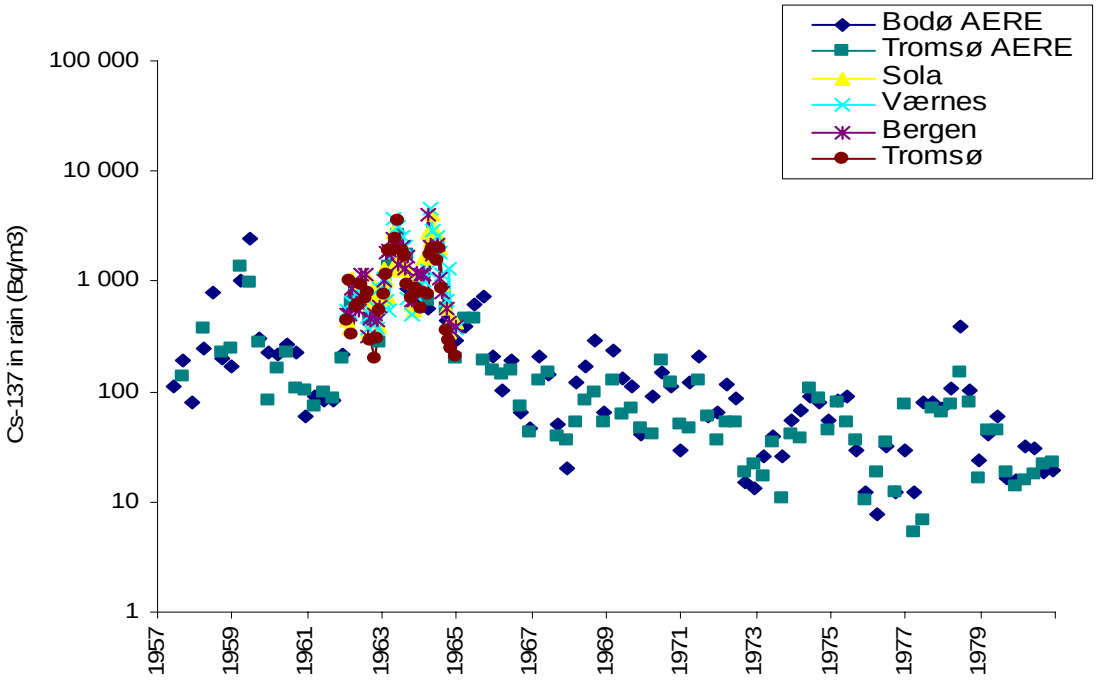


Figure 8. *^{137}Cs concentrations in rain water, Norwegian stations, decay corrected to 01.01.1965. Bodø AERE and Tromsø AERE are data from the global monitoring network, measured every third month, whereas the other stations were monitored every month.*

We have here applied the common approach, determining a relationship between total annual deposition and annual precipitation rate at locations with concurrent time series for precipitation and deposition. Estimates of total annual deposition can then be calculated at sites with no observations of deposition, if precipitation time series are available for the sites.

According to the work in EcoDoses 2004 by Pálsson et al., the total accumulated annual decay corrected deposition (Bq/m^2) may be related to the average annual precipitation rate (m/y) in the following way:

$$D_R = k \cdot \overline{P_R} \qquad k = \frac{D_R}{\overline{P_R}} = \frac{1}{m}\sum C_{R_i} \qquad \overline{P_R} = m \cdot \frac{\sum_i w_i \cdot P_{R_i}}{\sum_i w_i}$$

R refers to a reference site. The index *i* specifies a given time period, and *m* is the number of time periods in a year. The weight factor w_i has the value 1 if the period *i* is selected in the calculations, and 0 otherwise. C_{Ri} is the (decay corrected) concentration in precipitation (Bq/m^3) of the given radionuclide at the reference site during period *i*. The method implies that *k* can be estimated without knowing the precipitation rates.

The constituent *k*, alternatively denoted $C_{R\Sigma}$, is the accumulated average annual concentration in precipitation (y Bq/m^3) for a period of time, and thus must be seen in close connection with the time period in question. We have calculated *k* for ^{137}Cs measurements from four different Norwegian sites for the period 1962 – 1964, as well as from the two Norwegian AERE sites for the period 1957 – 1980. The data has been decay corrected to 1 January 1965.

Table 1. *Calculated k for two different time periods.*

Time period	Based on monthly measurements (y Bq/m^3)				Based on quarterly measurements (y Bq/m^3)	
	Sola	Værnes	Bergen	Tromsø	Tromsø	Bodø
1962 – 1964	3173	3423	3270	2846	2994	2491
1957 – 1980	-	-	-	-	5501	5978

The suggested model for the relationship between the total accumulated annual deposition and the average annual precipitation rate has been evaluated for Norwegian applicability. The calculated values of *k* show some differences between the different Norwegian sites, with values deviating up to ~10 percent of the average value. The calculated value of *k* for Tromsø shows a larger degree of deviance than the calculated values for the other sites.

As Norway is an elongated country with a large climatic variability, the model is less applicable for Norwegian conditions compared to Iceland and the Faroe Islands. However, the results suggest that annual deposition levels can be estimated for locations with known annual precipitation rate with an uncertainty of approximately 20 percent.

Additionally, calculated *k* values from quarterly ^{137}Cs measurements from Tromsø and Bodø have been compared to quoted *k* values from ^{90}Sr measurements from the Faroese sites Tórshavn and Klaksvík (in this report). The Norwegian data in the following table has been decay corrected to 1 June 1962 in accordance with the Faroese values.

Table 2. *Comparison of Norwegian and Faroese estimates of k.*

Time period	From Norwegian ^{137}Cs measurements (y Bq/m^3)			From Faroese ^{90}Sr measurements (y Bq/m^3)		
	Tromsø	Bodø	Average	Tórshavn	Klaksvík	Average
1963 – 1969	2810	2595	2702	2318	2245	2282

The deviance between the Norwegian and the Faroese calculated values of *k* is similar to the deviance within the Norwegian values.

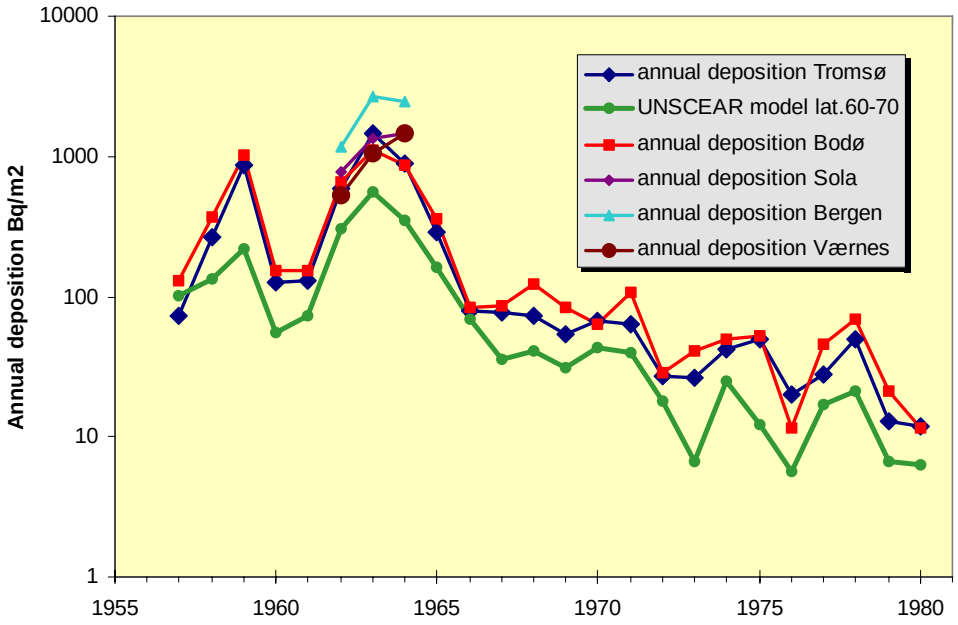


Figure 9. *Annual deposition of ^{137}Cs compared with the UNSCEAR-model for 60-70° North*

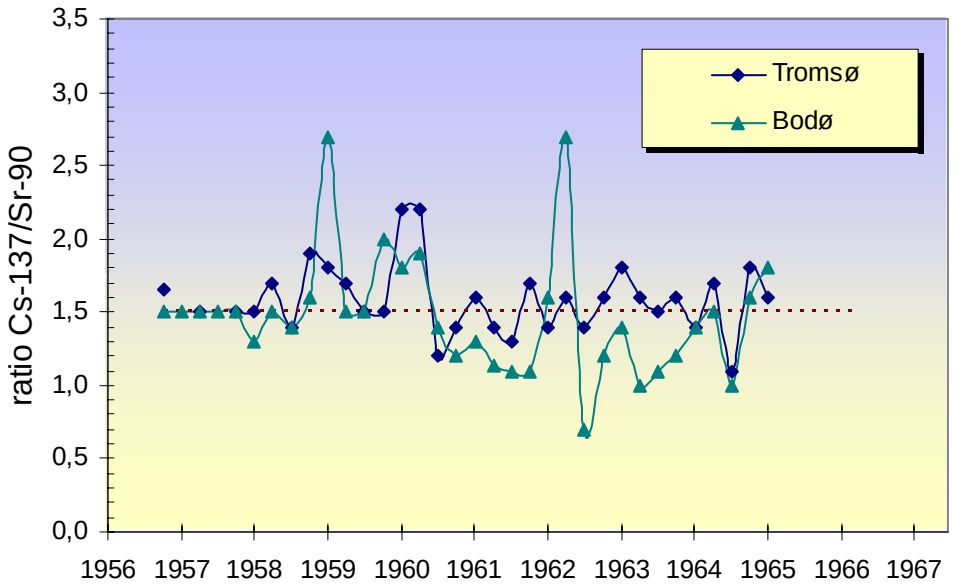


Figure 10. *A more closely look at the ratio between ^{137}Cs and ^{90}Sr in precipitation. Although we normally use a ratio of 1.5 between the two isotopes, this is not always the case.*

2.5 Deposition model

Different models for deposition are well known. However, these models were proposed to describe observation data either in a particular place or in several places with similar conditions. In the present paper the model must suit for several monitoring stations located in different part of Norway. The conditions in these stations are not similar:

1. The stations are located at different altitudes, even though the most of them are located along the coast, or at sea level altitude.
2. The climate conditions are different: Some stations located at the coast, the other inland. Precipitation levels and numbers of days with precipitation are different. There are also different types of precipitation for stations from northern and southern parts of the country.
3. Topography is different.

For these reasons the refined models have limited applicability. The preference should be given to a robust model, which fits the variable geographical conditions throughout Norway.

We originally started with grouping the precipitation in classes, and looking at a linear relationship between air activity and deposition.

Deposited activity, y (Bq/m^2) per month was expressed as:

$$y=a*x,$$

where x is average air activity for that month (mBq/m^3)

Looking into making the a-factor a function of precipitation, we saw that a was an exponential function of precipitation, where:

$$a = b*e^{cz}$$

b is a constant (for no precipitation b becomes the dry deposition at the site), and z is monthly precipitation (mm/month). c varies for the different stations, but is in the range 0.0181 (Røros) to 0.0016 (Værnes).

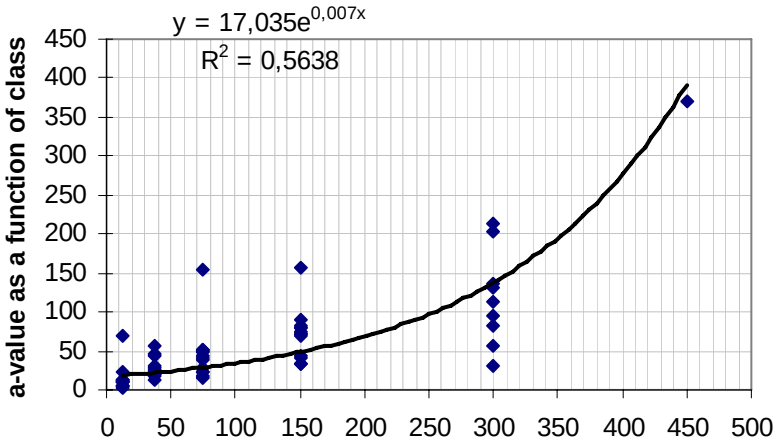


Figure 11. *a-value as a function of precipitation class, all sites*

Thus, the monthly deposition of total beta could be expressed as:

$$y=a_1*e^{bz}*x,$$

where a_1 and b are constants, x is average air activity for that month (mBq/m^3) and z is monthly precipitation (mm/month) for the same month.

Non-linear regression gave:

Site	a	b	Number of entries used
Bergen	30,775	0,006333	286
Bodø	14,288	0,006923	275
Finse	15,242	0,116767	90
Gardermoen	16,122	0,008154	272
Kjeller	12,536	0,010980	281
Sola	13,747	0,010635	253
Tromsø	24,479	0,008907	275
Vadsø	10,372	0,006495	217
Værnes	12,389	0,016147	275
Ålesund	5,576	0,013598	200
Ålesund corrected	18,723	0,00867	199 (one point removed)
Kjevik	29,033	0,00688	217
Røros	4,667	0,02122	150
Røros corrected	15,457	0,007023	149 (one point removed)
Bardufoss	20,412	0,01083	275
ALL SITES	**21,318**	**0,00761**	**2783**
All coastal sites	**23,201**	**0,00733**	**1780**
All inland sites	**16,0780**	**0,00916**	**1003**

2.6 Conclusions

There is an initiative to assess the deposition of radioactive fallout in Norway from nuclear weapons tests. So far, all available data on ^{137}Cs in air and precipitation has been collated, and relationships between ^{137}Cs and other radionuclides in fallout are well established. In order to further assess the deposition, it is necessary to model it based on non-radiometric measurements. Hence, it is of interest to study the relationship between radioactive deposition and precipitation. Several approaches have been considered in this regard, and it seems to be most prudent to divide the country into four distinctive regions, based on precipitation levels. The precipitation dependency of the deposition is found to be roughly uniform within these regions.

Acknowledgements

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3 Accumulated ^{90}Sr deposition in the Faroe Islands from nuclear weapons tests

Hans Pauli Joensen, Faculty of Science and Technology, University of the Faroe Islands.

3.1 Introduction

The Faroese environment has received anthropogenic radionuclides from the nuclear weapons tests and from the Chernobyl accident, primarily as wet deposition. The annual precipitation varies across the country, from around 820mm to around 3260mm (Lysgaard, 1969; Cappelen & Laursen, 1998). This implies large geographical variations in the concentrations of deposited radionuclides.

This study covers the pre-Chernobyl period. A relationship between total accumulated ^{90}Sr deposition and average annual precipitation is established at two Faroese sites with long time series of ^{90}Sr in rainwater. Using these as reference sites, estimates are given for total accumulated ^{90}Sr deposition at other sites, where no deposition data are available.

3.2 Material

The ^{90}Sr activity concentration has been measured in rainwater from the capital Tórshavn in the central part of the country and from Klaksvík in the north. The measurements go back to the early 1960's. Fig. 1 shows the pre-Chernobyl deposition time series.

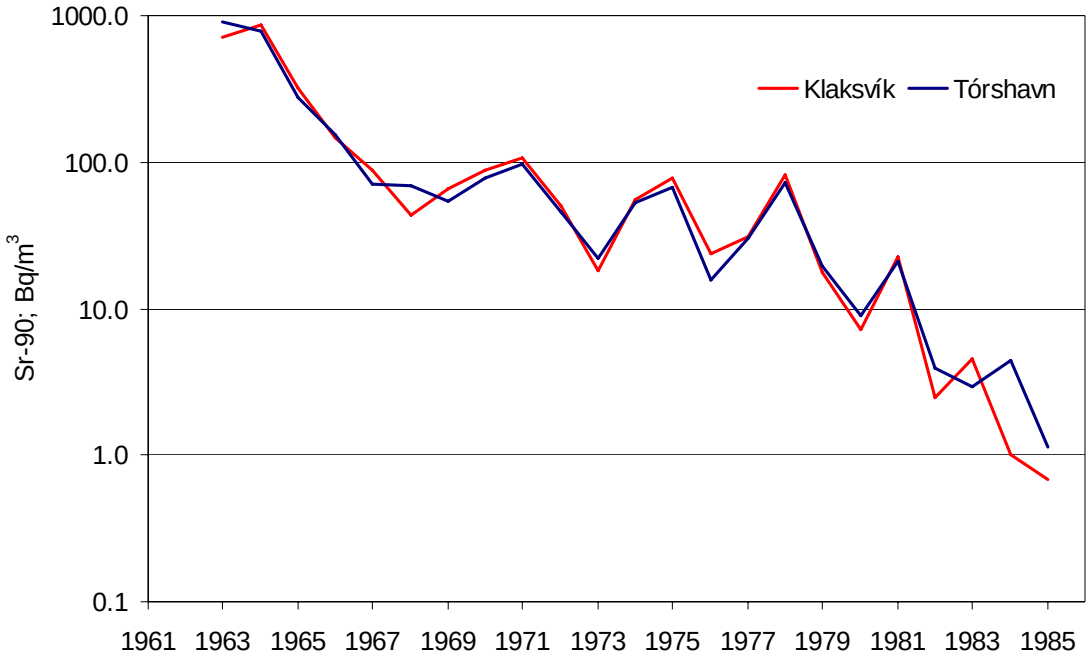

Figure 1. *^{90}Sr activity concentration in rainwater from Tórshavn and Klaksvík.*

The annual precipitation rates in Tórshavn, Klaksvík and five other sites are presented in Fig. 2. The highest precipitation rates are found in Klaksvík, and the lowest rates are observed in Akraberg in the south. The annual precipitation rates vary across the country with a factor around 3. The geographical locations of the selected sites can be seen in Fig. 3.

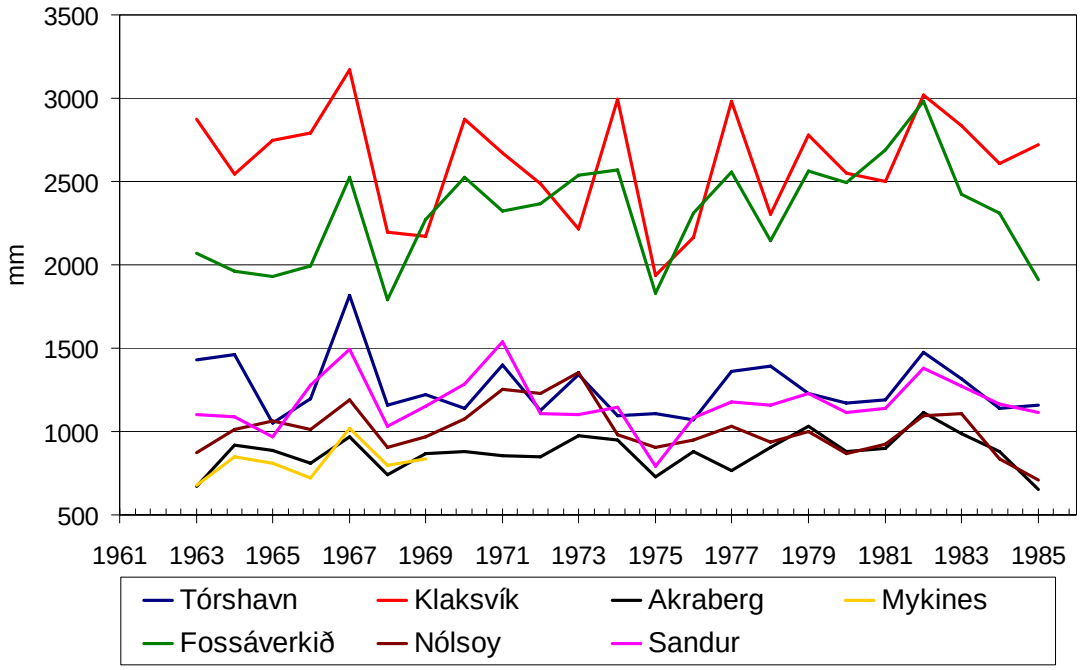

Figure 2. *Annual precipitation rates at selected sites. (Data from Cappelen & Laursen, 1998)*

The sites represent a wide spectrum of precipitation climate, and they have been incorporated in the synoptic weather measurement program of the Danish Meteorological Institute for many years, with the Tórshavn time series going back to the early beginning in 1875.

3.3 Methods

It has been shown that deposition from nuclear weapons tests is proportional to the precipitation rate, particularly at sites with high precipitation rates (Pálsson *et. al.*, in press; AMAP, 1998). A relationship between total annual deposition and annual precipitation rate is established at locations with concurrent time series for precipitation and deposition. Estimates of total annual deposition can then be calculated at sites with no observations of deposition, if precipitation time series are available for the sites.

According to Pálsson *et. al.*, the total accumulated annual decay corrected deposition (Bq/m^2) may be related to the average annual precipitation rate (m/y) in the following linear way:

$$D_R = k \cdot \overline{P_R} \qquad k = \frac{D_R}{\overline{P_R}} = \frac{1}{m}\sum C_{R_i} \qquad \overline{P_R} = m \cdot \frac{\sum_i w_i \cdot P_{R_i}}{\sum_i w_i}$$

R refers to a reference site. The index i specifies a given time period, and m is the number of time periods in a year. The weight factor w_i has the value 1 if the period i is selected in the calculations, and 0 otherwise. C_{Ri} is the (decay corrected) concentration in precipitation (Bq/m^3) of the given radionuclide at the reference site during period i. The method implies that k can be estimated without knowing the precipitation rates.

Figure 3. *The red spots show the locations involved in the study*

The periods 1963-69 and 1963-85 are considered in this study. Monthly values for precipitation and deposition are available for both periods. Thus m=12, and w_i is 1 for each month in each period and 0 otherwise. C_{Ri} is then the concentration at the reference site for month *i*.

3.4 Results

The ^{90}Sr activity concentrations in rainwater from Tórshavn and Klaksvík have been used to estimate the value of *k* in the model. The results are presented in Table 1.

Table 1. *The values of k as estimated from ^{90}Sr activity concentrations in rainwater from Tórshavn and Klaksvík. The activity concentrations are date corrected to 1 June 1962. The average value of k is also presented. The unit is Bq/m^3.*

Period	Tórshavn	Klaksvík	Average
1963-69	2318	2245	2282
1963-85	2861	2833	2847

The *k*-values are practically the same for both sites, and the average has been used in estimating the total accumulated annual deposition at the other five locations. The results are presented in Fig. 4.

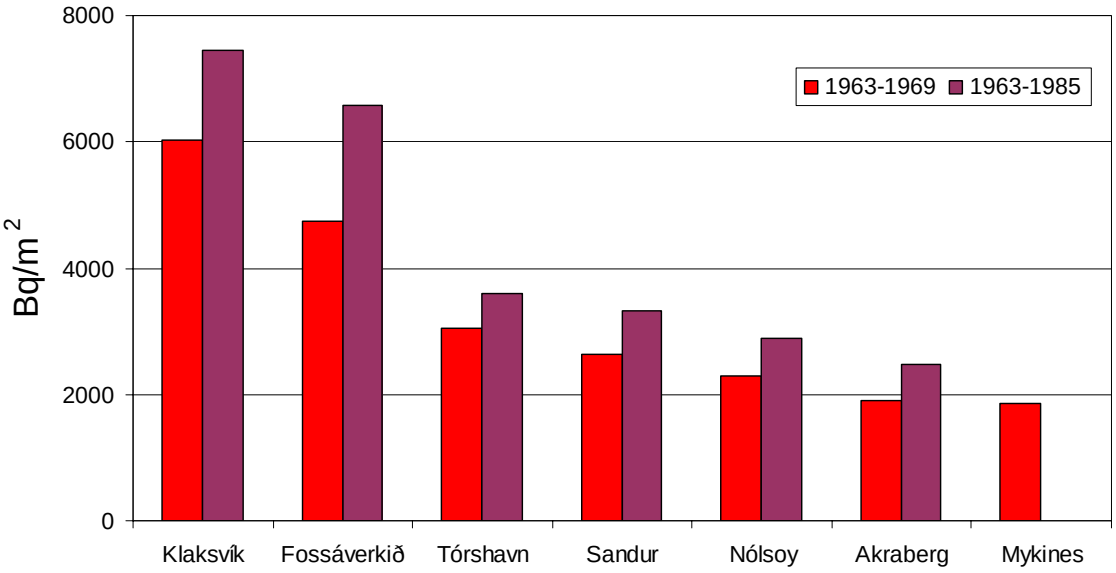

Figure 4. *Estimated accumulated annual ^{90}Sr deposition for two time periods at 7 sites in the Faroe Islands.*

As can be seen from Fig. 4, the major part of the ^{90}Sr deposition was acquired during the 1960's. The shorter period counts for 74-86% of the deposition between 1963 and 1985. No precipitation data were available for Mykines beyond 1969.

The highest deposition values are found in the northern part of the country. The lowest values are found for Akraberg and Mykines, respectively in the far south and the far west of the country. Both locations are characterized as being close to open sea, and exposed to wind from open sea. In the other end, Klaksvík is a site surrounded by mountains.

3.5 Conclusions

The suggested model for the relationship between total annual deposition and annual precipitation rate was established for two locations, giving consistent results for the parameter *k*. This should be expected, as the Faroe Islands cover a small geographical area. The average value of *k* was used in the model for other locations, and the accumulated decay corrected deposition at the sites was calculated to 1900-6000 Bq/m^2 and 2500-7400 Bq/m^2 for, respectively, the time periods 1963-69 and 1963-85. The precipitation rates vary among the sites by a factor of around 3. This is reflected in the ^{90}Sr deposition at the sites. The shorter period 1963-69 counts for 74-86% of the deposition between 1963 and 1985.

Acknowledgement

Thanks are extended to NKS for financial support and to the scientists in the EcoDoses group for valuable discussions.

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4 GIS supported calculations of ^{137}Cs deposition in Sweden 1962-1966 following nuclear weapon tests based on precipitation data

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4.1 Abstract

The spatial variation of the quarterly ^{137}Cs deposition over Sweden during the period 1962-1966 due to nuclear weapon tests was calculated in this study. Deposition maps over the Swedish territory was made with a Geographical Information System (GIS) using quarterly values of ^{137}Cs deposition per unit precipitation at four reference sites and values of quarterly precipitation at 62 weather stations distributed over Sweden. Sweden was divided into four areas related to each reference site. The extent of these areas varied with the seasons, depending on the distribution of mean measured precipitation 1961-1990.

The quarterly deposition density (Bq/m^2) was used for calculations of integrated (total) ^{137}Cs deposition density 1962-1966 and cumulative (decay corrected) deposition density 1962-1966 corrected for decay to 1985 and 1994. For comparisons with other studies, the integrated ^{137}Cs activity deposited over Sweden was calculated by multiplying the mean value of integrated ^{137}Cs deposition density over Sweden with the area of Sweden.

The lowest levels of integrated and cumulative ^{137}Cs deposition density were noted in the north-eastern and eastern Sweden and the highest levels in the western parts of Sweden.

Comparisons between the predicted values of this study show a good agreement with measured values and other studies.

4.2 Introduction

Methods of predicting the spatial variation in ^{137}Cs deposition following nuclear accidents or nuclear weapon explosions as accurate as possible are of highest interest. Such information is useful to calculate past deposition events as well as creating information systems for future situations in state of alert. An advantage of performing these predictions in a Geographical Information System (GIS) is the ability to easily vary the input of the model, such as precipitation and deposition density per mm precipitation, and quickly achieve a deposition map over an area of interest. The aim of this study is to predict the deposition of ^{137}Cs due to fallout from nuclear weapon tests 1962-1966 and visualize the results in deposition maps over Sweden.

4.3 Methods

The ^{137}Cs deposition maps were created using the ^{137}Cs deposition density per unit precipitation [Bq/m^2/mm] at four reference sites in Sweden and Norway: Kiruna, Vaernes, Göteborg and Grindsjön. These reference sites were chosen as they represented four different mean quarterly precipitation rates and because of their completeness in data. This approach takes into account that the precipitation rate would influence the transference of ^{137}Cs from air to precipitation. Each reference site represents an area of Sweden that shows the same quarterly mean precipitation rate as the reference site itself. At sites within these areas where precipitation is measured, the precipitation [mm] at each of those sites was multiplied with the ^{137}Cs deposition density per unit precipitation [Bq/m^2/mm] of the reference site to determine the ^{137}Cs deposition density [Bq/m^2] at the site. This calculation was carried out for each quarter of the period 1962-1966.

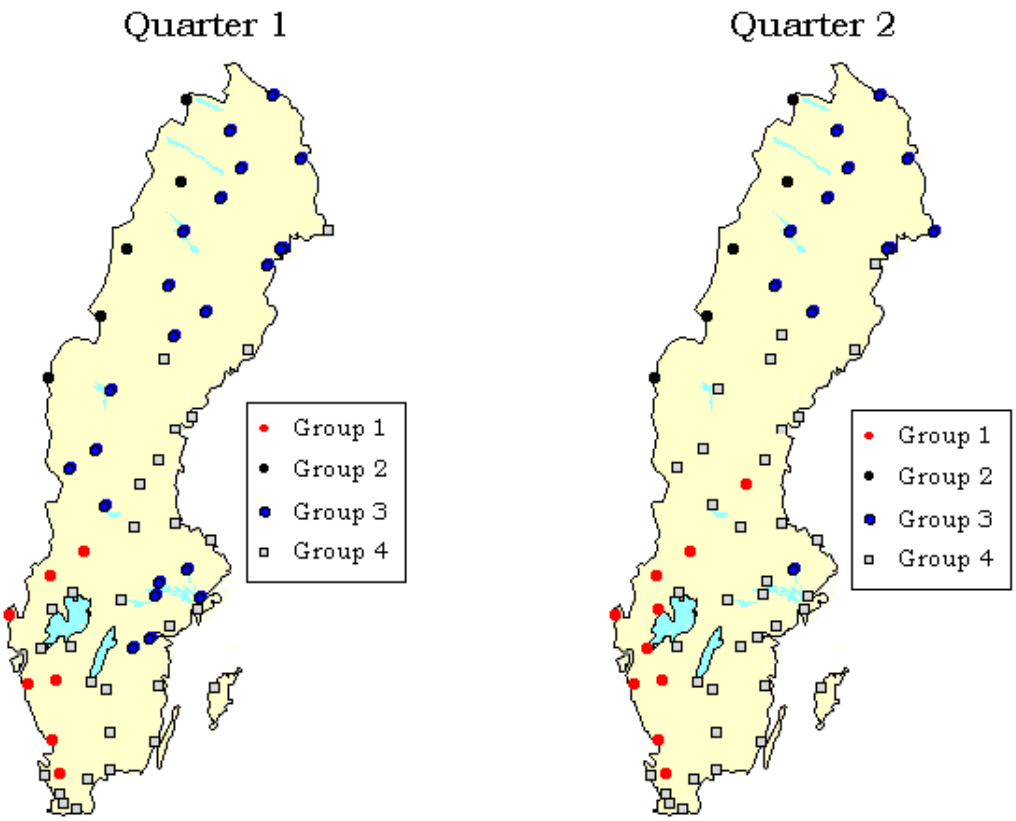
Data on quarterly deposition density [Bq/m^2] of ^{137}Cs during 1962-1966 was collected from measurements carried out by the National Defense Research Establishment (FOA74). To calculate the ^{137}Cs deposition density per unit precipitation [Bq/m^2/mm] of the reference sites, the data on quarterly deposition was combined with the data on total quarterly precipitation for the reference sites. As a base of the interpolations, data on the total quarterly precipitation during the years 1962-1966 for 61 weather stations distributed over Sweden was collected from the monthly journals of the Swedish Institute of Meteorology and Hydrology. The coordinates of the weather stations was collected from the Swedish Institute of Meteorology and Hydrology's list of weather station measuring precipitation (SMHI04). Data on Deposition per unit precipitation for Værnes, Norway (Bergan04) was also used in this study.

Concerning periods of time where data for one or more stations is missing, no attempt was made to estimate a value by comparisons with other stations. As discussed later on in this study, precipitation will be considered as a geostatistical variable. Therefore, substitutes for missing data should not be created through interpolation or other processes based on mathematical functions. Instead, the station/stations with missing data were excluded from the following interpolation procedures.

The interpolation was performed with ArcView GIS 3.3 (ESRI, Environmental Systems Research Institute, Redlands, California, ESRI04) and the ordinary kriging method with

exponential approximation to the semi-variogram. The choice of lag was 300 000 m and the minimum of sample counts in the interpolation calculations were 12 samples. The cell width of the interpolated grid was 6754 m and consisted of 227 rows and 97 columns.

The distribution of precipitation rates over Sweden varies with the seasons and therefore, the areas related to a certain reference point should also preferably vary with the seasons. From mean precipitation maps over the period 1961-1990 it is seen that the precipitation most often shows a pattern that form a western, an eastern, a northern area and an area representing the north-western mountains. Based on these areas, the weather stations were divided into groups according to Figure 1.



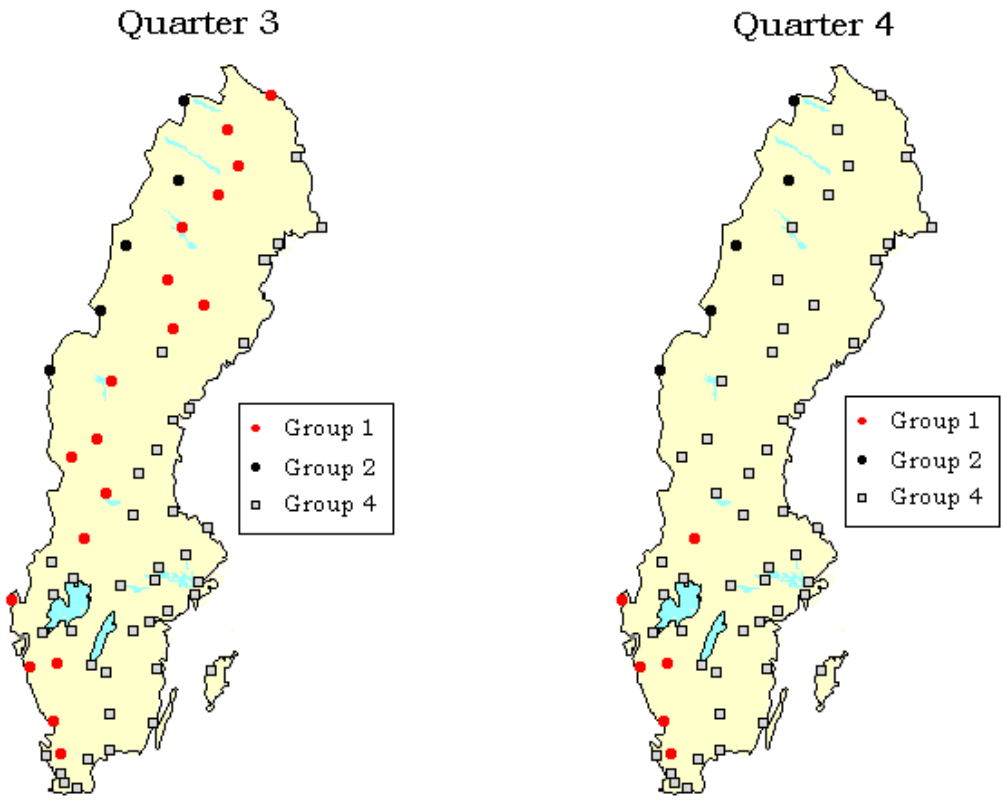


Figure 1. *The grouping of weather stations varies with the seasons according to the patterns of mean precipitation values of appendix A. Reference point of group 1 is Göteborg, group 2 Værnes, group 3 Kiruna and group 4 Grindsjön*

For the first and second quarters of the year, Göteborg was chosen as the reference point of the western group, Grindsjön as the reference point of the eastern group, Kiruna the reference point of the northern group and Norwegian Værnes was chosen as the reference point for the mountain area. For the third and fourth quarter, the spatial variation in precipitation rate was of such nature that no more than three groups were needed. In these quarters, Værnes, Göteborg and Grindsjön were used as reference sites.

Four alternatives were investigated. Alternative 1 involved all four reference points for the first and second quarter and three reference points for the third and fourth quarter. In alternative 2, the northwestern mountain area was integrated into the western area with Göteborg as reference point for the first and second quarter. During the third and fourth quarter the sampling stations were divided into an eastern and western area with Göteborg and Grindsjön as reference points. Thereby three reference sites, Göteborg, Kiruna och Grindsjön, were used for quarter 1 and 2, and two reference sites were used for quarter 3 and 4. Alternative 3 kept Göteborg as reference point for whole Sweden and alternative 4 kept Grindsjön as reference point for the same area.

4.4 Results & discussion

Comparisons made with measured values of ^{137}Cs deposition published by FOA (FOA74) shows a good agreement between predicted values brought out in this study and measured FOA values. The comparisons were performed with quarterly deposition density values of stations that did not serve as reference sites. Ljungbyhed, Tumba and Lycksele were used for this purpose. The value of R^2 = 0.92 of this study can be compared with the R^2= 0.96 of the Icelandic study (Pálsson02) and R^2=0.5071 of the AMAP study, keeping in mind the very different methods of sampling.

The interpolated values of deposition density of each cell, each quarter 1962-1966 according to the different alternatives were summed to calculate the integrated ^{137}Cs deposition density. An example of a map of integrated deposition density can be seen in Figure 2. The variance of the interpolation error grows stronger as the density of measurement stations lessens. A comparison with the results from the AMAP-study (Wright99) and from UNSCEAR (UNSCEAR93) is made in Table 1.

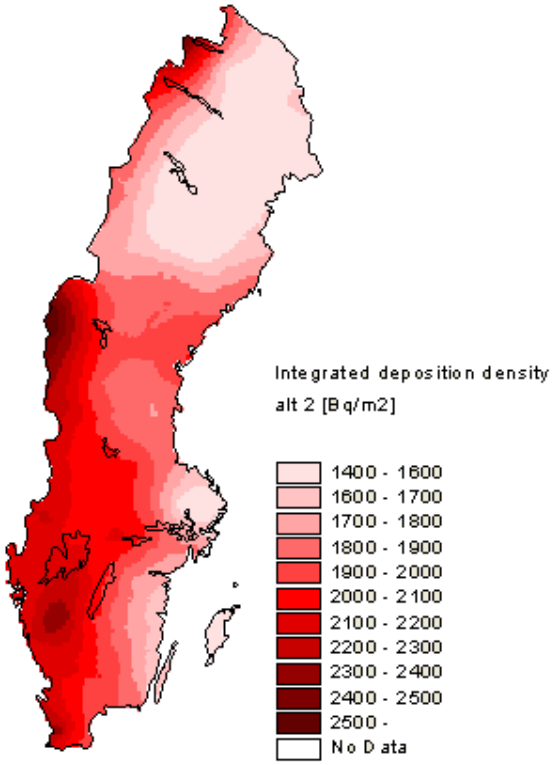


Figure 2. *Integrated deposition density of Cs-137 over Sweden during 1962-1966 interpolated according to alt. 2. Mean value: 1853 Bq/m^2 and range 1416 – 2695 Bq/m^2*

Table 1. *The integrated deposition of ^{137}Cs in Sweden, above 60ºN, due to nuclear weapon tests calculated for the different alternatives and the integrated deposition according to the UNSCEAR study and the AMAP study.*

Alternative	*Integrated deposition [PBq]*
1	1.19
2	1.16
3	1.13
4	1.22
AMAP	1.1
UNSCEAR	0.82

The interpolated values of each cell according to alternative 2, each quarter 1962-1966 were also decay corrected for 1985 and summed to calculate the cumulative ^{137}Cs deposition. Calculations were also performed concerning cumulative ^{137}Cs deposition decay corrected to 1994 showed in fig. 2. The mean value was 945.3 Bq/m^2 with the range 724.2-1369.9 Bq/m^2

A comparison was also made between the kriging interpolation procedure and an inverse distance weighted interpolation procedure. The differences is most apparent in the areas were we also notice higher values of the variance in the interpolation error. This comparison would serve as an indicator of locations needing a higher density of measuring sites.

The value of kBq/m^2 of ^{137}Cs per 1000 mm precipitation was calculated for the period 1962-1966 and decay corrected to 1966 to 2.35 Bq/m^2 per 1000 mm. Although not including deposition that occurred before 1962, this value is somewhat low compared with previously reported values. Wright et. al. (Wright99) reported 3.69 ± 0.97 Bq/m^2 per 1000 mm of the cumulative deposition for the period 1955-1985. T. Bergan (Bergan02) reported a value of 3.23 ± 1.2 Bq/m^2 per 1000 mm during the period 1955-1975.

4.5 Summary and conclusion

The Calculations performed in this study can be considered as successful comparing with other studies. The study shows lower values of R^2 than the Icelandic study, but higher values than the AMAP (Wright99) study. This could be expected since the resolution in measurement points of this study is somewhere in-between the two mentioned studies.

The conclusion gives some alternatives of interpolating the deposition density. Alternative 1 was considered as the most accurate, however, the uncertainty of its validity along with the interpolation method speaks against alternative 1. Recommending an alternative for interpolations is a complex issue, considering the uncertainties in the

materials of comparisons. However, comparisons between the predicted and measured values indicated that alternative 2 would make a good base for calculations of deposition.

The method investigated in this report represents a simplified model of the deposition. It could be interesting to study the influence of other meteorological parameters such as the difference between snowfall, rainfall and humidity. Also the topology of Sweden could influence the calculations. The grouping of the weather stations might be different if one also considers natural barriers such as mountains and ridges.

ArcView simplifies a rather extensive mathematical model by defining layers for each parameter, such as distribution of soil types, in the calculations. After interpolating the grid in an appropriate way, the calculations are consisting of basic matrix manipulation. With a more complete model, as discussed above, an estimation of the radiation dose to the Swedish population could be calculated.

In this study, it was found that alternatives with as many reference points as possible gave the best results of creating maps visualizing the ^{137}Cs deposition 1962-1966 due to nuclear weapon tests. The recommended alternative for interpolations would be alternative 2 with Kiruna, Göteborg and Grindsjön as reference points as the comparisons between measured and predicted values of deposition density showed a good agreement.

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5 Radionuclides in milk

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5.1 Introduction

Data concerning milk contaminated with caesium-137, strontium-90 and I-131 have been collated from all Nordic countries for both NWF and the post-Chernobyl period. All results have been registered in an excel database.

Information about time-series from Denmark, Faeroe Islands and Iceland is given in Bergan and Liland (2003). No new data from these countries have been collated for the present study. For Finland, concentrations of ^{137}Cs and ^{90}Sr from four regions are now available: Eastern, western, south-western and northern Finland. The new data series from western and eastern Finland consist of monthly samples of dairy milk. The western-Finland data cover the periods 1966-73 and 1978-2004, whereas data from the eastern region are only available for the period 1978-2004. The time-series from south-west Finland and Lappland (northern Finland) were described in Bergan and Liland (2003).

Unfortunately, only a limited amount of Swedish data from the NWF-period has been available for inclusion in the database. Since last year, series of quarterly measurements of ^{137}Cs from two regions have been collated - these data are from Stockholm and Malmöhus län and cover the time-periods 1958-2003 and 1962-2003, respectively.

In Norway, samples have been collected from many dairies and farms from most parts of the country. However, some of the time series are rather short. The longest and most consistent series were described in Bergan and Liland (2003). Since last year, more milk-data from the NWF-period have been discovered and these are now included in the database. The new data are time series of ^{137}Cs from 1962-68 and cover a large amount of dairies. Moreover, post-Chernobyl data from the Norwegian Institute for Food and Environmental Analysis are now included in the database. This is a large dataset consisting of more than 10 000 measurements of ^{137}Cs, ^{134}Cs and ^{131}I in different types of milk (i.e. consumer milk, dairy milk and farm milk) from most parts of Norway.

5.2 Summary of available data – Caesium-137 and strontium-90

Available data for ^{137}Cs and ^{90}Sr in cow`s milk from all the Nordic countries are shown in Figures 1 and 2, respectively. These are updated versions of the figures shown and discussed in Bergan and Liland (2003) – with the above mentioned data series included.

Figure 1. *Caesium-137 in cow`s milk from the Nordic countries*

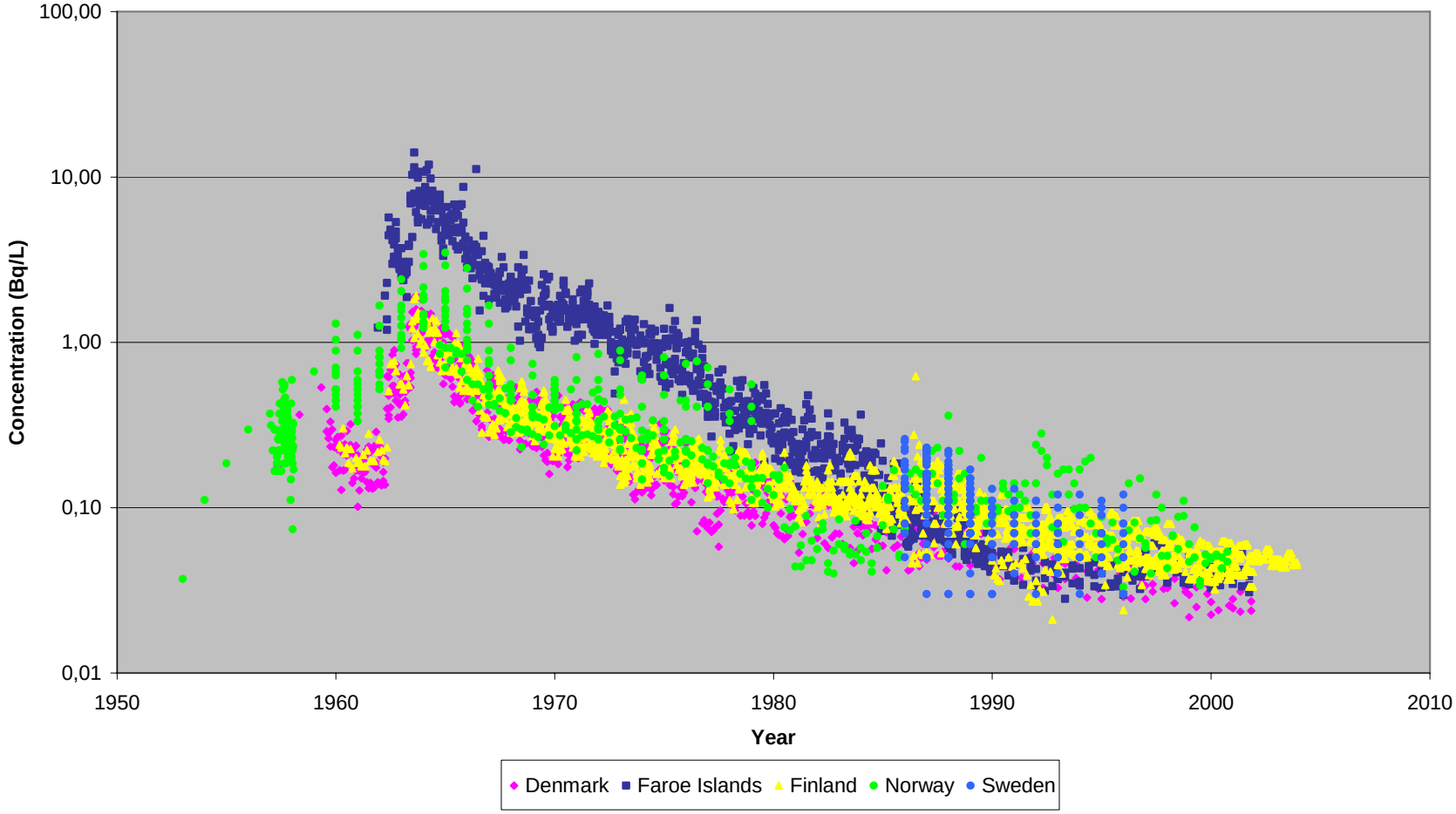

Figure 2. *Strontium-90 in cow`s milk from the Nordic countries*

5.3 Effective ecological half-lives of ^{137}Cs in cow's milk (post-Chernobyl)

Previous studies (e.g. Hansen and Andersson, 1994; Kostiainen and Rissanen, 2003) have shown that when using a single exponential approach, the effective ecological half-life increases with time. This suggests that there is actually a two-component decrease with one fast half-life early on followed by a longer component. A dual regression approach was thus used for the NWF-period to explain contamination developments with time in last year´s report (Bergan and Liland, 2003). A similar method was also applied in AMAP (2004).

It was decided to also use dual regression analyses for the post-Chernobyl time-series for the present work. The time-series most suitable for this approach were the two Danish series (Jutland and the Danish Islands), the three series from the Faeroe Islands (Thorshavn, Klaksvig and Tvøroyri) and four series from Finland (Rovaniemi, western, eastern and south-western Finland). These time-series are detailed and consistent for the period of interest (1986-present) - monthly values are generally reported. In addition three time-series from the large pool of Norwegian dairy milk data were selected, based on contamination levels and consistency, namely: Oslo, Fosheim, and Sandnessjøen. These series are, however, not as consistent as the other nine and a considerable fraction of the measurements are close to (and in some cases below) detection limits[1].

For all the analyses, SPSS 11.0 non-linear regression analysis was applied. To reduce the impact of inhomogeneous variance, the data were ln-transformed. The model expression was as follows:

$$Y = ln\left[A1^{-\frac{ln2 \cdot t}{T1}} + A2^{-\frac{ln2 \cdot t}{T2}} \right]$$

where,
A1: Start activity, component 1
T1: Effective ecological half-life for component 1 (fast component)
A2: Start activity, component 2
T2: Effective ecological half-life for component 2 (slow component)
t : Time elapsed since reference date

Since the milk data show considerable seasonal variation, the monthly values were combined to an annual average before the regression analysis was performed. For the Norwegian series only data from summer were available for the whole time-period. Starting point of the regression was 1986 (summer), end-point was according to the length of the available time-series (2002-2004).

[1] Detection limit has been about 1 Bq/l since 1990. Before that, the analytical uncertainty was higher (±1 Bq/l around zero).

Figure 3 shows the results for the time-series from Western Finland, Rovaniemi in northern Finland and Jutland in Denmark. The regression lines seem to represent the time development of ^{137}Cs-contamination in milk fairly well.

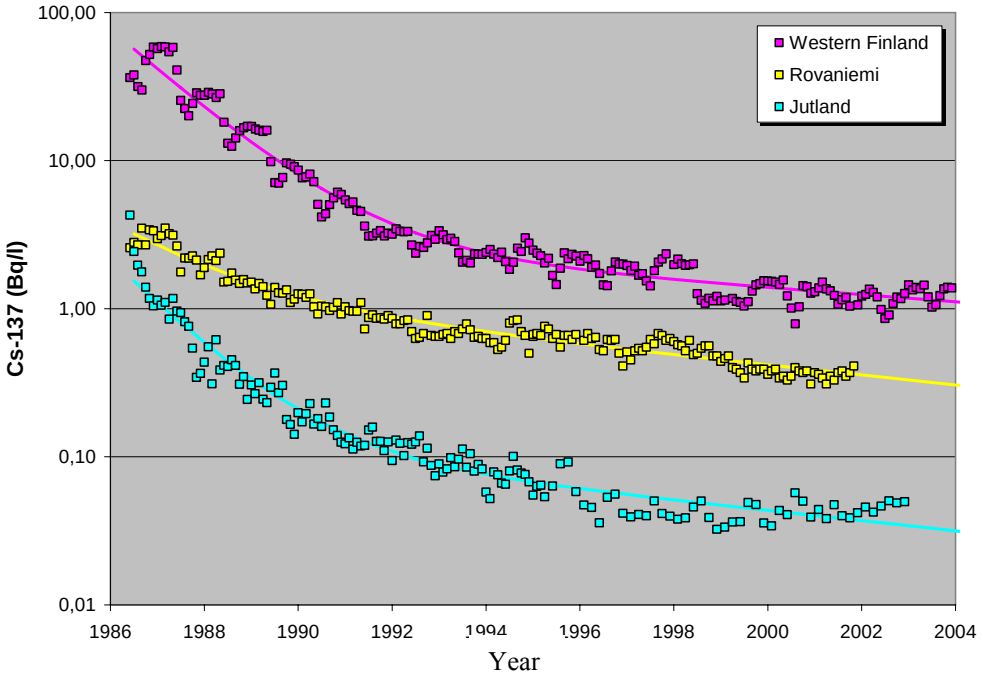

Figure 3. *Cesium-137 dual exponential regression analysis for three time-series after the Chernobyl accident*

Effective ecological half lives for all of the twelve investigated time-series (including the three above) are summarised in Table 1.

Table 1. *Effective ecological half lives for ^{137}Cs in milk from various Nordic areas*

	Effective ecological half-life 1±SE[2] (years)	**Effective ecological half-life 2±SE[2]** (years)
West-Denmark (Jutland)	1.0±0.1	8,8±1.3
East-Denmark (Islands)	0.5±0.0	6.6±0.6
Faroe Islands (Thorshavn)	1.1±0.2	8.0±1.0
Faroe Islands (Klaksvig)[3]	(1.4±0.3)	-
Faroe Islands (Tvøroyri)[3]	(1.6±0.2)	-

[2] Asymptotic standard error

[3] T2 showed anomalous results with very large appurtenant standard error and has not been presented. T1 is therefore presented in brackets.

North Finland (Rovaniemi)	1.3±0.2	9.0±1.0
West Finland	1.1±0.1	13±2
East Finland	0.8±0.1	8.3±0.7
South-West Finland[3]	(1.1±0.1)	-
Norway (Oslo)[3]	(1.1±0.2)	-
Norway (Fosheim)[3]	(1.7±0.4)	-
Norway (Sandnessjøen)[4]	-	-

Looking at the results (Table 1), we see that T1 is around 1 year for all sites. There seem to be geographical variations for the long component (T2). The shortest T2 half-life is for the Danish Islands (about 7 years), while the data from western Finland gives a T2 half-life of about 13 years. However, some of the dual regression analyses did not give satisfactory (or even "meaningful") effective ecological half lives for the slow component (T2). This, for instance, applies to the series from South-western Finland and Tvøroyri (Faeroe Islands). For these two series, no decrease in concentrations of ^{137}Cs was observed for recent years (Figure 4). Accordingly T2 will be very high (with a large appurtenant uncertainty), and practically useless for our purpose.

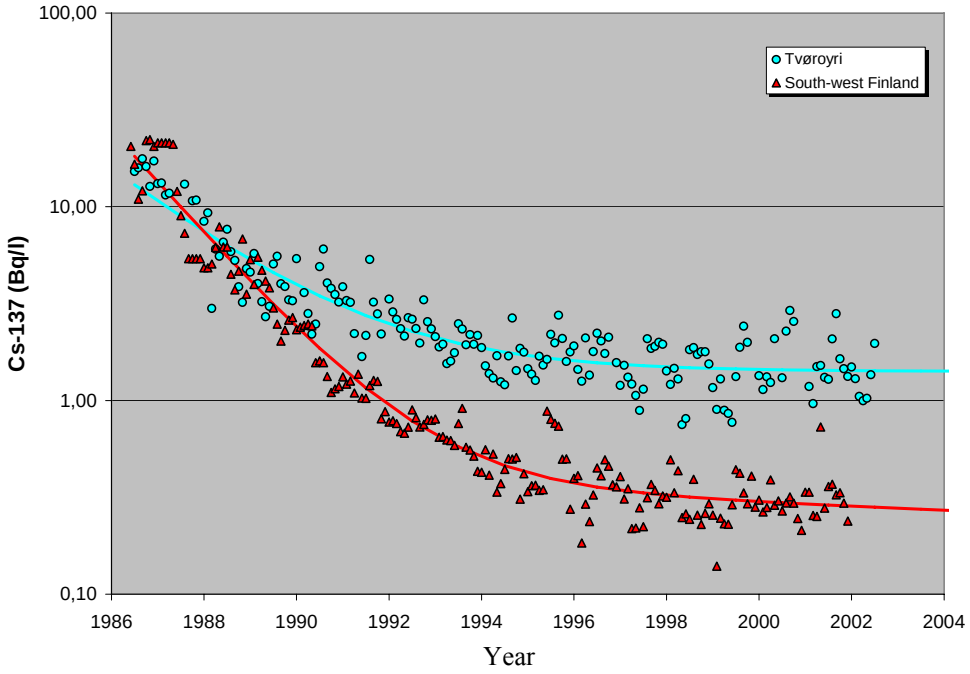

Figure 4. Cs-137 in milk from two locations where anomalous effective half lives for the "slow component" were observed. Estimated dual exponential regression lines are indicated.

[4] Dual exponential regression not suitable

Two of the Norwegian data-series (Oslo and Fosheim) seem to follow a similar trend as shown in Figure 4. For the third series (i.e. Sandnessjøen) – the method of dual exponential regression analysis proved inapplicable. A single component analysis was more appropriate. The estimated effective ecological half life using a single component approach was 3.4±0.2 years for Sandnessjøen (1986-2004). No considerable change in ecological half-life was observed when adjusting the starting point to 1990 or 1992 (indicating a single component decrease of ^{137}Cs). For the other two Norwegian series, single component analyses gave effective ecological half lives of 3.2±0.2 and 3.5±0.3 years for Oslo and Fosheim, respectively (For these series, the effective ecological half-lives increased when the starting point of regression was shifted to 1990 and 1992).

Finally, a recent study by Gjelsvik (in prep.) using data from the Norwegian "Summer monitoring programme"[5] has shown that effective ecological half-lives for farm milk from Nordland (1991-2004) and Oppland (1989-2004) were 6.6±0.6 years and 10.1±1.5 years, respectively. Since this monitoring programme was initiated several years after the Chernobyl accident, a dual exponential approach was not applicable for the study.

5.4 Iodine-131

Iodine-131 measurements in milk from the NWF period and to some extent post-Chernobyl were presented in last year's report. For the present study, post-Chernobyl ^{131}I measurements from Norway will be presented in more detail:

The first two month after the Chernobyl accident more than 400 milk samples were analysed for iodine-131 in Norway (Bråthen and Stray-Pedersen, 1989). All measurements - categorised according to type of milk, are shown in Figure 5.

[5] Time-series from the Summer monitoring programme are also included in the EcoDoses database

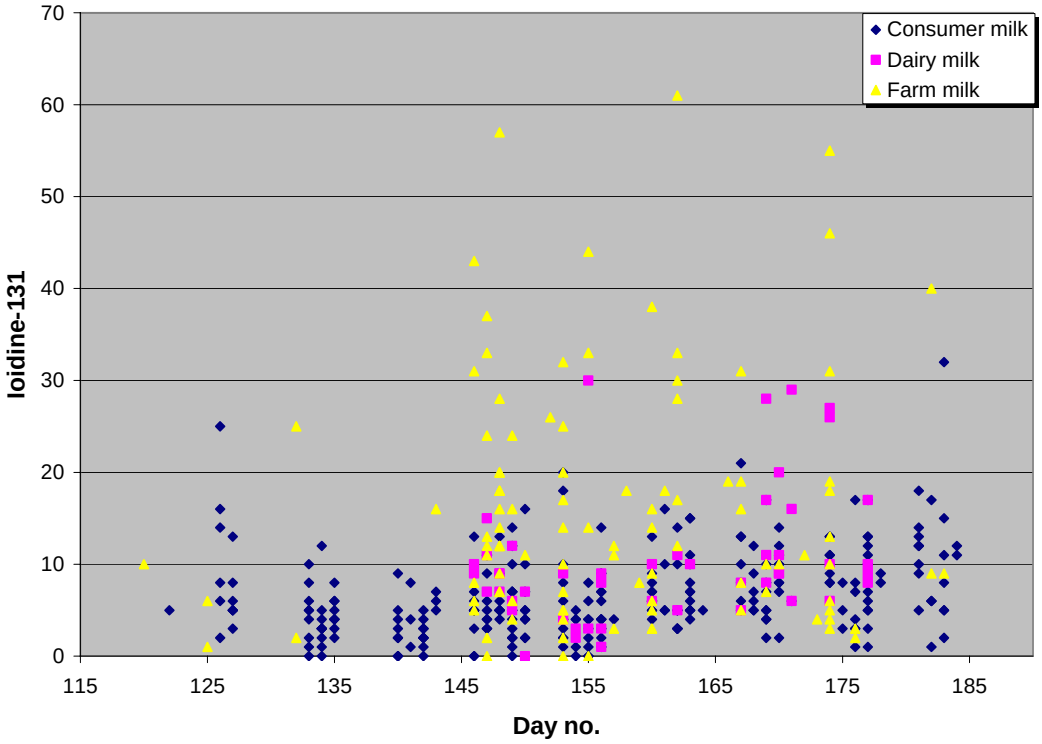

Figure 5. *Activity concentrations of Iodine-131 in cow`s milk from Norway (Bq/l)*

The highest levels of ^{131}I in Norwegian milk was found in farm milk (up to 61 Bq/l), whereas the highest levels in dairy milk/consumer milk were about 30 Bq/l. Time-trends of ^{131}I in consumer milk from selected dairies are shown in Figure 6.

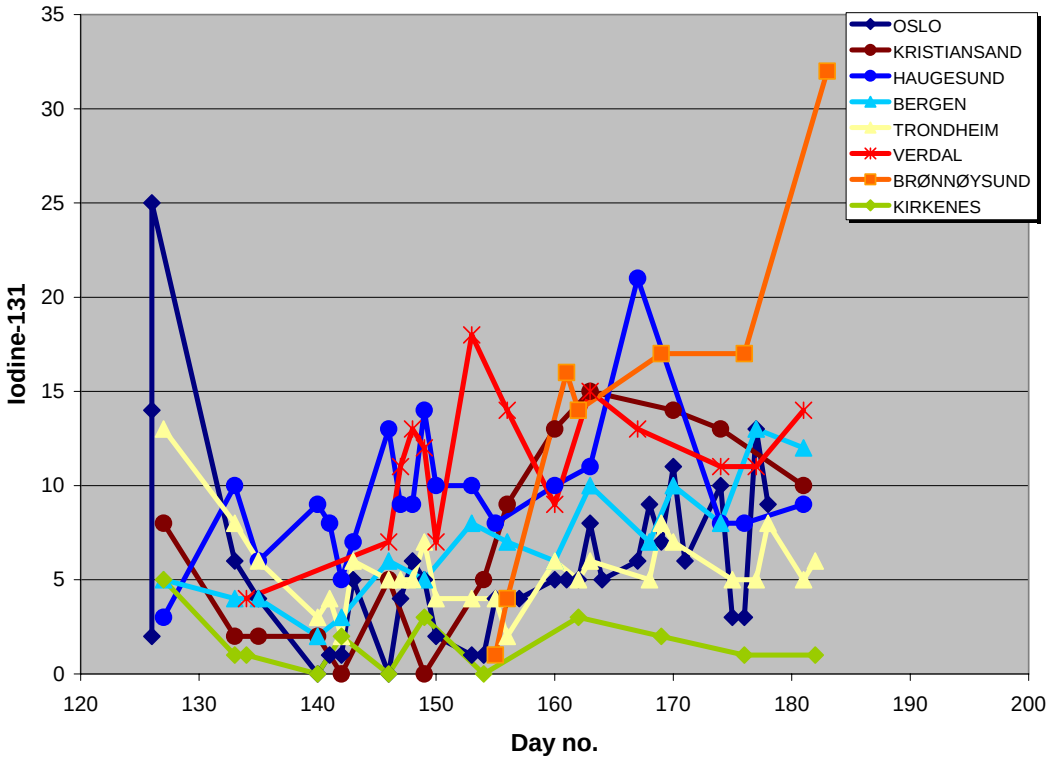

Figure 6. *Activity concentrations of I-131 (Bq/l) in consumer milk from 8 dairies in different parts of Norway (1986).*

As shown in Figure 6, there seem to be an increase of ^{131}I in milk from May-July 1986, rather than a decrease – as should be expected from the short radioactive half-life for this nuclide (8.1 days). However, at the time of the Chernobyl accident most dairy cows in Norway were inside, and the only exposure pathways for iodine-131 were through air and water. Later, when the animals were let out the levels in milk started increasing as a result of intake of contaminated grass. In many areas of Norway, levels of ^{131}I in grass were still high (even after several half lives of ^{131}I). Consequently, if the fallout had occurred in June or July there would have been much higher levels of ^{131}I in Norwegian milk after the Chernobyl accident (Bråthen & Stray-Pedersen, 1989).

5.5 Conclusions

Activity concentrations of ^{137}Cs, ^{90}Sr and ^{131}I in milk from all Nordic countries for the NWF and the post-Chernobyl periods have previously been collated in an excel database. In 2004 the database was further extended by including new data from Finland, Sweden and Norway. In order to explain the time development of contamination in different Nordic regions dual regression analyses of some selected time-series were performed. Since the NWF period was subject to similar investigations in previous year's report, the present study focused on the post-Chernobyl period (1986-). Effective ecological half

lives of Cs-137 in milk from 12 regions were estimated. The fast component (T1) was about 1 year for all series (except Sandnessjøen in Norway), while the slow component (T2) was more variable (7-13 years) - and in some cases not applicable.

Acknowledgements

This work has been supported by NKS. Thanks to the scientists in the EcoDoses group for providing milk data from their respective countries.

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6 Modelling integrated transfer of ^{137}Cs to cows milk in the Faroe Islands, Norway and Sweden

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6.1 Introduction

The terrestrial environments in Norway, Sweden and the Faroe Islands have received radioactive debris from the nuclear weapons tests and from the Chernobyl accident 26 April 1986. This study uses the UNSCEAR model to estimate the integrated transfer coefficients of ^{137}Cs from wet deposition to cows milk from selected sites in the three countries. The model relates the concentration of a radionuclide in a sample from a given year to the deposition rate of the radionuclide from precipitation in the given year and in the year before, and to the accumulated deposition from previous years.

6.2 Material

The data for the study cover ^{137}Cs activity concentration in cow milk (Bq/liter) from Bodø in Norway, Malmö and Stockholm in Sweden, and from Klaksvík, Tórshavn and Tvøroyri in the Faroe Islands (respectively in the north, middle and south of the Faroe Islands). Observations of wet depositions (Bq/m^2) were available from the sites in Norway and the Faroe Islands. Wet deposition data from Risø in Denmark were used as representative for Malmö. No deposition data series were available for Stockholm. The observations are presented in Figs. 1 and 2.

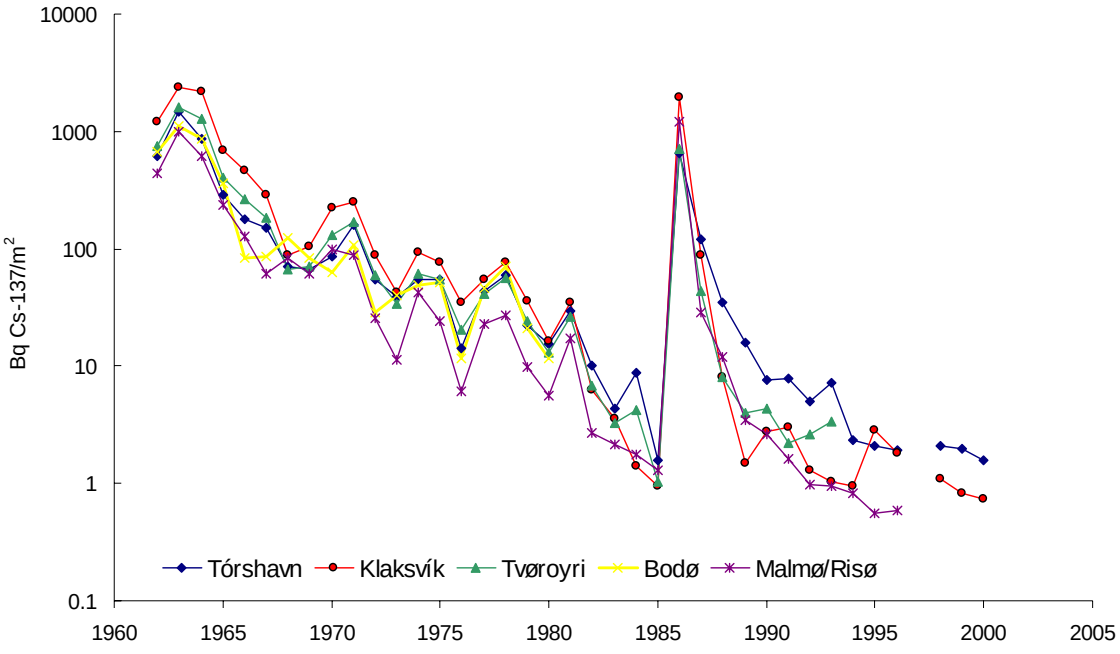

Figure 1. *Annual ^{137}Cs deposition at the sites. Observations at Risø in Denmark have been used to represent Malmö in Sweden.*

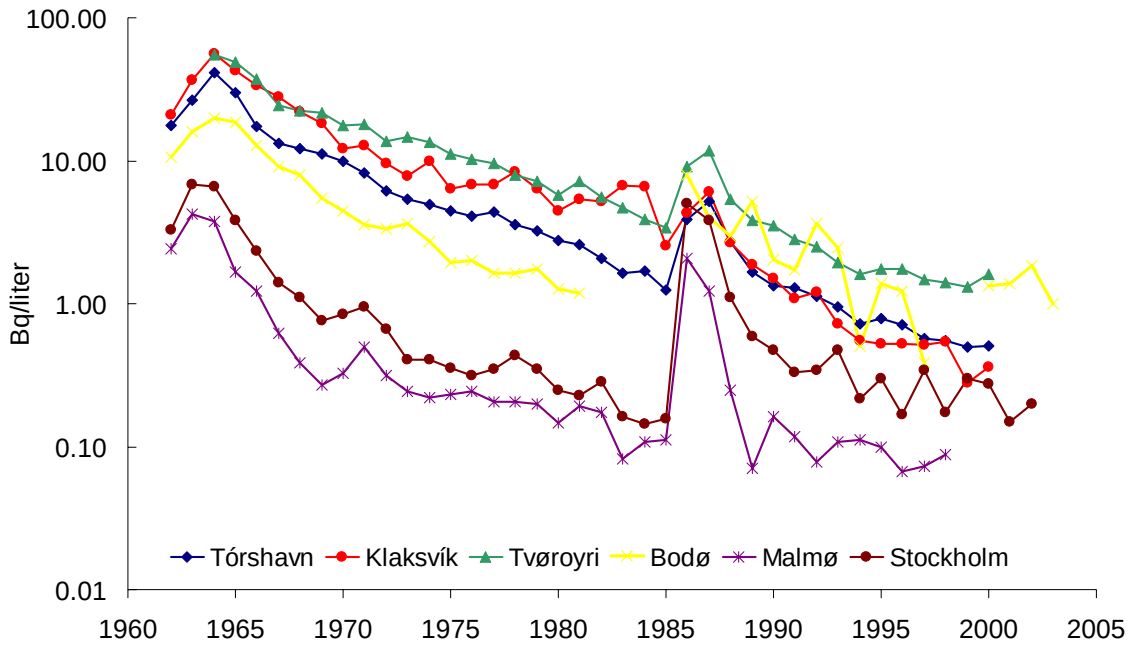

Figure 2. *Cs-137 activity in cows milk from the sites. Stockholm have been included for comparisons, although no deposition data were available from Stockholm.*

Milk data from Klaksvík and Tvøroyri derive from samples from local producers, while data from Tórshavn derive from a dairy collecting milk across the country. The milk samples from Bodø and Malmö are dairy samples.

Maximum deposition values were observed in 1963 at all the selected sites. The ^{137}Cs deposition levels in 1986 were similar to the values in the early 1960's, but the early decrease was faster after the Chernobyl accident. This should be related to the fact that fallout from the Chernobyl accident came from an explosion of a nuclear reactor while the nuclear weapons fallout derives from tests carried out in a period of several years. No deposition data were available from Bodø after 1980.

The ^{137}Cs activity concentration in milk follows the same general trend with time as the ^{137}Cs deposition. The ^{137}Cs activity in milk from Klaksvík does, however, not reflect the signal in wet deposition in Klaksvík after the Chernobyl accident. This may partly be due to a different feeding practice of the cows in Klaksvík just after the Chernobyl accident, but a more complete explanation remains to be found.

The highest ^{137}Cs activity concentration in milk is found at the Faroese sites, while the lowest concentrations are found at the Swedish sites. The concentration was at maximum in 1964 at all sites, with the fastest early decrease in Sweden. The largest impact from the Chernobyl accident was observed in Swedish milk, with lower concentrations in Malmö as compared to Stockholm, and with an increased difference between the two Swedish sites after 1986. The maximum concentrations in milk after the Chernobyl accident occurred in 1987 in the Faroe Islands and in 1986 in Norway and Sweden.

6.3 Method

The relation between radioactivity in a sample and fallout rates is modelled as follows (UNSCEAR, 1977; Aarkrog, 1979; AMAP, 1998):

$$C_i = b_1 \cdot d_i + b_2 \cdot d_{i-1} + b_3 \cdot \sum_{k=1}^{k=\infty} d_{i-k} \cdot e^{-\lambda \cdot k} \qquad (1)$$

The index i corresponds to a given year, C_i is the concentration of a radionuclide in a sample from year i, d_i is the observed fallout rate (kBq/m^2) in year i, λ is the decay constant $\lambda = \ln(2)/T$, and T is an estimated effective halflife of the considered radionuclide, as determined from the multi-regression analyses between concurrent observations of wet deposition and activity concentration in milk. The summation is carried out over the deposition of all preceding years, each weighted by an exponential term describing the combined physical decay of the radionuclide and any decrease in the availability to the foodstuff.

The model-based estimate of the integrated transfer coefficient (ITC) of a radionuclide from fallout to foodstuff is given by:

$$ITC = b_1 + b_2 + b_3 \cdot e^{-\lambda} (1-e^{-\lambda}) \qquad (2)$$

6.4 Results

The results are presented in Table 1 and Figs. 3-7, showing fairly good correlation between observations and model. As seen from Figs. 3-7, the model generally overestimates the activity concentration in milk after 1985. The results express a geographical variation of the ITC's, also within the Faroe Islands, although the country has a total geographical extent of only 1399 km^2. The highest and lowest ITC's are found in Tvøroyri and Malmö, respectively. The value in Tvøroyri is one order of magnitude higher than the value from Malmö. The estimated effective radioecological halflife of ^{137}Cs is shortest in Bodø (2.0 years) and longest in Malmö (17 years). It should be noted that wet deposition at Risø in Denmark was used in the model for Malmö, and this may affect the estimates found for Malmö.

Table 1. *Model-calculated integrated transfer coefficients (ITC). T is the estimated effective ecological half-life in years. The coefficients in the model are given by b_1, b_2 and b_3. R^2 is the square regression coefficient. p-values are given in brackets for the b_1, b_2 and b_3.*

	b_1	b_2	b_3	T Years	R^2	ITC (Bq/l)y per kBq/m^2
Tvøroyri	0.00829 (0.04)	0.02101 (<0.0001)	0.00546 (<0.0001)	4.5	0.992	62.1
Tórshavn	0.00944 (<0.0001)	0.01889 (<0.0001)	0.00359 (<0.0001)	3.5	0.989	44.7
Klaksvík	0.00829 (<0.0001)	0.01010 (<0.0001)	0.00383 (<0.0001)	3.0	0.983	33.1
Bodø	0.00694 (<0.0001)	0.00719 (<0.0001)	0.00422 (<0.0001)	2.0	0.991	24.3
Malmö	0.00396 (<0.0001)	0.00120 (<0.0001)	$3.77 \cdot 10^{-5}$ (0.02)	17	0.989	6.07

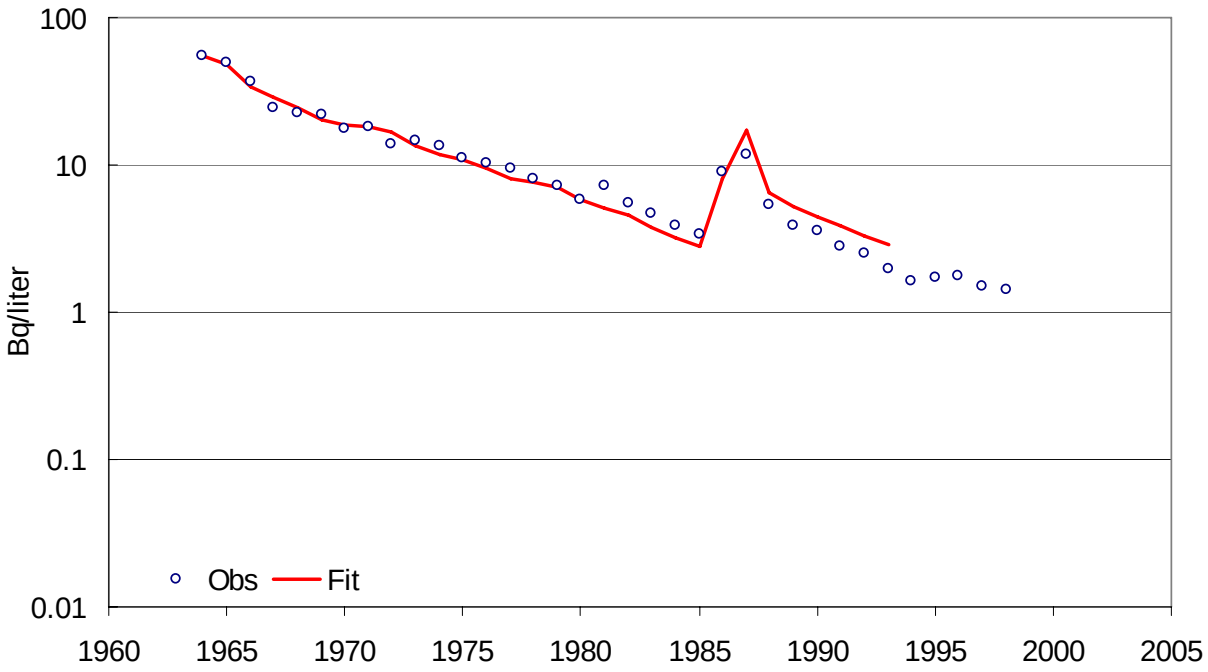

Figure 3. *Cs-137 in milk from Tvøroyri. Observations and model results.*

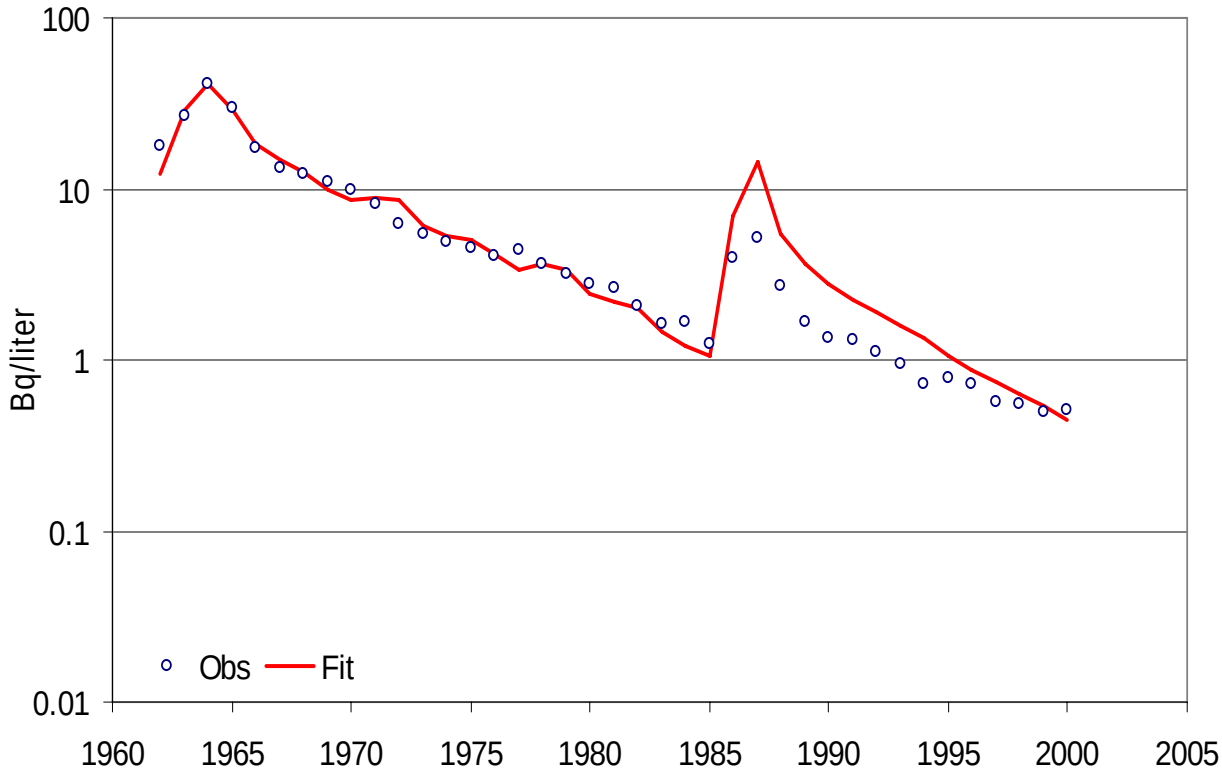

Figure 4. *Cs-137 in milk from Tórshavn. Observations and model results.*

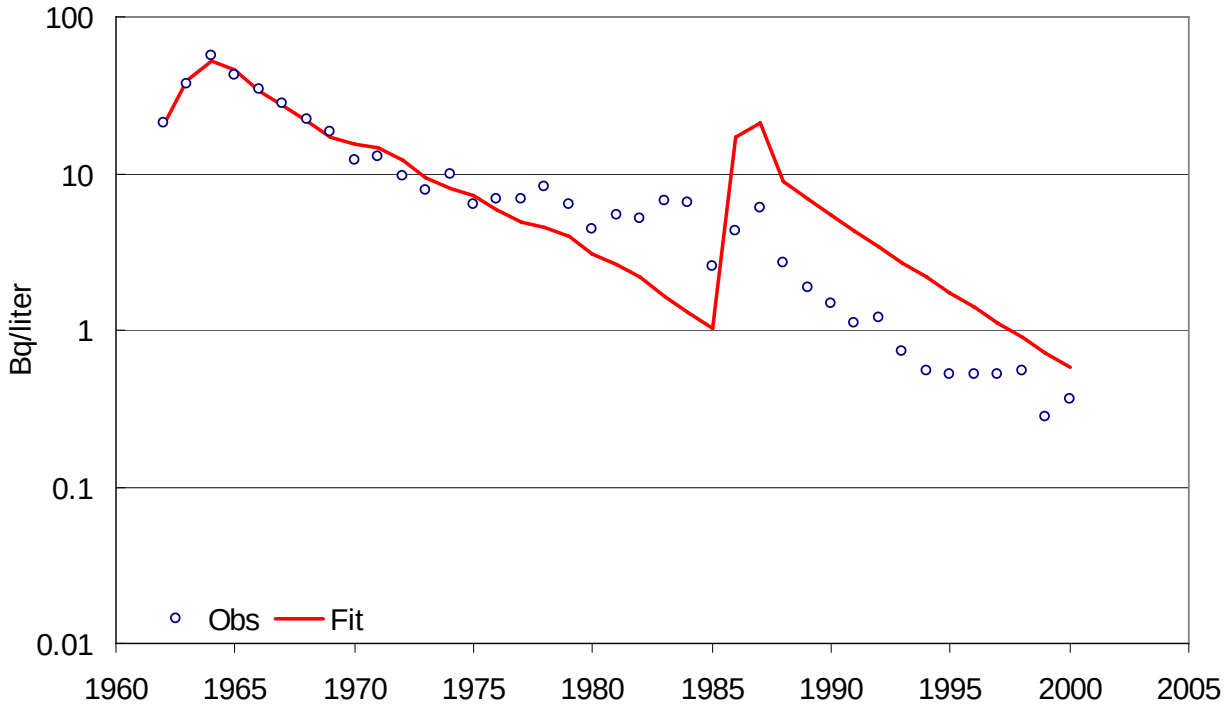

Figure 5. *Cs-137 in milk from Klaksvík. Observations and model results.*

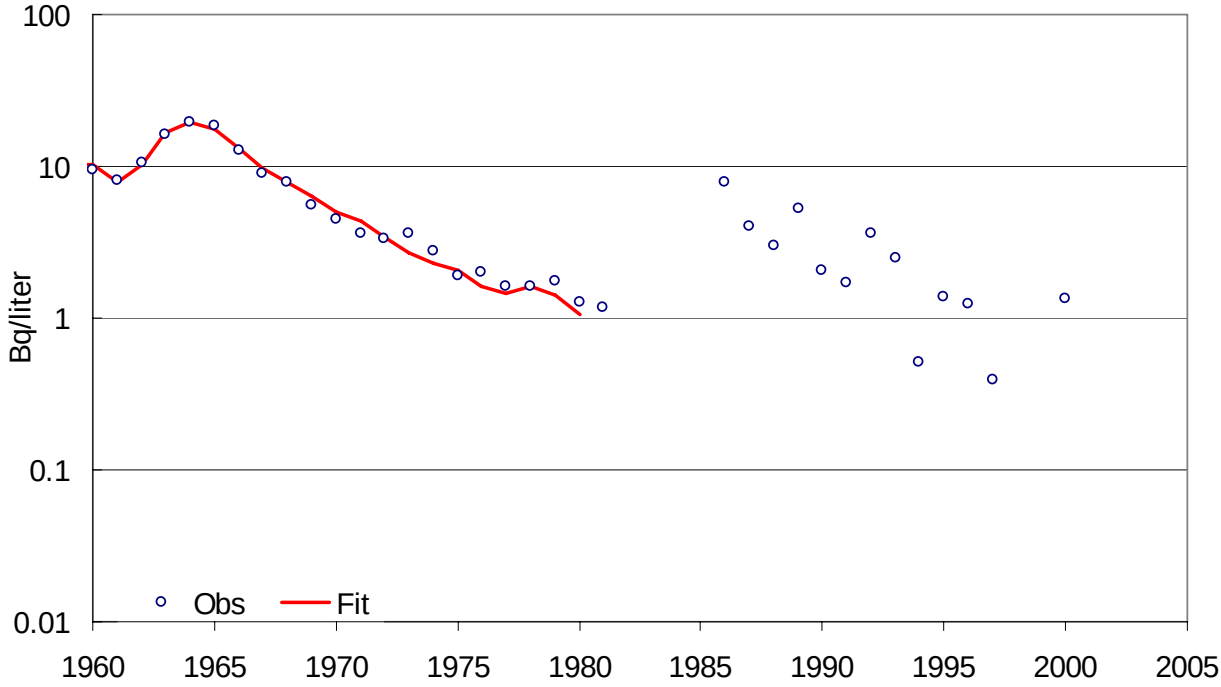

Figure 6. *Cs-137 in milk from Bodø. Observations and model results. No deposition data were available from Bodø after 1980.*

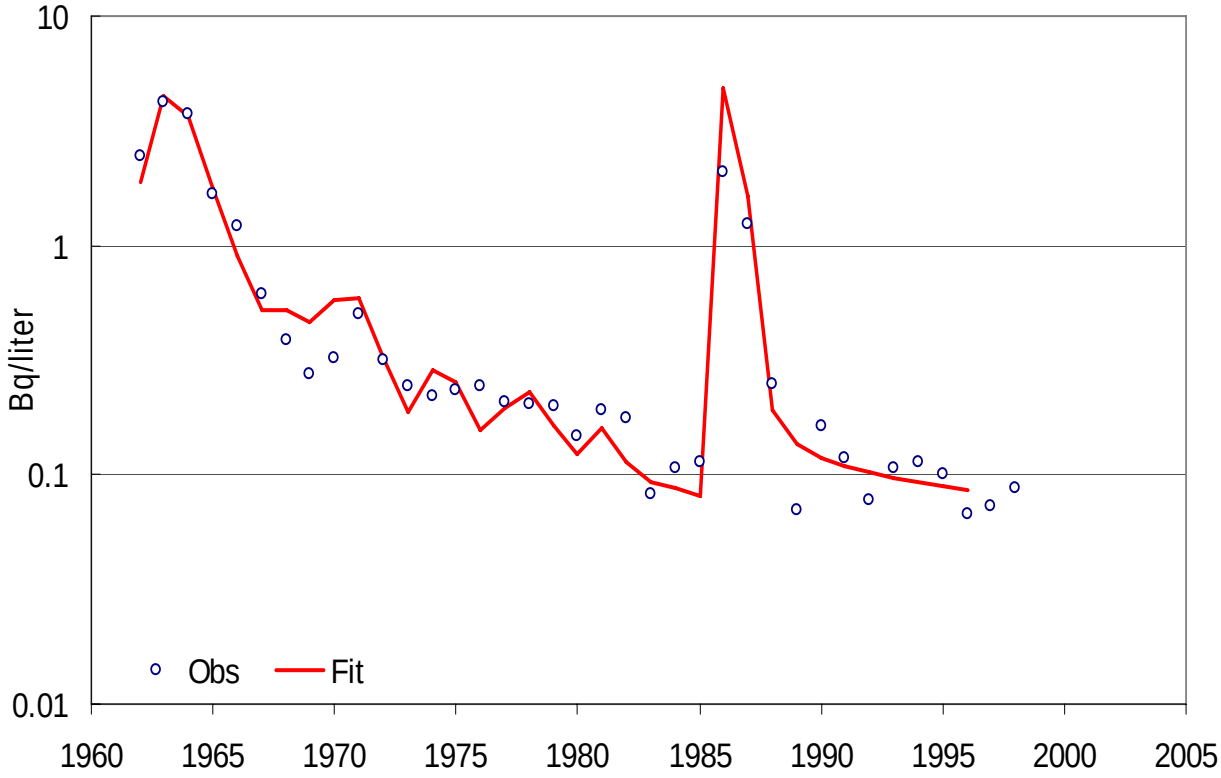

Figure 7. *Cs-137 in milk from Malmö. Observations and model results.*

6.5 Conclusions

The integrated transfer coefficients are found to be higher at the Faroese sites than at the Norwegian and Swedish sites, indicating relatively high individual doses from ingestion of milk in the Faroe Islands.

The integrated transfer coefficients of ^{137}Cs to cow milk in the Faroe Islands are also high compared to other countries. UNSCEAR, 1977, reports ITC for cow milk in different countries around the world, using the unit $Bq(gK)^{-1}y$ per $kBq \cdot m^{-2}$. UNSCEAR reports the highest value of 27.51 for the Faroe Islands followed by 15.48 for Norway. The lowest value of 3.23 was reported for Denmark.

The ITC's are found to vary also within small geographical areas. They vary with a factor of two between the Faroese sites. The reason for this may partly be due to differences in the soil characteristics at the localities. This could, however, not be tested in the present study because of lack of data.

Acknowledgements

Thanks are extended to the Nordic Nuclear Safety Research (NKS) for financial support of the study. Thanks are also due to colleagues in the NKS EcoDoses group for valuable discussions.

6.6 References

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7 Cs-137 in freshwater fish in Finland, Norway and Faroe Islands with examples of ecological halftimes

Ritva Saxén, Astrid Liland, Håvard Thørring, Hans Pauli Joensen

7.1 Finland

7.1.1 Introduction

The deposition from Chernobyl in spring 1986 was most unevenly distributed in Finland and elevated the ^{137}Cs contents of freshwater fishes significantly. Finland can be divided into five categories on the basis of the average deposition of ^{137}Cs in each municipality [1] (Figure 1).

Radiocesium in fish has been regularly studied at STUK since the Chernobyl deposition in 1986 [2-5]. More than 6000 fish samples from approximately 350 lakes have been analysed for ^{137}Cs after the Chernobyl accident in Finland. This is a relatively small number of lakes compared to the fact that in Finland there are more than 180 000 lakes larger than 500 m^2, and 2 300 lakes larger than 1 km^2, and a few very large lakes, around 1000 km^2 by area [6]. From certain lakes long-term follow-up was carried out. This gives a possibility to estimate ecological halftimes of ^{137}Cs observed in fish from various lakes. The ecological halftime is not a constant, but changes with time, therefore, it is necessary to give the time interval for which the ecological halftimes are estimated. Consequently, to estimate differences in the recovery rate of various lakes, it is necessary to compare the halftimes estimated for the same time interval.

7.1.2 Sampling in 1998 - 2002

In 1998 and 2002 also water of the lakes sampled for fishes were analysed for ^{137}Cs to get a picture on the variation range of ^{137}Cs both in water and in fishes when several processes have affected on the distribution of the deposited ^{137}Cs. Concentration factors from water to perch 12-16 years after the deposition were determined.

The lakes studied for fish and water in 1998 and/or 2002 are located in southern and central parts of Finland (Figure 1). All the five deposition categories (Fig. 1) are represented by the lakes. Both large lakes, being most important for freshwater fishing, and a few relatively small lakes were included in the study.

7.1.3 ^{137}Cs in fish and lake water

Activity concentrations of ^{137}Cs in lake waters varied from 4 to 330 Bq/m^3 in 1998 and 2002 (Figure 2 and Table 1). ^{137}Cs was highest in lakes Vehkajärvi and Siikajärvi, which are located in the area of the highest deposition in Finland, and lowest in lakes from eastern Finland with a low deposition. Deficiency of nutrients in water, abundance of humic substances and/or low sedimentation rate were recognized characteristics in certain

lakes with relatively high ^{137}Cs concentrations in water in 2002 in addition to the high deposition of ^{137}Cs in the area.

Contents of ^{137}Cs in perch *(Perca fluviatilis)* from various lakes varied from 19 to 1 700 and from 38 to 7 800 Bq/kg in 1998 and 2002, respectively (Figure 2 and Table 1). Each sample consisted of several individual fishes. ^{137}Cs in perch in 2002 from various lakes varied by a factor of 200, although the original amount deposited in the sampling municipalities varied by a factor of 50.

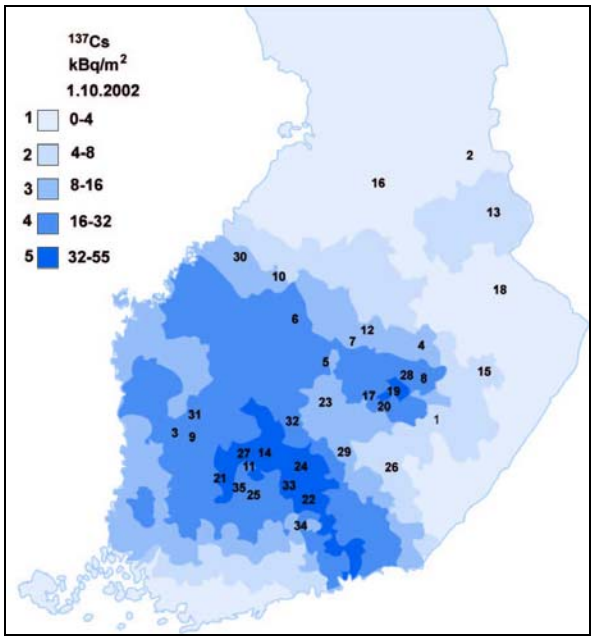


Figure 1. *Location and size of the lakes sampled for water and fishes in 1998 and/or 2002 and the five deposition areas of ^{137}Cs in Finland [1], corrected for radioactive decay to October 1, 2002. Areas of the lakes are taken from [6].*

	km^2		km^2		km^2
1. Haukivesi	620	13. Ontojärvi	95	25. Pälkänevesi	45,9
2. Hyrynjärvi	18,3	14. Oriselkä	<10	26. Saimaa (Mikk.mlk)	1147
3. Jämijärvi	9,2	15. Orivesi	536	27. Siikajärvi	0,96
4. Kallavesi	513	16. Oulujärvi	893	28. Sorsavesi	50,8
5. Keitele	500	17. Pieksänjärvi	25	29. Suontee	149
6. Kivijärvi	155	18. Pielinen	868	30. Ullavanjärvi	13,3
7. Konnevesi	187	19. Pieni Ahveninen	<1	31. Vahojärvi	<10
8. Kuore-Kaita	<1	20. Pyhäjärvi (Pieks.mlk)	10,9	32. Valkeajärvi	<10
9. Kyrösjärvi	96,2	21. Pyhäjärvi (Pirkkala)	124	33. Vehkajärvi	24,6
10. Lestijärvi	65	22. Päijänne (Asikkala)	1054	34. Vesijärvi (Hollola)	108
11. Längelmävesi	178	23. Päijänne (Jyväsk. mlk)	1054	35. Vesijärvi (Kangasala)	40,2
12. Nilakka	163	24. Päijänne (Kuhmoinen)	1054		

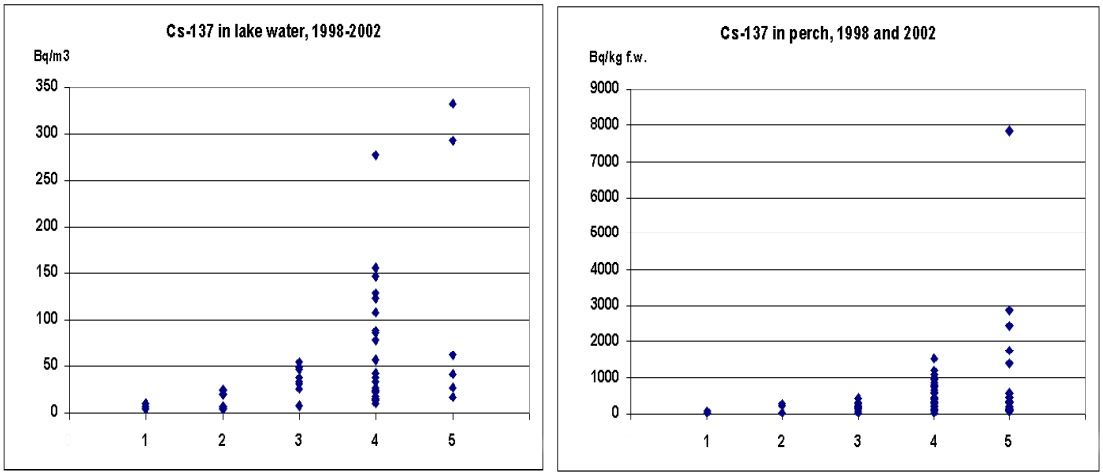


Figure 2. *^{137}Cs in lake water (n=47) and in perch (Perca fluviatilis) (n=86) in the five deposition areas of Finland in 1998 and 2002. Numbers on the x-axis refer to the deposition areas given in Figure 1.*

Table 1. *Activity concentrations of ^{137}Cs in lake water (Bq/m^3) and in perch (Perca fluviatilis) (Bq/kg fresh weight) and concentration factors (Bq/kg in perch/Bq/kg in water) in the lakes studied in 1998 and 2002.*

Lake	Sampling municipality	^{137}Cs in Water Bq/m^3 1998	^{137}Cs in Water Bq/m^3 2002	^{137}Cs in Perch Bq/kg (f.w.) 1998	^{137}Cs in Perch Bq/kg (f.w.) 2002	CF 1998	CF 2002
1. Haukivesi	Rantasalmi	19		61		3 200	
2. Hyrynjärvi	Hyrynsalmi	6		59		9 800	
3. Jämijärvi	Jämijärvi	18					
4. Kallavesi	Kuopio	7		21		2 800	
5. Keitele	Äänekoski	38		624		16 400	
6. Kivijärvi	Kannonkoski	57	42				
7. Konnevesi	Vesanto	54		326		6000	
8. Kuorekaita	Leppävirta		78		314		4 000
9. Kyrösjärvi	Ikaalinen	22	13	134	106	6 100	8 200
10. Lestijärvi	Lestijärvi	49	30	254	207	5 200	6 900
11.Längelmävesi	Kangasala	16	24	126	165		6 900
12. Nilakka	Tervo	25		267		10 700	
13. Ontojärvi	Kuhmo		24		244		10 200
14. Oriselkä	Orivesi		17		117		6 900
15. Orivesi	Liperi	4		37		9 200	
16. Oulujärvi	Vaala	10		40		4 000	
17. Pieksänjärvi	Pieksäm. mlk	277		932		3 400	
18. Pielinen	Lieksa	4		34		8 500	
19. Pieniahveninen	Pieksäm. mlk		128		439		3 400
20. Pyhäjärvi	Pieksäm. mlk	123	155	956	1082	7 800	7 000

21. Pyhäjärvi	Pirkkala	27	16	106	75	3 900	4 700
22. Päijänne	Asikkala	41		396		9 700	
23. Päijänne	Jyväskylä mlk	37		240		6 500	
24. Päijänne	Kuhmoinen	61	41	247	102	4 000	2 500
25. Pälkänevesi	Pälkäne	14	10	66	42	4 700	4 200
26. Saimaa	Mikkeli mlk	7		21		3 000	
27. Siikajärvi	Orivesi		259		7 836		30 300
28. Sorsavesi	Leppävirta	107	88	806	545	7 500	6 200
29. Suontee	Joutsa	33		303		9 100	
30. Ullavanjärvi	Ullava		47		143		3 000
31. Vahojärvi	Parkano	86		452		5 300	
32. Valkeajärvi	Jämsänkoski	147		1011		6 900	
33. Vehkajärvi	Padasjoki	332	292	1558	2657	4 700	9 100
34. Vesijärvi	Hollola	26		34		1 300	
35. Vesijärvi	Kangasala	33	25	237	155	7 200	6 200

7.1.4 Concentration factors

Concentration factor is determined here as the following ratio:
CF = ^{137}Cs in fish (Bq/kg f.w.)/^{137}Cs in lake water (Bq/kg)
Concentration factors for perch from various lakes varied between 1 300 and 30 000 in 1998 or 2002 (Table1). The lake with the lowest CF (Vesijärvi, Hollola) is a eutrophic lake and the lakes with the highest CFs (e.g. Nilakka, Päijänne (Asikkala), Siikajärvi, Vehkajärvi, Suontee) are oligotrophic; Siikajärvi and Vehkajärvi have additionally very low sedimentation rate. Transfer of ^{137}Cs to fish is a complicated process affected by several factors affecting alone and simultaneously. The conditions vary from lake to lake and even in various parts of a single lake. Besides the lake parameters, also the types of catchment affect the secondary input to the lake during the years, and vary from lake to lake. These parameters are not easily available making the more detailed analyses of the results difficult.

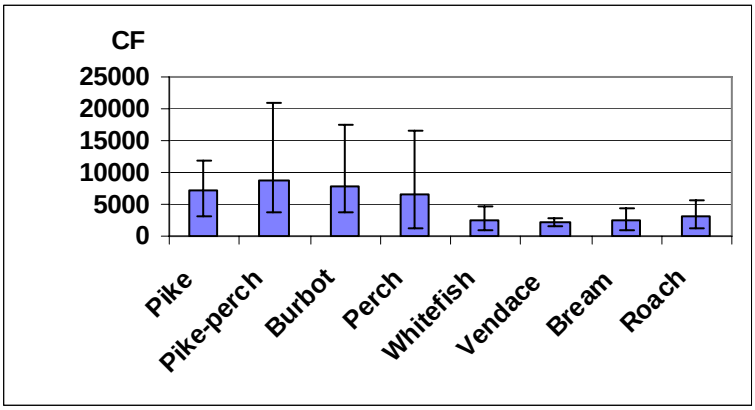


Figure 3. *Concentration factors of ^{137}Cs for various fish species in certain Finnish lakes. CFs are clearly higher for predatory fishes as pike, pike-perch, burbot and large perch than for non-predatory fish as vendace, bream and roach.*

7.1.5 Ecological halftimes of ^{137}Cs in fish

The results of the lakes studied regularly for ^{137}Cs in fish after the Chernobyl accident give a chance to estimate ecological halftimes of ^{137}Cs. The time describes recovery rates of the lakes after the accidental contamination. The ecological halftime is dependent on the time period for which it has been estimated. Here they were estimated for the time period of 1988-2002. The year 1988 was selected as a starting point because the peak contents had usually already passed by then. The shortest halftimes were approximately 3 years and the longest approximately 9 years. The longest halftime was found in a lake with high contents of humic substances (colour over 200 mg Pt/l) (Lake Pieni Ahveninen (Pieksämäki)), but in a clear water lake nearby the halftime was only a little shorter (Lake Pyhäjärvi (Pieksämäki)). The shortest halftime was found in a lake with rather high amounts of nutrients and colour number approximately 100 mg Pt/l (Lake Kyrösjärvi). In clear water oligotrophic lakes the ecological halftimes of ^{137}Cs in perch were typically about 5-6 years, as in lakes Vehkajärvi, and Sorsavesi in Figure 4.

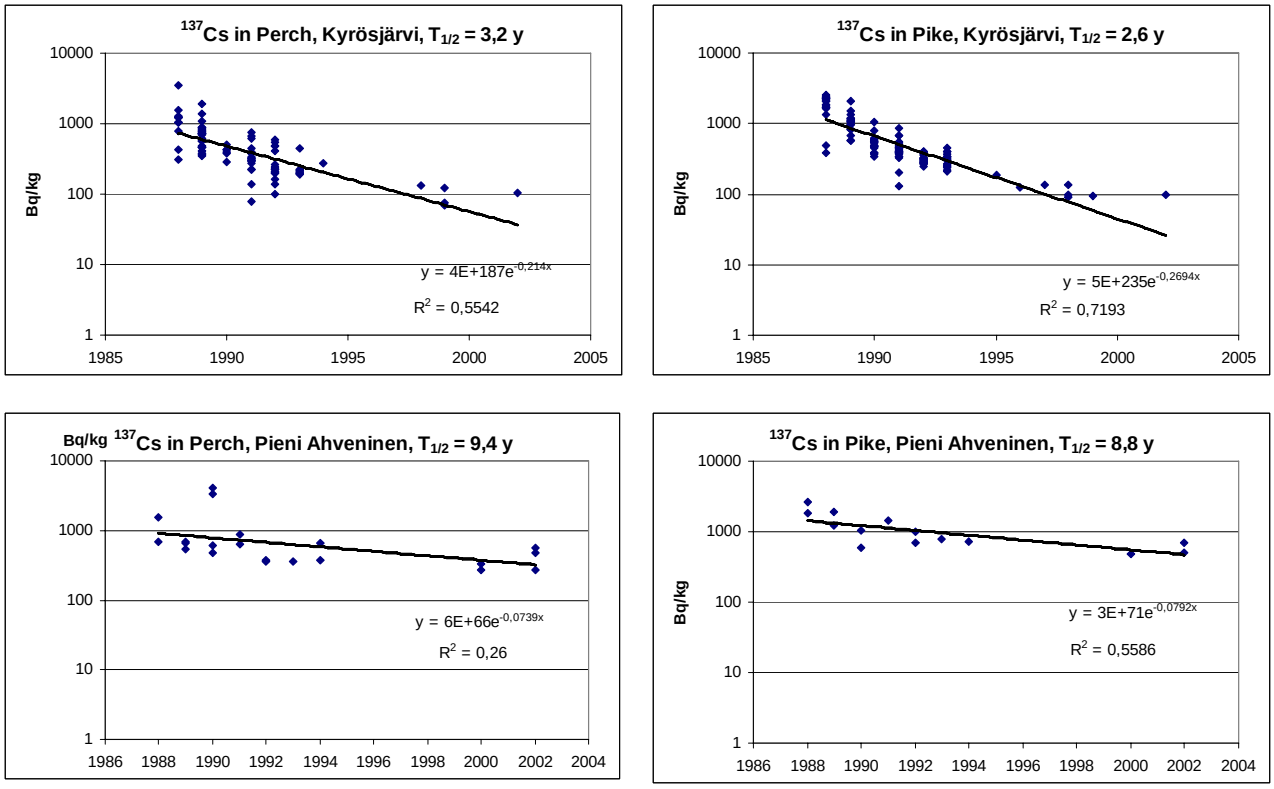
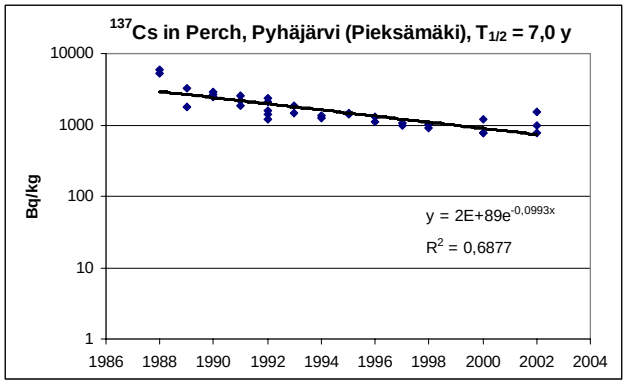
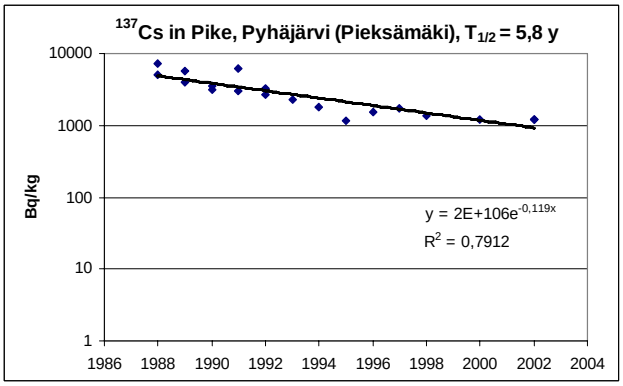
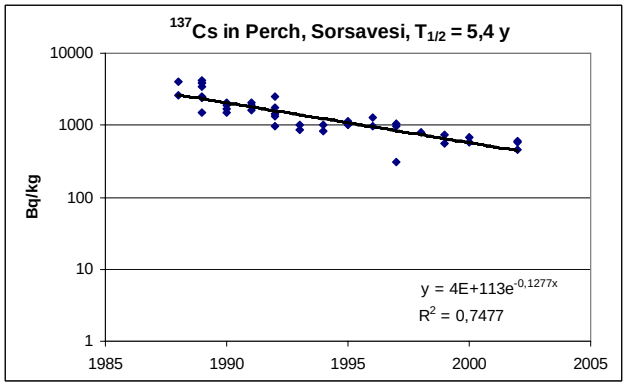
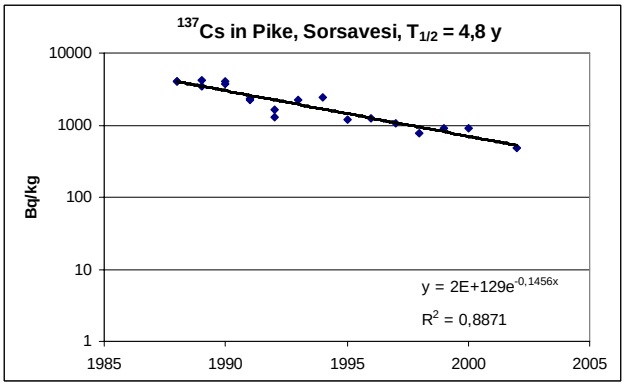


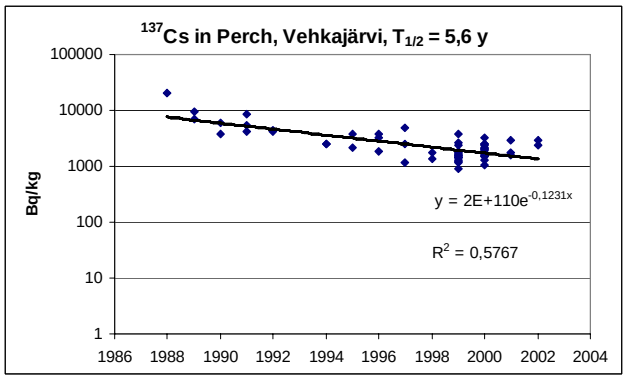
Figure 4. *To be continued.*

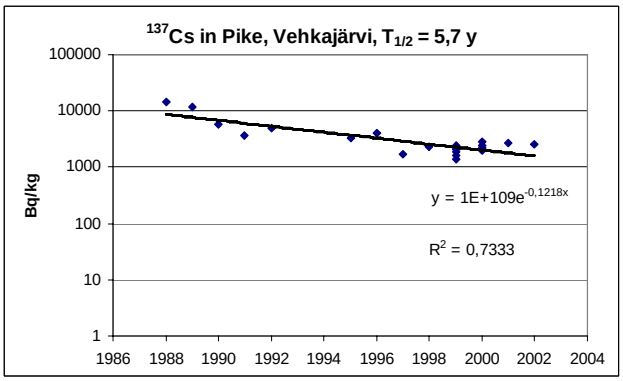


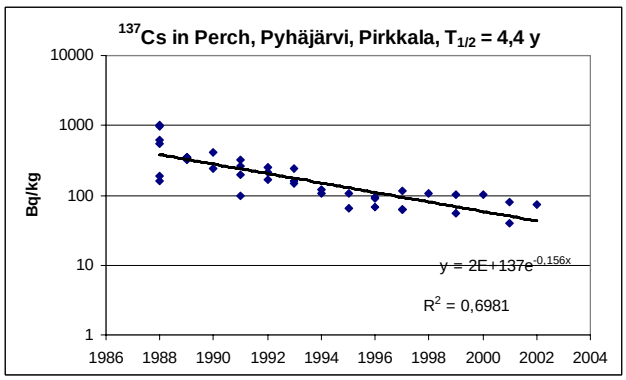


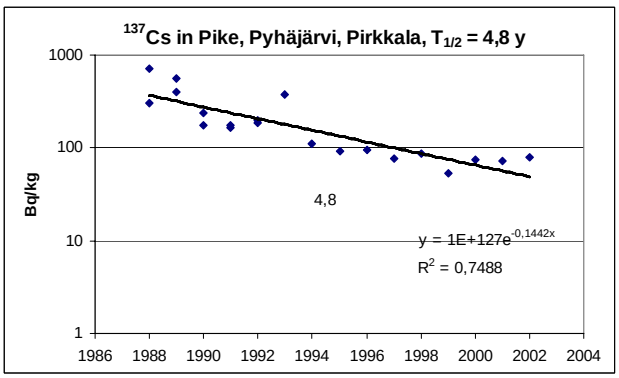












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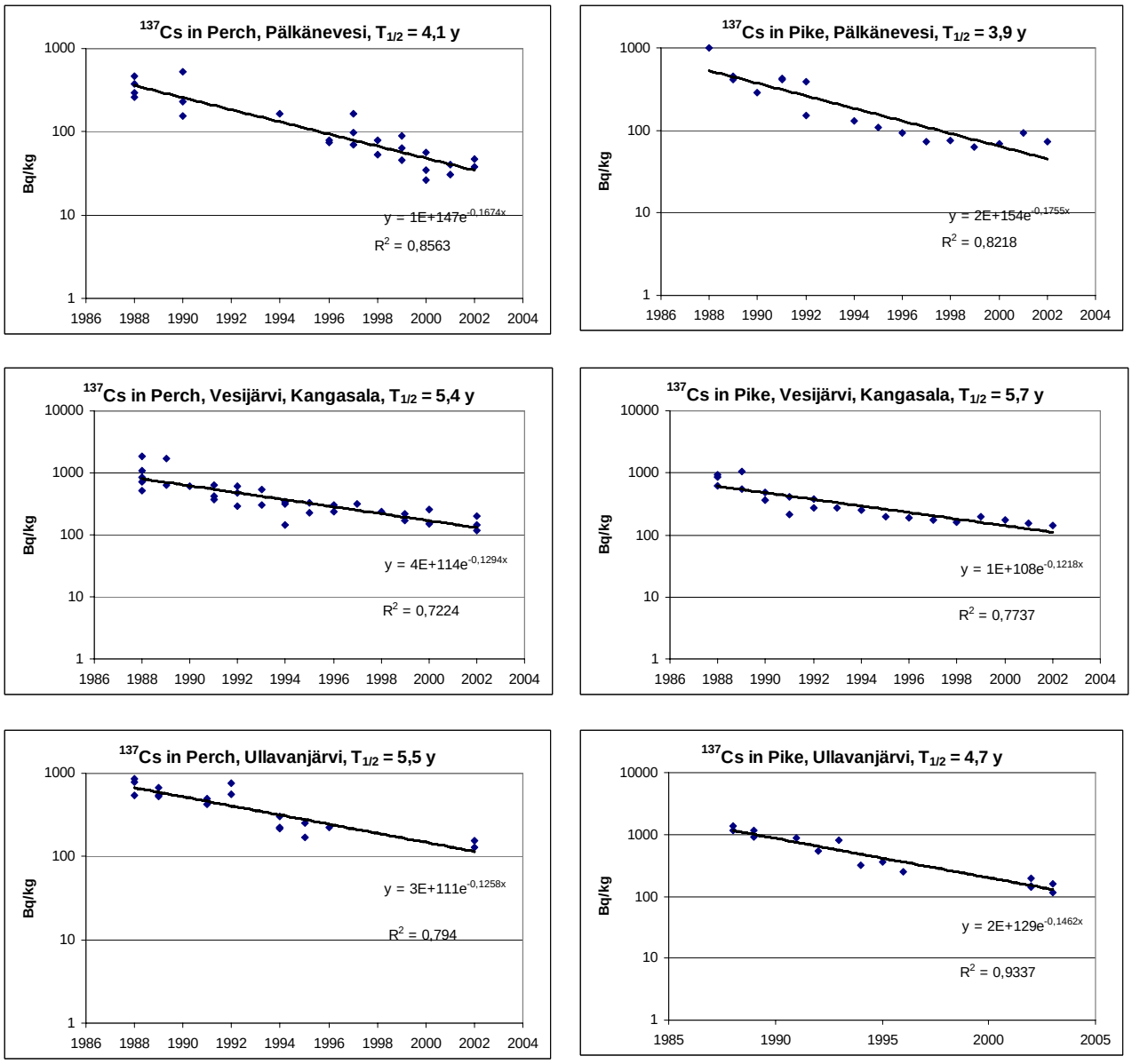


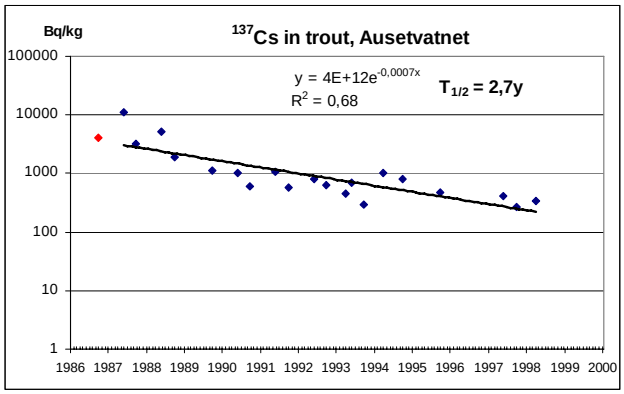
Figure 4. *^{137}Cs in perch and pike in certain Finnish lakes and the observed ecological halftimes of ^{137}Cs in 1988-2002. Location of the lakes with information on their size is given in Fig. 1.*

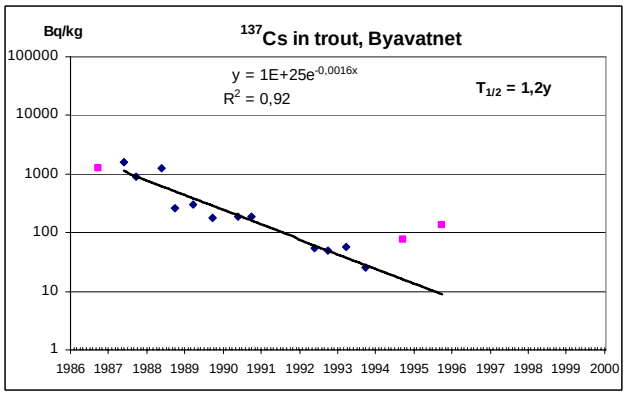
7.2 Norway

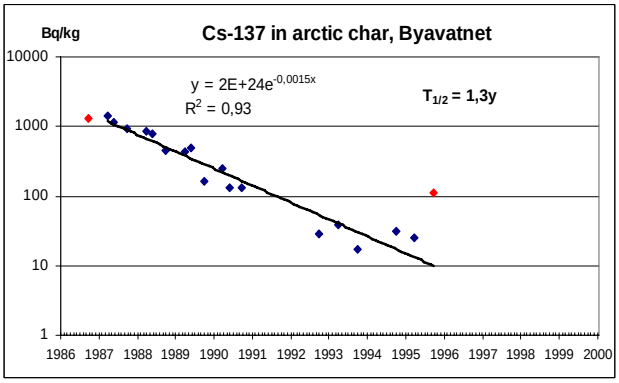
7.2.1 ^{137}Cs in trout and arctic char

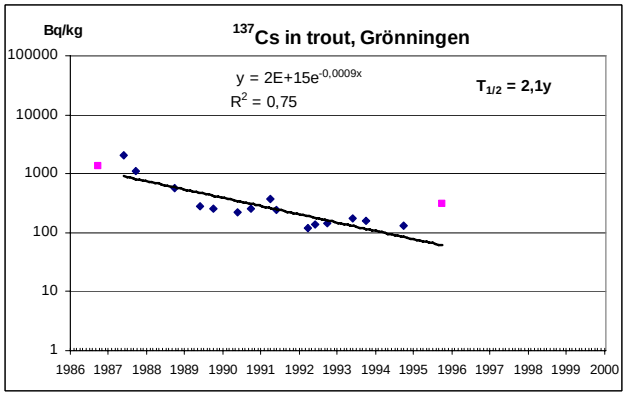
In Norway ^{137}Cs in trout and /or Arctic char from 14 lakes has been determined after the Chernobyl accident until 1990's or 2000 (Fig.5). The data-series were taken from [7]. Different behaviour of ^{137}Cs was noticed in various lakes. Ecological halftimes of ^{137}Cs in trout and arctic char were estimated for the time period for which results from each lake

and fish species exist (Fig. 5). To be able to compare the results for different lakes with each other the time period for the estimations should be the same. In three Norwegian lakes (Langåsdammen, Tomtvatnet and Vestre Sonvatn) there are clearly two components in the decrease rate. In Tomtvatnet and Vestre Sonvatn activity concentrations of ^{137}Cs in trout seem to stay at the same level, about 100 Bq/kg, from 1992 onwards. The environmental processes and the type of lake and/or its catchment give explanations to the differences in the temporal behaviour of ^{137}Cs.









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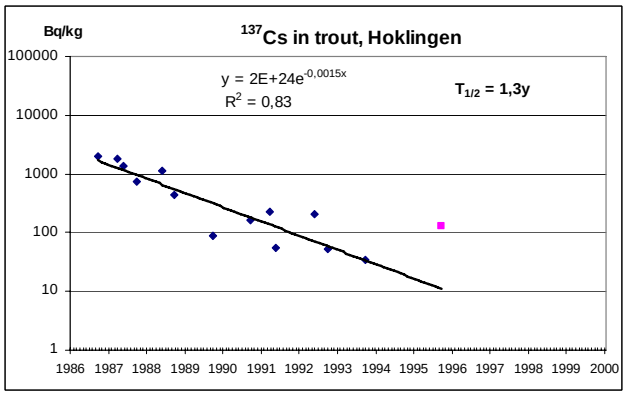

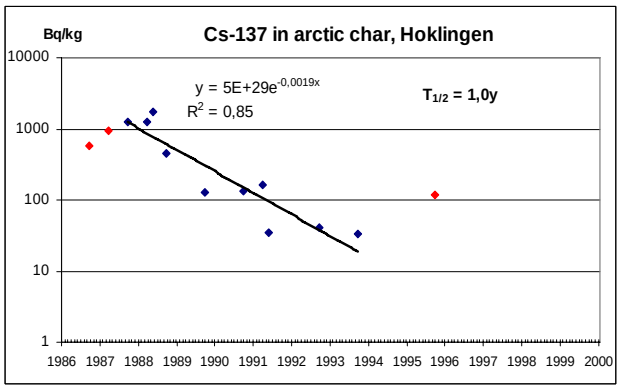

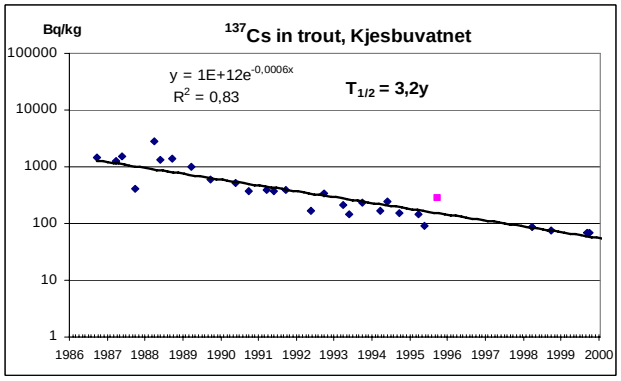

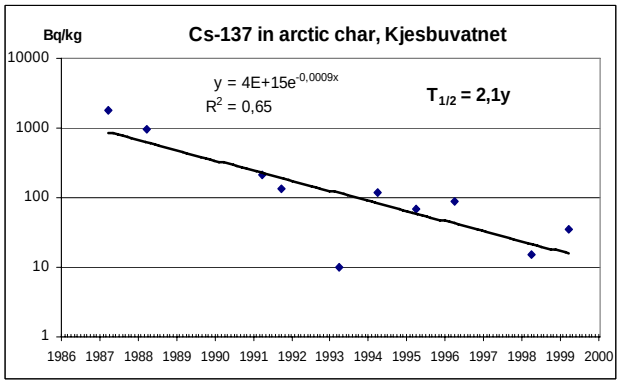

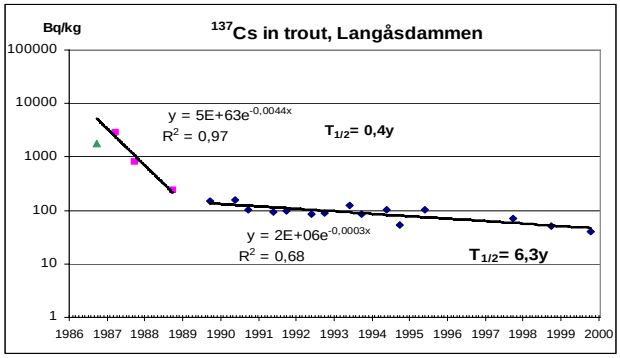

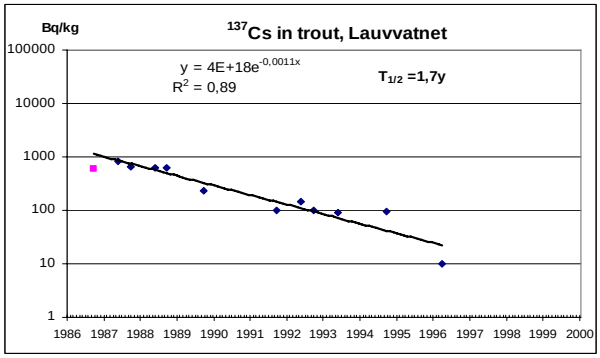

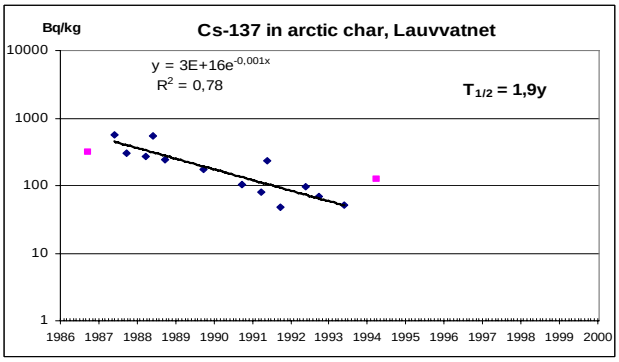

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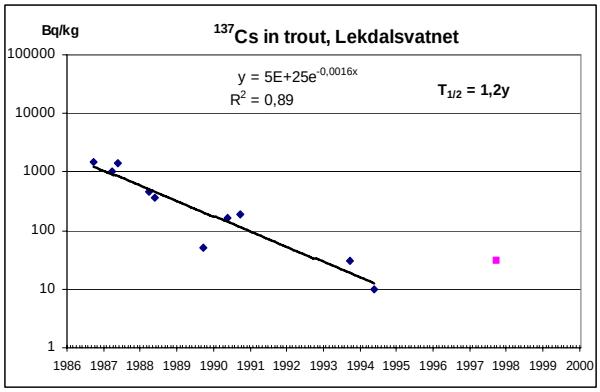

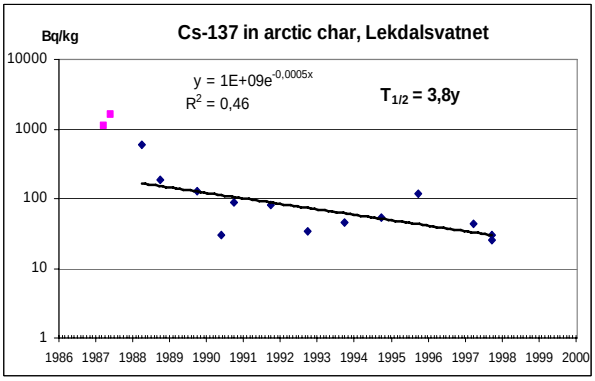

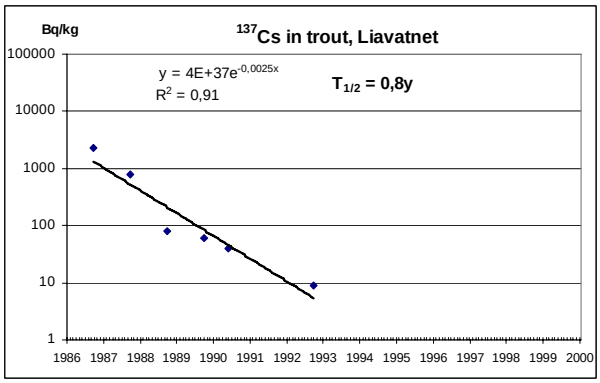

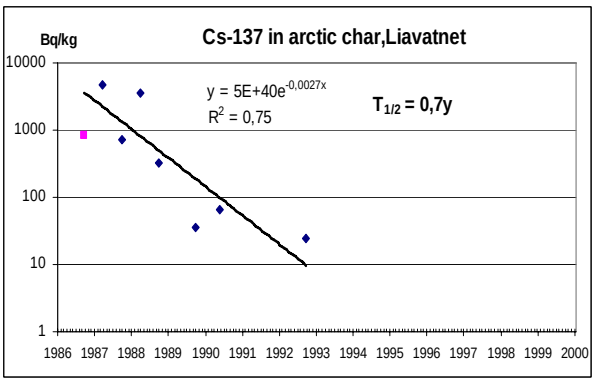

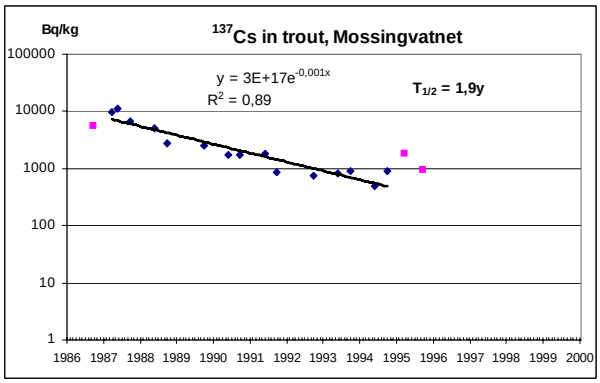

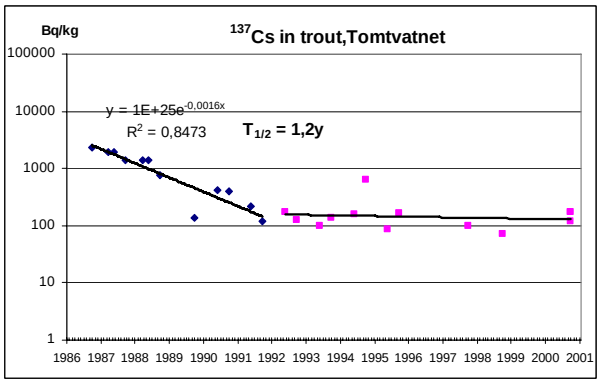

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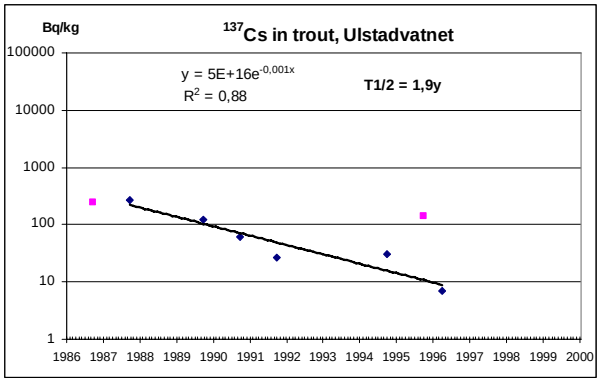

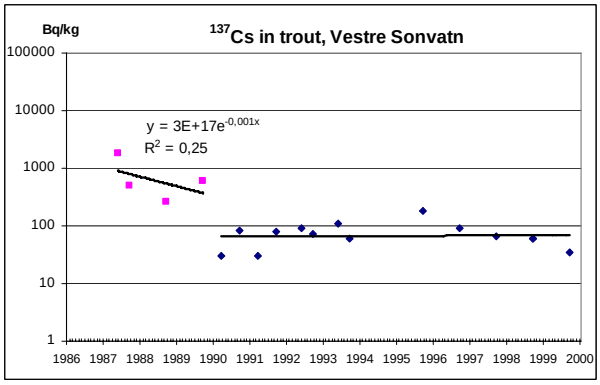

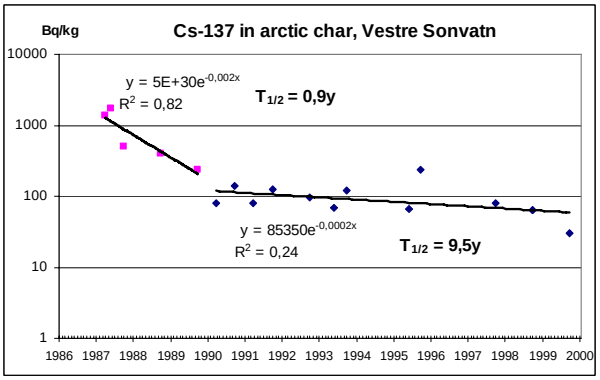

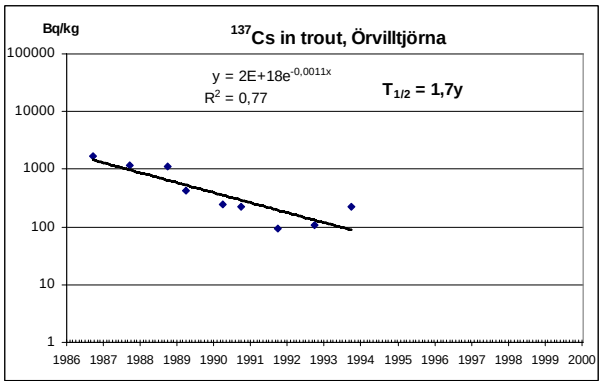

Figure 5. *^{137}Cs in trout and Arctic char in certain Norwegian lakes and the observed ecological halftimes. The halftimes given in the figures have been estimated for the whole time interval of the results, but red points are not included in the fittings or have their own fitting.*

7.3 Faroe Islands

7.3.1 Sampling lakes

Two lakes were selected for freshwater sampling in 2002. In 2003 brown trout were sampled from two quite different freshwater lakes, Leitisvatn and Stóravatn in the islands Vágoy and Sandoy, respectively. Leitisvatn is an oblong relatively deep lake gradually

descending towards a center line, while Stóravatn is shallow with an almost uniform depth. Physical data for the lakes can be found in Table 2 [8, 9].

Table 2. *Topographic data about the lakes.*

	Altitude, m	Surface area, km^2	Max depth, m	Volume, m^3
Toftavatn	15	0.509	22	$2.11 \cdot 10^6$
Leitisvatn	32	3.42	59	$81.6 \cdot 10^6$
Stóravatn	26	0.160	1.8	$0.150 \cdot 10^6$

7.3.2 ^{137}Cs in brown trout and lake water in 2002 and 2003

^{137}Cs in brown trout was low, the mean values 10 Bq/kg or less (Table 3). Physical statistics about the trout in Table 3 can be found in Table 4. The relationship between live weight and length of trout is given by the power function $W=K \cdot L^x$, where W is the live weight and L is the length; K is a proportionality constant. For trout from Leitisvatn we get $K=13.0 \cdot 10^{-3}$ and x=2.90. It was not possible to make the corresponding fit for trout from Toftavatn, as no intestines were included with the trout samples.

Table 3. *^{137}Cs in Brown trout (Salmo trutta) and lake water from the lakes Toftavatn and Leitisvatn in 2002. Trout were catched on 15 August in both lakes. Lake water was sampled on 3 September from Toftavatn and 6 September from Leitisvatn.*

Lake	Salmo trutta					Water
	Number of trout	Mean	St. dev	Min	Max	
		Bq/kg f.w.	Bq/kg f.w.	Bq/kg f.w.	Bq/kg f.w.	Bq/m^3
Toftavatn	9	9.88	4.20	5.85	19.8	5.51±0.32
Leitisvatn	10	5.31	1.99	4.02	10.7	3.45±0.27

Table 4. *Length and live weight of Brown trout (Salmo trutta) from lakes Toftavatn and Leitisvatn. (*) Without intestines.*

		Mean	St. dev	Min	Max
Toftavatn	Length (cm)	25.9	2.27	23.0	29.7
	Weight (g) (*)	148.9	42.7	97.7	216.0
Leitisvatn	Length (cm)	24.3	2.16	20.9	28.9
	Weight (g)	131.2	38.8	89.6	232.4

Results for ^{137}Cs activity in Salmo trutta from the lakes are presented in Table 5. The trout from Stóravatn has significantly higher ^{137}Cs concentration than the trout from Leitisvatn. This may be a reflection of feeding habit of the trout. The stomach contents in

the trout were, however, not studied, but a study in July 1987 and July 1988 showed that trout from Stóravatn feed mainly on benthic fauna followed by diptera, while trout from Leitisvatn feed almost equally on dipteria and benthic animals. There is only one trout from each lake.

Table 5. *^{137}Cs in Brown trout (Salmo trutta) from the lakes Stóravatn and Leitisvatn in 2003, one trout from each lake. ^{137}Cs activities are given with 1counting standard deviation.*

	Sampling time	Weight (g)	Length (cm)	^{137}Cs activity; Bq/kg f.w.
Leitisvatn	23 July 2003	181.81	26.5	1.26 ± 0.22
Stóravatn	1 June 2003	222.87	29.1	16.2 ± 1.00

7.3.3 Data for 1975-1976 and 1987-1999

Tables 6 and 7 show existing data from the freshwater environment. The ^{134}Cs/^{137}Cs ratio for lake water in 1987 was 0.161 and 0.241 in Leitisvatn and Leynavatn, respectively. The corresponding ratio was 0.101 in Leitisvatn in 1989.

Table 6. *Measurements of radiocesium in lake water after the Chernobyl reactor accident. All values are given in Bq/m^3. ND: No Data.*

	July 1987		July 1989		August 1991	June 1993	Sept. 1999
	^{134}Cs	^{137}Cs	^{134}Cs	^{137}Cs	^{137}Cs	^{137}Cs	^{137}Cs
Leitisvatn	1.60	9.94	0.63	6.23	6.24	6.24	ND
Leynavatn	0.90	3.74	ND	1.84	2.60	2.30	1.26
Toftavatn	ND	ND	ND	ND	ND	ND	4.17

Measurements of ^{137}Cs and ^{90}Sr in trout can be found in Table 7. The trouts from 1987 were catched in Leitisvatn, and they contained almost only radiocesium from the Chernobyl nuclear accident. The average ^{134}Cs/^{137}Cs ratio from 18 trouts was 0.377.

Table 7*. Measurements of ^{137}Cs and ^{90}Sr in rainbow trout flesh (Salmo irideus) in the Faroe Islands (the site has not been registered). One trout from each of the years 1975 and 1976. In 1987, the data represent averages in flesh from 18 Brown trout (Salmo trutta) from the lake Leitisvatn.*

1 August 1975				1 June 1976				July 1987	
^{137}Cs		^{90}Sr		^{137}Cs		^{90}Sr		^{134}Cs	^{137}Cs
Bq/kg f.w.	Bq/kg K	Bq/kg f.w.	Bq/kg Ca	Bq/kg f.w.	Bq/kg K	Bq/kg f.w.	Bq/kg Ca	Bq/kg f.w.	Bq/kg f.w.
0.78	196	0.17	207	0.45	126	0.22	207	42.4	115.4

7.4 Summary

The deposition from Chernobyl in spring 1986 was most unevenly distributed in Finland and other Nordic countries. The deposition elevated the ^{137}Cs contents of freshwater fishes significantly in Finland and also in Norway, but very little in Faroe Islands. High activity concentrations of ^{137}Cs (some thousand Bq/kg f.w.) still occur in fish in certain Finnish lakes in the areas of the highest deposition. Activity concentrations of ^{137}Cs in perch varied from 20 to 7 800 Bq/kg f.w.and those in lake water from 4 to 330 Bq/m^3 in 1998 and 2002. In Norwegian lakes activity concentrations of ^{137}Cs in trout seem to vary between 10 and 100 Bq/kg. In the deep lakes of Faroe Islands activity concentrations of ^{137}Cs in brown trout *(Salmo trutta)* were low, 2-20 Bq/kg f.w. in 2002 and activity concentrations of ^{137}Cs in lake water were 3.5 and 5.5 Bq/m^3 at the same time. Very low pre-Chernobyl values for ^{137}Cs and ^{90}Sr, less than 1 Bq/kg f.w., in rainbow trout in Faroe Islands are reported. Due to the Chernobyl deposition they were increased to 115 Bq/kg f.w.

Concentration factors (Bq/kg in perch / Bq/kg in lake water) in Finnish lakes ranged from 1 300 to 30 000 in 1998-2002. In Finland, transfer to fishes was higher in oligotrophic lakes than in eutrophic lakes. In the deep lakes of the Faroe Islands CFs in 2002 were 1 500-1 800, being thus of the same order of magnitude as the lowest CFs of the Finnish lakes.

The observed ecological halftimes of ^{137}Cs in perch in certain Finnish lakes varied by a factor of about three. The longest halftime of ^{137}Cs in perch was approximately 9 years and the shortest approximately 3 years, determined for the time period of 1988-2002. The Norwegian lakes differ also from each other with respect to the decrease rates of ^{137}Cs in fish. In some cases there were clearly two components in the reduction of ^{137}Cs. Ecological halftimes of ^{137}Cs in trout and Arctic char varied from 1.4 y to 4.7 y in 1988-1994.

There is an indication of somewhat more rapid reduction of ^{137}Cs in fish in certain Norwegian lakes compared to Finnish ones, although ecological halftimes for the Norwegian and for the Finnish lakes were estimated for different time intervals in the examples, and are thus not directly comparable. However, in two of the studied Norwegian lakes ^{137}Cs in trout seems to stay at the same level, about 100 Bq/kg, from 1990 onwards, which is the case in no of the Finnish lakes studied.

7.5 References

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8 Radioecological transfer of ^{137}Cs from ground Deposition to Man from Chernobyl Debris and from Nuclear Weapons Fallout in Different Swedish Populations

Evaluation of a National database

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8.1 Introduction

The era of major global dispersion of anthropogenic radionuclides started in the beginning of the 1950s with the program of nuclear weapons testing in the atmosphere (UNSCEAR, 1977; UNSCEAR 1982). The debris consisted of long-lived nuclides such as ^{90}Sr ($T_{½,phys}$=28 y), ^{137}Cs ($T_{½,phys}$=30.2 y) and short-lived radionuclides such as ^{131}I ($T_{½,phys}$ = 8.06 d). These radionuclides are important in terms of radiological consequence due to their elemental properties, giving rise to high specific uptakes in living tissues. In a study from 1961 it was discovered that reindeer herders in Scandinavia had significantly higher body burdens of ^{137}Cs compared with what was found in urban areas (Lidén, 1961). During the following decades several studies on the body burden of ^{137}Cs in reindeer herders in the Nordic countries were carried out as well as in other Arctic populations (Soumela and Rahola, 1994; Wright et al., 1997; Miettinen et al., 1964; Haanson et al., 1996). Certain ecosystems were then demonstrated to be more sensitive to transfer of radioactive deposition to man, especially within the Sub-Arctic ecosystems where populations mainly lived on herding of the caribou or reindeer (UNSCEAR, 1977; UNSCEAR 1982; Lidén 1961; Lidén and Gustafsson, 1966; Howard et al., 1995; Johansson and Ågren, 1994; Falk et al., 1991; Ågren, 1998). After the Partial Test Ban Treaty was signed by the superpowers in 1963, the number of atmospheric detonations decreased considerably, leading also to gradually decreasing global fallout.

After the Chernobyl accident in 1986, which resulted in large fallout of ^{134}Cs and ^{137}Cs in Sweden many of the human body burden studies were re-launched. This time the deposition was much more inhomogeneously distributed, where certain areas obtained more than 100 kBq m^{-2} of ^{137}Cs, compared with, on average, 2-3 kBq m^{-2} from the global fallout (Edvarsson, 1991; Wright et al., 1999; Vintersved et al., 1991; Isaksson and Erlandsson, 1998). Studies were also conducted on other critical populations in Sweden, such as hunters and farmers living in regions with high deposition of radiocaesium (Ågren, 1998).

The Swedish government has assigned the Swedish Radiation Protection Authority, SSI, the responsibility for obtaining and assuring one of the fifteen national environmental

quality objectives, A Safe Radiation Environment (Swedish Governement, 2001). One of the criteria for a safe radiation environment is that no human receives dose contributions from the sum of all man-made sources higher than 1 mSv per year. It is therefore important to compile existing experimental data on internal contamination levels in man and other organisms, and relate these values to the levels of radioactive contaminants in the environment. During spring 2001 SSI launched a project where data on body burdens of radioactive cesium in various Swedish populations during the past four decades were compiled into a single database for a general assessment. The aim of the database is to study the various exposure pathways and identify which of these pathways could be of most importance in a future exposure scenario. It is also intended to be used as a reference data set in the national environmental monitoring program by the SSI.

In this assessment we aim to investigate the magnitude and dispersion of the transfer of ground deposition of radiocesium to man in Sweden. A comparison of the estimated committed effective dose per unit activity deposition on ground is made between different critical groups that are known to be more sensitive to radioecological transfer. We also intend to compare the radioecological transfer to some Swedish populations from ^{137}Cs originating from the nuclear weapons fallout versus the Chernobyl fallout.

8.2 Material and Methods

Data from body burden studies of various Swedish populations conducted by the Swedish Defense Research Agency (FOI), the National Radiation Protection Authority (SSI), Departments of Radiation Physics in Lund, Malmö, Göteborg and Umeå, have been pooled to one database in a spreadsheet format. It contains data on the age of the investigated subjects, place of residence, time at the whole body counting, occupation, body-weight and the body burdens of ^{137}Cs, ^{134}Cs (after Chernobyl accident in 1986) and ^{40}K. The radionuclide ^{40}K is an important chemical analogue to cesium and the body potassium content is often obtained simultaneously in connection with the whole-body counting (Leggett, 1983). The identities of the participating subjects in the database are coded. The place of residence of the individuals is recorded in the form of coordinates as defined by the Swedish RT90-system (Lantmäteriet, 2003) as well as by the name of the home municipality (and county) of the residence. In this study, however, the populations are not primarily divided into their geographical habitation, but rather after their occupation. Some occupations are associated with dietary habits that are known from previous studies to be particularly sensitive to transfer of radioactive cesium (Lidén, 1961). The following categorization of the population was thus done; i.) farmers, ii.) hunters, iii.) reindeer herders, iv.) rural non-farming populations and v.) urban populations.

8.2.1 Aggregate transfer factor

For the global fallout in the 1950s, 60s and 70s the ground deposition occurred continuously over the years, albeit with a considerable variation in the annual rate (Aarkrog et al., 1995). The Chernobyl accident was, on the other hand, a single deposition event where the major part of the fallout occurred within weeks after the accident in April and May 1986 (Mattsson and Vesanen, 1988). In order to relate long-

term consequences from a deposition event in terms of committed effective dose, it is preferable to consider the time-integrated body burdens and the cumulated activity depositions over a certain period of interest.

In this study the aggregate transfer of radiocesium to the investigated populations has been calculated in two ways. Both methods are based on a time integration or summation of the mean ^{137}Cs body burdens (Bq kg^{-1} y) and the accumulated total deposition on ground (kBq m-2) in an area that is assumed to supply the main fraction of foodstuff to the population considered. UNSCEAR presented in 1977, a definition of a time integrated aggregate transfer from ground to man, here denoted as $T_{ag,int,UNSCEAR}$ (Bq g^{-1} K y/ kBq m^{-2});

$$T_{ag,\mathrm{int},UNSCEAR} = \frac{\int_{t_0}^{t_1} (^{137}Cs/K)_{avg}(t)\,dt}{\sum_{t=t_0}^{t=t_1} A_{ann}(t)} \quad = \frac{\sum_{t=t_0}^{t_1} (^{137}Cs/K)_{avg}(t)\cdot \Delta t}{\sum_{t=t_0}^{t_1} A_{ann}(t)} \quad \text{or} \quad (1)$$

where

$(^{137}Cs/K)_{avg}(t)$	average ratio of body burden of ^{137}Cs and potassium (g K) at time t for a given population (Bq g^{-1} K);
$A_{ann}(t)$	annual ground deposition density of ^{137}Cs (Bq m^{-2} y^{-1});
t_0	beginning of the time period considered for deposition cumulation (y);
t_1	end of the time period considered (y);
Δt	time interval between consecutive observations of $(Q_{Cs\text{-}137}/Q_K)_{avg}(t)$ when using trapezoid summing

This method is suitable when considering populations confined to a well-defined area, such as the administrative divisions of countries in counties and municipalities, over which the fallout is averaged. A further advantage of this method is the possibility to convert the time-integrated transfer of ^{137}Cs from a single deposition event to humans into a committed effective dose from internal contamination per unit activity deposition density, $E_{ag,int,UNSCEAR}$ (mSv / kBq m^{-2}), using the following relationship;

$$E_{ag,\mathrm{int},UNSCEAR} = \frac{\int_{t_0}^{t_1} C(^{137}Cs)_{avg}(t) \cdot E(w = 70kg)dt}{\sum_{t=t_0}^{t=t_1} A_{ann}(t)}$$

or

$$= \frac{\sum_{t=t_0}^{t_1} C(^{137}Cs)_{avg}(t) \cdot E(w = 70kg) \cdot \Delta t}{\sum_{t=t_0}^{t_1} A_{ann}(t)} \quad \textbf{(2)}$$

where

$C(^{137}Cs)_{avg}(t)$	average body concentration of ^{137}Cs at time t for a given population (Bq kg^{-1});
E(w=70kg)	dose conversion factor (mSv Bq^{-1} y^{-1}) for homogeneous distribution of ^{137}Cs in an adult male of body size w=70 kg, as adopted by Falk et al., 1991 [11];
$A_{ann}(t)$, t_0 , t_1, Δt	as in Eq. 1.

Some of the populations investigated here are dispersed over large geographical areas (illustrated in Fig. 1), which make the definition of the aggregate transfer in Eq. 1 somewhat unsuitable. The reindeer herders and hunters that were investigated after the Chernobyl fallout live at different locations with a highly varying amount of ground deposition density. In order to enable a general comparison between different populations with respect to dietary habits rather than place of residence, an alternative method of estimating the transfer has been used here (Eq 3). The modified transfer factor, $T_{ag,int,This\ work}$ (Bq g^{-1} K y/(kBq m^{-2})), is the population mean of the ratio between the individual ^{137}Cs/K-ratio (Bq g^{-1} K) and the average cumulated activity deposition density, $A_{cum,decay}$, corrected for the physical decay of the radionuclide (kBq m^{-2}). The individual value at time t of the ^{137}Cs/K-ratio is thus divided by $A_{cum,decay}(t)$ [kBq m^{-2}], at the location (municipality or county) which the individual inhabit. This ratio is in turn averaged over all individuals, i, belonging to the population considered, irrespectively of where they live:

$$T_{ag,\mathrm{int},Thiswork} = \int_{t_0}^{t_1} \left\langle \frac{(^{137}Cs/K)(t)}{A_{cum,decay}(t)} \right\rangle_{avg} dt \qquad T_{ag,\mathrm{int},Thiswork} = \sum_{t=t_0}^{t_1} \left\langle \frac{(^{137}Cs/K)(t)}{A_{cum,decay}(t)} \right\rangle_{avg} \cdot \Delta t$$

or (3)

where

$\langle(^{137}Cs/K)/A_{cum,decay}\rangle_{avg}$	observed population mean value of the ratio between the potassium normalized ^{137}Cs content and $A_{cum,decay}$ at time t;
$A_{cum,decay}(t)$	cumulated deposition density of ^{137}Cs (kBq m^{-2}) at time t corrected for physical decay averaged over the *i.)* county or *ii.)* municipality;
t_0, t_1 and Δt	as in Eq 1.

Previous studies show that between 1965 and 1985, and especially after 1986, human body burden levels are likely to follow a linear increase reaching a peak value about 1 year after the on-set of the fallout. These peak values are followed by an exponential decrease with time, corresponding to the ecological elimination rate, or half-time, of ^{137}Cs in that population (e.g. Ågren, 1998). Curve fits of Eqs 1 and 3 for the Chernobyl fallout studies using mono- or dual exponential expressions as a function of time were carried out by means of non-linear regression. For pre-Chernobyl fallout studies trapezoid summing was used instead due to the highly fluctuating ^{137}Cs *in-vivo* concentration levels in the beginning of the 1960s, making non-linear regression unsuitable.

8.2.2 Estimation of cumulated ground deposition of ^{137}Cs in Sweden prior to and after the Chernobyl accident

In Sweden a detailed mapping has been carried out of the ground deposition of ^{137}Cs from the Chernobyl fallout based on air surveys performed after 1986 (Byström, 1990; Byström 2000). The deposition values have been processed into various data sets, one of which gives the average equivalent surface deposition of ^{137}Cs in kBq m^{-2} for each Swedish municipality (Lindgren et al., 2002). The equivalent surface deposition values were scaled upwards by the factor 1.7, corresponding to the mean ratio between the total and equivalent surface deposition in Sweden as determined in a soil sampling study by Edvarsson, 1991. From this data set it is possible to generate various regional and local averages for the deposition values (Fig.2).

The temporal variation of the pre-Chernobyl fallout in Sweden has been reconstructed by combining Danish data on annual ^{137}Cs fallout from 1950 and onward (Aarkrog et al., 1995), with meteorological records, purchased from the Swedish Meteorological and Hydrological Institute, on annual precipitation at various locations (resolved into a 5*5 km grid) in Sweden (SMHI, 2002). The same meteorological data set has been used and combined with soil sampling data performed immediately after the Chernobyl fallout (Edvarson, 1991; Vintersved et al., 1991) in order to reconstruct the geographical variation of the pre-Chernobyl fallout. The reconstructed values were averaged over municipalities and counties (Fig.2). The influence of the size of the geographical area considered in the transfer of a population has been investigated by using both municipality and county averages. The average size (±1 STDV of mean) of a municipality in Sweden is 1,416±147 km^2. The average county size in Sweden is 14,500±3,330 km^2 (SCB, 2001).

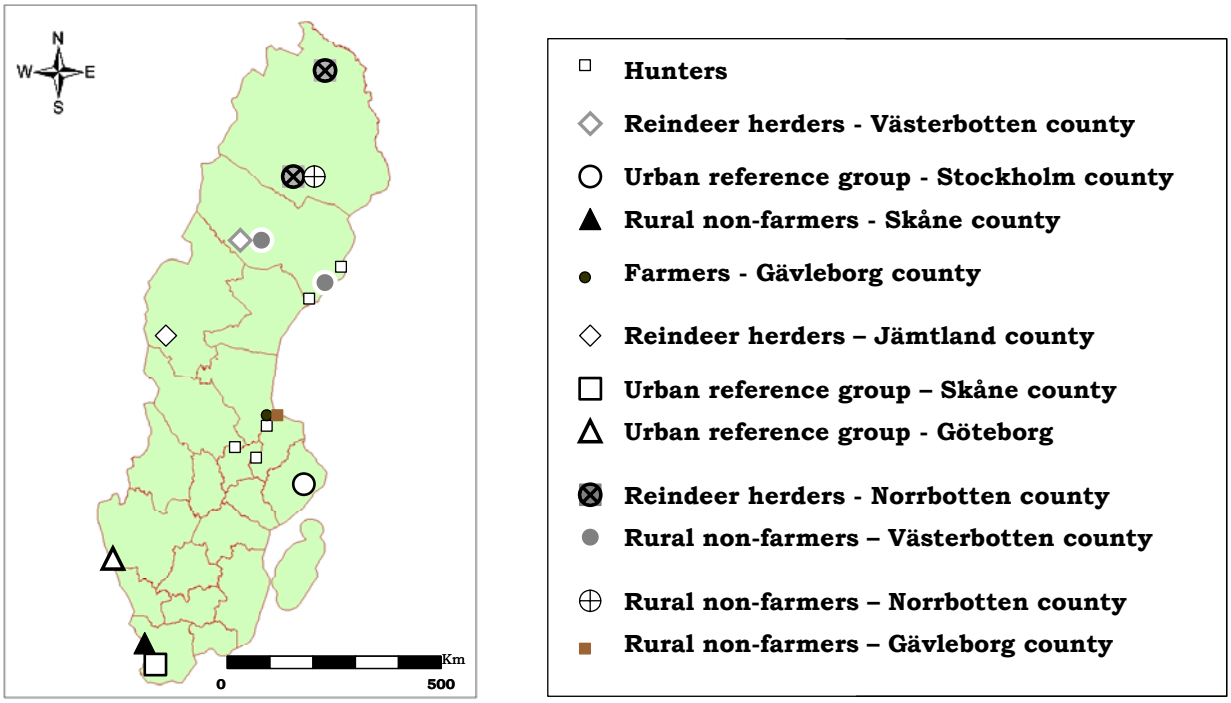

Figure.1. *Map over Sweden and the location of the various populations investigated in this study.*

8.3 Results

8.3.1 Time-integrated aggregate transfer

In Table I an estimate of the time integrated aggregate transfer of ^{137}Cs (as defined by Eq. 3) from ground deposition to man in the studied populations over the period 1959 to 2002 is given. In Fig. 3 is illustrated the time-pattern of the aggregate transfer of the Chernobyl fallout to various Swedish populations, using municipality and county average, respectively.

From Table I and in Fig.3 it can be seen that higher values of the time integrated aggregate transfer is obtained for populations that consume large amounts of locally produced food (such as farmers and their families). Higher values are also obtained for most populations when using county averages of the ^{137}Cs ground deposition. A marked agreement in the time integrated aggregate transfer is achieved when considering the average deposition over the county for the reference groups in the metropolitan areas (Lund/Malmö, Göteborg and Stockholm), with values around 10 [Bq g^{-1} K y/(kBq m^{-2})]. The corresponding value for the reindeer herders in Västerbotten County appears to be at least 20 times higher. The reindeer herders investigated in Norrbotten county exhibit an even higher transfer of ^{137}Cs, which is up to 40 times higher than the urban reference population.

8.3.2 Committed effective dose per unit activity deposition from Chernobyl fallout

Using the UNSCEAR definition of the aggregate transfer (Eq. 1) the committed effective dose from internal contamination of radiocesium over 50 y per unit activity deposition from the Chernobyl fallout has been estimated for the populations considered in this study (Table II). The reindeer herders are estimated to obtain, on average, more than 0.9 mSv from internal contamination of Chernobyl ^{137}Cs per 1 kBq m^{-2} deposition in their county of residence, compared with 0.03 to 0.05 mSv/kBq m^{-2} for the urban reference groups.

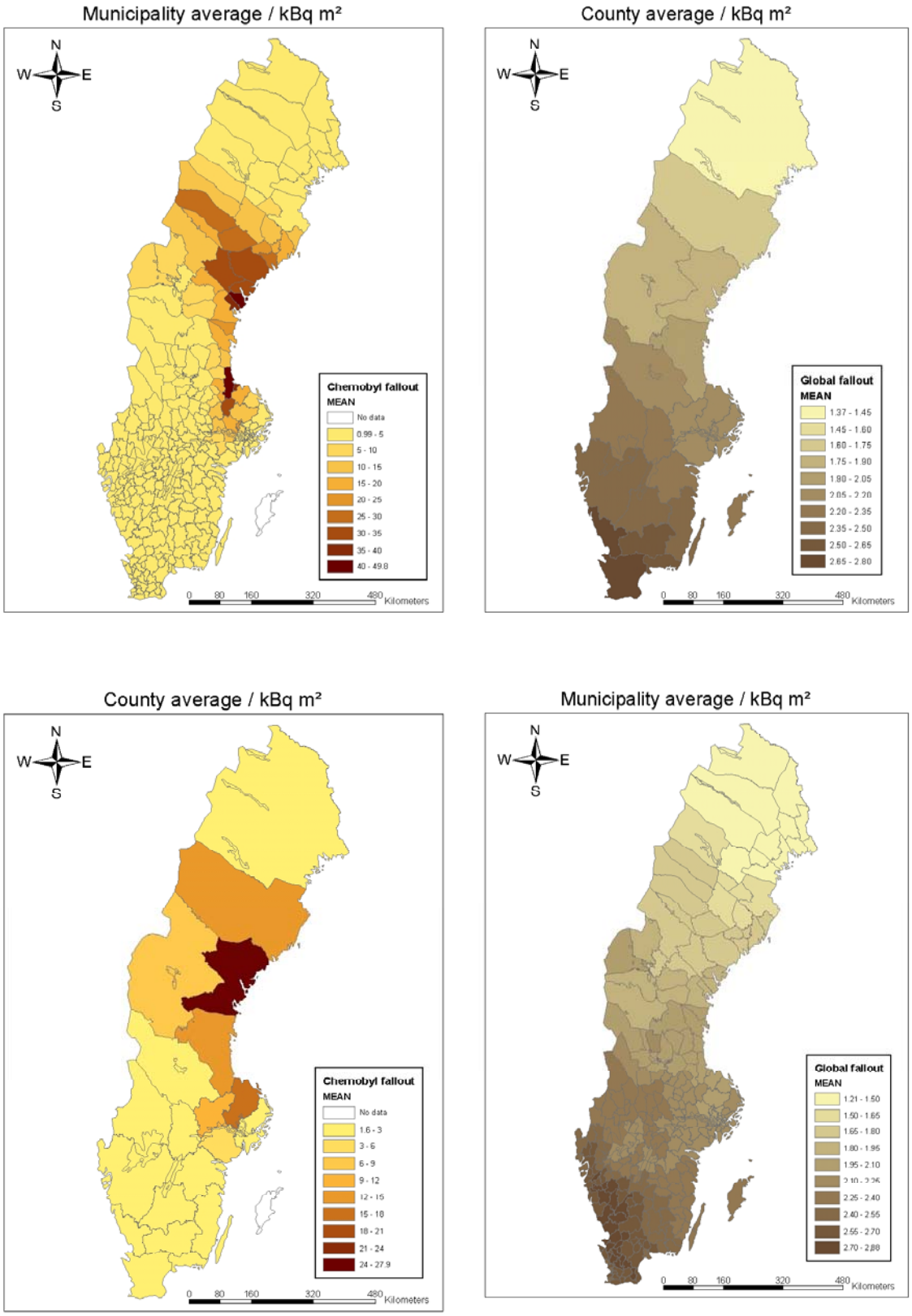

Figure 2. *Estimation of ground deposition of ^{137}Cs from nuclear weapons fallout as per 1 July 1985 (prior to the Chernobyl fallout) and Chernobyl fallout as per 1 May 1986.*

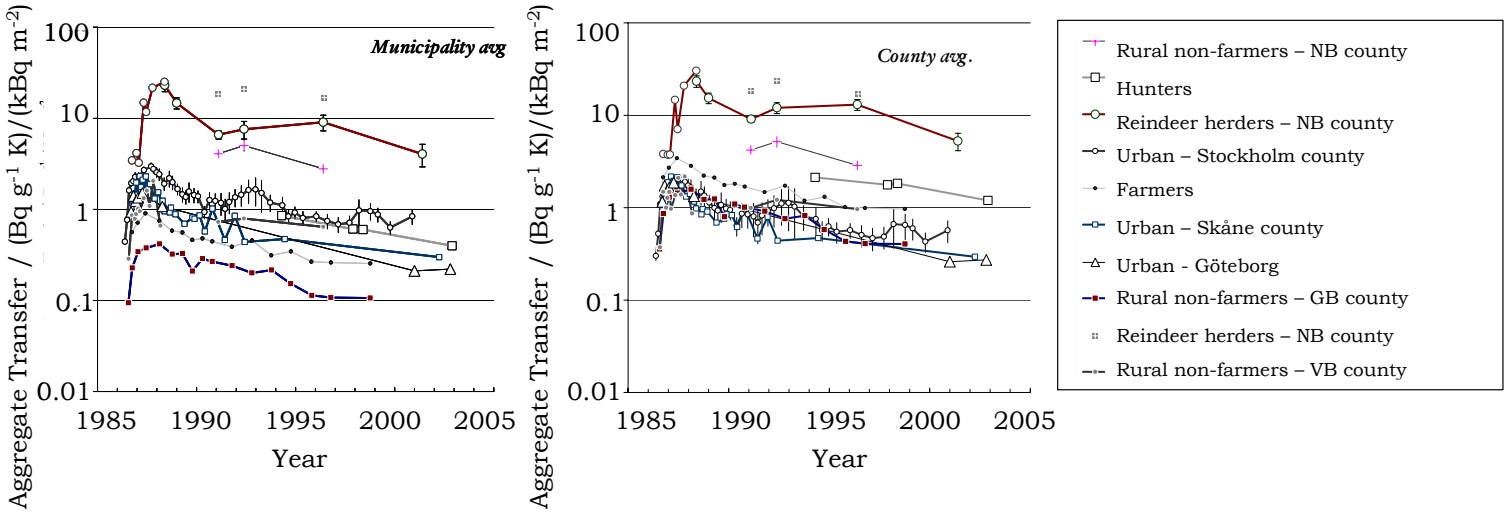

Figure 3. *Aggregate transfer of ^{137}Cs from ground deposition of Chernobyl fallout to body burden, normalized to the potassium content, in various Swedish populations after 1986.*

Table I. *Time-integrated aggregate transfer of ^{137}Cs [Bq g^{-1}K y/(kBq m^{-2})] normalized to natural potassium for nuclear weapons fallout and Chernobyl debris.*

Population	Global Fallout (1945-1995)		Chernobyl Fallout (1986-2036)	
	Municipality average	County average	Municipality average	County average
Farmers			4.1	16
Hunters			12	30
Hunters (Gävle)			10	38
Reference group (Lund/Malmö)	22	22	8	8
Reference group (Göteborg)			12	9
Reference group (Stockholm)	29	29	14	10
Reindeer herders (Härjedalen)	1930	1980		
Reindeer herders (Norrbotten			210	420
Reindeer herders (Västerbotten)			100	260
Rural non-farmers (Gävle)			2	7
Rural non-farmers (Norrbotten)			46	47
Rural non-farmers (Västerbotten)			8.2	12

Table II. *Projected time integrated aggregate transfer factor of ^{137}Cs as defined by UNSCEAR from the Chernobyl fallout and the internal effective dose commitment between 1986 and 2036 per unit deposition in the county (μSv kBq m^{-2}).*

Population	$T_{ag,int,UNSCEAR}$	$E_{ag,int,UNSCEAR}$
	Bq g^{-1}K y / kBq m^{-2}	μSv / kBq m^{-2}
Farmers	14	54
Hunters	26	93
Hunters (Gävle)	32	100
Reference group (Lund/Malmö)	5.0	18
Reference group (Göteborg)	7.3	26
Reference group (Stockholm)	7.6	28
Reindeer herders (Norrbotten)	170	540
Reindeer herders (Västerbotten)	100	460
Rural non-farmers (Gävle)	6.5	24
Rural non-farmers (Västerbotten)	9.4	38
Rural non-farmers (Norrbotten)	34	110

[a] Dose values refer to a adult male of 70 kg body size.

8.4 Discussion

The highest aggregate transfer, independent of which of the two definitions is used (Eqs 1-3), was found among the reindeer herder populations, after which followed (in order of decreasing transfer) the rural non-farming population in Norrbotten county, hunters in the Swedish counties dominated by forest vegetation, farmers living in the municipality most affected by the Chernobyl fallout in Sweden (Gävle), the rural non-farming population living in the same municipality and urban populations in the Swedish metropolitan areas (Malmö/Lund and Stockholm). The time integrated aggregate transfer for the latter group is about 10 to 20 times lower than for the reindeer herders in Sweden (Table I.).

The results also indicate the influence of the size of the area for which the activity deposition is considered in the estimates of the time-integrated transfer. A marked accordance between the three major urban areas (Malmö/Lund, Göteborg and Stockholm) is observed when using county averages (Table I.). The urban populations will mostly be subjected to transfer of radiocaesium from dairy products and beef. Dairy milk is, however, still produced, distributed and consumed regionally in Sweden. Since this produce is one of the key transfer pathways of cesium (e.g. Möre, 1994), it is logical to assume that the aggregate transfer to the urban population is best described by the ratio between the body burden and the average deposition level in the county instead of the municipality. The results indicate also homogeneity of the dietary habits of the urban populations in Sweden, which live mostly on foodstuff that are distributed by the major food industry chains. These distribution chains tend to even out local variations in the concentration levels of foodstuffs other than dairy milk. This may also be the explanation why the rural non-farming population in the Gävle municipality exhibited a similar transfer of radiocesium as the urban population in the major metropolitan.

For some populations (farmers and hunters) using county averages yield lower transfer factor values than using municipality averages. This indicates that the ^{137}Cs content in these populations is more dependent on the contamination levels in food produced locally

(e.g. game, berry, mushrooms, domestically grown vegetables, milk and beef from the local farms) rather than in the foodstuffs handled by the major distribution chains in Sweden.

Previous studies in Sweden show that the transfer of radiocaesium to key diet components and to human populations, was higher for the nuclear weapons fallout than for the Chernobyl debris (Hanson et al., 1996; Aarkrog, 1988; Rääf, 2000). According to this study the time-integrated aggregate transfer to urban populations appears to be about 2-3 times higher for the nuclear weapons fallout than for the Chernobyl fallout. The main pathway of radiocaesium from soil deposition to urban populations is by direct contamination of growing fodder crops and grazing, rather than the root uptake of the element previously deposited in soil into the edible parts. Since the continuous global fallout in the 1960s and 70s occurred over the growing seasons, the short-term transfer of radiocaesium resulted in higher contamination levels in the diet and in man compared with the Chernobyl scenario (see also e.g. Aarkrog, 1988). In addition to the time-pattern of fallout, the amounts of countermeasures taken in the form of restricted distribution of foodstuff and recommendations issued by the authorities have influenced the transfer to human populations. Especially for reindeer herders in the Västerbotten county the significantly lower radioecological transfer of ^{137}Cs after the Chernobyl accident is an effect of the greater amount of countermeasures undertaken after Chernobyl compared with the 1950s and 60s (Ågren, 1998). This is further supported by the fact that the reindeer herders in the county of Norrbotten, which was to a much lower extent affected by the Chernobyl fallout, exhibit transfer values that are higher than for similar populations in the southern county of Västerbotten where certain areas were heavily affected by Chernobyl fallout.

Based on the UNSCEAR definition of radioecological transfer of ^{137}Cs to man the projected aggregate transfer over a 50 y period after the Chernobyl fallout in Sweden results in a committed effective dose per unit activity deposition of about 0.05 μSv/kBq m^{-2} in Swedish urban populations (Table II). From an event similar to the Chernobyl fallout scenario, including similar remedial actions taken in terms of restricted distribution of contaminated foodstuffs, it is predicted that an activity deposition of 1 kBq m^{-2} of ^{137}Cs in the northern counties in Sweden will result in a committed effective dose of 0.8 to 0.9 mSv in the reindeer herders and about 0.1 mSv to rural non-farming populations.

8.5 Conclusions

- The time-integrated aggregate transfer of ^{137}Cs for the global fallout was 2-3 times higher than from Chernobyl debris for Swedish urban populations. For reindeer herders this difference is even more marked, with a factor of three to four higher time-integrated transfer factor of nuclear weapons fallout. A part of this difference is attributed to the different time-patterns of the fallout, where the main fraction of nuclear weapons fallout occurred continuously over the spring seasons, giving rise to repeated short term transfer of ^{137}Cs to humans.

- Considering the transfer of Chernobyl ^{137}Cs debris the time-integrated transfer factor appears to be more than 25 times higher for reindeer herders in Sweden than for the urban reference groups. Hunters exhibit, on average, a factor of 3 times higher values, and farmers a factor of 2 times higher. An even more pronounced relative difference between the time integrated aggregate transfer was observed between reindeer herders and urban reference populations for the pre-Chernobyl fallout (a factor of 30).

- The projected committed effective dose from internal contamination of Chernobyl ^{137}Cs per unit activity deposition is observed to be 20–30 μSv/kBq m^{-2}. The highest values in Sweden are obtained for reindeer herders with an estimated radioecological transfer of 0.5 mSv/kBq m^{-2}.

- Using deposition density values averaged over the counties in Sweden appears to be preferred from using the average deposition values in the immediate localities for urban populations in the metropolitan areas when aiming at making relative comparisons to other populations.

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9 Foodchain Modelling for Nordic countries

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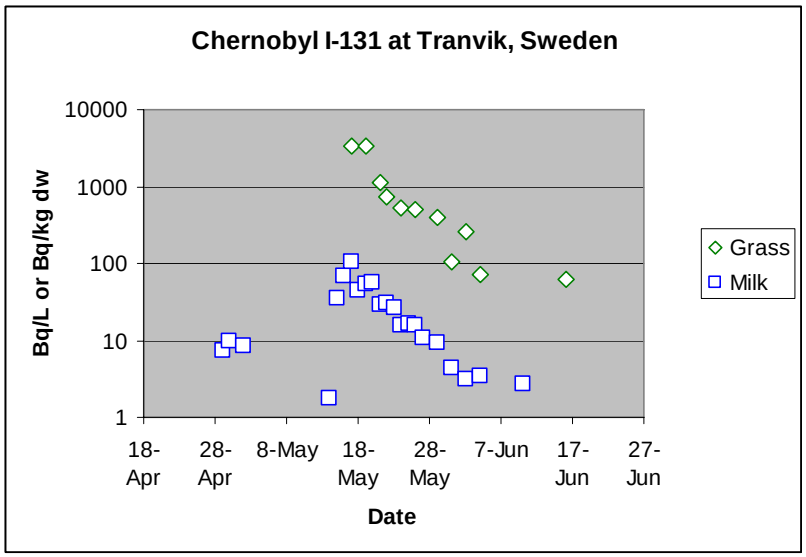
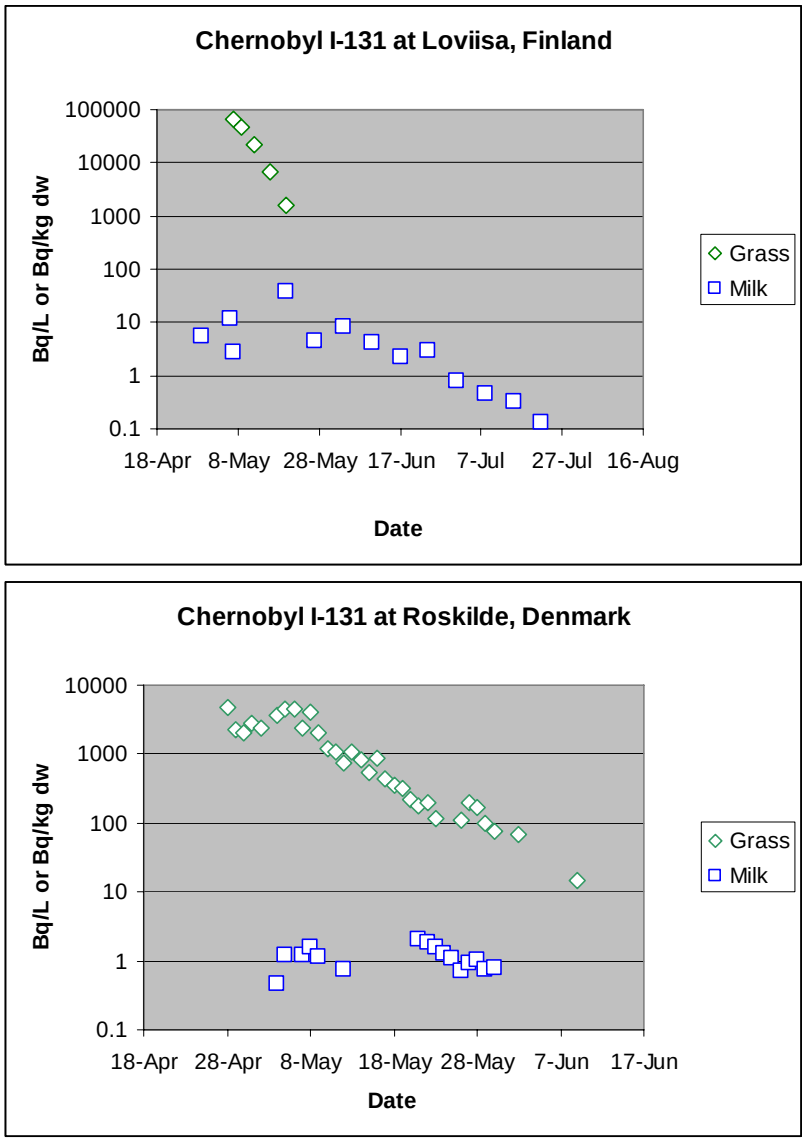
9.1 Background

The decision-support system ARGOS developed by the Danish Emergency Management Agency incorporates and integrates data of relevance to large-scale radioactive contamination of the environment. ARGOS includes a radioecological module FDM (Food and Dose Module) for estimating doses to humans from ingestion of contaminated food. The module is intended for predicting consequences of short-term accidental releases of radioactivity. For the purpose of model validation or testing, a special version of FDM has been developed, which allows for multiple deposition events as well as full access to all model parameters. This version of the model is used in the EcoDoses Project to predict levels of radionuclides in the environment from extended deposition events, e.g. fallout from the Chernobyl accident. Model assumptions and parameter values may be adjusted to minimize the difference between predicted and observed values, and these adjustments may then be implemented in the ARGOS FDM.

9.2 Nordic data on I-131 in milk

Nordic data on ^{131}I in milk have been identified for model testing and tuning. Chernobyl data from 1986 are available from Sweden, Finland and Denmark as shown in the graphs below. Data on atmospheric concentrations and precipitation are also available.





9.3 Adjustment of model parameters

Preliminary work in 2004 with the FDM has indicated need to adjust and change a number of model assumptions and parameters from default values based on Central European conditions to those characteristic for Nordic countries, e.g. growing seasons, harvest times, crop yields, animal feeding regimes, human habits.

A more complete list of parameters and assumptions is given in the following.

The parameters are categorised according to

- Element-independent
- Element-dependent and
- Nuclide-dependent

parameters.

The **element-independent parameters** describe the boundary conditions of the exposure; these parameters are:

- Leaf area indices, growth periods and yields of agricultural crops
- Weathering half-life and half-lives for growth dilution
- Period of preparing winter feed
- Storage times for food- and feedstuffs
- Age-dependent consumption rates
- Seasonality of the consumption rates of foods
- Restrictions for food consumption
- Occupancy times
- Age-dependent inhalation rates
- Inhalation of resuspended soil particles by humans
- Animal specific feeding rations
- Age of animals at slaughter
- Inhalation by animals
- Parameters to estimate the contamination of skin
- Contamination of plants by resuspension
- Soil ingestion of animals
- Soil mass of the rooting zone

The **element-dependent parameters** quantify in particular the behaviour of the radionuclides in the environment and the transfer between different model compartments, these parameters are:

- Translocation factors
- Deposition velocities
- Parameters for estimating the interception of activity deposited during rainfall
- Transfer factors soil-plant
- Migration, fixation and desorption of radionuclides in soil
- Enrichment of radionuclides in the resuspendable soil fraction
- Transfer factors feed to animal food products
- Biological half-lives
- Processing factors for food- and feedstuffs
- Parameters to estimate the time-dependence of the external exposure from radionuclides deposited on the ground

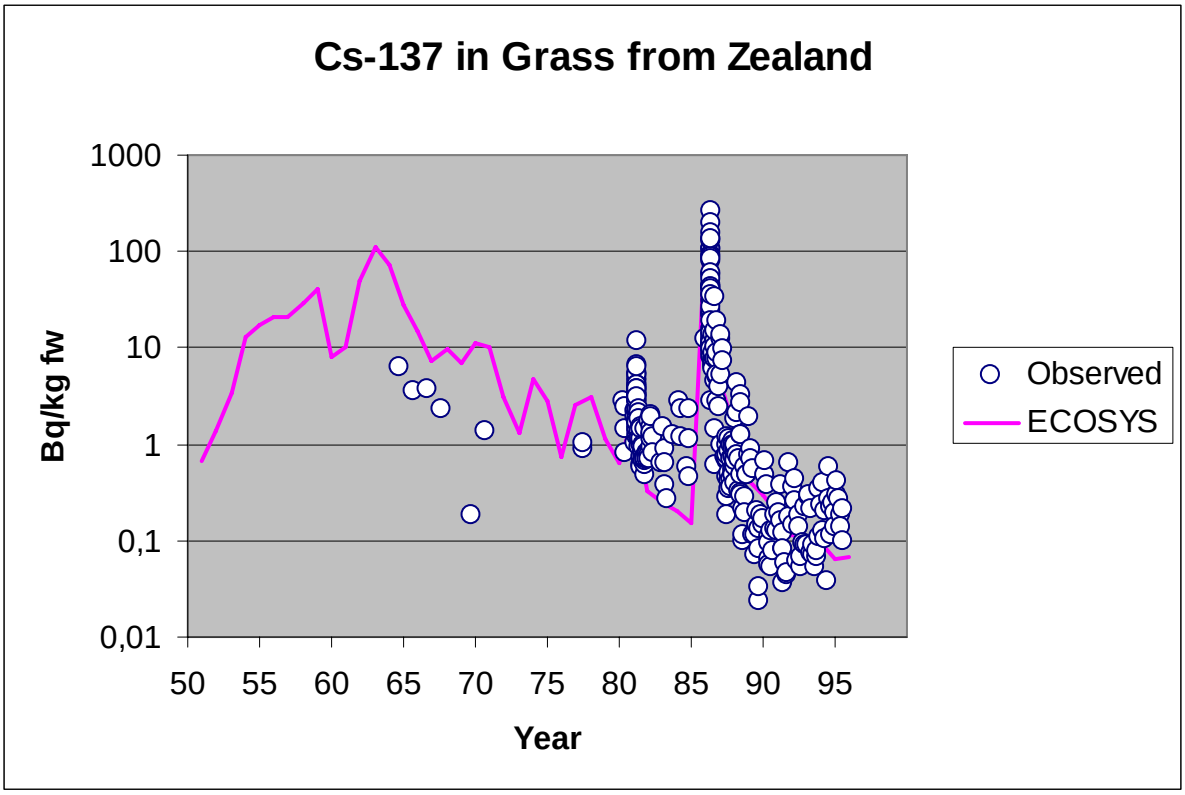
The **nuclide-dependent parameters** describe in particular physical and dosimetric quantities as:

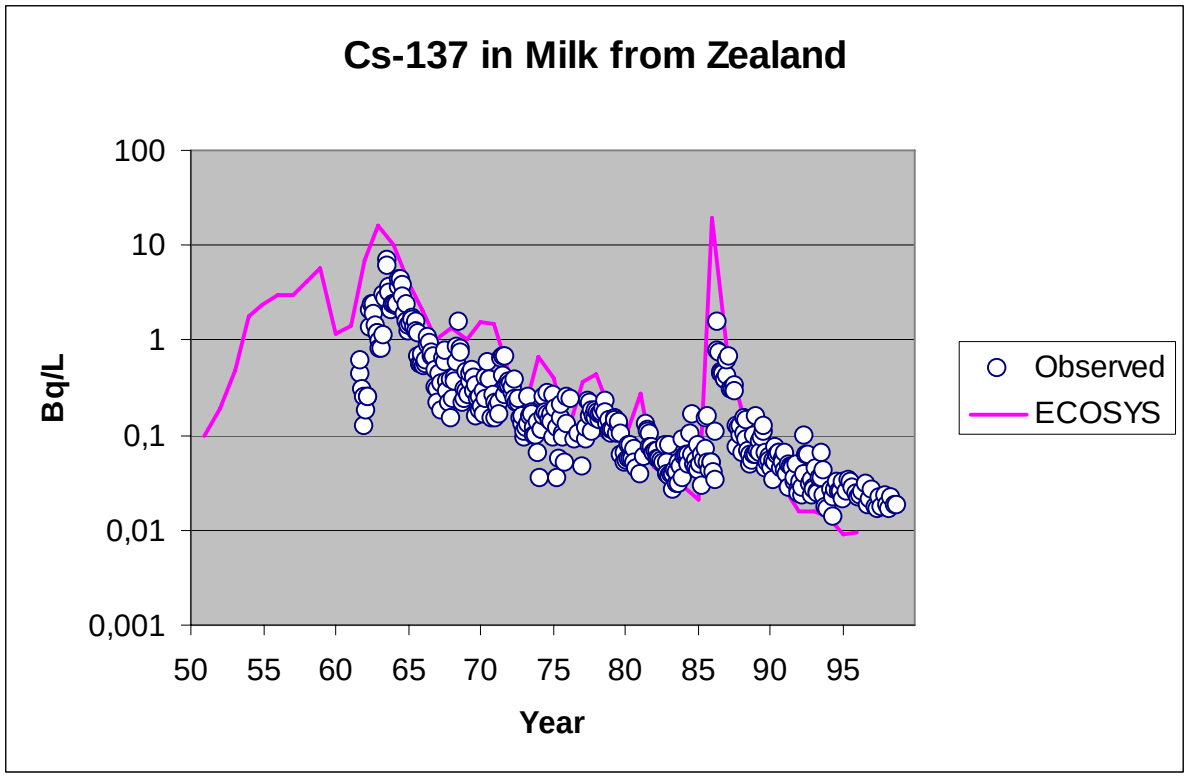
- Physical half-lives
- Age-dependent dose factors for internal exposure due to ingestion
- Age-dependent dose factors for internal exposure due to inhalation

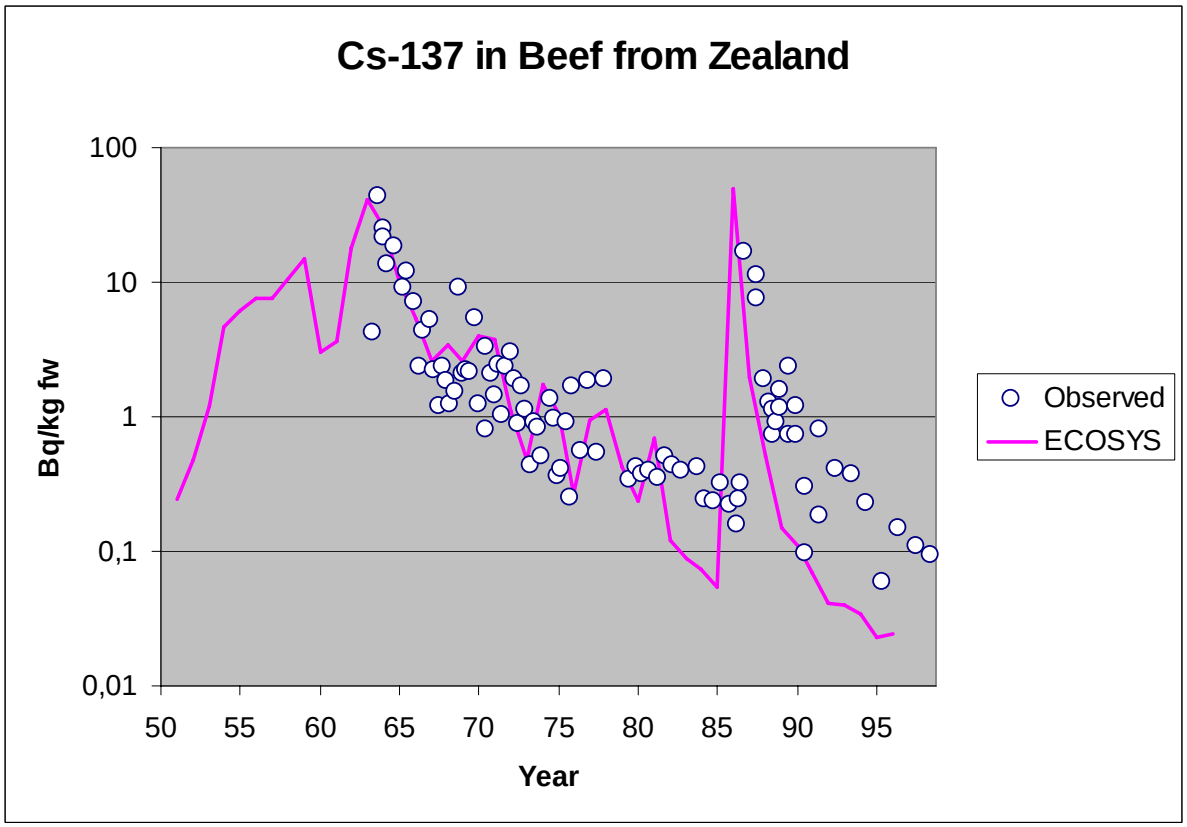
- Age-dependent dose factors for external exposure from activity deposited on the ground
- Age-dependent dose factors for external exposure from activity in air and
- Dose factors for skin contamination
- Shielding factors for different locations.

9.4 Model testing

The following graphs illustrate observed data for the period 1950-1996 on ^{137}Cs in grass, milk and beef in Denmark compared with predictions made with the ECOSYS model.




Cs-137 in Milk from Zealand
100
10
1
0,1
0,01
0,001
Bq/L
50
55
60
65
70
75
80
85
90
95
Year
Observed
ECOSYS


Cs-137 in Beef from Zealand
100
10
1
0,1
0,01
Bq/kg fw
50
55
60
65
70
75
80
85
90
95
Year
Observed
ECOSYS

10 Summary of works for the second project year

Deposition of radionuclides following nuclear weapon tests

It has previously been shown that the predictions made by global deposition model used by UNSCEAR significantly underestimate the fallout in Nordic countries. The model reproduces the deposited fallout on a global scale, but looking at the deposition of fallout in the Scandinavian countries, the amount of precipitation must be taken into account. A better approach for estimating global fallout on a regional or national scale has been developed based on a correlation between precipitation and deposition rates. The EcoDoses project demonstrated in its first phase that a more precise technique for determining deposition from global fallout could be developed. The technique was tested for Icelandic data, and proved successful. For the second phase of EcoDoses separate studies have been done concerning deposition of radionuclides from atmospheric nuclear weapon tests:

- **Norway:** Previously unpublished measurements of radioactivity in air and rainwater at different Norwegian stations have been collated and based on these data we have established the dependence of the deposition on precipitation and air concentration of radioactive debris. Monitoring data show that not only the air concentration is relatively uniform over large areas, but also the concentration in precipitation (e.g. Bq/litre) is relatively uniform over the same areas.

- **Faroe Islands:** The approach mentioned above has also been employed for Faroese data and a relationship between total accumulated ^{90}Sr deposition and average annual precipitation has been established at two Faroese sites (Torshavn and Klaksvik) with long time series (1963-69 and 1963-85) of ^{90}Sr in rainwater. These sites have been used as references in order to estimate the total accumulated ^{90}Sr deposition at other sites, where no deposition data are available. According to this study, the major part of the ^{90}Sr deposition was acquired during the 1960s. The shorter period 1963 to 1969 accounts for 74-86% of the deposition between 1963 and 1985. The highest deposition values are found in the northern part of the country and the lowest values are found for the far south and the far west of the country.

- **Sweden:** The aim of the study was to predict the deposition of ^{137}Cs due to fallout from nuclear weapon tests 1962-1966 and visualize the results in deposition maps. The spatial variation of the quarterly ^{137}Cs deposition over Sweden during the period 1962-1966 due to nuclear weapon tests was calculated. The quarterly deposition density (Bq/m^2) was used for calculations of integrated (total) ^{137}Cs deposition density 1962-1966 and cumulative (decay corrected) deposition density 1962-1966 corrected for decay to 1985 and 1994. For comparisons with other studies, the integrated ^{137}Cs activity deposited over Sweden was calculated by multiplying the mean value of integrated ^{137}Cs deposition density over Sweden with the area of Sweden. The lowest levels of integrated and cumulative ^{137}Cs

deposition density were noted in the north-eastern and eastern Sweden and the highest levels in the western parts of Sweden. Comparisons between the predicted values of this study show a good agreement with measured values and other studies.

Radionuclides in milk

Activity concentrations of ^{137}Cs, ^{90}Sr and ^{131}I in cow's milk from all Nordic countries for the NWF and the post-Chernobyl periods have previously been collated in an excel database. In 2004 the database was further extended by including new data from Finland, Sweden and Norway. In order to explain the time development of contamination in different Nordic regions dual regression analyses of some selected time-series were performed. Since the NWF period was subject to similar investigations in previous year's report, the present study focused on the post-Chernobyl period (1986-). Effective ecological half lives of Cs-137 in milk from 12 regions were estimated. The fast component (T1) was about 1 year for all series (except Sandnessjøen in Norway), while the slow component (T2) was more variable (7-13 years) - and in some cases not applicable.

Integrated transfer coefficients of ^{137}Cs from wet deposition to cow's milk from selected sites in Norway, Sweden and the Faroe Islands were estimated using the UNSCEAR model. The integrated transfer coefficients were found to be higher at the Faroese sites than at the Norwegian and Swedish sites, indicating relatively high individual doses from ingestion of milk in the Faroe Islands. The integrated transfer coefficients of ^{137}Cs to cow milk in the Faroe Islands are also high compared to other countries. The ITC's are found to vary also within small geographical areas. They vary with a factor of two between the Faroese sites. The reason for this may partly be due to differences in the soil characteristics at the localities. This could, however, not be tested in the present study because of lack of data.

Radiocaesium in freshwater fish

High activity concentrations of ^{137}Cs still occur in fish in certain Finnish lakes in the areas of the highest deposition. The observed ecological halftimes of ^{137}Cs in perch in certain Finnish lakes varied by a factor of about three. The longest halftime of ^{137}Cs in perch was approximately 9 years and the shortest approximately 3 years, determined for the time period of 1988-2002. The Norwegian lakes differ also from each other with respect to the decrease rates of ^{137}Cs in fish. In some cases there were clearly two components in the reduction of ^{137}Cs. Ecological halftimes of ^{137}Cs in trout and Arctic char varied from 1.4 y to 4.7 y in 1988-1994. There is an indication of somewhat more rapid reduction of ^{137}Cs in fish in certain Norwegian lakes compared to Finnish ones, although ecological halftimes for the Norwegian and for the Finnish lakes were estimated for different time intervals in the examples, and are thus not directly comparable.

Human populations – radioecological sensitivity

A comparison of the estimated committed effective dose per unit activity deposition on ground was made between different critical groups in Sweden. The time-integrated

aggregate transfer of ^{137}Cs for the global fallout was 2-3 times higher than from Chernobyl debris for Swedish urban populations. For reindeer herders this difference is even more marked, with a factor of three to four higher time-integrated transfer factor of nuclear weapons fallout. Considering the transfer of Chernobyl ^{137}Cs debris the time-integrated transfer factor appears to be more than 25 times higher for reindeer herders in Sweden than for the urban reference groups. An even more pronounced relative difference between the time integrated aggregate transfer was observed between reindeer herders and urban reference populations for the pre-Chernobyl fallout (a factor of 30).The projected committed effective dose from internal contamination of Chernobyl ^{137}Cs per unit activity deposition is observed to be 20–30 μSv/kBq m^{-2}. The highest values in Sweden are obtained for reindeer herders with an estimated radioecological transfer of 0.5 mSv/kBq m^{-2}.

Food-chain modelling

The radioecological food-and dose module in the ARGOS decision support system was tested in EcoDoses phase one, and found useful and suited for predicting radiological consequences of nuclear fallout. Further work with the model has indicated need to adjust and change a number of model assumptions and parameters from default values based on Central European conditions to those characteristic for Nordic countries, e.g. growing seasons, harvest times, crop yields, animal feeding regimes, human habits.

Further work

Further work in EcoDoses will focus on the doses to man, by improving the fallout models and implementing the collected data into food and dose models. Focus will thus be on internal doses. Also work on the human data on ^{137}Cs body content will be further systemized and compared with the modelled data. Reliable long-time series of radioactive contamination in foodstuffs are important both to validate radioecological models and to calculate the effective ecological half- lives of radionuclides in different food chains. A good understanding of radioecology and good modelling tools are important for implementing adequate countermeasures in a nuclear emergency situation. The continuation of EcoDoses will hopefully contribute to reaching these goals in a successful manner.

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Abstract	The NKS B-programme EcoDoses project started in 2003 as a collaboration between all the Nordic countries. The aim of the project is to improve the radiological assessments of doses to man from terrestrial ecosystems. The present report sums up the work performed in the second phase of the project. The main topics in 2004 have been: (i) A continuation of previous work with a better approach for estimating global fallout on a regional or national scale, based on a correlation between precipitation and deposition rates. (ii) Further extension of the EcoDoses milk database. Estimation of effective ecological half lives of ^{137}Cs in cow's milk focussing on suitable post-Chernobyl time-series. Modelling integrated transfer of ^{137}Cs to cow's milk from Nordic countries. (iii) Determination of effective ecological half lives for fresh water fish from Nordic lakes. (iv) Investigate radioecological sensitivity for Nordic populations. (v) Food-chain modelling using the Ecosys-model, which is the underlying food- and dose-module in several computerised decision-making systems.
Key words	Nuclear weapons fallout, deposition modelling, food-chain modelling, ecological half-lives in milk and freshwater fish, radioecological sensitivity for Nordic populations

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