Nordisk kernesikkerhedsforskning
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Pohjoismainen ydinturvallisuustutkimus
Nordisk kjernesikkerhetsforskning
Nordisk kärnsäkerhetsforskning
Nordic nuclear safety research

NKS-123
ISBN 87-7893-184-3

EcoDoses
Improving radiological assessment of doses to man from terrestrial ecosystems.
A status report for the NKS-B project 2005

Edited by Sven P. Nielsen and Kasper Andersson
Risø National Laboratory, Denmark

April 2006

Abstract

Considerable variations in activity concentrations in milk of ^{137}Cs and ^{90}Sr were observed between countries or regions due to precipitation patterns, soil types and inhomogeneity of Chernobyl fallout. Time trends indicate that factors influencing ecological half-lives for ^{90}Sr are not the same as for ^{137}Cs in the pasture–milk system.

Internal doses to Faroese people derive mainly from dairy products, lamb and potatoes. The largest doses were received from nuclear weapons fallout in the early 1960's. ^{137}Cs causes higher doses than ^{90}Sr, and the regional variability is larger for ^{137}Cs than for ^{90}Sr.

^{137}Cs deposition maps were made of Sweden. Values of ^{137}Cs deposition and precipitation were used in the calculations of Nuclear Weapons Fallout (NWF). The deposition of ^{137}Cs from the Chernobyl accident was calculated for western Sweden. Lowest levels of NWF ^{137}Cs deposition density were noted in the north-eastern and eastern Sweden and the highest levels in the western parts. The Chernobyl ^{137}Cs deposition is highest along the coast and lowest in the south-eastern part and along the middle. The calculated deposition from NWF and Chernobyl in western Sweden was compared to observed deposition and showed good agreement.

Ecological halftimes of ^{137}Cs in perch in Finnish lakes vary by a factor of three. The longest halftime of ^{137}Cs in perch was 9 y and the shortest 3 y. Norwegian lakes differ from each other with respect to the rates of decrease of ^{137}Cs in fish. Ecological halftimes of ^{137}Cs in trout and Arctic char varied from 1 to 5 y. A more rapid reduction of ^{137}Cs in fish is found in certain Norwegian lakes compared to Finnish lakes. In two Norwegian lakes the ^{137}Cs concentrations in trout remain at about 100 Bq/kg since 1990.

The European decision support systems, ARGOS and RODOS, include foodchain modules with default parameters derived from southern Germany. Many parameters describing foodchain transfer are subject to considerable variation according to local conditions. Such parameters include soil type, sowing and harvesting times, feeding regimes for animals, human consumption habits, and dependence of plant development on season. Model features and parameter values need adjustment for the model to produce reliable predictions for Nordic areas. Further generic inadequacies of the modelling system relate to dry deposition processes.

Key words

Nuclear weapons fallout, deposition modelling, food-chain modelling, ecological half-lives, radioecological sensitivity

NKS-123
ISBN 87-7893-184-3

Electronic report, April 2006

The report can be obtained from
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1 Introduction

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

The EcoDoses activity focuses on collation and review of published and unpublished data from the Nordic countries for the nuclear weapons fallout period and the post-Chernobyl period. This includes data on radionuclides in air, precipitation, soil, milk and reindeer. Based on this, improved models for estimating radioactive fallout based on precipitation data during the nuclear weapons fallout period are developed. Effective ecological half-lives for ^{137}Cs and ^{90}Sr in milk are calculated for the nuclear weapons fallout period. The data are also used to compare modelling results with observed concentrations. The importance of applying case-specific and updated data of, e.g., geological, seasonal, climatic and demographic nature, in the modelling is demonstrated.

The present report sums up the work performed in 2005. In this third phase the main topics have been:

- Improved approaches for estimating radioactive fallout on a regional or national scale, based on correlation between precipitation and deposition rates. Part of the work (by Sigurður Emil Pálsson/Geislavarnir) is not reported here since it is described in a paper which has been submitted to an international journal. This will be reported in the next EcoDoses report.
- Doses to man from foodstuffs. Estimation of effective ecological half lives of ^{137}Cs and ^{90}Sr in cow’s milk focussing on suitable post-Chernobyl time-series.
- Effective ecological half lives for fresh water fish from Nordic lakes.
- Food-chain modelling using the radioecological food-and-dose module in the ARGOS decision support system.

2 Radioactive contamination of milk from the Nordic countries

Håvard Thørring, Norwegian Radiation Protection Authority, Norway

2.1 Introduction

For the NKS-B EcoDoses activity – “Improving radiological assessment of doses to man from terrestrial ecosystems”, data concerning ^{137}Cs and ^{90}Sr in cow’s milk were collated from all Nordic countries for both the **N**uclear **W**eapons **F**allout and the post-Chernobyl periods. An overview of the collated data for ^{137}Cs is shown in Figure 2.1.

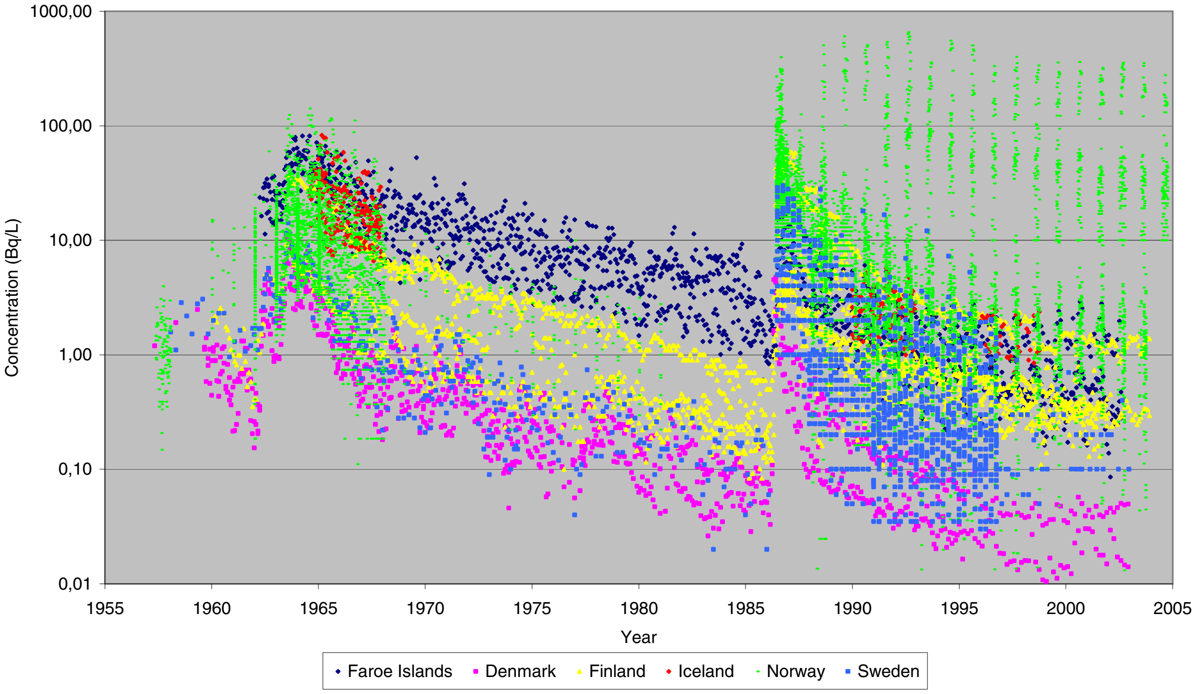

Figure 2.1. *Caesium-137 in cow’s milk from the Nordic countries*

2.2 Summary of data

2.2.1 Caesium-137

For the NWF-period, the contamination levels of caesium-137 in milk vary considerably - dependent on factors such as deposition level and soil properties in different regions. Generally, precipitation rich areas such as the Faroe Islands, Iceland and western parts of Norway show the highest activity concentrations of ^{137}Cs. The importance of soil properties for milk concentrations is demonstrated by comparing the data from Lapland (North-Finland) and south-western Finland. During the NWF-period the deposition levels were similar in these two regions, yet the contamination level in milk from Lapland is several times as high as the corresponding levels from the south west. In northern Finland there are predominantly nutrient deficient organic soils which give a higher transfer of ^{137}Cs compared to the clayish soils in the south west. Denmark shows the generally lowest levels of caesium-137 for the NWF-period, most likely due to the clayish soils in these areas.

Looking at Figure 2.1, the post-Chernobyl data are clearly much higher in certain parts of Norway compared to other Nordic countries. This is mainly due to high deposition in some Norwegian areas. Many farms joined the summer monitoring program in 1988-89 which explains why the peak values are found around these years instead of in 1986-87. There are regional differences in the reported data for Sweden, Finland and Denmark as well - the higher level samples are from the mid-eastern part of Sweden, western Finland and Jutland in Denmark.

2.2.2 Strontium-90

The Faroese data show the highest Nordic contamination levels for the NWF-period, while the Norwegian data generally are highest for the post-Chernobyl period. There is a gap in contamination levels for the NWF data for Norway. The higher levels are found in Bergen and Florø, situated on the west coast of Norway. Due to the high precipitation rate in this coastal area the estimated deposition was higher here than in other parts of the country. No large regional differences within other countries are apparent for ^{90}Sr. This indicates that soil types are less important in determining the transfer factors to milk for ^{90}Sr than for ^{137}Cs.

A more thorough description of the Nordic milk data is given in the EcoDoses annual reports 2003 and 2004 (Bergan *et al.* 2004, 2005).

2.3 Time trends and effective ecological half lives

From the collated milk data, long and detailed data series with good consistency were selected for a more thorough study of time trends and effective ecological half lives – emphasising regional variations. These series are briefly described in Table 2.1. Unfortunately, the selected data series comprises only three of the Nordic countries, namely Denmark, Faroe Islands and Finland.

Table 2.1. *Selected time series from Nordic countries*

DATA SERIES	MILK TYPE	SAMPLING	TIME PERIOD
West Denmark (Jutland)	Dry milk	~Monthly	1959-02
East Denmark (Islands)	Dry milk	~Monthly	1959-02
Faroe Islands (Thorshavn)	Dairy milk	~Monthly	1962-02
Faroe Islands (Klaksvig)	Locally produced milk	~Monthly	1962-02
Faroe Islands (Tvøroyri)	Locally produced milk	~Monthly	1962-02
North Finland	Dairy milk (Kursu) Dairy milk (Rovaniemi)	~Monthly	1963-88 1986-02
South-west Finland	Dry milk Dairy milk	~Monthly	1960-89 1986-02
West Finland	Dairy milk	~Monthly	1966-73 1978-04
East Finland	Dairy milk	~Monthly	1978-04

Dual exponential regressions were performed on each data-series. Since the milk data show considerable seasonal variation, the monthly values were combined to an annual average before the regression analysis was performed. The model expression was as follows:

$$Y = ln\left[A1^{-\frac{ln 2\cdot t}{T1}} + A2^{-\frac{ln 2\cdot t}{T2}} \right]$$

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

For ^{137}Cs, the starting point of the NWF-period regressions was ~1964, and the end point was 1985 (December). For the post-Chernobyl period the starting point was 1986 (summer), whereas the end points were according to the length of the available time-series (see Table 2.1).

Strontium-90 regressions were performed for the whole period (1964-present). In addition, regressions were run for the NWF-period to allow direct comparison with caesium-137.

2.3.1 Caesium-137

Figure 2.2 shows the results for the time-series from Western Finland, Jutland in Denmark, and Thorshavn (Faroe Islands). The regression lines seem to represent the time development of ^{137}Cs-contamination in milk fairly well. Effective ecological half lives for all the investigated time-series (including the three above) are summarised in Table 2.2.

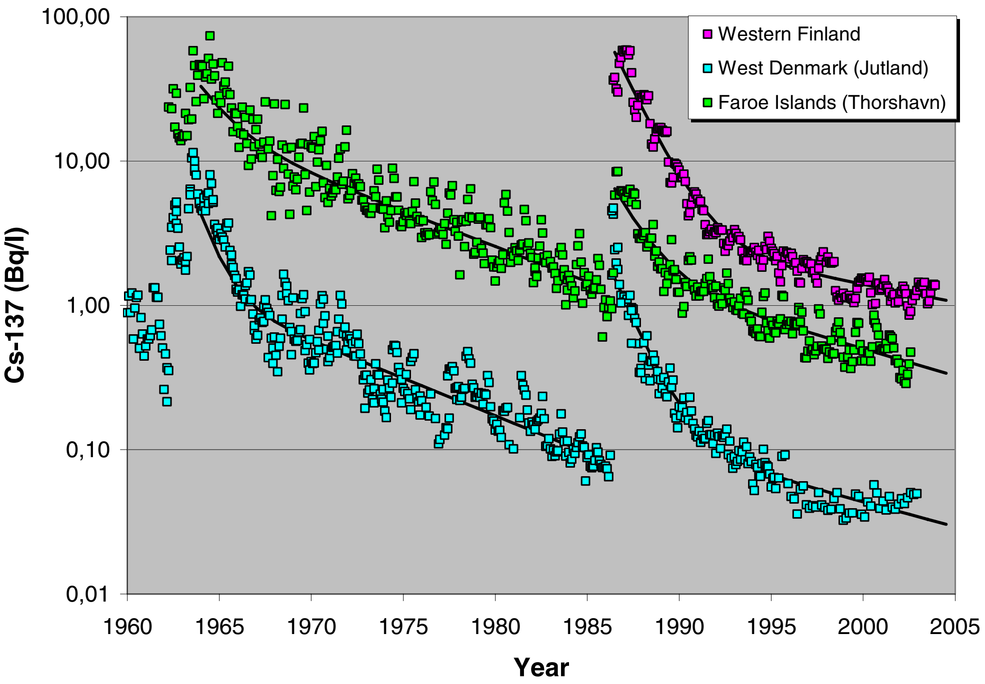

Figure 2.2. *Caesium-137 dual exponential regressions for selected time-series before and after the Chernobyl accident*

Table 2.2. *Effective ecological half lives for* ^{137}*Cs in milk from various regions in three Nordic countries.*

Caesium-137	**T1±SE**[1] (years)	**T2±SE**[1] (years)	**R**^{2}
NWF-period			
West Denmark (Jutland)	0.7±0.1	5.8±0.2	0.91
East Denmark (Islands)	0.8±0.1	6.0±0.3	0.88
Faroe Islands (Thorshavn)	1.1±0.2	6.2±0.4	0.88
Faroe Island (Klaksvig)[2]	(1.9±0.3)	-	(0.81)
Faroe Island (Tvøroyri)	1.0±0.3	6.5±0.3	0.85
North Finland (Kursu)	1.0±0.1	5.4±0.1	0.97
South-western Finland	1.0±0.1	7.2±0.4	0.93
Post-Chernobyl			
West Denmark (Jutland)	1.0±0.1	8.8±1.3	0.94
East Denmark (Islands)	0.5±0.0	6.6±0.6	0.90
Faroe Islands (Thorshavn)	1.1±0.2	8.0±1.0	0.89
Faroe Islands (Klaksvig)[2]	(1.4±0.3)	-	(0.77)
Faroe Islands (Tvøroyri)[2]	(1.6±0.2)	-	(0.82)
North Finland (Rovaniemi)	1.3±0.2	9.0±1.0	0.94
West Finland	1.1±0.1	12.6±2.2	0.95
East Finland	0.8±0.1	8.3±0.7	0.83
South-West Finland[2]	(1.1±0.1)	-	(0.94)

[1] Asymptotic standard error

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

Looking at the estimated effective ecological half lives, we see that T1 is around 1 year for all sites for both periods. For the NWF-period, T2 is around 6 years for all localities except for south-western Finland that shows a slightly longer T2 half-life (about 7 years). T2 half-lives for the post-Chernobyl period are generally longer. In addition there seem to be more pronounced geographical variations: The shortest T2 half-life is found for the Danish Islands (about 7 years), while the data from western Finland gives a T2 half-life of about 13 years.

2.3.2 Strontium-90

Effective ecological half lives for all of the investigated time-series are presented in Table 2.3. Generally, the regression lines represent the time development of ^{90}Sr-contamination in milk quite well (as evident from R^2 values).

Table 2.3. *Effective ecological half lives for ^{90}Sr in milk from various regions in three Nordic countries*

Strontium-90	**T1±SE**[1] (years)	**T2±SE**[1] (years)	$\mathbf{R^2}$
NWF-period			
West-Denmark (Jutland)	0.9±0.1	7.0±0.2	0.96
East-Denmark (Islands)	1.1±0.1	7.6±0.3	0.94
Faroe Islands (Thorshavn)	0.8±0.4	3.8±0.1	0.96
Faroe Islands (Klaksvig)	0.8±0.2	4.2±0.1	0.95
Faroe Islands (Tvøroyri)	0.7±0.2	4.4±0.1	0.94
North Finland (Kursu)	1.6±0.1	11.9±1.2	0.94
South-western Finland	1.2±0.1	12.0±0.6	0.95
Whole period			
West-Denmark (Jutland)	1.4±0.1	8.5±0.2	0.97
East-Denmark (Islands)	1.8±0.1	10.6±0.4	0.96
Faroe Islands (Thorshavn)[2]	(3.4±0.1)	-	(0.98)
Faroe Islands (Klaksvig)[2]	(3.5±0.1)	-	(0.97)
Faroe Islands (Tvøroyri)[2]	(3.8±0.1)	-	(0.96)
North Finland (Kursu)	1.6±0.1	12.0±0.3	0.96
South-western Finland	1.2±0.1	11.6±0.2	0.93

[1] Asymptotic standard error

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

T1 for ^{90}Sr for the NWF-period is about 1 year for all sites. In contrast, there is a considerable geographical variation in T2 half-lives for this period: The shortest T2 half-lives were found for the Faroe Islands (about 4 years), whereas T2s for the Finnish data are about 12 years.

The Danish sites show slightly longer half-lives re both components (T1 and T2) using 2003 as the end point of regression, whereas the half lives for the Finnish sites do not seem to differ much considering either the whole period or the NWF-period. Note that the Faroese series do not give satisfactory effective ecological half-lives for T2. The reason for this is that there has been no decrease in concentrations of ^{90}Sr in milk after ~1990 (Figure 2.3). Accordingly, T2 half lives for these series will be very high (with a large appurtenant uncertainty). T2s for the Faroese series have therefore not been reported in Table 2.3. A similar trend is also observed for some of the ^{137}Cs time series. This, for instance, applies to the post-Chernobyl ^{137}Cs-series from South-western Finland and Tvøroyri (Faroe Islands) (Table 2.2).

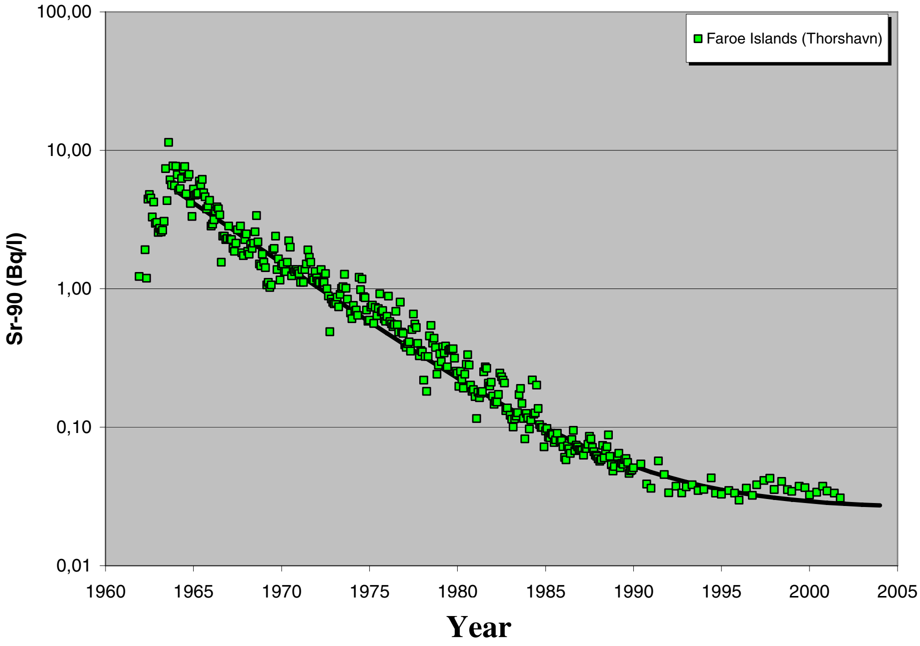

Figure 2.3. *Strontium-90 in milk from Thorshavn (Faroe Islands) where anomalous effective half lives for the "slow component" were observed. Estimated dual exponential regression lines are indicated.*

2.4 Conclusions

Considerable variations in activity concentrations of ^{137}Cs and ^{90}Sr were observed between countries or regions due to factors such as different precipitation patterns, soil types and Chernobyl deposition. The observed time trends indicate that the factors influencing the ecological half-life for ^{90}Sr are not entirely the same as for ^{137}Cs in the pasture – milk system. For ^{137}Cs the effective ecological half-lives seem to be fairly equal for the different investigated regions. Slightly longer T2s were observed for the post-Chernobyl period for this radionuclide. For ^{90}Sr the long component varies between 4 and 12 years. Finally, for some series (both ^{137}Cs and ^{90}Sr) a "no decrease" in activity concentrations has been observed for recent years.

2.5 Acknowledgements

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

2.6 References

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3 Doses to man from ^{137}Cs and ^{90}Sr in foodstuffs in the Faroe Islands

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3.1 Introduction

Information about food consumption in the Faroe Islands is limited. It is likely that the relative proportions of the different food groups have changed over time, and that the relative proportions of the different food groups vary across the country. It is difficult to get reliable data on food consumption rates as some of the food is acquired privately. There are two main nutritional studies for the Faroe Islands, the first in 1936 (Knudsen, 1940) and the second in 1981-82 (Vestergaard and Zachariassen, 1987). The calculations presented in this paper are based on data from the second study.

Radioactivity has been measured in Faroese foodstuffs since the early 1960's. The most complete data series exist for cow milk, but fairly good series exist for lamb meat, white bread, potatoes and drinking water, although with some gaps. The paper presents results from a preliminary study of doses to man from ^{137}Cs and ^{90}Sr in these foodstuffs.

3.2 Material and Methods

3.2.1 Sampling and data

The Faroese terrestrial environment has received radioactive debris from the nuclear weapons tests in the 1950's and 1960's and from the Chernobyl accident 26 April 1986. The measured fallout rates are presented in Figure 3.1. The sampling at Tvøroyri ends in 1993, and there is a gap in the series after 1996 at the two other sites.

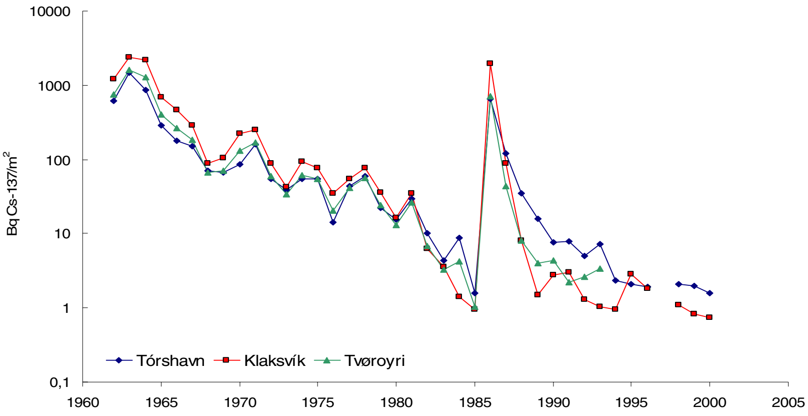

Figure 3.1. Annual wet deposition of ^{137}Cs at three Faroese

The wet deposition varies across the country, showing maximum values in 1963 and a pronounced ^{137}Cs signal from the Chernobyl accident in 1986. Precipitation and cow milk have been sampled at three different locations: Klaksvík in the north of the country, the capital Tórshavn in the central part and Tvøroyri in the south. The annual mean precipitation for the 30-year period 1961-90 was 1284mm in Tórshavn and 2334mm in Klaksvík (Cappelen & Laursen, 1998). There are no meteorological statistics available from Tvøroyri. The Faroese drinking water is obtained from surface water, and the samples have been collected as tap water in Tórshavn. Data for lamb meat, potatoes and grain products derive from countrywide samplings. The analyses in the paper are selected to end in 1996, i.e. 10 years after the Chernobyl accident.

3.3 Results and Discussion

Doses

The average per capita consumption of dairy products, grain products, potatoes and mutton in the Faroe Islands is 142 liter/year (mostly cow milk), 78 kg/year, 70 kg/year and 25 kg/year, respectively (Vestergaard and Zachariassen, 1987). According to unpublished information, the lamb meat consumption is about 72% of the total mutton consumption, i.e. 18 kg/year.

The dose from a given radionuclide may be calculated for 5 year intervals from equation (1):

$$D = 5 \cdot DF \cdot \Sigma I_i \quad , \mu\text{Sv} \qquad (1)$$

I_i is the annual intake of the radionuclide in 5-year interval i, and DF is the dose factor for ingestion of the radionuclide. For adults, DF is equal to $1.3 \cdot 10^{-2}$ and $2.8 \cdot 10^{-2}$ µSv/Bq for ^{137}Cs and ^{90}Sr, respectively (ICRP, 1993).

Based on data from 1962-96, the doses from ^{137}Cs to man were 0.71 mSv and 0.64 mSv via consumption of dairy products and lamb meat, respectively. The estimate for dairy products is calculated from activity concentrations in cow milk. There is a clear regional variation in the doses, as can be noted from Figure 3.2. Doses from ^{137}Cs in dairy products were 0.93 mSv, 0.73 mSv and 0.47 mSv at, respectively, Tvøroyri, Klaksvík and Tórshavn.

There is no information about which sites have been used for lamb meat samplings, but other studies (Joensen, 1999) indicate large regional variation regarding doses from meat consumption.

The internal dose from ^{90}Sr (see Figure 3.3) to man via dairy products is estimated to 0.16 mSv for the period 1962-96. The values were 0.18 mSv, 0.16 mSv and 0.15 mSv at, respectively, Klaksvík, Tvøroyri and Tórshavn. There is no registered information about water consumption, but 1 litre per day would correspond to 5.3 µSv from ^{90}Sr during the period 1962-96.

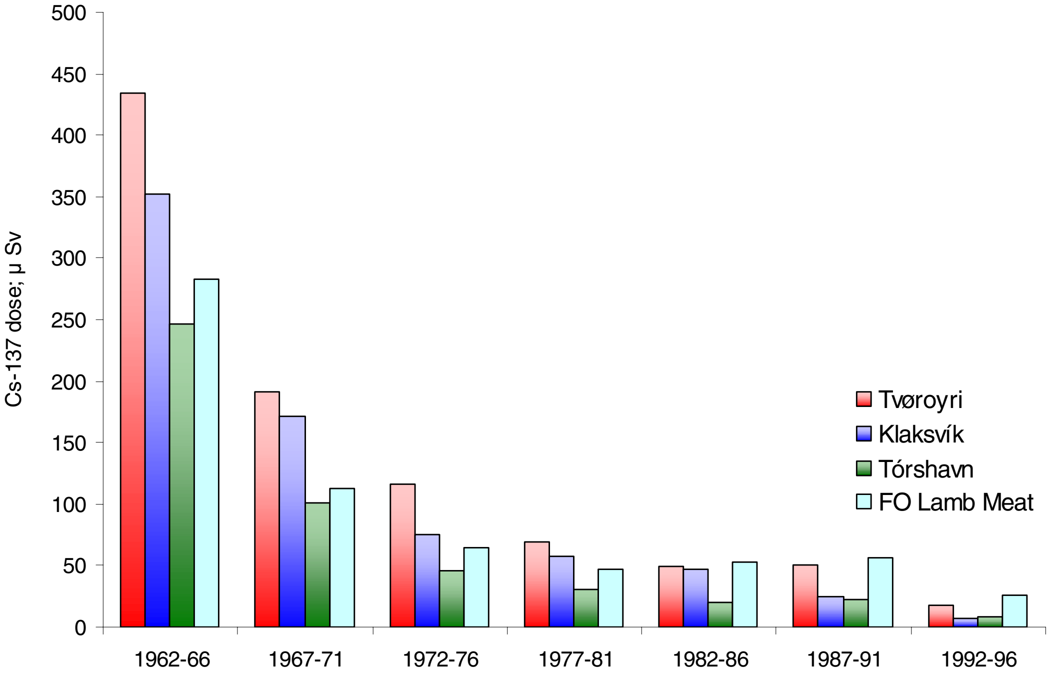

Figure 3.2. Cs-137 doses (in five year intervals) from dairy products at three sites and from lamb meat. Lamb meat has not been sampled from the same pastures every year.

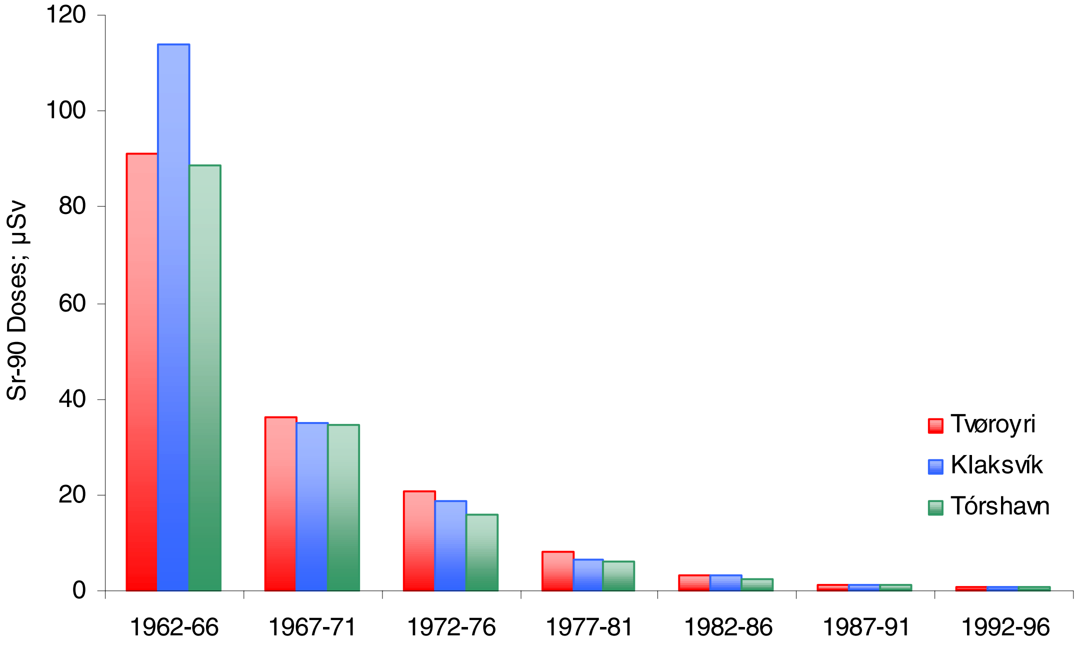

Figure 3.3. Sr-90 doses (in five year intervals) from dairy products at three sites.

Cs-137 doses from potatoes and grain products are presented in Figure 3.4. The calculations are based on data in the AMAP database. The ^{137}Cs dose from grain products was 56 µSv in the period 1960-99; the estimate is calculated from the ^{137}Cs activity concentration in white bread. The ^{137}Cs dose from potatoes was 0.30 mSv in the same period. A regional variability should be expected in activity concentrations in locally produced potatoes. Grain products and large part of the potatoes are, however, imported from abroad.

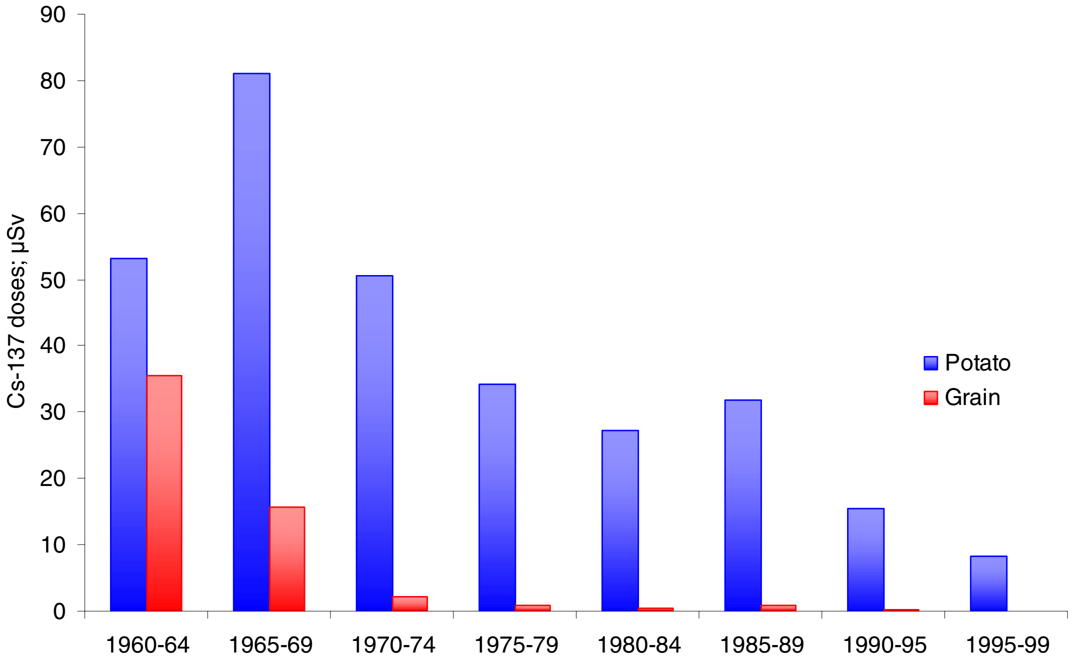

Figure 3.4. Cs-137 doses (in five year intervals) from potato and grain products.

3.4 Conclusions

Internal doses to people in the Faroe Islands derive to a large extent from dairy products (mostly cow milk), lamb meat and potatoes. The internal dose from ^{137}Cs in these food groups was 1.65 mSv during the years from 1960 to 1996. The largest doses were received in the early 1960's in accordance with the weapons fall out. A regional variability is observed in the dose estimates, as should be expected from variability in precipitation rates and variability in soil types. ^{137}Cs implies higher doses than ^{90}Sr, and the regional variability is observed to be larger for ^{137}Cs as compared to ^{90}Sr.

The estimated doses are subject to considerable uncertainties. This is to a large extent due to limited or missing documentation of food consumption during time, as well as missing documentation of differences in food habits across the country. It may, e.g., be expected that the amount of privately acquired food varies considerably across the country, and that there are considerable differences in food selection among age groups in the population.

3.5 Acknowledgements

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

Sven P. Nielsen, Risø National Laboratory, Denmark, for delivering data from the Risø databases.

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4 GIS supported calculations of ^{137}Cs deposition in Sweden based on precipitation data

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4.1 Introduction

Nuclear weapons fallout (NWF) over Sweden from has occurred since the 1940s over Sweden, where most of this deposition can be attributed to tests carried out between 1962 and 1966 on Novaya Zemlya, although Chinese tests also made a contribution in the ´70s. The accumulated deposition density over Sweden from nuclear weapons tests is about 3 kBq/m^2: De Geer et al. (1978), and, in addition to this, the Chernobyl accident contributed with a deposition density varying from close to zero to well over 100 kBq/m^2, within a restricted area, SGAB (1986).

Several studies have shown that the variations in deposition density are closely related to the precipitation, e.g. Bergan, 2002; Schuller et al., 2004. The deposition of radioactive elements could therefore be estimated by relating the measured activity concentration in the precipitation (Bq L^{-1} = Bq m^{-2} mm^{-1}) at a reference site to the amount of precipitation in a geographical region (e.g. Isaksson et al., 2000; Wright et al., 1999). The point-estimates could then be interpolated to a deposition map using a Geographical information system (GIS). The development of reliable methods for predicting the spatial variation and amount of ^{137}Cs deposition following nuclear accidents or nuclear weapons explosions are of interest in e.g. emergency preparedness and by including weather forecasts from meteorological data sources a prediction of the effects of a release of radioactive elements to the atmosphere could be made. The aim of this study was to determine the deposition of ^{137}Cs due to fallout from nuclear weapons tests (NWF) over the whole area of Sweden and from the Chernobyl accident in a predefined area in the western part, visualize the results in deposition maps and compare the maps with measurements.

4.2 Material and methods

Nuclear Weapons Fallout: For the estimation of NWF three reference sites in Sweden (Kiruna, Grindsjön and Göteborg) were initially chosen since they represent areas with different mean quarterly precipitation rates and also since they had an almost complete data record of quarterly ^{137}Cs deposition density for the time period studied, 1962-1966. The period 1962-1966 was chosen since the major part of the radioactive debris was injected into the atmosphere during the periods 1952-1958 and 1961-1962 (UNSCEAR, 2000), and because no data was available prior to 1962. The deposition density per unit precipitation (Bq m^{-2} mm^{-1}) at the reference sites was found by dividing the quarterly deposition density by the quarterly precipitation. The quarterly precipitation during the years 1962-1966 at 61 weather stations, distributed over Sweden was provided by the Swedish Institute of Meteorology and Hydrology (SMHI), as well as the coordinates of the weather stations. Each reference site was then assumed to represent an area of Sweden with approximately the same quarterly mean precipitation as the reference site itself. Due to seasonal variations in the precipitation pattern these reference sites were used in different combinations to find the best way of accurately representing the deposition density over the Swedish territory. The quarterly ^{137}Cs deposition density at a weather station was found by multiplying the amount of precipitation with the deposition density per unit precipitation at the corresponding reference site for each quarter during the period 1962-1966. This was then used to calculate the integrated and cumulative deposition density for the whole period. Deposition maps were created with ordinary Kriging interpolation in the GIS software ArcView (ESRI, Environmental Systems Research Institute, Redlands, California).

The Chernobyl fallout: This study has been concentrated to an area with a radius of approximately 120 kilometres with Göteborg in the centre. Earlier, 27 reference sites have been established for environmental monitoring, which gives the opportunity to compare the results of fallout estimations to measurements performed at those sites. In a similar way as for the NWF the ^{137}Cs deposition in the area was related to the precipitation. Göteborg was chosen to be the reference site because measurements of activity concentration in precipitation and deposited material were made at the time of the accident: Mattsson and Vesanen, (1988). The main part of the total ^{137}Cs deposition came in the rain that fell in Göteborg on the 8th of May, 1986. The activity concentration in the rain water decreased rapidly with the first millimetres and at a slower rate when the amount of rain increased, which can be well approximated by a double exponential function, Equation (1). After integration the total amount of deposited caesium is a function of the local precipitation according to

$$A = 2690 - 609e^{-x_{\max}/0.34} - 2080e^{-x_{\max}/5.07} \quad [\mathrm{Bq/m^2}] \qquad (1)$$

$x_{\max}$ is the total amount of rain. The parameters were obtained by fitting the double exponential to the data by Mattsson and Vesanen (1988). We assume that the main part of the Chernobyl fallout was wet deposited in the rainfall on the 8th of May and that equation 1 is valid in the whole region. A precipitation map for the 8th of May was derived by ordinary Kriging interpolation in a GIS with data provided by SMHI from 46 rain gauge stations relatively well spread out in the region. Equation 1 was then applied to the precipitation layer in the GIS resulting in a deposition map of the area. The deposition layer could easily be merged with the ones from the NWF calculations thus representing the total integrated or cumulative ^{137}Cs deposition in western Sweden. The Chernobyl deposition map was compared with aerial measurements, SGAB (1986) and the total deposition, corrected for decay until 2003, with the accumulated activity in soil samples from the 27 sample locations.

4.3 Results and discussion

The Chernobyl fallout: The mean value of the predicted deposition density over the integrated area of western Sweden is found to be 1.756 kBq/m^2 (range: 822-2.613 kBq/m^2). The highest values are found in the western parts along the coast and the lowest in an area between the coast and the lake Vänern, which can be seen in Figure 4.1a. The depositions from the two different sources are similar in the selected region. Calculated deposition from the Chernobyl accident was compared to aerial measurements: SGAB, 1986 and the mean ratio between calculated and measured deposition densities was 1.05±0.32. Excluding one site from the calculations because of large variations of neighbouring cells the comparison with aerial measurements yields a ratio of 0.996±0.13.

NWF: The deposition density of ^{137}Cs for each quarter was interpolated and summed to an integrated and a cumulative (decay corrected to 1994 and 1985, respectively) deposition density 1962-1966. The integrated deposition density can be seen in Figure 4.1b, where the mean is 1.853 kBq/m^2 (range: 1.416-2.695 kBq/m^2). In general, the lowest values of integrated ^{137}Cs deposition density are found in the northeast and east of Sweden where the northern area is an area with low precipitation. The highest values are found in the mountain areas in northern Sweden and in western Sweden. A comparison with the measured deposition each quarter at three sites, not used as reference sites, show good agreement.

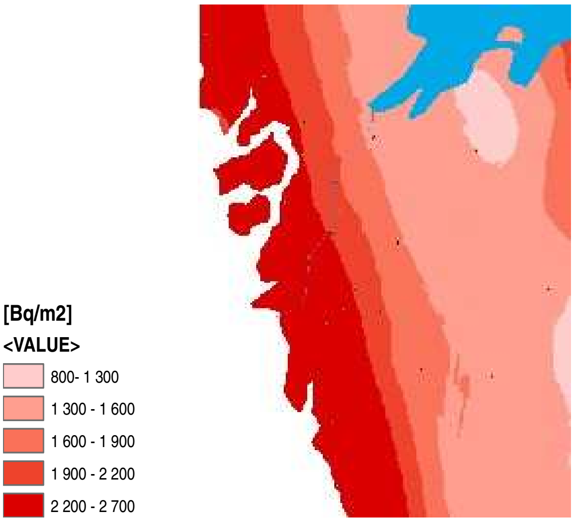

Figure 4.1a: Chernobyl fallout

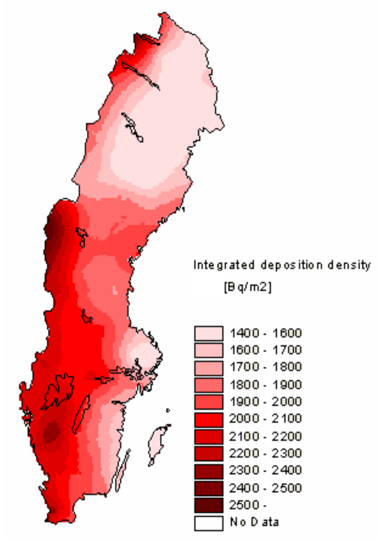

Figure 4.1b: Integrated deposition density of ^{137}Cs due to NWF

NWF+Chernobyl: The total deposition was compared to ^{137}Cs activities in soil samples and shows good agreement. The mean ratio between calculated and measured deposition densities is 1.28±0.62. If eight sites for soil sampling with large deviations are excluded the mean ratio of total calculated deposition and total accumulated activities measured in soil samples is 1.01±0.13. The predicted depositions from the precipitation are often overestimated compared to the soil samples. The soil was sampled down to a depth of about 15 cm for most of the sites, but at some only to 12 cm. At some places this might not be enough to cover the whole inventory. There can also be local deviations in the precipitation pattern and much could have happened to the soil in the long time period since the deposition.

The method used represents a simplified model of the deposition. It would be interesting to study the influence of other parameters such as snow, humidity, topography etc. The grouping of the weather stations might also be different if natural barriers such as mountains and ridges also are considered. With knowledge of the dependence of the activity concentration in rain on the amount of precipitation and activity concentration in air it would be possible to predict the deposition based on measurements of the activity concentration in air and meteorological forecasts.

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5 Cs-137 in freshwater fish in Finland, Norway and Faroe Islands

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5.1 Activity concentrations of ^{137}Cs

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.

5.2 Concentration factors, CF

Concentration factors for perch *(Perca fluviatilis)* (Bq/kg in fish / 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 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. CFs were clearly higher for piscivorous fish as pike, pike-perch, burbot and large perch than for non-piscivorous fish as vendace, bream and roach (Fig. 5.1).

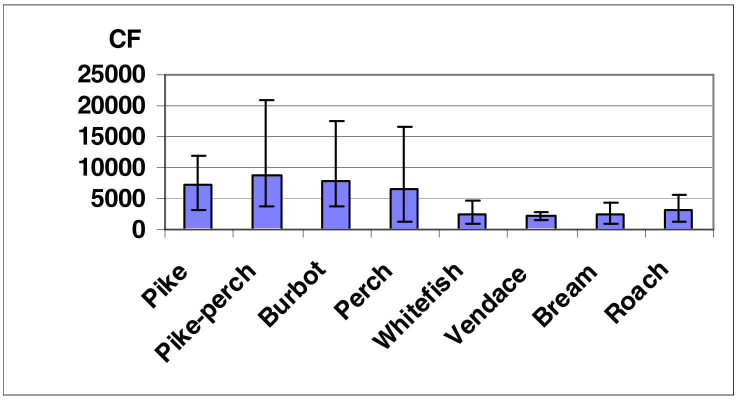

Figure 5.1. *Concentration factors of ^{137}Cs for various fish species in certain Finnish lakes in 1998and 2002.*

5.3 Ecological halftimes

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. Examples on different long-term behaviour of ^{137}Cs in fish from various Nordic lakes are given in Figures 5.2 and 5.3.

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 none of the Finnish lakes studied.

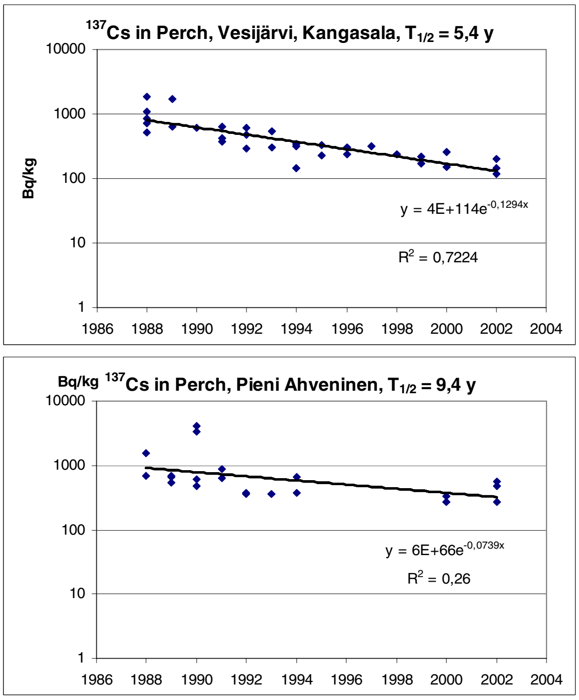

***Figure 5.2**. ^{137}Cs in perch in two Finnish lakes and the observed ecological halftimes of ^{137}Cs in 1988-2002.*

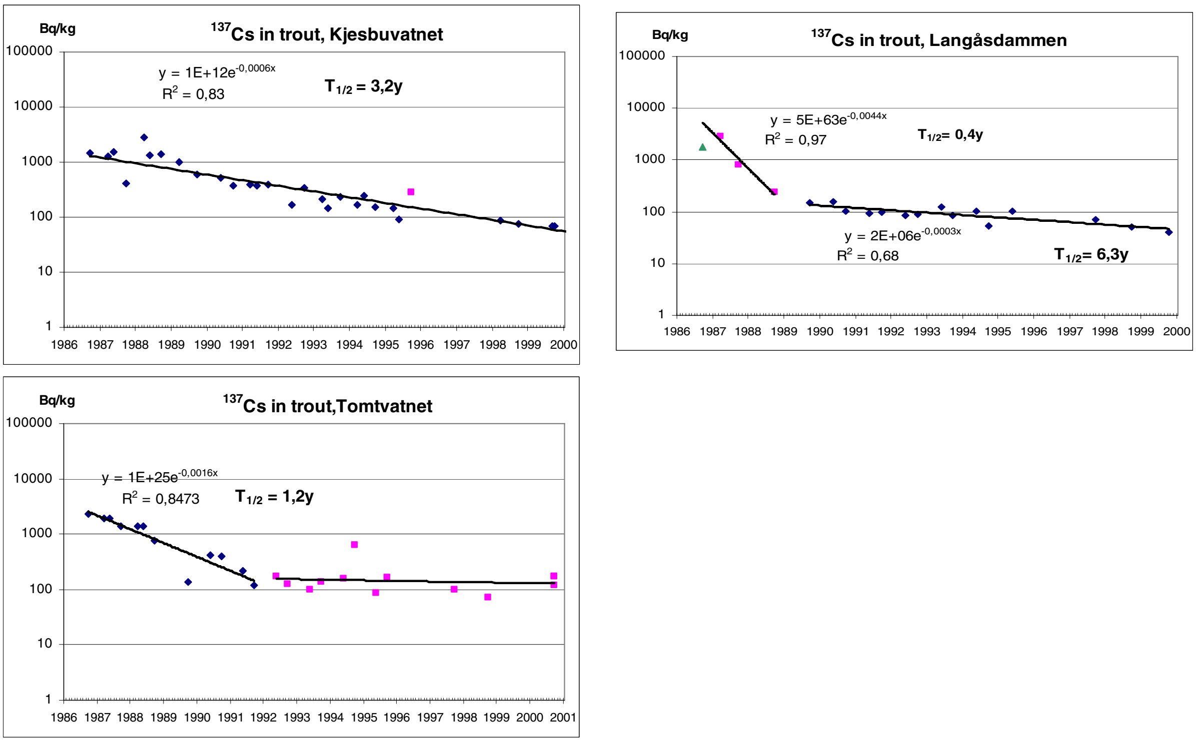

***Figure 5.3.** ^{137}Cs in trout in three Norwegian lakes and the observed ecological half-times.*

6 On the adaptation of ECOSYS for Nordic foodchain modelling

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In the European state-of-the-art decision support systems, ARGOS and RODOS, the modules for simulating the transfer of radioactive material in foodchains, respectively FDM and FDMT, are in essence identical with the ECOSYS model developed by the Heinz Müller and Gerhard Pröhl of the company ConRad. The ECOSYS model default parameters were derived from experience obtained in central Europe, or more specifically, southern Germany. Many of the parameters describing the processes determining the foodchain transfer of radionuclides may however be subject to considerable variation according to local conditions. Such parameters include soil type and condition, sowing times, harvesting times, and feeding regimes for animals, human consumption habits, and dependence of plant development on season. It is the purpose of this note to pinpoint main features of the ECOSYS model that would need to be addressed/altered for the model to be applicable in a Nordic area. A number of alternative input parameters are described and their implications for contaminant contents in food products, and thereby for ingestion dose, are discussed.

6.1 Agricultural crops and animal production

Agricultural traditions will differ between different countries. For instance, the agricultural products of a land area in a Nordic country will not on average be the same as the products of a corresponding land area in southern Germany. These are dictated by factors such as local consumption habits, export traditions, climate and geology. The ECOSYS model works with local consumption figures rather than production figures. It is in ECOSYS possible to allow for that only a fraction of the food consumed in the area of interest is produced locally (the rest is assumed to have been produced in an uncontaminated area). However, a significant part of the food might be produced for export, and the implications of this can not be assessed with ECOSYS. It is very important to apply reliable and representative age-specific survey data for consumption rates and import fractions. The defaults in ECOSYS are for Bavarian conditions, and reflect local traditions specific to that area. The applied data should ideally have been acquired recently, as consumption habits may change significantly over a period of few years. The latest surveys of Danish consumption habits were initiated in the period 2000-2002, where a total of 4000 persons in age groups between 4 and 75 years contributed (Fagt et al., 2002). Since then, annual follow-up surveys have been made, incorporating input from about 1000 individuals per year. Compared with the previous survey from 1995, for instance, the intake of morning cereals by children (ages 4-14) is in 2002 halved, whereas it is unchanged for adults. The same pattern is seen for the consumption of rye bread.

Also, the butter consumption has gone down by about one-third, but the consumption of green salad and fruit has gone up by more than 50 %. The survey also revealed that there can be some (rather limited, but significant) geographical variation within the country. For instance, inhabitants of Copenhagen consume about one-third less potatoes than do villagers (Groth & Fagt, 2002). ECOSYS works with discrete values for consumption rates, and not with statistical distributions. Therefore, 'critical group' individuals consuming higher than average rates of particularly strongly contaminated food products might be missed out. However, a German study has been carried out to investigate the correlation structure in consumption rates, and concluded that various positive and negative intake correlations exist, which would be expected to limit the variation in radiation dose due to food consumption (Breuninger et al., 2003). In ECOSYS, the user can enter the seasonality of consumption of the various crops, but what is perhaps even more crucial, particularly in a Nordic country, would be the seasonality of import of the crops, which can not be entered in the model.

6.2 Growth periods and deposition parameters

The stage of development of the canopy of crops at the time of contaminant deposition is highly important to consider in the estimation of both dry deposition velocities and wet deposition interception factors. The deposition process thus has a pronounced seasonality. This seasonality in turn is location specific, as for instance growth seasons in Nordic countries are significantly different from those in Southern Germany, for which ECOSYS default parameters apply. In the ECOSYS model, this is generally accommodated by the incorporation of the leaf area index (LAI), which is defined as the one-sided leaf area in the crop canopy per unit ground area. The effect on dry deposition velocity (v_d) of the stage of crop development, or in other words of the plant canopy mass per unit of soil area, is illustrated in Table 6.1. As can be seen, for all measured radionuclides the v_d varied considerably between the four sampling locations, which were in fact close to one another. However, when the mass per unit area was taken into account, as is the case with the bulk deposition velocity, B_d, the figures are much more alike, and reflect that the near-ground aerosol concentrations were practically the same for all four locations.

Table 6.1. Measured deposition velocities (V_d; 10^{-4} m s^{-1}) and bulk deposition velocities (B_d; 10^{-4} m^3 s^{-1} kg^{-1}) to grass in the Roskilde area after the Chernobyl accident (Roed, 1990).

Location no.	Parameter	^{137}Cs	^{134}Cs	^{131}I
1	V_d	1.8	1.5	18
	B_d	10	8.7	100
2	V_d	8.8	7.2	93
	B_d	10	8.5	110
3	V_d	6.0	6.6	86
	B_d	7.9	8.7	110
4	V_d	7.9	9.4	120
	B_d	9.1	10.2	140

The influence of LAI on deposition velocity is in ECOSYS incorporated by the formula: $v_d = v_{d,\,max}\ LAI_d / LAI_{max}$, where $v_{d,\,max}$ is the maximum deposition velocity for the given plant type, assuming fully developed foliage, LAI_{max} is the corresponding LAI for the fully developed plant, and LAI_d is the LAI at the actual time of deposition. If there are differences in the stage of plant development at the time of harvest in different countries, this should thus be addressed by adjusting these parameters. A potential problem in using the ECOSYS model is that it by default only distinguishes between aerosols, elemental iodine and organic iodine. This means that all aerosols are treated the same way, regardless of size, and judging from the default deposition velocities, the 'standard' aerosol has an aerodynamic diameter of some few microns. Table 6.2 shows some typical measured values of v_d of aerosols of different sizes to fully developed vegetation (wheat and lettuce) (Watterson & Nicholson, 1996). For the smallest aerosols, Brownian diffusion will be the dominant mechanism of deposition, but for supermicron aerosols, gravitational settling will become increasingly important the larger the aerosol, and also inertial impaction will here have influence. The figures speak for themselves: if the default values of ECOSYS are not changed to adequately represent the aerosol size with which the radionuclide in question is associated, the deposition estimates can be wrong by several orders of magnitude. Even if only sparse information is available in the early phase on the nature of the contaminating incident, this will give some idea of likely particle sizes of the key contaminants.

Table 6.2. Representative measured values of $v_{d,\,max}$ for wheat and lettuce.

Particle diameter [µm]	$v_{d,\,max}$ [10^{-4} m s^{-1}]
0.5	4
4	15
10	50
20	300

For grass, it is more convenient to describe the stage of development by the yield (kg m^{-2}) than by the LAI. The leaf area index for grass, LAI_g, can then be calculated by the ECOSYS model using the formula: $LAI_{g,d} = LAI_{g,max}\ [1-\exp(-k\ Y_g)]$, with the default values $k = 1\ m^{-2}\ kg^{-1}$, $LAI_{g,max} = 7\ m^2\ m^{-2}$ (Müller & Pröhl, 1993).

The values of LAI_d have been investigated experimentally by the Danish Institute of Agricultural Sciences for a number of crops, including winter wheat, spring wheat, spring barley, winter barley, grass, clover grass, peas, spring rape, carrots, winter rye, triticale, lupin, beets, maize, oats and potatoes. Based on the findings, a model was developed to describe LAI from sowing times, harvesting times, fertilising status and soil temperature. These parameters would be expected to govern most of the geographical variation in LAI, so that the Danish model could be used for any given area, by inserting location-specific parameters. In general, most of the plant growth will occur exponentially with time, according to the formula: $LAI = LAI_i\ \{[\exp(2.4 \frac{S_t - S_E}{S_m - S_E}) -1] / 10\}$ (Plauborg & Olesen, 1991). Here, LAI_i is the initial LAI prior to the main plant development, S_t is the temperature sum (sum of the products of days by average diurnal temperatures) from the start of growth to the time in question, S_E is the temperature sum from growth start, at which the exponential growth starts, and S_m is the temperature sum from growth start required to fully develop the plant. Needless to say, all these temperature sums are plant specific. Figure 6.1 shows an example of soil temperature curves registered in Denmark by the Royal Veterinary and Agricultural University of Denmark (KVL). The temperatures are here given according to depth in soil. However, as can be seen, the soil temperature variation with depth will not be highly significant over depths that would be relevant to the rooting zone of most crops.

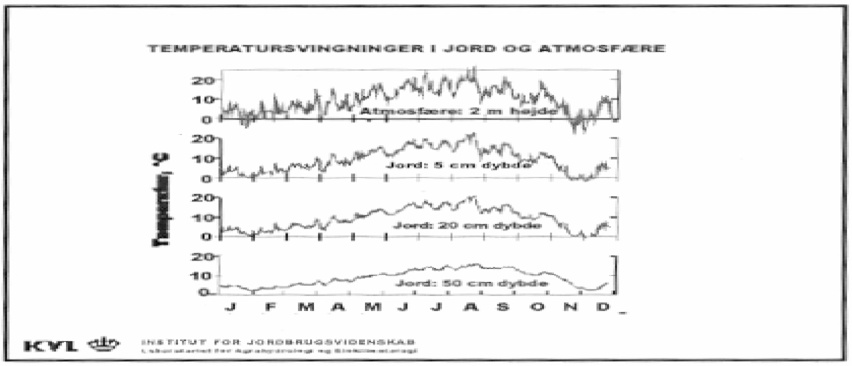


Fig. 6.1. Danish example of temperature variation in an agricultural area over the year. Temperatures are given for the atmosphere at 2 m above the ground, as well as for depths of 5, 20 and 50 cm in soil.

Figure 6.2 shows an example of application of the LAI model. The seasonal LAI variation is here shown for both intensive and extensive agriculture. In general, intensive agriculture will lead to greater LAI and longer period of maximum LAI.

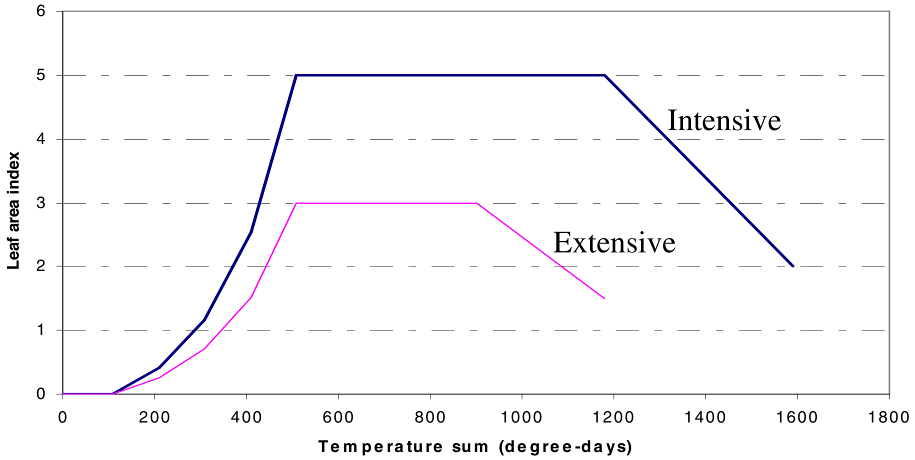


Fig. 6.2. Example of output of the LAI model developed by the Danish Institute of Agricultural Sciences. The crop is here spring barley.

The sensitivity of dry deposition to variations in LAI is demonstrated by Tables 6.3 and 6.4, which show results of runs of the ECOSYS model with its default values, assuming a dry deposition on respectively the 15th of May and the 15th of June. A corresponding variation could be observed on the same day in different countries, due to differences in climate. The figures clearly show that the contents of radiocaesium in the crops would in the first year after deposition be very sensitive to the time of deposition, but not in the following years, where root uptake is the dominant mechanism of contamination.

Table 6.3. ECOSYS run example showing crop contaminant concentrations after a dry deposition of caesium on the 15th of May.

			Activity concentration in Bq/kg			
Time	*Sp wheat whole*	*Sp wheat flour*	*Sp wheat bran*	*Wi wheat whole*	*Wi wheat flour*	*Wi wheat bran*
1day	0	0	0	0	0	0
1 week	0	0	0	0	0	0
2 weeks	0	0	0	0	0	0
1 month	0	0	0	0	0	0
6 months	1.6E-01	7.9E-02	4.7E-01	2.0E+00	9.8E-01	5.9E+00
1 year	1.6E-01	7.8E-02	4.7E-01	1.9E+00	9.7E-01	5.8E+00
2 years	2.1E-03	1.0E-03	6.2E-03	2.1E-03	1.0E-03	6.3E-03
5 years	1.4E-03	7.0E-04	4.2E-03	1.4E-03	7.0E-04	4.2E-03
10 years	8.1E-04	4.1E-04	2.4E-03	8.1E-04	4.1E-04	2.4E-03
50 years	1.0E-05	5.0E-06	3.0E-05	1.0E-05	5.0E-06	3.0E-05
70 years	1.1E-06	5.5E-07	3.3E-06	1.1E-06	5.5E-07	3.3E-06

Table 6.4. ECOSYS run example showing crop contaminant concentrations after a dry deposition of caesium on the 15th of June.

			Activity concentration in Bq/kg			
Time	*Sp wheat whole*	*Sp wheat flour*	*Sp wheat bran*	*Wi wheat whole*	*Wi wheat flour*	*Wi wheat bran*
1day	0	0	0	0	0	0
1 week	0	0	0	0	0	0
2 weeks	0	0	0	0	0	0
1 month	0	0	0	0	0	0
6 months	5.9E+00	2.9E+00	1.8E+01	9.0E+00	4.5E+00	2.7E+01
1 year	5.8E+00	2.9E+00	1.7E+01	8.9E+00	4.4E+00	2.7E+01
2 years	2.1E-03	1.1E-03	6.4E-03	2.1E-03	1.1E-03	6.4E-03
5 years	1.4E-03	7.1E-04	4.3E-03	1.4E-03	7.1E-04	4.3E-03
10 years	8.2E-04	4.1E-04	2.5E-03	8.2E-04	4.1E-04	2.5E-03
50 years	1.0E-05	5.0E-06	3.0E-05	1.0E-05	5.0E-06	3.0E-05
70 years	1.1E-06	5.6E-07	3.3E-06	1.1E-06	5.6E-07	3.3E-06

As mentioned above, the LAI will also affect the wet deposition interception factors of plants. This is in the ECOSYS model taken into account by the formula (Müller & Pröhl,

$$f_{w,i} = \frac{LAI_i \cdot S_i}{R} \cdot \left(1 - \exp\left(\frac{-\ln 2}{3 \cdot S_i} \cdot R\right)\right)$$

1993):
where $f_{w,i}$ is the interception factor for plant type i, S_i is the retention coefficient of plant type i, LAI_i is the leaf area index of plant i at the time of the event, and R is the amount of rainfall in the event. A different approach has been suggested by Watterson & Nicholson, 1996), where $f_{w,i}$ is described by the following formula:

$$f_{w,i} = 1 - \exp(-\mu B),$$

where B is the canopy dry mass of herbage per unit area, and μ is a coefficient. This model has been tested and found to be the most accurate model assuming B according to time in the growth season (Pinder et al., 1989). The coefficient, μ, can accommodate differences in particle size. For instance, it has been measured that for wheat, μ is 1.57 and 1.18 m^2 kg^{-1} for 4 and 22 μm particles, respectively (Chamberlain & Garland, 1991). A much higher coefficient would be expected for particles in the 0.5 μm range. Such particle size influence is not incorporated in the ECOSYS model for interception.

It should be noted that both the interception factor and the dry deposition velocity are highly important factors, particularly in governing the first year ingestion doses.

6.3 Animal specific feeding rations and their seasonal variation

Feeding regimes for the various farm animals will vary between countries, or even smaller areas, according to both tradition and climate. In Table 6.5, the ECOSYS default feeding regime (Southern Germany) is compared with a typical Danish feeding regime, based on information acquired from the internet site of the Danish Agricultural Advisory Service and from communication with experienced Danish farmers.

Table 6.5. Comparison of typical feeding regimes for Southern Germany and Denmark.

	Southern Germany	Denmark
Lactating cattle	Hay until 10th May, grass until 9th Nov., hay until 31st Dec.	Maize silage (70 %), grass silage (30 %) all year.
Beef cattle	96 % maize silage, 2 % winter barley, 2 % winter wheat all year	Grass silage until 15th May, grass until 15th Oct, grass silage until 31st Dec.
Goats/sheep	Hay until 10th May, grass until 9th Nov., hay until 31st Dec.	Hay/straw until 15th May, grass until 15th Sept., hay/straw until 31st Dec.
Pigs	50 % winter barley, 50 % winter wheat all year	90 % winter barley, 10 % soy flour all year.
Chickens/hens	Winter wheat all year	Winter wheat all year

As can be seen, there are significant differences, particularly in what cattle are fed. One of the feedstuffs is not by default considered in ECOSYS (soy flour), and the model implications of using silage products is not clear. There are also significant differences in the grazing periods, due to differences in climate.

In relation to the influence of feedstuffs on dose, it has previously been demonstrated that a decisive parameter is the time of the year at which the contamination occurs (Riesen et al., 1996). Table 6.6 shows an example of the impact that the feeding regime could have on the (dry deposited) contaminant concentrations in food products, unless countermeasures are actively taken. The difference between results of German and Danish feeding regimes is here rather extreme, as it is assumed that the contamination occurs just before the German animal grazing season starts. In contrast, ECOSYS by default assumes that there is no direct dry deposition on maize.

Table 6.6. An example of ^{137}Cs contents in cream, butter and beef 6 months after an accidental dry contamination on the 1st of May. ECOSYS model results. The code 'D' designates that the animals were fed according to the Southern German feeding regime, whereas code 'DK' is for the Danish feeding regime.

Product	Bq/kg after 6 months (D)	Bq/kg after 6 months (DK)
6.3.1.1 Cream	$1.8\ 10^{0}$	$5.4\ 10^{-3}$
Butter	$5.2\ 10^{-1}$	$1.5\ 10^{-3}$
Beef (cow)	$8.6\ 10^{0}$	$2.3\ 10^{-2}$

6.4 Fixation and migration rates

Fixation rates are used in ECOSYS to describe the natural decrease in availability of radionuclides to plant uptake, due to strong fixation in soil substances. In ECOSYS, fixation rates are considered to practically exclusively have importance for radiocaesium (and to a much lesser extent for radiostrontium) (Müller & Pröhl, 1993). This is reasonable due to the very strong, selective fixation of the caesium cation on frayed edge surfaces of the lattice of certain clay minerals. Only rather small amounts of clay minerals need be present in the soil to facilitate virtually irreversible fixation of the trace amounts of radiocaesium deposited after a conceivable nuclear accident. However, the presence of organic matter may play a role in delaying the fixation process. This is because the amount of caesium initially held by biodegradable organic complexes can be relatively large in certain soils (Route, 1990; Livens & Baxter, 1988). The data applied in ECOSYS to describe the fixation/migration processes partially date back to pre-Chernobyl experiments conducted to mimic the behaviour of radionuclides released after an accident (Bachhuber et al., 1984). However, the fixation process will be critically dependent on the physicochemical form of the radionuclides at deposition. The most recent reference applied for the parameterisation seems to be from 1987 (Frissel and Koster, 1987). The caesium fixation half-life applied by default in ECOSYS is 8.7 years. Since the Chernobyl accident, other workers have investigated the dynamics of the process of natural fixation of caesium in soils, using broadly consistent methods based on the protocol described by Tessier et al (1979). Even in loamy sand with comparatively little clay, Krouglov et al (1998) found that the process of fixation of caesium, to an extent where it could only be removed by strong acid dissolving minerals, had a half-life of only 2.6 years. This suggests that the amount of caesium available for root uptake might be significantly overestimated by using the ECOSYS default parameter. Also for instance investigations made by Andersson & Roed (1994) in Russian and Swedish soils suggest that by far the majority of the radiocaesium deposited from the Chernobyl accident (80 % +) was virtually irreversibly fixed after four years. In very sandy areas where the clay content is extremely low, as well as in very organic-rich soils, the fixation process can be slower. This will be reflected by an increased downward contaminant migration. The illustrations below (Fig.6.3) show an example of the influences of clay content on fixation/migration. Both illustrations show the vertical radiocaesium distribution in an undisturbed soil in the Bryansk Region (Russia), ten years after the Chernobyl accident (Roed et a., 1998). The conditions of contaminant deposition are reported to be identical. However, the profile shown to the left is for a very shallow, sandy soil, whereas the one to the right had a clay content comparable to that typically found in Scandinavian soils.

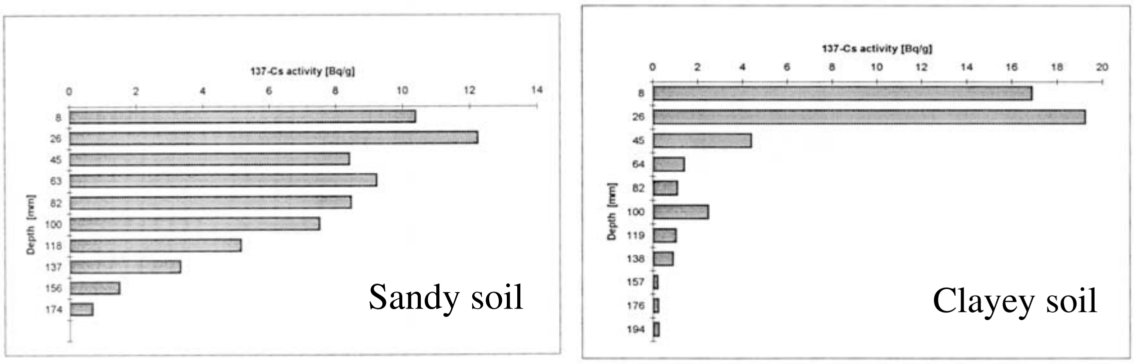


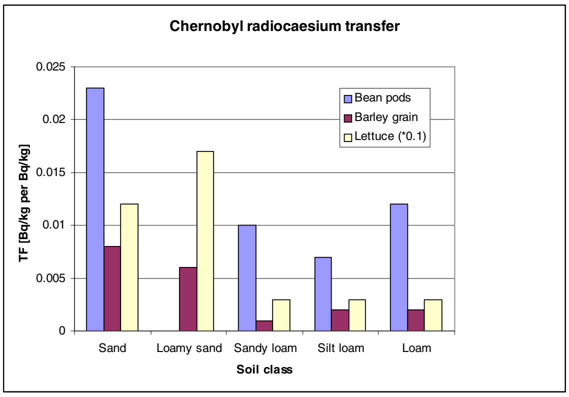
Fig. 6.3. Vertical radiocaesium profiles in two soils in the Bryansk region. Samples taken 10 years after the Chernobyl accident contaminated the area.

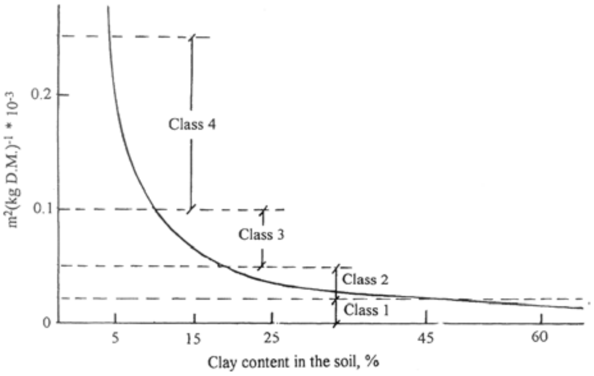
The difference in ingestion dose estimates between assuming a caesium fixation half-life of 8.7 years and 2.6 years is easily found by running the ECOSYS model. Naturally, the influence is negligible the first year, but could become important in calculating long term dose prognoses if it were assumed that no doses are received from the first year's harvest (a consumption ban may be introduced here if the contamination level is high). The difference in dose received from 3rd year's harvest will be some 30 %, whereas it will be about a factor of 6 for the dose from the 10th year’s harvest.

'Leaching rates' or 'migration rates' are applied in ECOSYS to describe the process of decrease in availability of contaminants for uptake by migration out of the root zone. This is a parameter that might possibly be problematic to give a general estimate of, as has been done in ECOSYS. These rates will depend on the depth of the root zone in the soil (by default in ECOSYS assumed to be 25 cm). This will in turn depend on the nutrient/fertilising status and soil type, and will be crop type specific, as root zone depths will differ between crops. It is difficult to assess how much this may matter, but in most cases, leaching rates, particularly of caesium, would be expected to be exceedingly slow. This seems to be adequately reflected by the ECOSYS default parameters. However, as demonstrated above, much higher migration rates must be expected for very sandy areas.

6.5 Transfer factors soil-plant

Due to the uptake competition between contaminant ions and their equivalent natural macro-nutrients, as well as variation in ion exchange potentials offered by different types of soil, both with respect to total cation exchange capacity and selective strong fixation of particularly caesium in minerals, contaminant transfer factors from soil to plant will in general be strongly dependent on soil type / fertilising status. Indeed, this is recognised in the ECOSYS model, where it is stressed next to the data table of default transfer factors that these are representative for intensive farm management in Germany. Figure 6.4 shows an example of results of a series of experiments to investigate the influence of soil type on the root uptake of caesium by different crops. It is clear that some crops take up much more Cs (and its corresponding macro-nutrient, potassium) than do others. It is also clear that soils with comparatively high content of clay rather than sand will retain much of the caesium effectively. Figure 6.5 shows the corresponding root uptake of strontium. Here it is the amount of soluble soil calcium and the crops' needs for calcium that govern the contaminant uptake. Fig. 6.6 demonstrates the great influence of clay content, especially at low clay concentrations, on the root uptake.





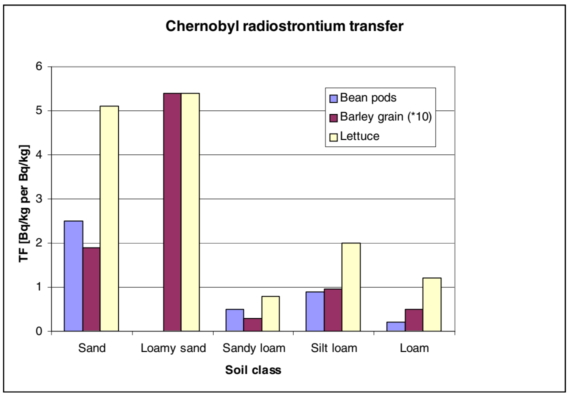


Fig 6.4. (top, left) shows an example of the soil root uptake of ^{137}Cs (concentration ratios plant/soil) (from Brechignac et al., 2000).

Fig. 6.5. (bottom, left) shows a corresponding example for root uptake of ^{90}Sr (from Brechignac et al., 2000).

Fig. 6.6. (above) shows the relation between soil clay and Cs transfer to barley grain (from Eriksson, 1997).

A comprehensive literature study of transfer factors of relevance also to Nordic conditions was published a few years back (Kostiainen et al., 2002). Transfer factors are here given for different soil characteristics. The influence of soil conditions on crop contaminant concentration can be demonstrated through a sample run of ECOSYS, assuming that a dry deposition of caesium took place on the 1st of May. The transfer factors were here changed from the ECOSYS defaults to recommended values for mineral soil, taken from the above literature study. This made the Cs concentrations in second year's leafy vegetable harvest rise by a factor of about 6, whereas the corresponding concentration in root vegetables rose by a factor of about 4.

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7 Summary

7.1 Dose to man from radionuclides in milk and other foodstuffs

Considerable variations in activity concentrations of ^{137}Cs and ^{90}Sr were observed between countries or regions due to factors such as different precipitation patterns, soil types and the inhomogeneity over Europe of Chernobyl fallout. The observed time trends indicate that the factors influencing the ecological half-life for ^{90}Sr are not entirely the same as for ^{137}Cs in the pasture – milk system. For ^{137}Cs the effective ecological half-lives seem to be fairly equal for the different investigated regions. Slightly longer half-lives were observed for the post-Chernobyl period for this radionuclide. For ^{90}Sr the long component varies between 4 and 12 years. Finally, for some series (both ^{137}Cs and ^{90}Sr) a "no decrease" in activity concentrations has been observed for recent years.

Internal doses to people in the Faroe Islands derive to a large extent from dairy products (mostly cow milk), lamb meat and potatoes. The internal dose from ^{137}Cs in these food groups was 1.65 mSv during the years from 1960 to 1996. The largest doses were received in the early 1960's in accordance with the weapons fallout. A regional variability is observed in the dose estimates, as should be expected from variability in precipitation rates and variability in soil types. ^{137}Cs implies higher doses than ^{90}Sr, and the regional variability is observed to be larger for ^{137}Cs as compared to ^{90}Sr.

The estimated doses are subject to considerable uncertainties. This is to a large extent due to limited or missing documentation of food consumption during time, as well as missing documentation of differences in food habits across the country. It may, e.g., be expected that the amount of privately acquired food varies considerably across the country, and that there are considerable differences in food selection among age groups in the population.

7.2 Deposition of ^{137}Cs estimated based on precipitation data

^{137}Cs deposition maps were made using kriging interpolation in a Geographical Information System (GIS). Quarterly values of ^{137}Cs deposition density per unit precipitation (Bq m^{-2} mm^{-1}) at three reference sites and quarterly precipitation at 62 weather stations distributed over Sweden were used in the calculations of Nuclear Weapons Fallout (NWF). The deposition density of ^{137}Cs, resulting from the Chernobyl accident, was calculated for western Sweden using precipitation data from 46 stations. The lowest levels of NWF ^{137}Cs deposition density were noted in the north-eastern and eastern Sweden and the highest levels in the western parts of Sweden. The Chernobyl ^{137}Cs deposition density is highest along the coast in the selected area and the lowest in the south-eastern part and along the middle. The sum of the calculated deposition density from NWF and Chernobyl in western Sweden was compared to accumulated activities in soil samples at 27 locations. Comparisons between the predicted values of this study show a good agreement with measured values.

7.3 Ecological halftimes for ^{137}Cs in freshwater fish

The observed ecological halftimes of ^{137}Cs in perch in certain Finnish lakes vary 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 rate of 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 a somewhat more rapid reduction of ^{137}Cs in fish in certain Norwegian compared to Finnish lakes. However, ecological halftimes for the Norwegian and for the Finnish lakes were estimated for different time intervals, and are thus not directly comparable. In two Norwegian lakes the ^{137}Cs concentrations in trout remain at about 100 Bq/kg since 1990. A corresponding phenomenon has not been observed in Finnish lakes.

7.4 Radioecological modelling

The European decision support systems, ARGOS and RODOS, include modules for simulating the transfer of radioactive material through foodchains. Default parameters for the ECOSYS model used in ARGOS and RODOS were derived from experience obtained in southern Germany. Many of the parameters describing the processes determining the foodchain transfer of radionuclides are subject to considerable variation according to local conditions. Such parameters include soil type and condition, sowing times, harvesting times, and feeding regimes for animals, human consumption habits, and dependence of plant development on season. Model features and parameter values need to be adjusted for the model to be able to produce reliable predictions for Nordic areas. Further, some generic inadequacies of the current version of the ECOSYS system were pinpointed, particularly in relation to the modelling of dry deposition processes.

Bibliographic Data Sheet NKS-123

Title	EcoDoses - Improving radiological assessment of doses to man from terrestrial ecosystems. A status report for the NKS-B project 2005
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ISBN	87-7893-184-3 *Electronic report*
Date	April 2006
Project/Sub Project	NKS-B / EcoDoses
No. of pages	36
No. of tables	7
No. of illustrations	17
No. of references	36

Abstract

Considerable variations in activity concentrations in milk of ^{137}Cs and ^{90}Sr were observed between countries or regions due to precipitation patterns, soil types and inhomogeneity of Chernobyl fallout. Time trends indicate that factors influencing ecological half-lives for ^{90}Sr are not the same as for ^{137}Cs in the pasture–milk system.

Internal doses to Faroese people derive mainly from dairy products, lamb and potatoes. The largest doses were received from nuclear weapons fallout in the early 1960's. ^{137}Cs causes higher doses than ^{90}Sr, and the regional variability is larger for ^{137}Cs than for ^{90}Sr.

^{137}Cs deposition maps were made of Sweden. Values of ^{137}Cs deposition and precipitation were used in the calculations of Nuclear Weapons Fallout (NWF). The deposition of ^{137}Cs from the Chernobyl accident was calculated for western Sweden. Lowest levels of NWF ^{137}Cs deposition density were noted in the north-eastern and eastern Sweden and the highest levels in the western parts. The Chernobyl ^{137}Cs deposition is highest along the coast and lowest in the south-eastern part and along the middle. The calculated deposition from NWF and Chernobyl in western Sweden was compared to observed deposition and showed good agreement.

Ecological halftimes of ^{137}Cs in perch in Finnish lakes vary by a factor of three. The longest halftime of ^{137}Cs in perch was 9 y and the shortest 3 y. Norwegian lakes differ from each other with respect to the rates of decrease of ^{137}Cs in fish. Ecological halftimes of ^{137}Cs in trout and Arctic char varied from 1 to 5 y. A more rapid reduction of ^{137}Cs in fish is found in certain Norwegian lakes compared to Finnish lakes. In two Norwegian lakes the ^{137}Cs concentrations in trout remain at about 100 Bq/kg since 1990.

The European decision support systems, ARGOS and RODOS, include foodchain modules with default parameters derived from southern Germany. Many parameters describing foodchain transfer are subject to considerable variation according to local conditions. Such parameters include soil type, sowing and harvesting times, feeding regimes for animals, human consumption habits, and dependence of plant development on season. Model features and parameter values need adjustment for the model to produce reliable predictions for Nordic areas. Further generic inadequacies of the modelling system relate to dry deposition processes.

Key words: Nuclear weapons fallout, deposition modelling, food-chain modelling, ecological half-lives, radioecological sensitivity

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