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Long-term decline of radiocaesium in Fennoscandian reindeer

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Abstract

The NKS-B project REIN was established to synthesize the available information on contamination levels and effective half-times for 137Cs in reindeer in Finland, Sweden and Norway. Several studies of radiocaesium contamination in reindeer have been carried out in the Nordic countries over the last 50 years. However, the current slow decline in concentrations, which will maintain the consequences of the Chernobyl deposition for Swedish and Norwegian reindeer husbandry for at least another 10-20 years, have not previously been observed nor predicted. In the Chernobyl affected areas 137Cs concentrations in reindeer initially declined by effective half-times of 3-4 years, whereas the current decline appears to be mainly governed by the nuclide's physical half-life (30 years).

The review of effective half-times of 137Cs in reindeer across Fennoscandia suggests that concentrations declined more rapidly in the northernmost areas. The reason(-s) remains unclear, and demonstrates the need for more long-term sampling of the various components of reindeer's diet. Such sampling should aim at covering climatically different areas, as climate may influence transfer of radiocaesium to reindeer via lichen growth and weathering rates, composition of plant communities and lichen availability, as well as soil-to-plant radiocaesium uptake. The lack of long-term data on radiocaesium in natural vegetation in the Nordic countries is one of the main limitations for the development of mechanistic models for radiocaesium in reindeer, and for further elucidation of the observed long-term trends in 137Cs concentrations in reindeer. Currently our understanding of the long-term trends observed in various areas is not good enough to predict how future radiocaesium deposition will behave.

The high transfer of nuclides to reindeer, the geographical extension of reindeer herding and the special position of the Sami population in Finland, Sweden and Norway, demonstrates the need for maintaining competence and further developing the common basis for Nordic fallout management and emergency preparedness related to this food-chain.

Key words

Radiocaesium, 137Cs, reindeer, lichen, long-term

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1 Introduction

Reindeer is the part of Nordic food production most vulnerable to radioactive contamination. Still (in 2009), twenty-three years after the Chernobyl accident, monitoring and/or countermeasures are required in 10 Norwegian and 16 Swedish reindeer herding districts before animals can be slaughtered for trade (i.e., contain less than 3000 Bq kg^{-1} in Norway and less than 1500 Bq kg^{-1} in Sweden). Furthermore, in Norway the Ministry of Health and Care Services is considering lowering the intervention limit, which will reintroduce countermeasures in other districts. Maximum concentrations in reindeer during the last 5 years reached 9,000 Bq kg^{-1} in Sweden, but during the last 2 years no samples have indicated concentrations above 3,000 Bq kg^{-1}. Similar concentrations are observed in Norway, although here several cases above 3,000 Bq kg^{-1} were reported also during 2007-2009, e.g. 5,000 Bq kg^{-1} in September 2007 (district Byrkije) and 7,000 Bq kg^{-1} in December 2007 (district Låarte). The dramatic consequences of the Chernobyl fallout for reindeer herding shows that a thorough understanding of reindeer radioecology is an inevitable prerequisite in Nordic nuclear emergency preparedness.

Several studies of radioactive contamination of reindeer have been made in the Nordic countries over the last 50 years. However, as time passes and new studies are carried out, new gaps in our understanding of reindeer radioecology emerge. The NKS-B project REIN was therefore initiated, in 2004, with the aim of:

- Synthesizing the available information on contamination levels and effective ecological half-times (hereafter referred to as “effective half-times”) for ^{137}Cs in reindeer.
- Using the available data, especially the vegetation data, to improve the estimates of uptake in vegetation and radiocaesium intake in an draft reindeer model developed by Åhman and Nylén (1998)
- Validating the model against updated long-term data series on ^{137}Cs concentrations in reindeer in Finland, Sweden and Norway.

The REIN project paid much attention and time focussing on long-term series on ^{137}Cs in plants, without much success. The project partners considers the lack of high quality long-term data series on transfer of radiocaesium from soil to plants on natural pastures in the Nordic countries as one of the main limitation for the development of mechanistic models for radiocaesium in reindeer and other grazing animals. Nevertheless, despite the lacking soil-to-plant transfer data, a dynamic model on ^{137}Cs in reindeer was developed by Åhman (2007).

This report is the late and final product of the REIN project. The aim is to summarize the available information on contamination levels and effective half-times of ^{137}Cs in reindeer in the Nordic countries, and to make a brief presentation of the model by Åhman (2007). With the well-known and acknowledged vulnerability of reindeer to radiocaesium fallout, it remains a challenge to the Nordic nuclear emergency preparedness organisations to implement this or other reindeer models in the decision support systems.

2 Basics on uptake of radiocaesium in reindeer pasture and reindeer

Contamination levels of grazing animals depend on a number of factors, including contamination levels in fodder, feed intake, gastrointestinal absorption and excretion (often described by the biological half-time, $T_{1/2}$). For example, in an initially uncontaminated animal having a constant daily intake I of a radionuclide, of which a constant fraction a is absorbed from the gastrointestinal tract, the increasing activity concentration in a tissue can be mathematically described by:

$$q(t) = I \cdot a \cdot \int_0^t e^{-\frac{\ln 2}{T_{1/2}} \cdot t} dt = \frac{I \cdot a \cdot T_{1/2}}{\ln 2} \cdot (1 - e^{-\frac{\ln 2}{T_{1/2}} \cdot t}) \qquad (1)$$

A discussion of various physiological parameters affecting the transfer of radiocaesium to animal tissues is given in Skuterud et al. (2005a).

The reindeer’s feed intake changes from a summer diet wide in vegetation species, to a diet high in lichens during winter (see Gaare and Staaland, 1994). Lichens absorb nutrients and contamination from air and precipitation, and a dry and well developed lichen carpet may absorb most of the fallout received by precipitation. Findings after the Chernobyl fallout (Golikov et al., 2004) corresponds to earlier observations that 1 Bq m^{-2} radiocaesium fallout results in concentration in lichens of around 1 Bq kg^{-1} dry mass (Lidén and Gustafsson, 1967). Thus, during the first years after nuclear fallout lichens will generally contain much higher radionuclide concentrations than vascular plants. Combined with the high intake of lichens during winter this results in considerably higher radionuclide concentrations in reindeer meat during winter than summer. Furthermore, the low protein and mineral content of lichens results in slower excretion of mineral elements like K and Cs during winter, and added to a reduced basal metabolism this amplifies the seasonal difference in radiocaesium concentrations in reindeer meat.

The biological half-times for Cs in reindeer reach 2-3 fold differences from about 7 days during mid summer to about 20 days during winter (Holleman et al., 1971; Holleman et al., 1975a,b; Åhman, 1996; Skuterud et al., 2004). The seasonal difference in half-time is one reason for seasonal differences in contamination levels in reindeer (cf. Eq. 1). Due to the relatively short biological half-time the contamination levels in these migrating animals will respond quickly to changing contamination levels in the pastures, e.g. in autumn when reindeer can eat large quantities of mushrooms and attain radiocaesium levels comparable to those during winter (Hove et al., 1990; Skuterud et al., 2005b).

Examples of seasonal variability in ^{137}Cs concentrations in Finnish, Swedish and Norwegian reindeer herds are given in section 4.

3 Time trends in radiocaesium concentrations in vegetation

Long-term trends in radiocaesium concentrations in reindeer will follow the trends in their feed. Lichens have traditionally been given particular attention in radioecological studies due to the importance of lichens as sources of radionuclides to reindeer.

Following deposition the concentrations of radionuclides in lichens are reduced through:

- mechanical removal by precipitation, wind and grazing,
- leaching from particles attached to the lichen surface,
- fresh lichen growth, and decomposition and humidification of old parts of the lichens.

The physical and chemical properties of the radionuclides will determine their behaviour. The content of radiocaesium in lichens has been found to diminish slower than the content of ^{90}Sr, ^{95}Zr, ^{103}Ru, ^{106}Ru, ^{110m}Ag, ^{125}Sb and ^{144}Ce (Nevstrueva et al., 1967; Tuominen and Jaakkola, 1974; Lehto et al., 2008), possibly because caesium is more efficiently taken up and retained by the lichen (together with nutrients such as potassium).

Post-Chernobyl studies of radiocaesium in lichens indicate effective half-lives of 3-6 years (e.g. Synnott et al., 2000; Gaare et al., 2000; Machart et al., 2007). Since lichens contain only the ^{137}Cs that is directly deposited or redistributed from dead lichen parts (in the bottom of the lichen mat), and since they grow slowly, Mattsson (1975) assumed that removal of ^{137}Cs from the lichen mat by grazing explained the relatively short effective half-times of ^{137}Cs. However, monitoring of ^{137}Cs in lichens in a non-grazed area in Sweden showed an effective half-time of about 3.1 y (Figure 1), similar to the initial half-times observed in reindeer in the Chernobyl affected areas (see section 4.1 below). Similarly, Lehto et al. (2008) observed average effective half-times of ^{137}Cs in lichens in southern Finland of about 2.6 y during 1986-1996, which was accompanied by an increase in ^{137}Cs content in the underlying soil. These studies indicate that weathering and leaching is probably more important in reducing ^{137}Cs concentrations than assumed by Mattson (1975). Lehto et al. (2008) observed about 50 % increase in the half-time for ^{137}Cs in lichens during 1996-2006 (to about 3.8 y) compared to 1986-1996. This may indicate a longer half-time for the fraction of radiocaesium actually absorbed into the lichen organisms, and may be important in assessments of trends in a longer time perspective.

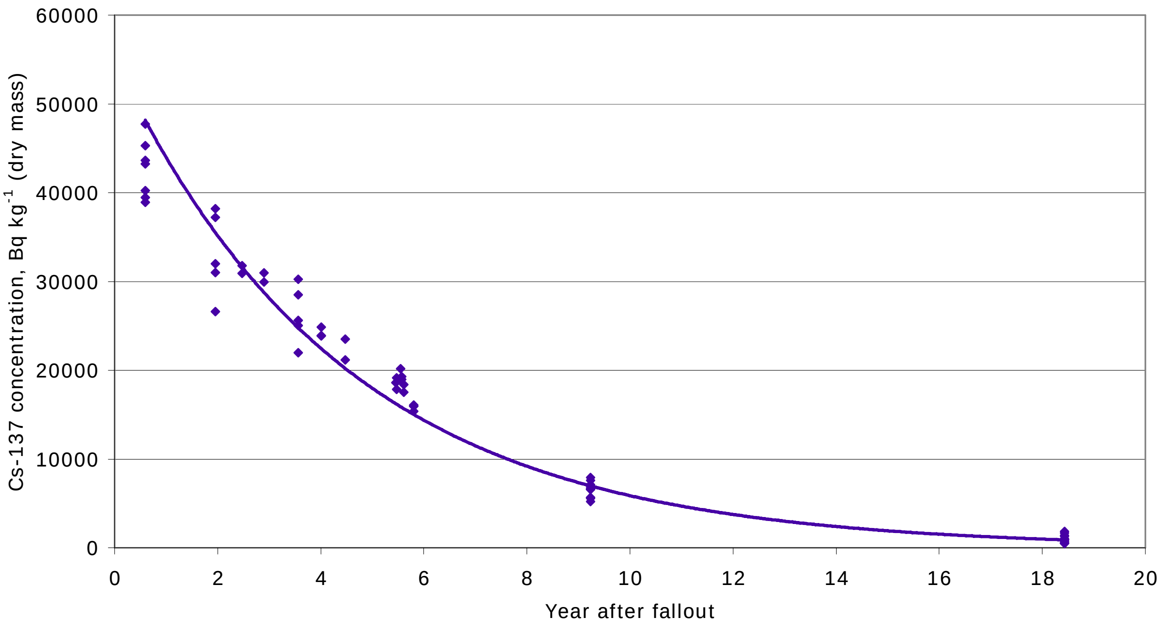

Figure 1 Caesium-137 in reindeer lichens (mixed *Cladina stellaris, Cladina arbuscula/mitis* and *Cladina rangiferina*, Bq kg^{-1} DM) collected during the period 1987 to 2004 from a pine heath 60 km north-west of Uppsala (Åhman, 2005). The curve is a fitted exponential model with halt-time of 3.1 years.

The Chernobyl fallout in spring 1986 caused external contamination also of vascular plants on natural pastures. External contamination of plants is reduced by many of the same processes as for lichens, in addition to effect of withering of annual growth of plants. According to Ehlken and Kirchner (1996, 2002) fixation of Cs to the soil matrix is complete 3 – 7 years after fallout, and thereafter there is little change in transfer rates to plants. In peat soils there are reports of lacking ageing processes for Cs (Ehlken and Kirchner, 1996; Rigol et al., 2002). Consequently, variable long-term trends in ^{137}Cs concentrations in plants in natural pastures have been reported (Gaare et al., 2000; Andersson et al., 2001; Strebl et al., 2002).

Removal of external contamination and fixation of Cs to soil particles are potential explanations for a relatively rapid decline observed e.g. in bilberries in Vindeln, Sweden, from 1986 to 1988 (Rissanen et al., 2005). Thereafter there was no observable decline in concentrations during 1988 – 1994. Of 11 different plants sampled in Kuusamo, Finland, during 1988 – 2003, only 6 species showed significantly declining ^{137}Cs concentrations (of which 2 species were mosses; Rissanen et al., 2005). Excluding the half-times in mosses, which were similar to those in lichens, the half-times observed by Rissanen et al. (2005) were 9-14 years.

Kuusamo was an area of relatively low Chernobyl fallout, and a significant proportion of remaining nuclear weapons fallout (50-80%; Rissanen et al., 2005) could contribute to the relatively long half-times observed in the plants. Unfortunately, few long-term studies on soil-to-plant transfer of radiocaesium have been continued in the more Chernobyl affected areas in the Nordic countries after about 1995.

Due to the relatively rapid and continuous decline of radiocaesium concentration in lichens, as opposed to the slower decline in many plant species, the initially elevated concentrations in lichens will ultimately become comparable to or lower than those in plants. The currently similar concentrations in lichens and plants in an area of low Chernobyl fallout are illustrated in Figure 2. Similarly, Figure 3 illustrates that concentrations in lichens and some plants are comparable even in some of the most contaminated areas of the Nordic countries.

With time the most contaminated constituents of the reindeer diet will be species with high root uptake, like some species growing on wetland and particularly on nutrient-poor mires (Rissanen and Ylipeiti, 2003).

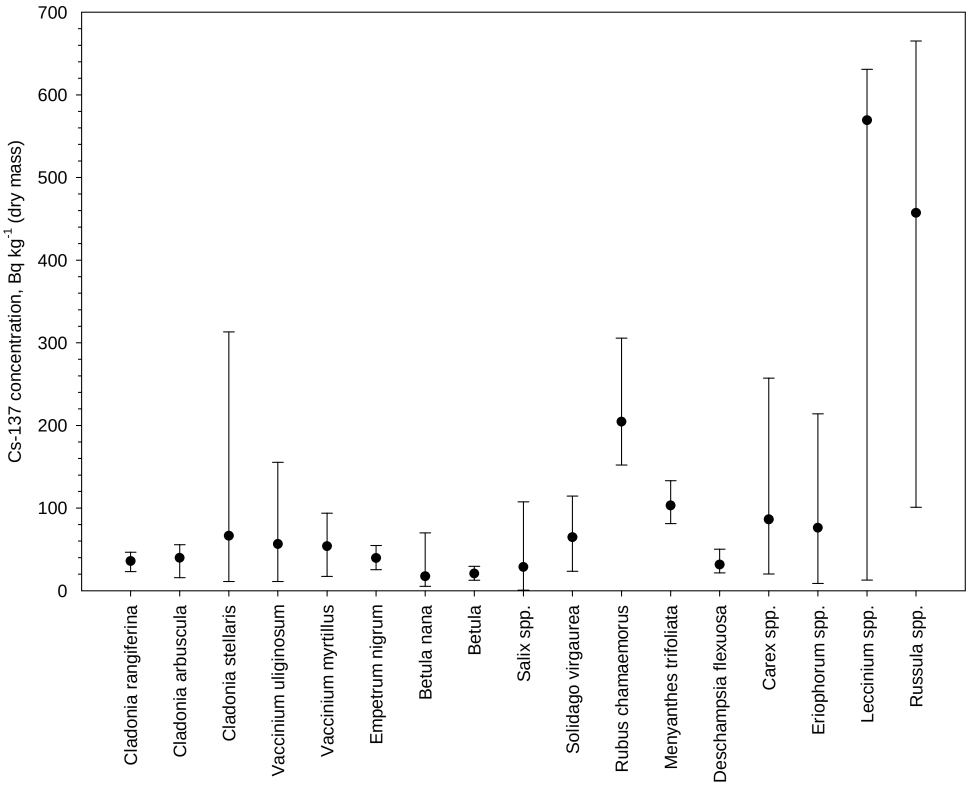

Figure 2 Cs-137 concentrations in 17 lichen, plant and fungi species sampled across three reindeer pastures in northern Finland during the period 2005-2008 (the Ivalo, Hammastunturi and Muddusjärvi districts). Dots give mean values; bars give minimum and maximum concentrations observed.

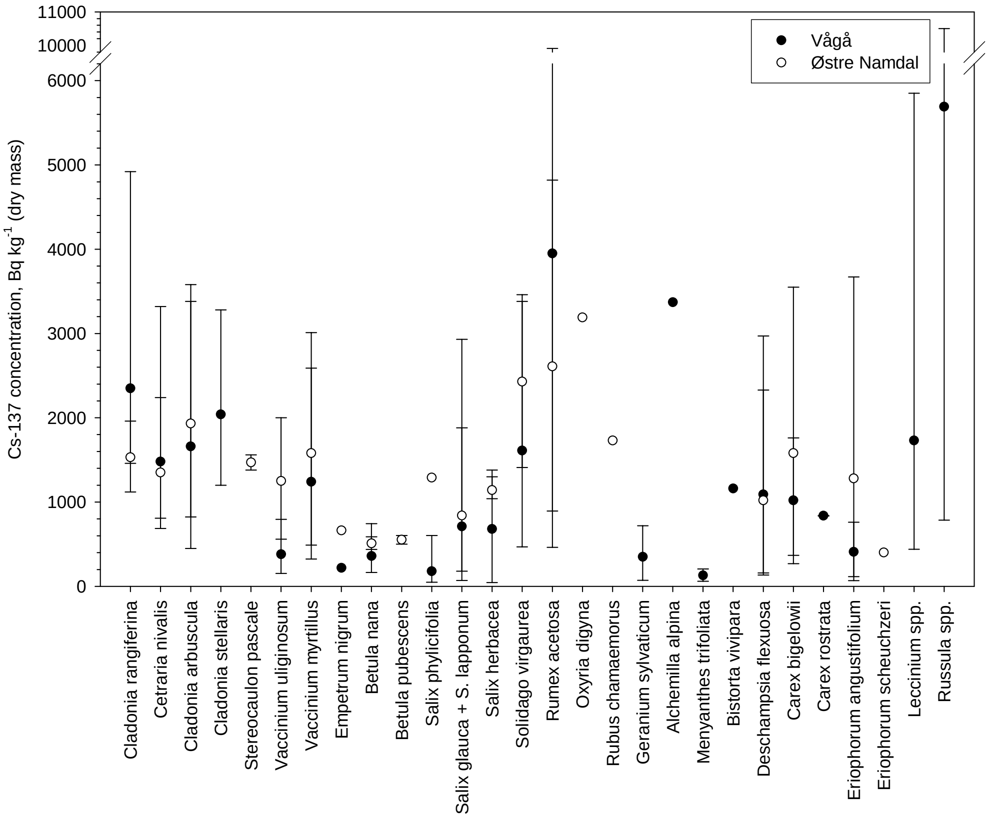

Figure 3 Cs-137 concentrations in 28 lichen, plant and fungi species sampled in two reindeer pastures in southern (Vågå, filled symbols) and central Norway (Østre Namdal, open symbols) during 2001-2003. Dots give mean values; bars give minimum and maximum concentrations observed (from Skuterud et al., 2005b).

4 Time trends in radiocaesium concentrations in reindeer in Fennoscandia

The seasonal changes in the diet of reindeer, from predominantly vascular plants during summer to a diet dominated by ground and arboreal lichens during winter, explain much of the pronounced seasonal differences in radiocaesium concentrations observed in reindeer (e.g., Åhman and Åhman, 1994). Reindeer may consume lichens during all seasons (5-10 % of the diet during the snow free season and 60-80 % in winter (Gaare and Staaland, 1994)), and reductions in contamination levels in reindeer will therefore reflect those in lichens as long as lichens are much more contaminated than other parts of the reindeer's diet. Subsequently, as lichens become less contaminated, the time trend in radiocaesium concentrations in reindeer will reflect that in other vegetation. Due to the faster decline in radiocaesium concentrations in lichens than in plants, Gaare and Staaland (1994) predicted reduced seasonal differences in radiocaesium concentrations in reindeer. However, the reindeer's slower excretion of radiocaesium during winter will increase their body concentrations in this season, even if the intake of radiocaesium is the same as in summer.

The underlying processes (i.e., the change in significance of lichens, compared to plants, to the intake of ^{137}Cs by reindeer) suggest that exponential models with more than one time-dependent component will reasonable describe long-term trends in radiocaesium contamination in reindeer. However, due to the large variability in the concentrations in reindeer it may be difficult to identify statistically significant components of such models, and methodologically this approach may therefore be questionable. The current REIN study has nevertheless chosen double-exponential models as base models, as they are ecologically reasonable. An alternative approach was applied by Åhman (2007), who divided the time period into the first 10 years and the following 10 years (year 10 – 20) after the Chernobyl fallout. Results using both approaches will be presented below.

4.1 Chernobyl affected areas in central and southern Scandinavia

Following the Chernobyl fallout, average radiocaesium concentrations in reindeer in central Sweden and Norway reached 40-50 kBq kg^{-1}, about an order of magnitude higher than the highest concentrations observed in the 1960s after the nuclear weapons fallout. During the first ~10 years after the accident, the ^{137}Cs concentrations in reindeer in winter declined with effective half-times of 3-5 years (Åhman and Åhman, 1994; Amundsen 1995; Gaare et al., 2000; Skuterud et al., 2005b). This decline was similar to that observed in lichens (see section 3), and reflected the role of contaminated lichens in diet of reindeer. However, from the mid 1990s onwards slower rates of decline in reindeer were observed both in Sweden and Norway (Åhman et al., 2001; Skuterud et al., 2005b).

A previous assessement of the two most studied reindeer herding districts in Norway (the districts Østre Namdal and Vågå) concluded that concentrations in reindeer during winter decreased until the late 1990s, whereas there was no significant decline in concentrations thereafter (Skuterud et al., 2005b). Furthermore, from about the same time, the seasonal differences in concentrations in reindeer in these districts were not longer significant (Figure 4). During the last 5 years there have been occasions of higher concentrations in autumn than winter (due to rich abundance of mushrooms) in both districts.

Table 1 summarizes various estimates of effective half-times in reindeer in the Østre Namdal and Vågå herds, using single and double exponential models. Splitting into time periods 1-10 and 10-20 years after the Chernobyl accident was made for comparison to data in Table 2, from Åhman (2007). The data in Figure 4, the analyses of the split time periods and the double-exponential models show that the rates of decline in concentration in reindeer after the Chernobyl accident have been slower the last years. Furthermore, the long-term half-time estimates in the double-exponential models do not represent a significant decline. In Østre Namdal and Vågå about 86 and 92 % of the initial ^{137}Cs concentration declined according to the short half-time, respectively. In these two Norwegian herds no significant decline in ^{137}Cs concentrations in reindeer in the autumn is detectable after the mid 1990s (Table 1).

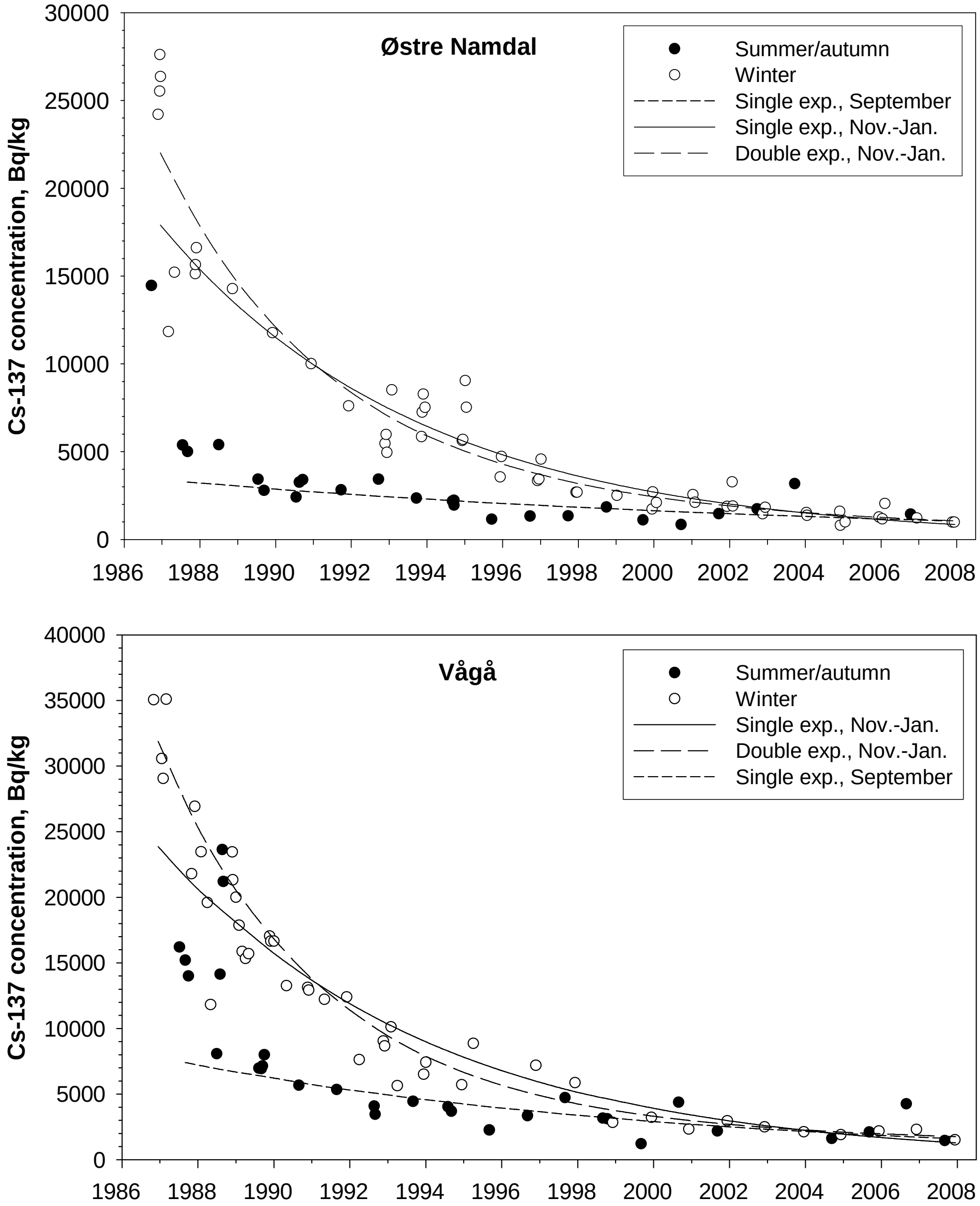

Figure 4. Average ^{137}Cs concentrations observed in reindeer in the Østre Namdal (upper) and Vågå (lower) reindeer herding districts, Norway. • indicates observed concentrations during July-October; o indicates concentrations observed during November-May. The curves are fitted single- and double-exponential models to values observed during September and November-January, respectively. See Table 1 for parameter details.

In the comprehensive study of long-term trends in ^{137}Cs concentrations in Swedish reindeer herds in various seasons, Åhman (2007) showed that the effective half-times during the first 10 years after the Chernobyl accident were considerably shorter than in the period 10-20 years after the accident. Examples from the three herds Vilhelmina norra, Ubmeje and Ran in Västerbotten are given in Table 2. An aggregated analysis of all the Swedish herds resulted in average effective half-times for the season November-December of about 3.5 and 7 years during the periods 1-10 and 10-20 years after the Chernobyl accident, respectively (Åhman 2007). These values correspond to those in the Norwegian herds in Table 1.

Table 1. Effective half-times (± standard error) for ^{137}Cs in reindeer during different seasons in the Østre Namdal and Vågå herding districts. T_{eff} gives the effective half-time estimated with a single-exponential model, and T_{eff} (1-10) and T_{eff} (10-20) the corresponding values during year 1-10 and 10-20 after the Chernobyl accident, respectively. T_{eff1} and T_{eff2} are the effective half-times in a double-exponential model. (ns) denotes values not significantly different from zero.

Herding district	Season	T_{eff} (all years), year	T_{eff} (1-10) , year	T_{eff} (10-20), year	Double-exponential model	
					T_{eff1}, year	T_{eff2}, year
Østre Namdal	September	12.4±4.1	4.88±0.91	No sign. decline	-	-
	Nov-Jan	4.78±0.20	4.11±0.36	6.62±0.84	3.1±1.1	12±18 (ns)
Vågå	September	9.2±2.1	4.10±0.64	No sign. decline	-	-
	Nov-Jan	4.99±0.29	3.91±0.42	6.6±1.5	2.98±0.87	27±84 (ns)

Table 2. Effective half-times (± standard error) for ^{137}Cs in reindeer during different seasons in three herding districts in Västerbotten, Sweden. See Table 1 for more details.

Herding district	Season	T_{eff} (all years), year	T_{eff} (1-10) , year	T_{eff} (10-20), year
Vilhelmina norra	September	4.5	2.7	14.2
	October	5.8	2.5	11.4
	Nov-Dec	5.0	2.9	6.9
	Jan-Apr	5.1	4.5	10.4
Ubmeje	September	6.7	3.1	No sign. decline
	October	7.9	2.1	20.6
	Nov-Dec	5.1	2.8	5.6
	Jan-Apr	5.5	4.5	7.9
Ran	September	5.1	2.5	7.6
	Nov-Dec	6.6	4.8	4.9
	Jan-Apr	6.8	7.0	7.5

Figure 5 presents a renewed analysis of long-term trends in reindeer during winter in the five southernmost Swedish herding districts. The parameters of the plotted double-exponential model in Figure 5 show that the ^{137}Cs concentrations in reindeer during winter declined with short- and long-term effective half-times of 2.5 and 30.8 years, respectively. Approximately 90 % of the initial ^{137}Cs concentration declined with the shortest half-time.

As opposed to the situation in the two Norwegian herding districts presented above, there are still pronounced seasonal variations in ^{137}Cs concentrations in reindeer in most of the Swedish herds studied by Åhman (2007). In some districts this may be a result of migration to areas with higher deposition and more lichen pastures in winter.

Due to the routine monitoring and slaughtering of semi-domesticated reindeer during different seasons there is more data available on radiocaesium contamination in reindeer herding than in wild reindeer in Fennoscandia. However, the available long-term autumn data from a wild reindeer herd in the Rondane mountains (Norway) show a similar long-term development as discussed above, i.e. an effective half-time during autumn from 1996 to 2008 of about 25 years (Gaare and Skuterud, 2009).

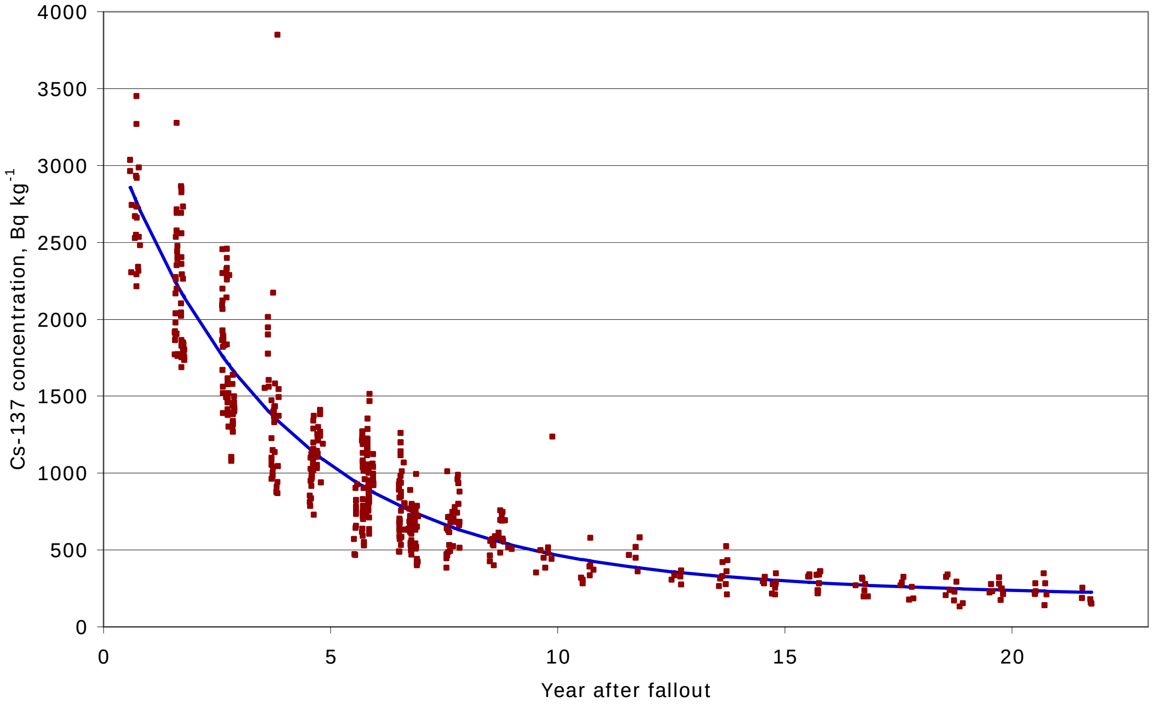

Figure 5. Long-term trends in ^{137}Cs concentrations in reindeer during winter (November-April). Data from the five Swedish herding districts Idre, Ruhvten, Mittådalen, Handölsdalen and Tåssåsen have been pooled and corrected for differences in contamination levels[i]. Each dot is average of minimum 10 animals (usually 30 animals). The curve is a fitted double-exponential model with half-times of 2.5 and 30.8 years (standard error intervals: 2.20-2.87 and -32.8-10.5).

4.2 Northern areas of low Chernobyl fallout

Studies of radiocaesium in reindeer and caribou prior to the 1986 Chernobyl accident were mainly confined to the northern parts of Fennoscandia and Russia, and North America (AMAP 1998). For instance Westerlund et al. (1987) and Macdonald et al. (2007) found that the decrease in ^{137}Cs concentrations in northern Norway and Canada from the mid 1960s onwards could be described by an effective half-time of about 6-7 years. On the other hand, Golikov et al. (2004) concluded that a double-exponential model with short and long-term effective half-times of 1-2 and 10-11 years respectively appropriately described both for the pre-Chernobyl data in Kautokeino (northern Norway) and the pre- and post-Chernobyl data in Kola and Nenets (northwest Russia). About 80-90 % of the initial activity concentration declined according to the short component (Golikov et al., 2004).

Figure 6 presents ^{137}Cs concentration in four reindeer herding districts in northern Finland and Norway. From the Ivalo district there are data available from summer in addition to the winter, showing that there is a continuous seasonal difference in concentrations, with on average 2.4 times higher concentrations in winter (these summer data are from accidentally killed animals). As shown in Table 3 the decline in concentrations in Paistunturi could best be described using a double-exponential model with effective half-times similar to those cited from Golikov et al. (2004) above. The trend in Kemin Sompio is similar, but there the short-

[i] Linear regression with log transformed concentration values were used to quantify differences in contamination levels between the districts. Thereafter the concentration values in the various districts were normalized before fitting a double-exponential model to the pooled dataset.

term component (T_{eff1}) was not significant and a single-exponential model was therefore also fitted. A double-exponential model was not appropriate for the concentrations during winter in Ivalo. No reindeer meat samples are available from Kautokeino the first years after the Chernobyl fallout, and a single-exponential model starting from 1990 suggests a T_{eff} of 9.5±1.2 years. This estimate is close to the value of 9.3 years estimated during 1986-2000 for two districts in northern Sweden for the season January-April (district Könkämä and Lainiovuoma and district Ståkke and Östra Kikkejaure; Åhman et al., 2001). The estimated half-times in northern Sweden and Norway are intermediate of the T_{eff} and T_{eff2} estimates in the Finnish districts.

Rissanen et al. (2003) attributed the faster initial decline in Paistunturi to a higher grazing pressure in the first years after the Chernobyl fallout. However, the trend is comparable to that described by Golikov et al. (2004).

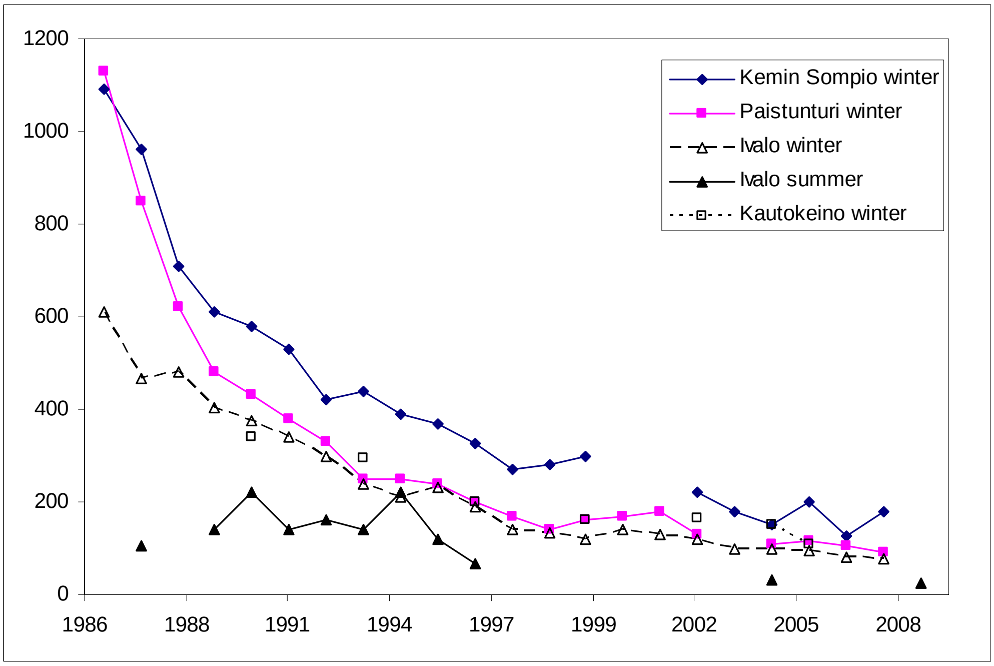

Figure 6. Average ^{137}Cs concentrations in reindeer meat from four different areas in northern Finland and Norway (Kautokeino).

Table 3. Estimated effective half-times (± standard error) for ^{137}Cs in reindeer during winter in three Finnish districts. See Table 1 for more details.

District	Single-exponential model	Double-exponential model	
	T_{eff}, year	T_{eff1}, year	T_{eff2}, year
Kemin Sompio	7.87±0.46	1.41±0.78 (ns)	9.6±1.3
Paistunturi		1.67±0.34	11.3±2.0
Ivalo[a]	7.25±0.30	4.5±1.8	43±220 (ns)

[a] Fitting the Ivalo data to a double-exponential model with T_{eff1} fixed at 1.5 years (based on the results of the two other Finnish districts and the results of Golikov et al. (2004) results in an estimated T_{eff2} of 8.3±0.5 years.

4.3 Regional differences in transfer and long-term trends

One aim of the REIN project was to assess regional differences in radiocaesium contamination in reindeer. This aim was motivated by the differences in half-times in Swedish herding districts observed by Åhman et al. (2001) and the role of climate in influencing transfer and long-term trends of radiocaesium in reindeer suggested by Skuterud et al. (2005b).

Climate may influence transfer of radiocaesium to reindeer, as well as long-term trends in concentrations in reindeer, by affecting:

- Weathering of ^{137}Cs from the lichen carpet (cf. Lehto et al., 2008). Weathering-rates are probably influenced by meteorological factors like wind and precipitation (total amounts, proportions as snow and rain etc.), and weathering-rates may therefore differ between climatically different areas.
- Lichen growth rates. Fresh growth of lichen will add mass and hence reduce the concentration of the deposited contamination, and may also affect weathering of external contamination. Lichens grow proportionally to amount of rainfall (Kärenlampi, 1971), thus growth-rates may vary with climate. Furthermore, climatic factors like temperatures and length of growing seasons will influence lichen growth.
- Composition of plant communities and thereby proportions of lichen and plants in the reindeer diet
- Soil-to-plant uptake of ^{137}Cs

This report provides further documentation on differences in long-term trends in ^{137}Cs in reindeer between areas with significant Chernobyl fallout and areas with nuclear weapons test fallout. According to single-exponential models, the effective half-time in the Chernobyl affected areas was about half of that in the most northern parts of Fennoscandia. However, analyses by double-exponential models suggest that radiocaesium contamination in the lichen – reindeer food chain initially declines with an effective half-time of 1-2 years in the northernmost areas, compared to about 3 years further south. In addition the slow component of the double-exponential model appears to have a faster component in the northernmost areas; about 11 years vs. about 30 years (or no significant decline at all).

Åhman et al. (2001) suggested that the effective half-times of 7-11 years in northern districts of low Chernobyl fallout (compared to about 4 years observed in districts further south) were caused by higher proportions of pre-Chernobyl caesium with an assumed effective half-time of 30.2 years (i.e., the physical half-life of ^{137}Cs). However, a slow component with this half-time is not indicated in the long-term data from the northern areas (Figure 6). Alternatively, the half-times observed by Åhman et al. (2001) in the northern districts may be explained by various components with half-times of 1-2 and 10-11 years as suggested by Golikov et al. (2004). This would give a better agreement with the continuous decline in concentrations indicated in Figure 6.

Figure 7 summarizes the current knowledge about long-term trends in ^{137}Cs concentrations in Fennoscandian reindeer, and illustrates the more rapid decline in concentrations in the northernmost districts compared to the areas of highest Chernobyl deposition. There are climatic differences between the northern areas represented in Figure 6 and the areas of higher Chernobyl deposition, e.g. with least precipitation in the northern areas. Thus, the various climatic factors mention above may be responsible for the differences in long-term trends observed. In addition, the deposited ^{137}Cs may have had different physical and/or chemical properties. Such differences may affect weathering of the external contamination as well as absorption and translocation of radiocaesium in the lichen organism.

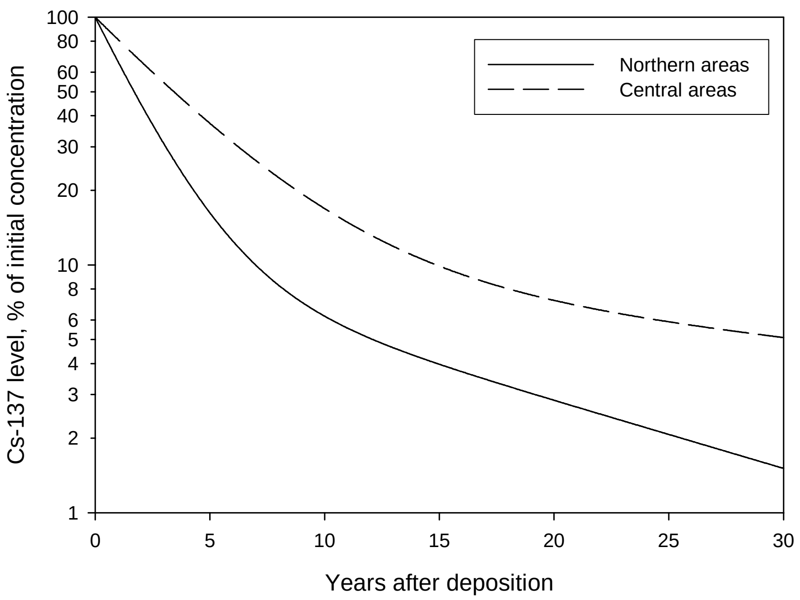

Figure 7 Summary of expected long-term trends in ^{137}Cs concentrations in reindeer in Fennoscandia following radiocaesium deposition (relative units). Short- and long-term effective half-times of 1.5 and 11 years, and 3 and 30 years, have been assumed in the northern and central areas respectively, and 90 % of the initial contamination was assumed to decline with the shortest half-time.

Unfortunately, to our knowledge, there are no comparable data on radiocaesium in lichens and vascular plants from various areas that could help explain the reasons for the observed differences in long-term trends. Furthermore, the lack of time series data on radiocaesium contamination of lichens and natural plants restricts the possibilities of making general assessment of importance of climate factors on long-term behaviour of radiocaesium in the lichen/plants – reindeer food chain.

5 Modelling radiocaesium in reindeer

Modelling transfer of radiocaesium to reindeer is a challenge compared to domestic animals, both due to seasonal differences in caesium retention and diet (total quantity as well as composition), seasonal migration into areas of different deposition density, and diversity in environments (e.g. forests, mountains and coastal areas). At the initiation of the REIN project no model for radiocaesium in reindeer existed as part of the Nordic nuclear emergency preparedness or for the ongoing Chernobyl fallout management in reindeer husbandry. REIN therefore aimed at contributing to the development of such a model.

A Microsoft Excel based dynamic model for radiocaesium in reindeer was presented by Åhman (2007). The model takes into account the reindeer's seasonal differences in caesium metabolism, seasonal and regional differences in diet composition and total feed intake. The diet was divided into four groups of vegetation. Model parameters (e.g. biological half-time in reindeer, diet composition, and transfer and effective half-times of radiocaesium in vegetation groups) were optimized using data on ^{137}Cs in reindeer from the Vilhemina norra district

(Figure 8). Initial deposition density is the input variable to the model, and by adjusting the deposition density the model was validated using data from the districts Ubmeje and Ran.

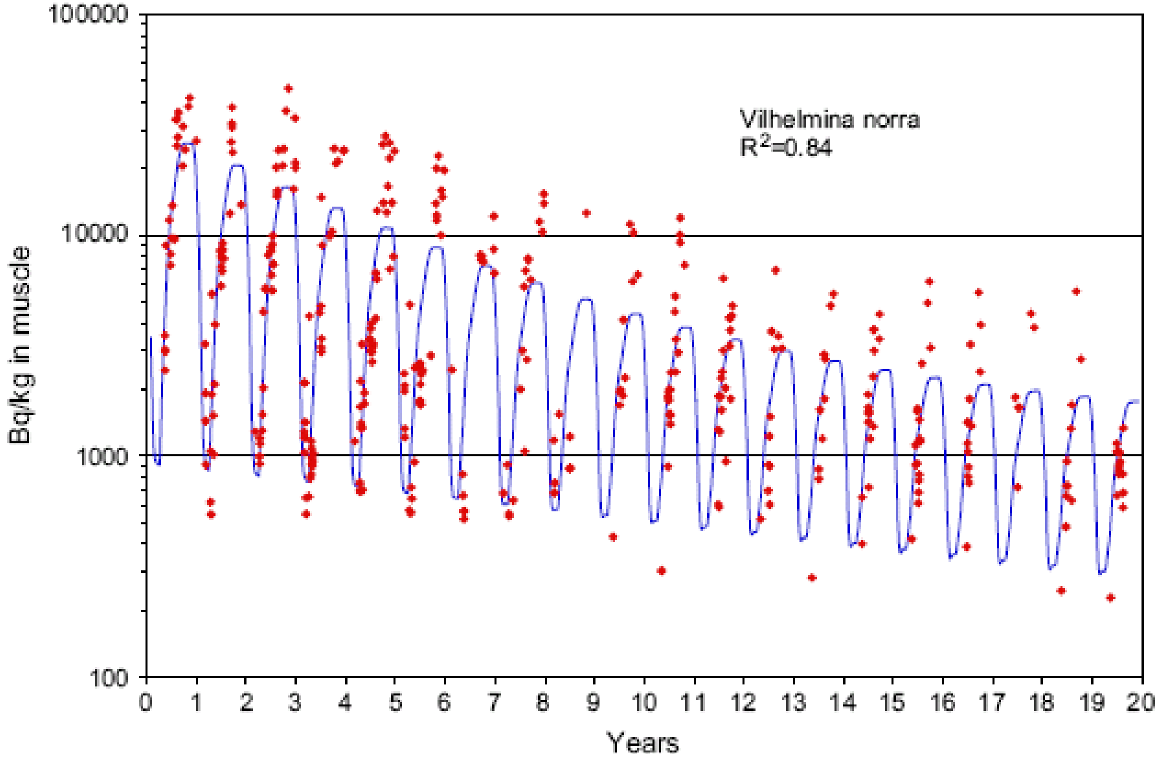

Figure 8 Comparison of simulated and observed activity concentrations of ^{137}Cs in reindeer from Vilhelmina norra reindeer herding district, Sweden. Dots are observed values (each representing 10 or more, mostly ≥30, individual reindeer) and the line is a modelled curve (from Åhman (2007)).

When adapted to the Vilhelmina norra dataset, the model could explain some 84 % of the variability in the dataset (interpreted from the R^2 value in Figure 8). This was obtained by keeping the gut absorption factor constant (not varying with season even though radiocaesium in lichens and plants may be of different bioavailability), using a biological half-time for radiocaesium in reindeer of 7 days during summer, gradually changing to a biological half-time of 30 days in mid and late winter. The latter is longer than reported in any study in the literature but showed to provide the best fit of the data.

Long-term trends in radiocaesium concentrations in reindeer reflect long-term trends in vegetation, and lacking time-series vegetation data is a limitation for model development. In the model by Åhman (2007) this was solved by including two groups of unknown vegetation with different transfer values and half-times. The modelling results show that the two dietary components mainly determining the radiocaesium concentrations in reindeer during winter was lichens (71 % of the diet; with an effective half-time of 3 years) and the unknown group Veg II (6 % of the diet; effective half-time of 30 years). As noted by Åhman (2007), these results support the analysis of the long-term trends in radiocaesium concentrations in reindeer using double-exponential models.

Åhman (2007) concluded that the usefulness of the model for predictive purposes is restricted by the lack of consistent data regarding uptake and depletion of radiocaesium in relevant plant species, and by the lack of knowledge of local and temporal variations in the reindeer diet. Furthermore the validation of the model in the Ubmeje and Ran districts showed that the model is sensitive to having appropriate knowledge of deposition information. Due to variable deposition within the vast grazing areas utilized by reindeer, average deposition density values will probably have to be supplemented by information on where within the districts the animals have been grazing.

In addition to the developing the dynamic model Åhman (2007) adapted linear regression models to various months or seasons (i.e., September, October, November-December, January-February). These models gave R^2 values comparable to the dynamic model. Åhman (2007) therefore concluded that the simple use of aggregated transfer coefficients (T_{ag}) and effective half-times (T_{eff}) probably could be more applicable for future predictions than the dynamic model, provided that the temporal and geographical limitations in these parameters are taken appropriately into account. For instance, the initial aggregated transfer coefficient for Vilhelmina norra and Ubmeje was found to be about 30 % higher than for Ran. However, in case of new fallout in a new situation, the dynamic model could be of high value. A dynamic model is particularly valuable in describing mechanisms and assessing how various changes in the system may influence on the activity concentrations of radiocaesium in reindeer.

6 Conclusions

This study has added further evidence for a slower decline in ^{137}Cs concentrations in reindeer in the Chernobyl affected areas during the last years. Whereas the concentrations during the first years declined by half-times of 3-4 years, the current decline appears to be governed by the physical half-life of ^{137}Cs. For reasons that remain unclear, a similar change in rate of decline is not identifiable in data on ^{137}Cs in reindeer from the northern areas, neither pre nor post Chernobyl. The current time-trends indicate that countermeasures and monitoring of reindeer in the Chernobyl affected areas of central Sweden and central and southern Norway will probably be needed for at least another 10 to 20 years.

Further elucidation of the long-term ^{137}Cs trends in reindeer would benefit from more studies of trends in soil-to-plant transfer in relevant vegetation species. The long-term Chernobyl problems in Swedish and Norwegian reindeer herding and the vulnerability of reindeer herding to future radiocaesium fallout warrant such studies, which should be designed to take various climatic conditions into account. Currently our understanding of the different long-term trends observed in various areas is not good enough to predict how future radiocaesium deposition will behave.

Previous radioecological studies on reindeer have focussed mainly on radionuclide transfer in the lichen – reindeer pathway because contaminated lichens caused the highest concentrations in reindeer during winter, and since reindeer husbandry traditionally was based on winter slaughtering of animals (when lichen is a dominant dietary item). However, in the long-term Chernobyl perspective ^{137}Cs concentrations in lichens decrease relatively rapidly, and persistent uptake of radiocaesium by plants seem to make plants gradually more important ^{137}Cs sources to reindeer. Furthermore, modern reindeer husbandry in Sweden and Norway includes slaughtering a large proportion of the herd in early autumn, when plants constitute the largest proportion of the diet and forest mushrooms instead can contribute significantly to the radiocaesium intake.

The high transfer of nuclides to reindeer, the geographical extension of reindeer herding and the special position of the Sami population in Finland, Sweden and Norway, demonstrates the need for maintaining competence and further developing the common basis for Nordic fallout management and emergency preparedness related to this food-chain.

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Abstract

The NKS-B project REIN was established to synthesize the available information on contamination levels and effective half-times for 137Cs in reindeer in Finland, Sweden and Norway. Several studies of radiocaesium contamination in reindeer have been carried out in the Nordic countries over the last 50 years. However, the current slow decline in concentrations, which will maintain the consequences of the Chernobyl deposition for Swedish and Norwegian reindeer husbandry for at least another 10-20 years, have not previously been observed nor predicted. In the Chernobyl affected areas 137Cs concentrations in reindeer initially declined by effective half-times of 3-4 years, whereas the current decline appears to be mainly governed by the nuclide's physical half-life (30 years).

The review of effective half-times of 137Cs in reindeer across Fennoscandia suggests that concentrations declined more rapidly in the northernmost areas. The reason(-s) remains unclear, and demonstrates the need for more long-term sampling of the various components of reindeer's diet. Such sampling should aim at covering climatically different areas, as climate may influence transfer of radiocaesium to reindeer via lichen growth and weathering rates, composition of plant communities and lichen availability, as well as soil-to-plant radiocaesium uptake. The lack of long-term data on radiocaesium in natural vegetation in the Nordic countries is one of the main limitations for the development of mechanistic models for radiocaesium in reindeer, and for further elucidation of the observed long-term trends in 137Cs concentrations in reindeer. Currently our understanding of the long-term trends observed in various areas is not good enough to predict how future radiocaesium deposition will behave.

The high transfer of nuclides to reindeer, the geographical extension of reindeer herding and the special position of the Sami population in Finland, Sweden and Norway, demonstrates the need for maintaining competence and further developing the common basis for Nordic fallout management and emergency preparedness related to this food-chain.

Key words: Radiocaesium, 137Cs, reindeer, lichen, long-term

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