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Concentrations of ^{137}Cs in lynx (*Lynx lynx*) in relation to prey choice

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Abstract

Concentrations of ^{137}Cs were determined in 747 lynxes killed in Norway during the period 1986–2001. Highly variable ^{137}Cs concentrations and aggregated transfer coefficient values were observed, probably caused by variable ^{137}Cs concentrations in prey and the lynx's extensive home ranges and roaming distances. Adult lynxes had higher ^{137}Cs concentrations than sub-adults, and lynxes killed in regions with extensive reindeer grazing areas were more contaminated than others. A model with ^{137}Cs deposition density, the year lynxes were killed, age, and extent of reindeer grazing area accounted for 50% of the variability in observed ^{137}Cs concentrations. The analyses were equivocal regarding the influence of stomach content on ^{137}Cs concentrations in lynx muscle, i.e., on the lynx's specialization in prey species. Gender was not significant. Information on caesium retention in lynx and better estimates of deposition densities in lynxes' home ranges are important for further elucidation of factors influencing ^{137}Cs contamination in lynxes.

Keywords: Lynx; Carnivore; Caesium-137; Reindeer; Roe deer; Food chain; Chernobyl

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1. Introduction

The Eurasian lynx (*Lynx lynx*) is the most numerous larger carnivore mammal in Norway with a population of 300–350 individuals in 2002 (Andersen et al., 2003), and is found in most parts of the country. The lynx is a solitary predator, preferring rugged forested terrain, with an average range in Norway of 250–1500 km^2 depending on prey density (Kvam and Jonsson, 1998). The population density of lynxes is only 3–10 animals per 1000 km^2, as there is little territorial overlap between individuals of the same sex (Solberg et al., 2003). Home ranges of male individuals are generally larger than of females; the largest recorded male home range in Norway reaching 3100 km^2 (Kvam and Jonsson, 1998).

Both male and female lynxes are fully grown by the age of 2 years, with average weights of 15–16 and 18–20 kg for females and males, respectively (Sunde and Kvam, 1997). The mating season lasts from the end of February through early April (Kvam, 1990, 1991) and female lynxes give birth for the first time at the age of 2 years (Kvam, 1990), with average litter sizes of 2–3 cubs. The cubs are born in May–June, and follow their mother for nearly a year (till February–May) before establishing separate home ranges. Six out of 18 tracked lynxes in Hedmark county established home ranges more than 150 km from their mother's (Andersen et al., 2000). Another sub-adult migrated about 400 km from Sarek (northern Sweden) to Steinkjer (central Norway). Average daily roaming distances, occurring mostly during the night, range from about 2 km for adult females to 5.3 km for adult males, with recorded extremes of 23.5 and 45 km. The latter was a male searching a female in the mating season (Andersen et al., 2000).

The size of lynx prey ranges from small rodents to larger cervids such as reindeer and moose. Stomach content analyses of 441 Norwegian lynxes showed that 67% had eaten cervids (mainly roe deer and reindeer), 25% small game (such as hare, capercaillie and grouse) and 8% other species (such as fox and rodents) (Sunde and Kvam, 1997). Roe deer is the favourite species. Lynxes take more cervids during winter than summer (Kvam and Jonsson, 1998; Andersen et al., 2000), and males can take slightly more cervids than females (Sunde and Kvam, 1997). For females, Sunde and Kvam (1997) found a tendency towards a body weight effect on food choice, indicating that the smallest individuals may have problems handling the largest prey species. Another study found no difference in prey choice due to gender and age groups (Andersen et al., 2000). Lynxes kill on average one animal every 5 days when cervids are the only prey (Kvam and Jonsson, 1998).

This study presents data on ^{137}Cs concentrations in lynx muscle in Norway from the 1986 Chernobyl accident up to the year 2001. Through knowledge of reindeer grazing areas and the results of stomach analyses of killed animals, we attempt to quantify the effect of prey selection and in particular reindeer predation, on ^{137}Cs concentrations in lynxes. Reindeer generally contain higher concentrations of radioactive caesium than other animals, especially during winter (e.g., Åhman and Åhman, 1994). Mohn and Teige (1968) found that most of the ^{137}Cs contamination in lynxes in Norway was traceable to reindeer, and Åhman et al. (2002) found higher

^{137}Cs concentrations in lynxes from reindeer grazing areas than in lynxes from areas without reindeer. Due to the expected higher ^{137}Cs concentrations in lynxes predating upon reindeer, systematic differences also in ^{137}Cs concentrations in lynx can be expected if individuals specialize in prey species (e.g., some predate only roe deer, others only reindeer).

2. Materials and methods

To assess potential ranges in ^{137}Cs concentrations in muscle of lynx predating upon animals with different ^{137}Cs concentration levels, a two-compartment model simulating ^{137}Cs uptake and retention in lynxes was developed in ModelMaker v.4. The model was similar to that used for wolf by Holleman et al. (1990). Parameter estimates were obtained by fit to a build-up curve for ^{137}Cs concentrations in a 20 kg animal with a biological half-time of 35 days (Mohn and Teige, 1968). Alimentary uptake of radiocaesium in ingested meat was assumed to be 100%.

The majority of bodies of lynxes killed, accidentally killed or found dead in Norway are routinely examined at the Norwegian Institute for Nature Research (NINA). Fig. 1 shows the number of lynxes from the different years included in this study, i.e. all lynxes with known location submitted to NINA by November 2001. In total 747 animals were sampled, of which two 1986 samples were animals killed prior to the Chernobyl accident. About 70% of the lynxes were killed during the period 1995–2001, and about 40% in the counties Nord-Trøndelag and Nordland. Hunting for lynx is only allowed between 1 February and 31 March, with a limit, that varies between regions, on the number of animals that can be killed each year. In this study,

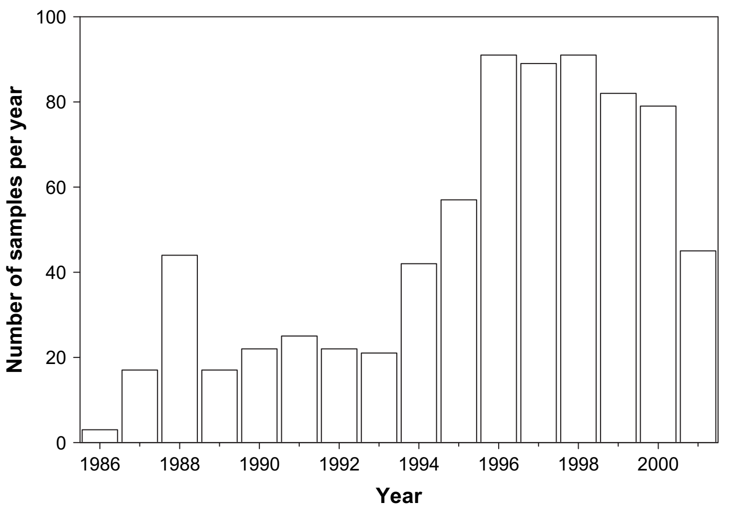

Fig. 1. Annual distribution of lynx muscle samples analyzed during the period 1986–2001.

approximately 93% of the available sample material was from animals killed during this period.

Muscle samples from the thigh (neck or shoulder if thigh was not available) were dried to constant weight at 70 °C and ground. A 3 inch NaI(Tl) well detector and a multichannel analyser (CompuGamma 1282) was used to determine ^{137}Cs. The detection limit was about 0.23–0.45 Bq depending on sample size. Obtained ^{137}Cs concentrations values were decay corrected to the date of killing, and the results are given in Bq kg^{-1} dry matter (DM).

Age (determined from teeth examination; Kvam, 1984) was used to categorize the lynx as sub-adult (0–24 months) or adult (>2 years). Information on killing date was used to classify the samples according to season: (1) winter from 1 December–31 May (in total only 3 animals from May), and (2) summer (1 June–30 November). Stomach contents were identified in 259 of the animals killed during 1986–1997 (Sunde and Kvam, 1997). The sampled animals were categorized according to their dominant stomach content: (1) reindeer, (2) roe deer, (3) hare, (4) unidentified cervid (including two cases identified as moose), (5) miscellaneous (e.g. birds (grouse, black grouse, capercaillie), mice, squirrel, dog, pig, sheep).

For some lynxes, killing date, gender or age was not determined, and different statistical analyses therefore involved different numbers of cases. In 45 cases no exact date of death was reported, and the date was set to 1 March in the respective years if there were no indications of killing outside the hunting season.

The Chernobyl fallout in Norway was highly heterogeneous, with average municipality ^{137}Cs deposition densities ranging from 0.06 to 100 kBq m^{-2} (Backe et al., 1986), with central Norway and the mountainous parts of southern Norway most contaminated. In an attempt to reduce variability in the dataset, ^{137}Cs concentrations in lynx were normalized by the total ^{137}Cs (i.e., ^{137}Cs from both nuclear weapons tests and Chernobyl fallout) deposition density in the municipality in which the lynx had been killed. The municipality (areas ranging from 74 to 4646 km^2) in which the lynx had been killed was taken as the lynx's home habitat. The total ^{137}Cs 1986 deposition density from Backe et al. (1986) was decay corrected to give separate deposition densities per year. The normalized values thus obtained are the aggregated transfer coefficients (*Tag*; unit m^2 kg^{-1}) (Hove and Strand, 1990; Howard et al., 1991).

Using manual overlay and visual inspection of 1:2 500 000 scale maps of municipality borders and grazing areas of wild and semi-domesticated reindeer, all municipalities were roughly classified as containing: (0) no grazing areas, (1) minor grazing areas, (2) larger grazing areas (up to 50% of the area), (3) grazing areas in most of the area, and (4) grazing areas all over the area.

Statistical analyses (analysis of variance, linear and non-linear regression) were carried out in SPSS release 11. Due to skewed data and in order to harmonize variances, the ^{137}Cs concentration, deposition and *Tag* values were log transformed prior to analyses. The influence of time after fallout and deposition level on concentrations in lynxes was reduced using analyses of the residuals obtained after regression of concentration values vs. time and deposition.

3. Results

3.1. Simulated ^{137}Cs concentrations in lynx

Fig. 2 shows model simulated ^{137}Cs concentrations in lynx muscle due to different diets: Concentrations in lynxes predating only reindeer, lynxes predating only other species, and lynxes eating reindeer for 5 and 10 days in December and January, respectively. The lynx's daily meat intake was set to 2 kg (fresh weight, FW) in accordance with the estimate of Mohn and Teige (1968) and corresponding to killing a cervid like an average sized roe deer every 5 days (Kvam and Jonsson, 1998). The calculations applied a concentration of 7000 Bq kg^{-1} (FW) in reindeer meat, representative of average concentrations in reindeer of Nord-Trøndelag county about 1989–1990 (Mehli et al., 2000). For other prey a concentration of 300 Bq kg^{-1} (FW) was applied, corresponding to data on moose from Nord-Trøndelag county (Ahlin, J.P. Norwegian Food Safety Authority, Namdal office, personal communication) and to estimated concentrations in roe deer in the same area using aggregated transfer coefficients from Johanson and Bergström (1994) and Kiefer et al. (1996). The difference in concentrations in prey determines the range in concentrations in lynx (in this simulation a factor of 23 difference). The simulation showed that a considerable variability in ^{137}Cs concentrations in lynx would be expected due to variable diets and variable ^{137}Cs concentrations in prey.

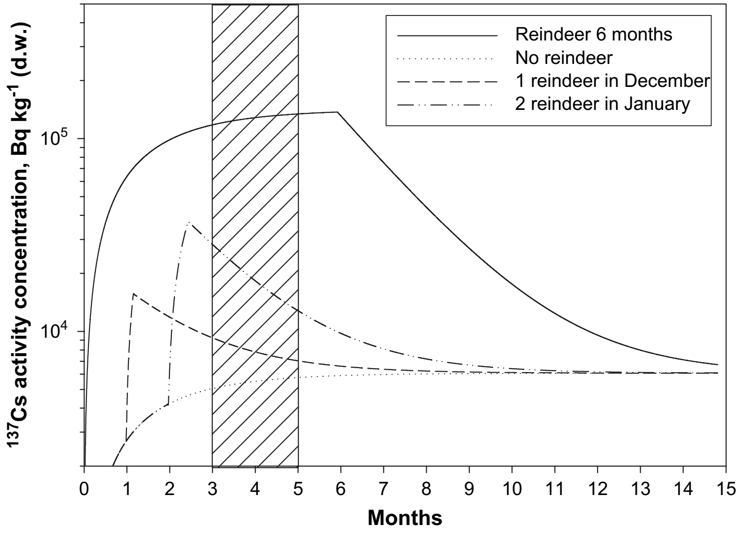

Fig. 2. Estimated ^{137}Cs concentrations in lynx muscle due to different diets. The simulation starts from 1 November (month 0). Solid line simulates concentrations in lynx killing only reindeer (containing 7000 Bq kg^{-1}) for 6 months; dot line simulates lynx not killing reindeer (prey containing 300 Bq kg^{-1}); dash line simulates lynx killing one reindeer in December, and dash-dot line simulates lynx killing two reindeer in January. The hunting season in February–March is indicated by the hatched area. See Section 3.1 for more details.

3.2. Observed ^{137}Cs concentrations and Tag values

Fig. 3a presents the ^{137}Cs concentrations in sampled lynx muscle. The simulated concentrations in Fig. 2 corresponded to those in the upper half of the range of observed values. The concentrations in the two animals killed prior to the Chernobyl accident were 670 and 800 Bq kg^{-1} (DM), while a maximum value of 125 000 Bq kg^{-1}

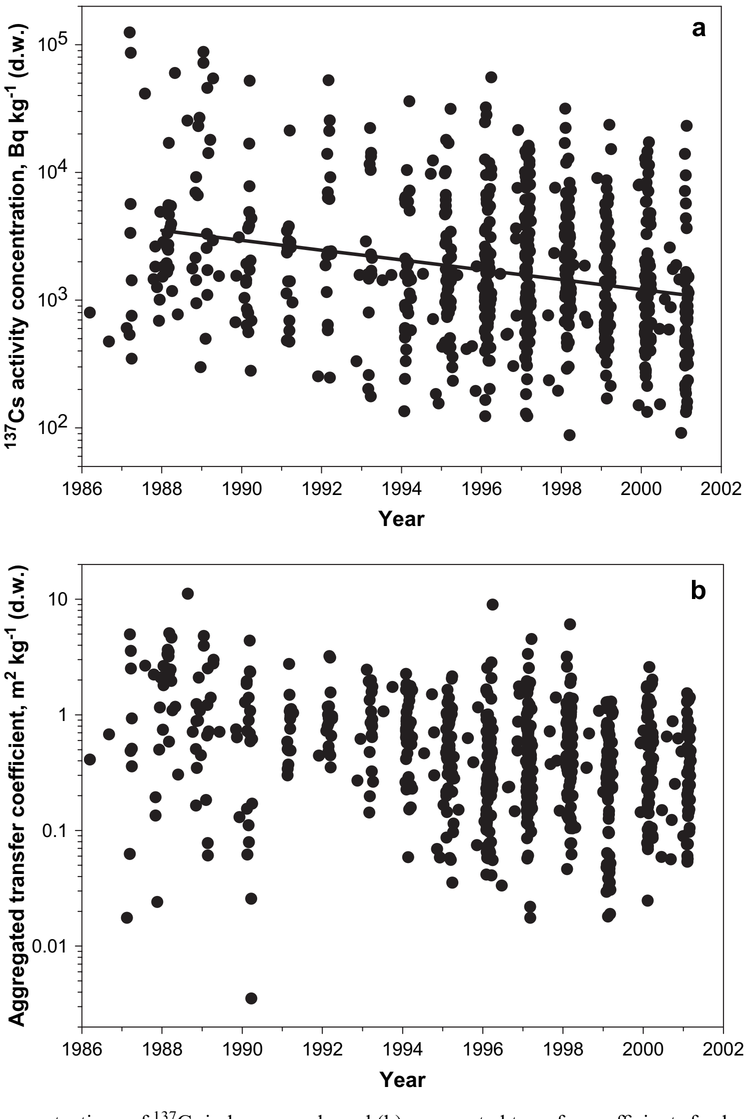

Fig. 3. (a) Concentrations of ^{137}Cs in lynx muscle and (b) aggregated transfer coefficients for lynx muscle in Norway during 1986–2001 (only samples with known date of killing). The line in (a) is the fitted linear regression model, Eq. (1).

(DM) was found in a 2 year old male lynx killed in Alvdal (Hedmark county) in March 1987. The highest average concentrations were found in 1988–1989. Annual maximum and minimum concentrations generally differed by more than a factor of 100. The difference was maintained throughout the whole 1986–2001 period, and was the same irrespective of season.

Normalizing the ^{137}Cs concentrations to the deposition values reduced the coefficient of variation (CV) (i.e., standard deviation in percent of sample mean) in the whole dataset from about 230% for the concentration values to 140% for the *Tag* values (Fig. 3b). *Tag* values ranged more than three orders of magnitude from below 0.01 to above 10 m^2 kg^{-1} (DM).

3.3. Factors influencing ^{137}Cs concentrations in lynx

Two-way analysis of variance was carried out to study the influence of ^{137}Cs deposition density, time after fallout (years), gender, age, season, extent of reindeer grazing areas, and stomach content on both concentration and *Tag* values. The analyses revealed that deposition density, age and extent of reindeer grazing area explained significant proportions of the variability ($P<0.01$, adjusted $R^2=0.82$). Furthermore, time after fallout was a significant factor ($P<0.01$). However, since deposition densities were obtained by decay correction of 1986 values, no degrees of freedom were left for assessment of the effect of time after fallout in two-way analyses of variance with deposition density included. Deposition density alone explained about 77% of the variability in the concentration values (adjusted R^2). Gender, stomach content and season ($P=0.12$) were found to be non-significant factors. Nevertheless, the 54 samples of lynx killed during summer were excluded from further analyses.

The residuals (e) from a linear regression of log transformed concentration values vs. deposition and time (after 1987) were assumed to be independent of the two factors, and were studied in an attempt to quantify the effect of the other factors. The obtained regression model was:

$$\ln A = 3.21(\pm 0.26) + 0.600(\pm 0.029)\ \ln D - 0.089(\pm 0.011)t + e \qquad (1)$$

where A is the ^{137}Cs concentration in lynx (Bq kg^{-1} DM), D is deposition density (Bq m^{-2}) and t is time (years; $t=0$ in 1988) ($N=636$, adjusted $R^2=0.43$). The estimated model is illustrated by the lines in Figs. 3a and 4. Regression of *Tag* vs. deposition and time gave identical residuals to those for concentration values (since *Tag* values were obtained by decay corrected 1986 deposition densities, and $\ln \mathrm{Tag} = \ln A - \ln D$ where $\ln A$ is given in Eq. (1)).

Two-way analysis of variances in the residuals gave results similar to those above. Stomach content and gender were again found insignificant, whereas age ($P=0.029$) and extent of reindeer grazing area ($P<0.001$) accounted for 14% of the variability in the residuals (adjusted R^2). Concentrations of ^{137}Cs were on average 23% higher in adults than in sub-adults (mean residuals of 0.111 ± 0.053 and 0.093 ± 0.051 for sub-adults ($N=285$) and adults ($N=343$) respectively).

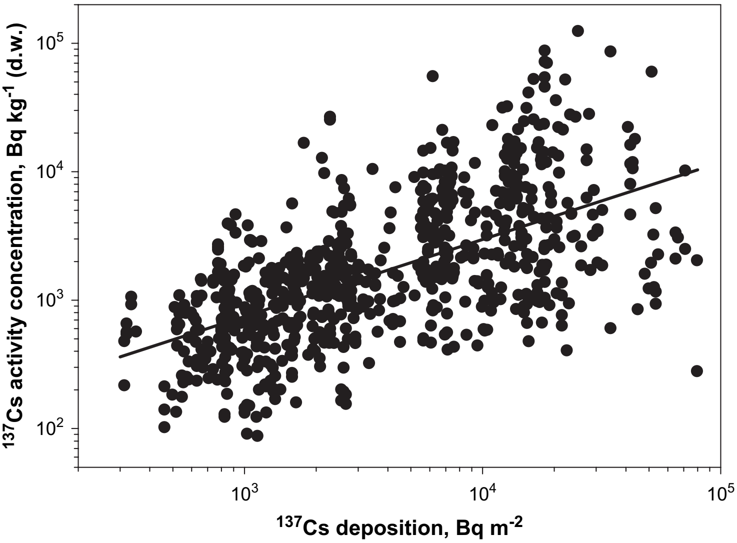

Fig. 4. Concentrations of ^{137}Cs in lynx muscle vs. deposition density. The line is the fitted linear regression model, Eq. (1).

The relationship between ^{137}Cs concentrations in lynxes and the extent of reindeer grazing area is illustrated in Fig. 5. Concentrations in lynxes killed in municipalities of category 4 were a factor of 2.6 higher than those of category 1 and a factor 1.6–2.0 higher than those of categories 0, 2 and 3 ($P<0.001$) (the factor is given by the difference in log transformed values (x) as e^x). Also, concentrations in lynxes from category 0 were higher than in those from category 1 by a factor 1.6 ($P=0.011$).

Summarizing the results into one model for ^{137}Cs concentrations in lynx muscle gives:

$$\ln A = 3.21 + 0.600\ \ln D - 0.089t + c_{\text{age}} + c_{\text{area}} \tag{2}$$

where A is the concentration in lynx (Bq kg^{-1} DM), D is the deposition density (Bq m^{-2}; decay corrected 1986 values), t is time (years since 1988), c_{age} is a constant depending on lynx age category (equal to −0.111 for sub-adults and 0.093 for adults), and c_{area} is a constant depending on category of extent of reindeer grazing area (equal to −0.142 in municipalities with no reindeer grazing areas, −0.625, −0.383 and −0.38 for those with intermediate extents of grazing areas respectively, and 0.313 in municipalities with reindeer grazing areas all over the area). All c_{area} values are not significantly different (cf. Fig. 5) but serve as best estimates. The model R^2 was 0.52. As expected the R^2 was lower (i.e., 0.49) when the model (Eq. (2)) was used to estimate concentrations in all samples from 1986 to 2001. The model underestimates the highest concentrations and overestimates the lowest ones.

The concept of aggregated transfer coefficients assumes that *Tag* values are independent of deposition densities, but Fig. 4 and Eq. (1) show that ^{137}Cs concentrations in lynx muscle did not increase linearly with deposition. One-way

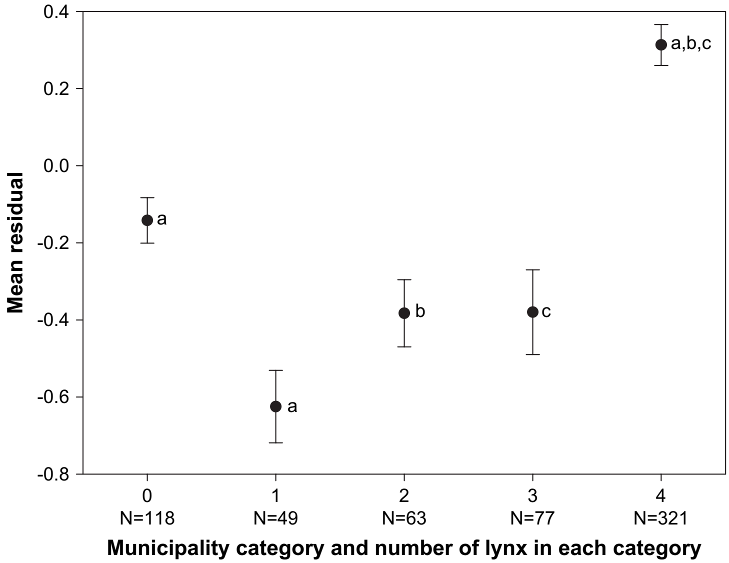

Fig. 5. Mean values (±SE) of residuals by extent of reindeer grazing areas. Category (0) no grazing areas, (1) minor grazing areas, (2) grazing area in up to 50% of the area, (3) grazing areas in most of the area, and (4) grazing areas all over the area. Mean values with similar letter were significantly different.

analysis of variance showed that stomach content had a significant effect on *Tag* values as well as residuals ($P=0.001$), and the mean *Tag* for lynxes with roe deer in their stomach was 45–48% of the *Tag* for lynxes with reindeer or unidentified cervid ($P=0.009$ and $P=0.012$, respectively, Fig. 6).

3.4. Effective ecological half-times

Regression analyses identified no systematic differences or pattern in effective ecological half-times for ^{137}Cs in lynx muscle with respect to extent of reindeer grazing areas or between counties, neither were there any differences in half-times in lynxes with different stomach contents. For the different grazing area categories and counties the analyses yielded results ranging from half-times of 3–4 years to no detectable decrease with time. Similarly, Åhman et al. (2002) estimated half-times in lynx of 2.2–4.2 years in some areas in Sweden in the period 1996–2001, while there was no significant decrease in other areas. The half-time estimated using all data (given by the time-dependent term in Eq. (1)) was 7.9 years (standard error range 6.9–8.9 years).

4. Discussion

The analyses of the dependency of aggregated transfer coefficients and ^{137}Cs concentrations in lynx muscle on stomach content gave equivocal results. One-way

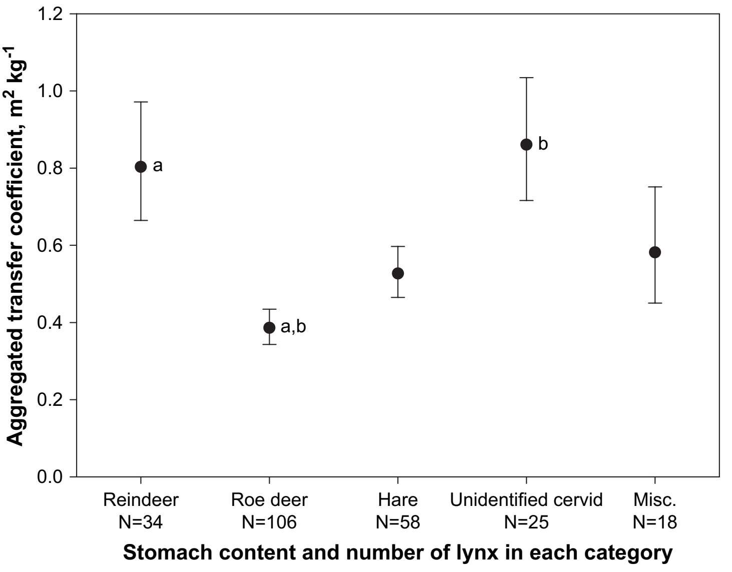

Fig. 6. Geometric mean (and SE) of *Tag* values for winter killed lynxes with different stomach contents. Mean values with similar letter were significantly different.

analyses of variance showed that stomach content was a significant factor, while two-way analyses of variance did not identify stomach content as significant. This indicated that the variable was correlated to other important factors. A slight but statistically significant correlation between stomach content and deposition ($R = -0.13$, $P = 0.044$) was the only possible explanation found (see further discussions regarding *Tag* below). Furthermore, if stomach content is insignificant, this may indicate that the lynx have a variable diet and do not specialize in prey species or that the stomach content at the time of killing did not give a representative indication of its diet. It may also reflect the variability in ^{137}Cs concentrations in lynxes resulting from spatial and temporal variable ^{137}Cs concentrations in prey species, as well as the extensive home ranges and mobility of particularly sub-adult lynxes and males during the mating season (which coincide with the hunting season). The variability in ^{137}Cs concentrations in reindeer following the Chernobyl fallout are illustrated in Åhman and Åhman (1994). Maximum concentrations in individual reindeer in central Norway reached 150 000 Bq kg^{-1} (FW) (Strand et al., 1992).

A reduction in the variability in ^{137}Cs concentrations in lynx due to different deposition levels in their home range was attempted by calculating *Tag* values based on average deposition densities, but the CV for *Tag* was also considerable. Since 21% of the municipalities where lynxes were killed have areas of less than 400 km^2, and 70% less than 1200 km^2, many lynxes will have home ranges extending beyond one municipality, and can even cross whole municipalities during one day's roaming. Furthermore, average deposition densities between neighbouring municipalities are up to a factor of 15–20 different (Backe et al., 1986) and a considerable variability in

Tag values would therefore be expected. Even lynxes living within the borders of one municipality may experience considerable heterogeneity in ^{137}Cs deposition.

Simulated ^{137}Cs concentrations in lynx muscle corresponded to those in the upper half of the range of observed values, which was reasonably since concentrations from some of the most contaminated areas in Norway were applied in the calculations. We know of no experiment on radiocaesium excretion rate or biological half-times in lynx or other felids that could be helpful in studying how variations in diet can cause variations in ^{137}Cs concentrations in lynx muscle. The biological half-time estimate of 35 days by Mohn and Teige (1968) was based on data from other species in Ekman (1967). In comparison, Holleman and Luick (1976) found half-times of 22–26 days in wolf and coyote. A shorter half-time than 35 days would give more rapid changes in ^{137}Cs concentrations in lynxes and lower maximum values than that indicated in Fig. 2, while the relative range in concentrations values due to differences in diet would be the same.

The *Tag* values estimated in this study were correlated to the deposition densities as indicated in Fig. 4 and Eq. (1). The correlation coefficient between log transformed *Tag* and deposition densities was $R = -0.44$ ($P < 0.001$). A substantial decrease from 1986 to 1995 in surface soil ^{137}Cs was reported by Bjerk et al. (1999) in most Norwegian counties. Thus the decay corrected values applied herein may have been overestimates, and could be one reason for the negative correlation with *Tag*. Another reason may be the importance of reindeer in the diet of lynxes in northern Norway receiving the lowest Chernobyl ^{137}Cs deposition, while other species may be more important prey in the most contaminated areas in central and southern Norway.

No definite explanation for the relatively high ^{137}Cs concentrations in lynx killed in regions with no grazing areas was found, but it appeared related to the fact that most of these municipalities are situated in southern Norway in areas of relatively low Chernobyl fallout and higher transfer to lynx (cf. the correlation between deposition density and *Tag*). Also, long ecological half-times for ^{137}Cs in the lynx's prey in these areas would contribute to relatively high concentration levels. Concentrations of ^{137}Cs in roe deer may increase significantly in autumn due to ingestion of fungi (e.g., Avila et al. (1999), and the ecological half-time for roe deer has been found to approach the physical half-life of 30 years (Johanson and Bergström, 1994).

Åhman et al. (2002) reported average *Tag* values for lynxes in Sweden during 1996–2001 corresponding to 0.16–0.28 $m^2\ kg^{-1}$ (DM) in areas with no or few reindeer, to 0.48–1.1 $m^2\ kg^{-1}$ (DM) in areas with reindeer present. These values are not directly comparable to those herein due to different methods of *Tag* estimation and categorization of presence of reindeer, but they appear lower than those estimated for Norwegian lynxes in the same period.

Prior to regression and calculation of residuals for concentrations vs. deposition density and year, a control was made of possible differences in time trends of concentrations in different reindeer grazing area categories, or in different counties. Shorter ecological half-times for ^{137}Cs in reindeer in areas with higher deposition density were reported by Åhman et al. (2001), thus a similar trend might be expected if lynxes depended heavily upon reindeer predation. Since no systematic differences in half-times between counties or grazing area categories could be detected all concentration values were applied in the regression analysis. The resulting estimate of 7.9 years appears long compared to effective ecological half-times of 3–5 years estimated for reindeer in both Norway and Sweden (Amundsen, 1995; Gaare et al., 2000; Hove and Staaland, 1997; Åhman et al., 2001; Åhman and Åhman, 1994).

5. Conclusions

1. Adult lynxes attained the highest ^{137}Cs concentrations in Norway following the Chernobyl accident, and concentrations in lynxes from municipalities with reindeer grazing areas all over the area were higher than in other regions.
2. This study did not give clear indications of specialization in prey species, but unambiguous conclusions were possibly prevented by the variability introduced by the heterogeneous Chernobyl deposition (causing variable ^{137}Cs concentrations in prey) and the lynxes' considerable roaming distances, and the uncertainty in estimated ^{137}Cs deposition densities.
3. Deposition density, time after fallout, animal age and extent of reindeer grazing area could account for 50% of the observed variability in ^{137}Cs concentrations in lynx muscle.
4. Average effective ecological half-times for ^{137}Cs in lynxes in Norway were estimated to be in the range 6.9–8.9 years.
5. Experimental data on caesium retention in lynx, and independent estimates of deposition density in the lynx's home ranges, seem important for further studies of transfer of ^{137}Cs through the food chain to lynxes in Norway.

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