Journal of Environmental Radioactivity xxx (2014) 1–8

Contents lists available at ScienceDirect

Journal of Environmental Radioactivity

journal homepage: www.elsevier.com/locate/jenvrad

Polonium-210 and Caesium-137 in lynx (*Lynx lynx*), wolverine (*Gulo gulo*) and wolves (*Canis lupus*)

Runhild Gjelsvik[a,*], Elis Holm[a,1], John Atle Kålås[b], Bertil Persson[c], Jessica Åsbrink[d]

[a] Norwegian Radiation Protection Authority, PO Box 55, NO-1332 Østerås, Norway
[b] Norwegian Institute for Nature Research, PO Box 5685 Sluppen, NO-7485 Trondheim, Norway
[c] Lund University, Medical radiation physics, Barngatan 2, SE-22185 Lund, Sweden
[d] National Veterinary Institute, Uppsala, Sweden

ARTICLE INFO

Article history:
Received 24 June 2013
Received in revised form
10 February 2014
Accepted 27 February 2014
Available online xxx

Keywords:
Polonium-210
Caesium-137
Doses
Lynx
Wolverine
Wolf

ABSTRACT

Wolves, lynx and wolverines are on the top of the food-chain in northern Scandinavia and Finland. ^{210}Po and ^{137}Cs have been analysed in samples of liver, kidney and muscle from 28 wolves from Sweden. In addition blood samples were taken from 27 wolves. In 9 of the wolves, samples of muscle, liver and blood were analysed for ^{210}Po. Samples of liver and muscle were collected from 16 lynx and 16 wolverines from Norway. The liver samples were analysed for ^{210}Po and ^{137}Cs. Only ^{137}Cs analyses were carried out for the muscle samples. The wolves were collected during the winter 2010 and 2011, while the samples for lynx and wolverines were all from 2011. The activity concentrations of ^{210}Po in wolves were higher for liver (range 20–523 Bq kg^{-1} d.w.) and kidney (range 24–942 Bq kg^{-1} d.w.) than muscle (range 1–43 Bq kg^{-1} d.w.) and blood (range 2–54 Bq kg^{-1} d.w.). Activity ratios, ^{210}Po/^{210}Pb, in wolf samples of muscle, liver and blood were in the ranges 2–77, 9–56 and 2–54. Using a wet weight ratio of 3.8 the maximal absorbed dose from ^{210}Po to wolf liver was estimated to 3500 μGy per year. Compared to wolf, the ranges of ^{210}Po in liver samples were lower in lynx (range 22–211 Bq kg^{-1} d.w.) and wolverine (range16–160 Bq kg^{-1} d.w.). Concentration of ^{137}Cs in wolf samples of muscle, liver, kidney and blood were in the ranges 70–8410 Bq kg^{-1} d.w., 36–4050 Bq kg^{-1} d.w., 31–3453 Bq kg^{-1} d.w. and 4–959 Bq kg^{-1} d.w., respectively. ^{137}Cs in lynx muscle and liver samples were in the ranges 44–13393 Bq kg^{-1} d.w. and 125–10260 Bq kg^{-1} d.w. The corresponding values for ^{137}Cs in wolverine were 22–3405 Bq kg^{-1} d.w. for liver and 53–4780 Bq kg^{-1} d.w. for muscle. The maximal absorbed dose from ^{137}Cs to lynx was estimated to 3000 μGy per year.

© 2014 Elsevier Ltd. All rights reserved.

1. Introduction

Animals are exposed to radioactive radiation both from natural and anthropogenic sources and receive significant doses. In north-western Europe the most important natural sources of such radiation to wild and semi domestic animals is ^{210}Po ($T_{1/2}$ = 138 d) which originates from deposition of ^{210}Pb from precipitation or exhaled from the ground as ^{222}Rn. The deposition of ^{210}Pb depends on surrounding land area, amount of uranium in the ground and precipitation. The deposition is also dependent on rainfall, distance from sea and local emanation of ^{222}Rn. The annual deposition of ^{210}Pb in Scandinavia is approximately 55 Bq m^{-2}. At 62 °N in Sweden the integrated areal concentration of ^{210}Po, which is the grand-daughter product of ^{210}Pb ($T_{1/2}$ = 22.3 a) via Bi, has been estimated to 2000 Bq m^{-2} (Persson, 1970, 1972) assuming radioactive equilibrium. ^{210}Po is highly radiotoxic and is the alpha emitter which gives the highest dose to humans via food intake (UNSCEAR, 2008).

At present the most important source of anthropogenic radiation in Scandinavian areas comes from ^{137}Cs which was deposited just after the Chernobyl accident in the end of April 1986. Total deposition of ^{137}Cs in Sweden and Norway were approximately 4.25 PBq (Edvarson, 1991) and 2300 ± 200 TBq (Bache et al., 1987). This deposition of ^{134}Cs and ^{137}Cs was very inhomogeneous, and in Scandinavia it varied between 1000 and 50000 Bq m^{-2} depending on the rainfall during the days after the accident (Edvarson, 1991). The deposition from nuclear tests was more homogeneously

* Corresponding author. Tel.: +47 67162500; fax: +47 67147407.
E-mail address: Runhild.Gjelsvik@nrpa.no (R. Gjelsvik).
[1] Present address: Department of Radiation Physics, Sahlgren Academy, University of Gothenburg, SE-41345 Gothenburg, Sweden.

http://dx.doi.org/10.1016/j.jenvrad.2014.02.026
0265-931X/© 2014 Elsevier Ltd. All rights reserved.

Please cite this article in press as: Gjelsvik, R., et al., Polonium-210 and Caesium-137 in lynx (*Lynx lynx*), wolverine (*Gulo gulo*) and wolves (*Canis lupus*), Journal of Environmental Radioactivity (2014), http://dx.doi.org/10.1016/j.jenvrad.2014.02.026

ARTICLE IN PRESS

distributed at about 2500 Bq m^{-2} in 1963. Almost all ^{134}Cs ($T_{½}$ = 2.065 y) has decayed in 2010–2011, considerable amount of ^{137}Cs ($T_{½}$ = 30.2 y) still remains in the ecosystems. The dose factor (Gy per Bq of oral intake) of ^{137}Cs (gamma emitter) is far lower than that of ^{210}Po (ICRP, 1996).

^{210}Po as well as ^{137}Cs are accumulated in the food chain. Especially reindeer are known to contain enhanced concentrations of radiocaesium and also polonium in soft tissues after feeding on lichen during the winter (Lidèn and Gustafsson, 1967; Persson, 1970, 1972). Eurasian lynx (*Lynx lynx*), wolverine (*Gulo gulo*) and wolves (*Canis lupus*) are on the top of the food chain in the sub-arctic environment in Scandinavia. The major prey species for lynx is roe deer, reindeer, hare, small rodents and birds (Åhman et al., 2004; Skuterud et al., 2005a). For wolverine the main food is smaller mammals, but larger animals like reindeer can also be taken. The wolverine also eats carrion from other animal's kills (Copeland and Whitman, 2003; The Wolverine Foundation, 2012). Wolf mainly feed on moose, but also reindeer, roe deer, hare and woodland birds can be on the menu (Fuller, 1989). It is likely that anthropogenic and natural radionuclides can be accumulated in these top carnivores reflecting the mechanisms from deposition to herbs and further through the food-chain to the top. Within the EU-projects Framework for Assessment of Environmental Impact of Ionizing Radiation (FASSET, 2004; Brown et al., 2008, 2011) it is concluded that there is more need of data regarding top predators.

Here we describe activity concentrations of ^{210}Po and ^{137}Cs in these three top predators from different regions in Scandinavia. In addition, we estimated absorbed doses from ^{210}Po and ^{137}Cs.

2. Material and methods

2.1. Sampling of wolf

Samples of muscle, liver and kidney were taken from nine wolves from Sweden in 2010 and 19 in 2011. Blood samples were take from nine wolves (Fig. 1 and Table 1). The wolves were collected over a large area and the counties Dalarna, Norrbotten, Jämtland, Härjedalen, Värmland were defined as Mid Sweden and wolves from the counties Gävleborg, Västra Götaland and Örebro were defined as South Eastern Sweden. The animals from 2010 were killed by traffic accidents during the months January to March (Wolf nr 1–9) and those from 2011 were killed in January or February (Wolf nr 10–28) by licensed hunting.

The wolf samples were obtained from the National Veterinary Institute, Uppsala, Sweden after storing at −20 °C. This institute determined sex, weight and age. Ages were between 1 and 8 years, and the age of the wolves was determined by Matson's laboratory (8140 Flagler road, Milltown MT 59851, USA) by a standardized cementum aging model.

2.2. Sampling of lynx

Muscle and liver samples of lynx (N = 16) were taken from animals shot during the ordinary hunting season. The samples were taken from two different areas in Norway (Mid Norway and Southern Norway) and standardized to include four males and four females from each area, all adults (age 1–8 years) and shot in late winter between February 1st and March 19 2011 (Fig. 1 and Table 1). The Norwegian Institute for Nature Research (NINA) organized the sampling and samples were stored frozen at − 20 °C until analyses.

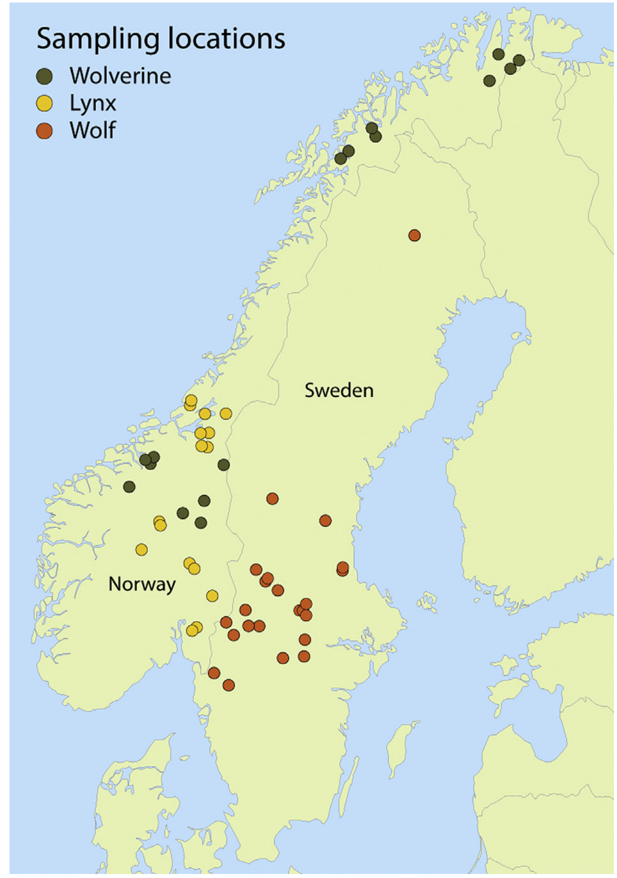

Fig. 1. Sampling location of wolverine and lynx in Norway and wolf in Sweden during the years 2010–2011.

2.3. Sampling of wolverine

Samples of muscle and liver from wolverine (N = 16) were made available from ordinary hunting, trapping or claim selection. The samples were also taken from two different areas in Norway, Mid and Northern Norway, and standardized to include four males and four females from each area. All the animals were adults, between 1 and 7 years of age and shot in late winter or early spring from February 3rd till May 20, 2011 (Fig. 1 and Table 1). The Norwegian Institute for Nature Research (NINA) organized the sampling and samples were stored frozen at − 20 °C until analyses.

2.4. Radiometric methods of ^{137}Cs

The activity concentrations of ^{137}Cs in muscle samples of lynx and wolverine were measured at Norwegian Institute for Nature Research using a Wizard 2480 (PerkinElmer) gamma counter. The ^{137}Cs analyses in different wolf organs were carried out at Lund University in Sweden. ^{137}Cs analyses for different wolf samples were measured by HpGe gamma spectrometry and NaI.

2.5. Radiometric methods of ^{210}Po and ^{210}Pb

The liver samples of lynx and wolverine were analysed in Norway by Norwegian Radiation Protection Authority. The samples were prepared by drying at 60 °C for approximately 30 h and grinding. The dry weight of liver samples as percentages of the wet weight were 32.4% ± 1.6 (SD), N = 16 and 33.2% ± 1.7 (SD), N = 16, for lynx and wolverine, respectively. The samples of wolves were

Please cite this article in press as: Gjelsvik, R., et al., Polonium-210 and Caesium-137 in lynx (*Lynx lynx*), wolverine (*Gulo gulo*) and wolves (*Canis lupus*), Journal of Environmental Radioactivity (2014), http://dx.doi.org/10.1016/j.jenvrad.2014.02.026

ARTICLE IN PRESS

Table 1
Sampling location, sex (female/male), total body weight (kg) and estimated age (years) of the lynx (*Lynx lynx*), wolverine (*Gulo gulo*) and wolves (*Canis lupus*) collected in Norway and Sweden in 2010 and 2011.

Species	Sample ID	Date of death	Region	County	Community	Sex	Weight	Age
Lynx	NO1	05.02.2011	Southern Norway	Hedmark	Ringsaker	F	15	1
Lynx	NO2	05.02.2011	Southern Norway	Hedmark	Ringsaker	F	16.5	3
Lynx	NO3	03.02.2011	Southern Norway	Hedmark	Vang	M	23	8
Lynx	NO4	18.02.2011	Southern Norway	Hedmark	Nord-Odal	M	18	1
Lynx	NO5	10.03.2011	Southern Norway	Akershus	Enebakk	M	22	1
Lynx	NO6	11.03.2011	Southern Norway	Akershus	Enebakk	F	19	2
Lynx	NO7	19.03.2011	Southern Norway	Oppland	Sel	F	14.2	4
Lynx	NO8	19.03.2011	Southern Norway	Oppland	Sel	M	19.8	1
Lynx	NO9	01.02.2011	Mid Norway	Nord-Trøndelag	Verdal	F	16.5	4
Lynx	NO10	05.02.2011	Mid Norway	Nord-Trøndelag	Mosvik	M	20.8	1
Lynx	NO11	06.02.2011	Mid Norway	Sør-Trøndelag	Åfjord	F	18.3	5
Lynx	NO12	09.02.2011	Mid Norway	Nord-Trøndelag	Stjørdal	M	22.5	1
Lynx	NO13	10.02.2011	Mid Norway	Nord-Trøndelag	Stjørdal	F	17.2	7
Lynx	NO14	20.02.2011	Mid Norway	Sør-Trøndelag	Åfjord	M	19.7	3
Lynx	NO15	06.03.2011	Mid Norway	Sør-Trøndelag	Selbu	F	16.2	1
Lynx	NO16	07.03.2011	Mid Norway	Sør-Trøndelag	Selbu	M	19.7	2
Wolverine	NO17	03.02.2011	Mid Norway	Møre og Romsdal	Surnadal	M	13.1	1
Wolverine	NO18	06.02.2011	Mid Norway	Møre og Romsdal	Rauma	M	13.5	4
Wolverine	NO19	13.02.2011	Mid Norway	Møre og Romsdal	Surnadal	M	13.5	5
Wolverine	NO20	13.02.2011	Mid Norway	Sør-Trøndelag	Tydal	M	14	6
Wolverine	NO21	15.02.2011	Mid Norway	Møre og Romsdal	Surnadal	M	13.2	1
Wolverine	NO22	28.03.2011	Mid Norway	Hedmark	Rendalen	F	11.3	7
Wolverine	NO23	06.04.2011	Mid Norway	Hedmark	Rendalen	F	10.3	4
Wolverine	NO24	05.04.2011	Mid Norway	Hedmark	Store-Elvdal	F	10.6	5
Wolverine	NO25	05.02.2011	Northern Norway	Finnmark	Tana	M	16.6	5
Wolverine	NO26	03.02.2011	Northern Norway	Finnmark	Lebesby	M	16.2	1
Wolverine	NO27	11.02.2011	Northern Norway	Finnmark	Porsanger	F	11.5	2
Wolverine	NO28	14.02.2011	Northern Norway	Troms	Lavangen	M	15.3	2
Wolverine	NO29	05.04.2011	Northern Norway	Troms	Skånland	M	14.1	3
Wolverine	NO30	03.05.2011	Northern Norway	Finnmark	Tana	F	9.8	6
Wolverine	NO31	05.04.2011	Northern Norway	Troms	Målselv	F	10.3	4
Wolverine	NO32	20.05.2011	Northern Norway	Troms	Balsfjord	F	9.2	3
Wolf	SW1	29.01.2010	Mid Sweden	Jämtland	Härjedalen	F	32.1	1
Wolf	SW2	03.02.2010	Mid Sweden	Jämtland	Härjedalen	M	34.9	1
Wolf	SW3	10.03.2010	Mid Sweden	Dalarna	Malung	M	40	0
Wolf	SW4	10.03.2010	Mid Sweden	Dalarna	Malung	M	41	1
Wolf	SW5	10.03.2010	Mid Sweden	Dalarna	Malung	F	28	0
Wolf	SW6	11.03.2010	Mid Sweden	Dalarna	Malung	F	29	0
Wolf	SW7	28.01.2010	South eastern Sweden	Örebro	Degerfors	M	48	1
Wolf	SW8	27.02.2010	Mid Sweden	Norrbotten	Gällivare	M	47	1
Wolf	SW9	19.02.2010	Mid Sweden	Jämtland	Härjedalen	F	32.6	1
Wolf	SW10	15.01.2011	South eastern Sweden	Gävleborg	Ockelbo	M	46.5	1
Wolf	SW11	15.01.2011	South eastern Sweden	Gävleborg	Ockelbo	F	34	1
Wolf	SW12	15.01.2011	Mid Sweden	Dalarna	Malung-Sälen	M	47	6
Wolf	SW13	15.01.2011	Mid Sweden	Dalarna	Ludvika	M	28	0
Wolf	SW14	15.01.2011	Mid Sweden	Dalarna	Ludvika	F	36	4
Wolf	SW15	15.01.2011	Mid Sweden	Dalarna	Vansbro	M	38	2
Wolf	SW16	15.01.2011	Mid Sweden	Dalarna	Ludvika	M		8
Wolf	SW17	16.01.2011	Mid Sweden	Dalarna	Ludvika	F	36	1
Wolf	SW18	15.01.2011	South eastern Sweden	Gävleborg	Ljusdal	M	49	6
Wolf	SW19	16.01.2011	South eastern Sweden	Västra Götaland	Mellerud	M	49.5	3
Wolf	SW20	16.01.2011	Mid Sweden	Värmland	Munkfors	F	40	1
Wolf	SW21	16.01.2011	Mid Sweden	Värmland	Sunne	M	32	0
Wolf	SW22	17.01.2011	Mid Sweden	Värmland	Eda	M	28	0
Wolf	SW23	16.01.2011	South eastern Sweden	Örebro	Örebro	F	37.5	1
Wolf	SW24	16.01.2011	Mid Sweden	Värmland	Arvika	F	38	3
Wolf	SW25	22.01.2011	South eastern Sweden	Örebro	Lindesberg	F	29	0
Wolf	SW26	24.01.2011	Mid Sweden	Värmland	Torsby	M	48	1
Wolf	SW27	26.01.2011	Mid Sweden	Värmland	Sunne	M	40	5
Wolf	SW28	05.02.2011	South eastern Sweden	Västra Götaland	Dals-Ed	F	38	5

analysed in Sweden. They were prepared at the same way as above, except from drying at 80° C. The blood samples were, however, wet ashed directly (Henricsson et al., 2011a). ^{210}Po was analysed by alpha spectrometry (ion implanted Si detectors) after wet ashing and spontaneous deposition on silver discs. ^{209}Po was used as radiochemical yield determinant (Henricsson et al., 2011a). Samples of wolves were analysed by similar methods at Lund University. In the first nine samples of wolves ^{210}Pb was also analysed. This was done by dry incineration of a larger amount of sample where Po evaporates. After waiting for about six months the build up ^{210}Po from ^{210}Pb was analysed. The ingrowth rate gives the concentration of ^{210}Pb. For all animals, the ^{210}Po and ^{137}Cs concentrations were decay corrected to date of death.

2.6. Calculation of radiation doses

The doses to the animals were calculated as μGy per year, i.e. no quality or weighting factors were applied. For ^{210}Po the calculations were straight forward with a locally absorbed energy of 5300 keV. The weight of the animals varied and the appropriate absorbed

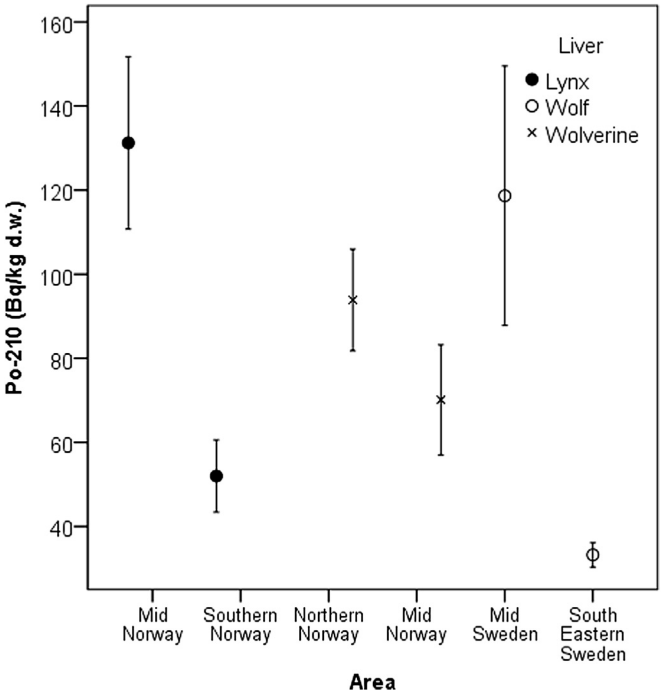

Fig. 2. ^{210}Po concentrations (Bq kg^{-1} d.w.) in liver from wolf, lynx and wolverine from different areas in Norway and Sweden. Mean (±SE) are presented.

fraction of photons were approximated as for an ellipsoid. This fraction is for example 0.28 for a weight of 30 kg for 662 keV photons from ^{137}Ba^{m}. A locally absorbed energy of 188 keV per disintegration from ^{137}Cs and a conversion factor of 0.095 for the 662 keV gamma photons (locally absorbed energy from beta radiation, conversion electrons and characteristic x-rays) were applied.

2.7. Statistical analysis

Because the type of data we here present rarely are normal distributed and often suffered by lack of homogeneity of variance we use non-parametric statistics to test for significance in variations between locations of activity concentration of ^{210}Po and ^{137}Cs in liver samples from lynx, wolverine and wolf.

We have designed our sampling to get a more general insight into the aspect of radiation doses to wild animals. We have mainly directed sampling towards animals where we expect to find the highest radiation doses (adult individuals from species at the top of the food chain, and late winter conditions). Because we have restricted information about variation in radiation doses between the sexes we have included equal number of males and females in the analyses. Sample sizes are too small to include sex as a variable in the statistical analyses. Our data are neither suited to do statistical tests for variation among species since species-pairs are not sampled from exactly the same area.

3. Results

3.1. ^{210}Po concentrations

3.1.1. Lynx

The concentrations of ^{210}Po in lynx liver samples from Mid Norway varied from 54 to 211 Bq kg^{-1} d.w. with median value of 127 Bq kg^{-1} d.w. (Fig. 2 and Table 2). Corresponding values from Southern Norway were 22–86 Bq kg^{-1} d.w. and 40 Bq kg^{-1} d.w. The median ^{210}Po concentration from Mid Norway was higher than ^{210}Po concentration in lynxes collected in Southern Norway (Mann–Whitney U test, $Z = -2.731$, $N = 16$, $P = 0.005$).

3.1.2. Wolverine

The concentrations of ^{210}Po in wolverine liver samples from Mid Norway varied within the range 16–109 Bq kg^{-1} d.w. with median

Table 2
Number of samples, median, minimum and maximum value of ^{210}Po and ^{137}Cs in different organs in lynx, wolverine and wolf in different areas in Norway and Sweden.

Nuclide	Species	Area	Sample	N	Median	Minimum	Maximum
Po-210 Bq/kg d.w.	Lynx	Mid Norway	Liver	8	127	54	211
		Southern Norway	Liver	8	40	22	86
	Wolverine	Mid Norway	Liver	8	81	16	109
		Northern Norway	Liver	8	83	61	160
	Wolf	Mid Sweden	Kidney	21	64	24	942
			Liver	20	57	20	523
			Muscle	20	2	1	43
			Blood (l^{-1})	19	6	2	54
		South Eastern Sweden	Kidney	7	37	27	48
			Liver	8	31	22	48
			Muscle	8	2	1	2
			Blood (l^{-1})	8	6	3	20
Cs-137 Bq/kg d.w.	Lynx	Mid Norway	Liver	8	487	56	13393
			Muscle	8	759	155	10260
		Southern Norway	Liver	8	148	44	437
			Muscle	8	315	125	1045
	Wolverine	Mid Norway	Liver	8	426	201	3405
			Muscle	8	833	321	4780
		Northern Norway	Liver	8	151	22	251
			Muscle	8	254	53	363
	Wolf	Mid Sweden	Kidney	21	104	31	3453
			Liver	20	118	36	996
			Muscle	20	198	70	1140
			Blood (l^{-1})	19	17	4	31
		South Eastern Sweden	Kidney	7	114	88	3200
			Liver	8	171	81	4050
			Muscle	8	252	142	8410
			Blood (l^{-1})	8	29	13	959

Please cite this article in press as: Gjelsvik, R., et al., Polonium-210 and Caesium-137 in lynx (*Lynx lynx*), wolverine (*Gulo gulo*) and wolves (*Canis lupus*), Journal of Environmental Radioactivity (2014), http://dx.doi.org/10.1016/j.jenvrad.2014.02.026

ARTICLE IN PRESS

value of 81 Bq kg^{-1} d.w. (Fig. 2 and Table 2). Corresponding values from Northern Norway were 61–160 Bq kg^{-1} d.w. and 83 Bq kg^{-1} d.w., respectively. ^{210}Po concentration in wolverine did not vary between areas (Mann–Whitney *U* test, $Z = -0.630$, $N = 16$, $P = 0.574$).

3.1.3. Wolf

The ^{210}Po concentration in liver measured in wolves from Mid Sweden varied from 20 to 523 Bq kg^{-1} d.w. with median value of 57 kg^{-1} d.w., values form South Eastern Sweden varied from 22 to 48 with median value of 31 Bq kg^{-1} d.w. (Table 2). The results included two extremely high values. The highest value of 523 Bq kg^{-1} d.w. was detected in liver sample from a young male wolf from Gällivare in Norrbotten county, northern Sweden (Table 1: wolf nr 8). The other outlier (456 Bq kg^{-1} d.w.) was detected in a young male wolf from Härjedalen in Jämtland county in Mid Sweden (Table 1: wolf nr 2). Statistical analysis showed higher concentrations of ^{210}Po in liver in wolves from Mid Sweden compared to wolf from South Eastern Sweden (Mann–Whitney *U* test, $Z = -2.188$, $N = 28$, $P = 0.028$, Table 3 and Fig. 3).

The median concentrations of ^{210}Po in kidney and muscle in wolves from Mid Sweden were 64 Bq kg^{-1} d.w. (range 24–942) and 2 Bq kg^{-1} d.w. (range 1–43) Bq kg^{-1} d.w., respectively. Corresponding values from South Eastern Sweden were 37 Bq kg^{-1} d.w. (range 27–48) and 2 Bq kg^{-1} d.w. (range 1–2). For both kidney and muscle the ^{210}Po concentrations were higher in wolves from Mid Sweden compared to South Eastern Sweden (kidney: Mann–Whitney *U* test, $Z = -1.990$, $N = 28$ $P = 0.048$, muscle: Mann–Whitney *U* test, $Z = -2.188$, $N = 28$, $P = 0.028$, Fig. 3). The median concentration in blood from Mid Sweden was 6 Bq l^{-1} (range 2–54). Corresponding values from South Eastern Sweden were 6 Bq l^{-1} (range 3–20) (Table 2).

The activity ratio ^{210}Po/^{210}Pb was generally very high, 10–60. The correction for *build up* of ^{210}Po from ^{210}Pb during sampling to analysis is then small and can be neglected which is also supposed to be the case for lynx and wolverine. Bone was not analysed and the ^{210}Po/^{210}Pb ratios is in the order of 0.3–0.9 (Kauranen et al., 1971; Thomas et al., 1994). In vivo *build up* of ^{210}Po from bone and transfer to other organs could be of importance but was not considered in this paper.

3.2. ^{137}Cs concentrations

3.2.1. Lynx

The median concentration of ^{137}Cs in lynx liver samples from Mid Norway was 487 Bq kg^{-1} d.w. (range 56–13,393) (Table 2 and Fig. 4). Corresponding value from Southern Norway was 148 Bq kg^{-1} d.w. (range 44–437). Highest values were observed in two female lynxes of four and five years from Mid Norway with approximately 13,400 Bq kg^{-1} d.w. and 1900 Bq kg^{-1} d.w. As for the fallout from Chernobyl, the ^{137}Cs activity in liver from lynx did vary a lot within both study areas and no significant differences were

Table 3
Summary of data on ^{137}Cs, ^{210}Po and ^{210}Pb in lynx, wolverine and wolf from different locations reported in other studies and this work. The values given are range, mean or median. Data from this study are in bold.

Matrix	^{137}Cs	^{210}Po	^{210}Po/^{210}Pb	N	Location, sampling period	Reference
	Bq kg^{-1} d.w.	Bq kg^{-1} d.w.				
Lynx						
Muscle	200–125000			747	Norway, 1986–2001	Skuterud et al., 2005a,b
Muscle	1000	4.9	60	3	SE Finland, 1968	Kauranen et al., 1971
Muscle	4100	6.5	110	2	Finnish Lapland, 1968	Kauranen et al.,1971
Liver		100	53	3	SE Finland, 1968	Kauranen et al.,1971
Liver		204	60	2	Finnish Lapland, 1968	Kauranen et al.,1971
Bone (w.w.)		5.9	0.92	3	SE Finland, 1968	Kauranen et al., 1971
Bone (w.w.)		8.5	0.81	2	Finnish Lapland, 1968	Kauranen et al., 1971
Muscle	49–96000			733	Sweden, 1996–2003	Åhman et al., 2004
Liver	**44–13393**	**22–211**		**16**	**Norway, 2011**	**This work**
Muscle	**125-10260**			**16**	**Norway, 2011**	**This work**
Wolverine						
Muscle	211	0.7	7	1	SE Finland, 1968	Kauranen et al., 1971
Muscle	4600–16200	10–31	91–105	8	Finnish Lapland, 1966, 1968	Kauranen et al.,1971
Liver		9.8	4.1	1	SE Finland, 1968	Kauranen et al., 1971
Liver		53–115	5.9–7.5	8	Finnish Lapland, 1966, 1968	Kauranen et al.,1971
Bone (w.w.)		5.9	0.57	1	SE Finland, 1968	Kauranen et al., 1971
Bone (w.w.)		8–17	0.71–0.89	8	Finnish Lapland, 1966, 1968	Kauranen et al.,1971
Liver	**22–3405**	**16–160**		**16**	**Norway, 2011**	**This work**
Muscle	**53–4780**			**16**	**Norway, 2011**	**This work**
Wolf						
Muscle	350	1.2	57	2	E Finland, 1968	Kauranen et al.,1971
Muscle	270–7000	1.7–7.8	30–80	2	N Finland, 1968	
Liver		6.8	22	2	E Finland, 1968	Kauranen et al.,1971
Liver		49–310	26–115	2	N Finland, 1968	
Bone (w.w.)		4.8	0.26	2	E Finland, 1968	Kauranen et al.,1971
Bone (w.w.)		4.2–25	0.29–0.70		N Finland, 1968	
Muscle		49		23	Canada, Baker Lake area, 1993	Thomas et al., 1994
Liver		1400	58	24	Canada, Baker Lake area, 1993	Thomas et al., 1994
Kidney			56	24	Canada, Baker Lake area, 1993	Thomas et al., 1994
Bone (w.w.)		29	0.29	24	Canada, Baker Lake area, 1993	Thomas et al., 1994
Muscle		29		23	Canada, Snowdrift area 1993	Thomas et al., 1994
Liver		551	30	23	Canada, Snowdrift area 1993	Thomas et al., 1994
Kidney		539	28	23	Canada, Snowdrift area 1993	Thomas et al., 1994
Bone (w.w.)		20	0.6	22	Canada, Snowdrift area 1993	Thomas et al., 1994
Blood (l^{-1})		17	19	23	Canada, Snowdrift area 1993	Thomas et al., 1994
Muscle	**70–8410**	**1–43**	**(2–77)**	**28 (9)**	**Sweden, 2010–2011**	**This work**
Liver	**36–4050**	**20–523**	**(9.4–56)**	**28 (9)**	**Sweden, 2010–2011**	**This work**
Kidney	**31–3453**	**24–942**		**28**	**Sweden, 2010–2011**	**This work**
Blood (l^{-1})	**4–959**	**2–54**	**(2.3–54)**	**27 (9)**	**Sweden, 2010–2011**	**This work**

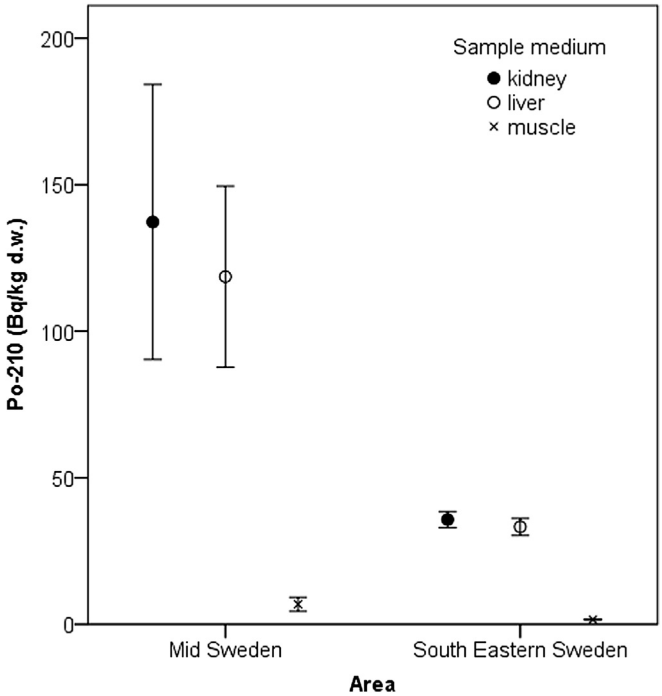

Fig. 3. ^{210}Po (Bq kg^{-1} d.w.) in kidney, liver and muscle samples of wolves from to areas in Sweden. Mean (±SE) are presented.

found between the two areas (Mann–Whitney *U* test, $Z = -1.629$, $N = 16$, $P = 0.105$). The median concentration of ^{137}Cs in lynx muscle samples from Mid Norway was 759 Bq kg^{-1} d.w. (range 155–10,260) (Table 2). No differences in ^{137}Cs concentration in muscle samples were found between the areas ((Mann–Whitney *U* test, $Z = -1.680$, $N = 16$, $P = 0.105$) Corresponding values from Southern Norway were 315 Bq kg^{-1} d.w. (range 125–1045).

3.2.2. Wolverine

The median concentration of ^{137}Cs in wolverine liver samples from Mid Norway was 426 Bq kg^{-1} d.w. (range 201–3405) (Table 2, Fig. 4). Corresponding values from Northern Norway were 151 Bq kg^{-1} d.w. (range 22–251). Mid Norway was one of the areas in Norway most affected by the radioactive fallout from the Chernobyl accident, while northern parts of Norway only got a small amount of radiocaesium fallout from this accident. The high ^{137}Cs activities of 3405 Bq kg^{-1} d.w. and 1148 Bq kg^{-1} d.w. were observed in the liver from two female wolverines from Hedmark county in Mid Norway. Not surprisingly, the ^{137}Cs concentration in wolverine liver differed significantly between the two investigated areas (Mann–Whitney *U* test, $Z = -3.151$, $N = 16$, $P = 0.001$, Fig. 4). The mean concentration of ^{137}Cs in wolverine muscle samples from Northern Norway was 833 Bq kg^{-1} d.w. (range 321–4780). Corresponding value from Northern Norway was 254 Bq kg^{-1} d.w. (range 53–363). The areas differed significantly (Mann–Whitney *U* test, $Z = -3.515$, $N = 16$, $P = 0.001$ Fig. 5, Table 2).

3.2.3. Wolf

Median activity concentration of ^{137}Cs in wolf liver samples from Mid Sweden was 118 Bq kg^{-1} d.w. (range 36–996). Corresponding value from South Eastern Sweden was 171 Bq kg^{-1} d.w. (range 81–4050) (Table 2, Figs. 5, Figure 6).

Median concentrations of ^{137}Cs in kidney, muscle and blood samples of wolf from Mid Sweden were 104 Bq kg^{-1} d.w. (range 31–3453), 198 Bq kg^{-1} d.w. (range 70–1140) and 17 Bq kg^{-1} d.w. (range 4–31), respectively. Corresponding values from South Eastern Sweden were 114 Bq kg^{-1} d.w. (range 88–3200), 252 Bq kg^{-1} d.w. (range 142–8410) and 29 Bq kg^{-1} d.w. (range 13–959), respectively (Table 2). The concentrations in liver, muscle and kidney varied a lot, and surprisingly no significant differences were found between the two areas (liver: Mann–Whitney *U* test, $Z = -1.628$, $N = 28$, $P = 0.110$, kidney: $Z = -1.035$, $N = 28$, $P = 0.321$, muscle: $Z = -1.628$, $N = 28$, $P = 0.110$, Fig. 6, and Table 2).

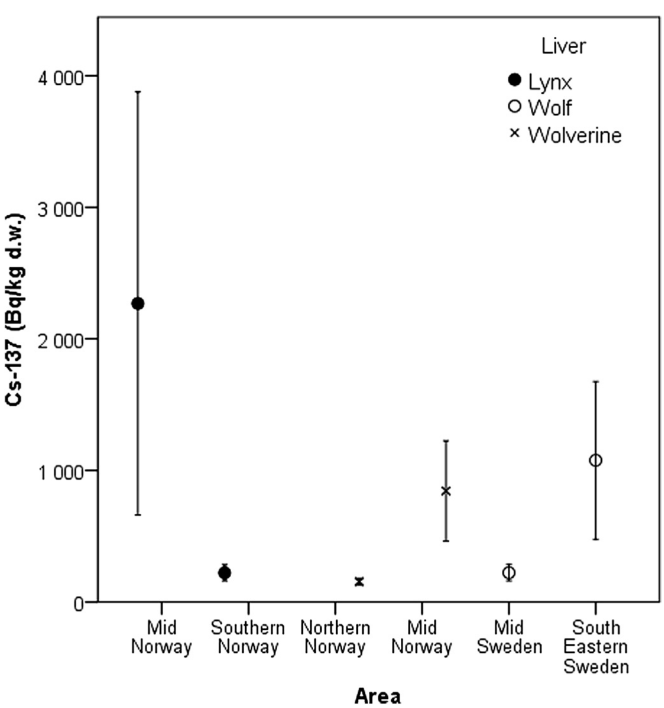

Fig. 4. ^{137}Cs concentrations (Bq kg^{-1} d.w.) in liver from wolf, lynx and wolverine from different areas in Norway and Sweden. Mean (±SE) are presented.

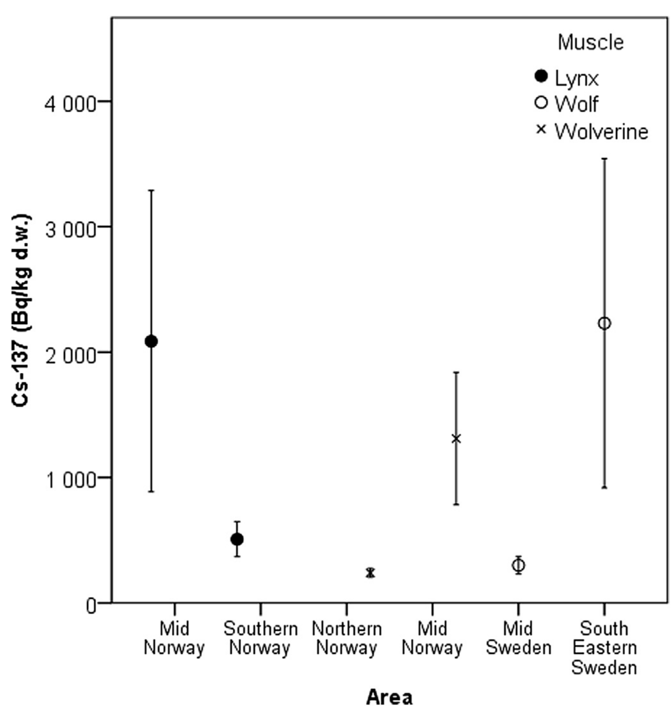

Fig. 5. ^{137}Cs concentrations (Bq kg^{-1} d.w.) in muscle from wolf, lynx and wolverine from different areas in Norway and Sweden. Mean (±SE) are presented.

ARTICLE IN PRESS

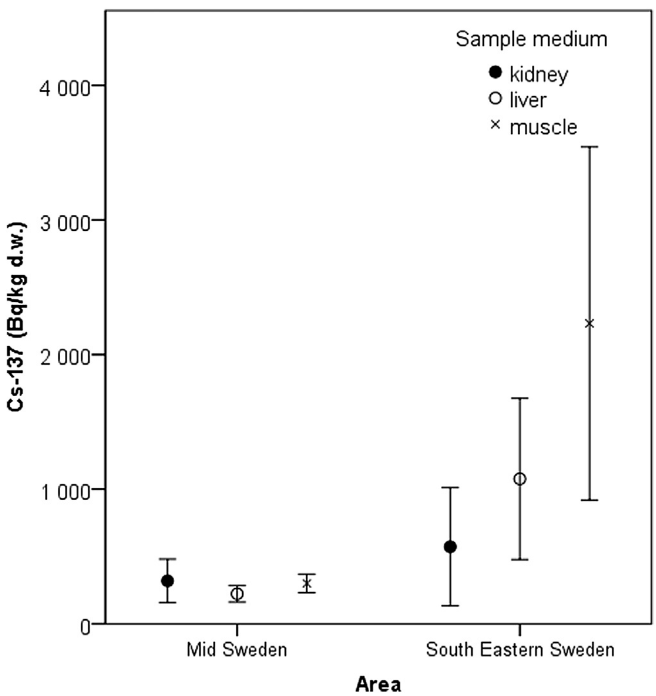

Fig. 6. ^{137}Cs concentrations (Bq kg^{-1} d.w.) in kidney, liver and muscle samples of wolves from to areas in Sweden Mean (±SE) are presented.

3.3. Radiation doses

Regarding ^{137}Cs, the concentrations are quite similar in different organs and the dose to muscle containing the major mass of the body was calculated. Annually estimated doses from ^{137}Cs to wolf, lynx and wolverine were 3300 μGy y^{-1}, 1500 μGy y^{-1} and 3600 μGy y^{-1}. The large spread in the data is due to the distribution of ^{137}Cs from the Chernobyl accident. The annual estimated doses from 210Po to lynx, wolverine and wolf are 1400 μGy y^{-1},1000 μGy y^{-1}, and 3400 μGy y^{-1}. The doses were estimated from concentrations of ^{137}Cs and ^{210}Po in muscle, liver and kidney samples (Table 4).

We do not know the biological residence time of polonium and caesium for these animals but are probably shorter than that for man, 50 days and 70 days respectively and there will be a significant seasonal variation in the body burdens (IAEA, to be published). The doses based on data from only January and February might then be over estimated.

4. Discussion

4.1. ^{210}Po

The annual deposition of ^{210}Pb in central Sweden is around 55 Bq m^{-2} (Persson, 1970, 1972). The integrated activity of ^{210}Pb, supposing the same amount is decaying as is introduced by precipitation, gives 2000 Bq m^{-2}. ^{210}Po has a distribution depending on the surrounding land mass and wet deposition. The activity ratio ^{210}Po/^{210}Pb in Scandinavian precipitation is around 0.1–0.2. The integrated deposition of ^{210}Po is then slightly lower for ^{210}Po than for ^{210}Pb since it takes about 2 years for ^{210}Po to come into radioactive equilibrium with ^{210}Pb. The mean activity concentration of ^{210}Pb in caribou muscle during 1998–2000 in Alaska was 4.8 Bq kg^{-1} w.w. and 0.2 Bq kg^{-1} w.w. in Muskoxen muscle (Hong et al., 2011). We found the levels of ^{210}Po in liver and kidney to be approximately twice the levels of ^{210}Po in muscle. Food is the major source of raising the levels of ^{210}Po. For ^{210}Po there is also *in vivo* build up from ^{210}Pb. Reindeer have enhanced levels of ^{210}Po especially after winter due to consumption of lichen (Skuterud et al., 2005a).

The bio-kinetics of polonium in the body is rather complicated. The fractional uptake by man has been reported from 0.1 to 0.8. The biological residence time has been reported to be between 20 and 80 days (Henricsson et al., 2011b). Thomas et al. (1994) have studied the transfer of ^{210}Po and ^{210}Pb through the lichen-caribou-wolf food chain of northern Canada where caribou was the main food item for the wolves. Their results are in good agreement with our data. Thomas et al. (1994), reported ^{210}Po/^{210}Pb activity ratios of 30–56 for liver and kidney. Fuller (1989) estimated that the average daily intake was 2.7 kg per day when eating caribou and 5.4 kg per day when eating moose. Howard et al. (1991) estimated the transfer coefficient F_f (d kg^{-1}) of ^{210}Po from caribou to wolves as the ratio of activity concentration in the muscle of wolf (Bq kg^{-1} w.w.) divided by the daily amount intake of caribou meat (kg w.w. d^{-1}) with the activity concentration of ^{210}Po in the quantity Bq kg^{-1} w.w. which gave a value of 0.089 d kg^{-1} w.w.

The wolves were considered to eat 2.7 kg w.w. of reindeer per day. The wet weight to dry weight ratio for soft tissue was 3.8. If we use the same coefficient for our wolves the food would contain between 8 and 170 Bq kg^{-1} d.w. The caribou from Canada contained 57–64 kq kg^{-1} d.w. (Thomas et al., 1994). In moose from Finland sampled in March the concentrations were 25 Bq kg^{-1} d.w. and in reindeer 45 Bq kg^{-1} d.w. (Kauranen et al., 1971). Thomas et al. (1994) estimated the consumption of moose to be higher, 5.4 kg^{-1} w.w. d^{-1} if the wolves mainly consumed moose. Kauranen et al. (1971) observed lower concentrations in wolves, lynx and wolverine in southern Finland compared to northern Finland. Regarding ^{210}Po, the concentrations of wolves from Sweden are significantly higher in the Mid Sweden (including the counties Jämtland, Dalarna and Norrbotten) where reindeer is present. The same pattern was found for lynx from Mid Norway compared to Southern Norway. The differences are mostly due to different diet, from reindeer in Mid Norway to mainly roe deer in Southern Norway.

4.2. ^{137}Cs

Due to the Chernobyl accident approximately 4.25 PBq of ^{137}Cs was deposited over Sweden (Edvarson, 1991). The deposition of ^{137}Cs ranged from 2000 to 100000 Bq m^{-2} with highest levels in central parts of Sweden (Persson et al., 1987). In Norway, the accident caused a total deposition of ^{137}Cs of 2300 ± 200 TBq. Like Sweden, Mid and central parts of Norway was most affected with some places receiving more than 20 kBq m^{-2} (Bache et al., 1987).

During the wintertime lichen is the main diet for the reindeer and enhanced levels of ^{137}Cs in reindeer in observed this part of the year (Skuterud et al., 2005b). Our data of ^{137}Cs in lynx, wolverine, and wolf shows higher concentrations in areas with the largest impact from the Chernobyl accident. Concentrations of ^{137}Cs are highest in the muscle tissue, twice as much as in kidney and liver, and ten times the concentration in blood. Large predators like the

Table 4
Estimated doses from ^{137}Cs and ^{210}Po in wolf, lynx and wolverine, μGy y^{-1}.

	^{137}Cs	^{210}Po	^{210}Po	^{210}Po
Wolf	46–5600 (muscle)	170–500 (liver)	160–8100 (kidney)	9–350 (muscle)
Lynx	26–7900 (liver)	190–1800 (liver)		
Wolverine	13–2000 (liver)	146–1380 (liver)		

ARTICLE IN PRESS

wolves, lynx and the wolverine are covering large areas and distances for finding prey and my influence the ^{137}Cs levels in prey influencing the transfer factor. Wild and domestic reindeer are mainly in Mid Norway and Mid Sweden, and rather high concentrations of ^{137}Cs are found in lynx and wolverines from Mid Norway and wolf from Mid Sweden.

The activity ratio ^{210}Po/^{137}Cs in wolf liver ranges from 0.011 to 4.0, in muscle from 0.002 to 0.05 and in kidney from 0.012 to 2.1. This shows the much larger accumulation in liver and kidney relative to ^{137}Cs. The large spread in the data is due to the impact of ^{137}Cs in different areas.

4.3. Doses from ^{137}Cs and ^{210}Po

The biological half-time of caesium in the human body is about 70 days but is supposed to be shorter for wolves both for caesium and polonium. Under an equilibrium situation doses can be calculated even if the biological half-time is not known but this is not possible under a dynamic situation. We suppose a stable condition and 35 days half-life. The maximal dose from ^{137}Cs to a wolf would be 3000 μGy per year using decay data and escape factors of 662 keV from ^{137}Ba. The maximal dose from ^{210}Po to liver would be 2600 μGy per year.

Concentrations of ^{137}Cs and ^{210}Po in different organs of top predators are reported in only a few other studies (Table 3). Very few data as for wolves can be found in the literature. As for wolves there is a large variation in concentrations of ^{137}Cs with a factor of 30 but also with a factor of 10 for ^{210}Po. This shows that diet is important in additional to the contamination from the Chernobyl fallout. The maximal doses from ^{137}Cs are estimated to 3300 per year for lynx and 1500 μGy per year for wolverine. The corresponding doses for ^{210}Po for lynx and wolverine are 1400 μGy and 1000 μGy per year, respectively. For wolf the maximum doses from ^{137}Cs are 3600 μGy per year to muscle, and 3400 μGy per year to liver from ^{210}Po.

Acknowledgements

We thank the Swedish Radiation Protection Authority, SSM, for financial support to the study of wolves. We also like to thank Fredrik Henricsson for compilation of the wolf data and for laboratory work. I addition we are grateful for administration of the financial support taken care of by Christer Samuelsson. The work of lynx and wolverine was financed by the Ministry of the environment as a part of the Program for the Monitoring of Radioactive Pollution in Norwegian Terrestrial and Freshwater System. The authors wish to thank the Norwegian Institute for nature research for getting samples of lynx and wolverine in Norway.

References

Åhman, B., Wright, S.M., Howard, B.J., 2004. Radiocaesium in lynx in relation to ground deposition and diet. Radiat. Environ. Biophys. 43, 119–126.

Bache, S., Bjerke, H., Rudjord, A.L., Ugletveit, F., 1987. Fall-out patters in Norway after the Chernobyl accident estimated from soil samples. Radiat. Prot. Dosimetry. 18, 105–107.

Brown, J.E., Alfonso, B., Avila, R., Beresford, N.A., Copplesstone, D., Pröhl, G., Ulanovsky, A., 2008. The ERICA tool. J. Environ. Radioact. 99, 1371–1383.

Brown, J., Gjelsvik, R., Roos, P., Kålås, J.A., Outola, I., Holm, E., 2011. Levels and transfer of ^{210}Po and ^{210}Pb in Nordic terrestrial ecosystems. J. Environ. Radioact. 102 (5), 430–437.

Copeland, J.P., Whitman, J.S., 2003. Chapter 32: Wolverine. In: Feldhamer, G.A., Thompson, B.C., Chapman, J.A. (Eds.), Wild Mammals of North America Biology, Management, and Conservation, second ed. The Johns Hopkins University Press, Baltimore and London, pp. 672–682.

Edvarson, K., 1991. Fallout over Sweden from the Chernobyl accident. In: Moberg, L. (Ed.), The Chernobyl Fallout in Sweden. The Swedish Radiation Protection Institute, Stockholm, Sweden, pp. 47–65.

FASSET, May 2004. Framework for assessment of environmental impact – technical annexes. In: EC 5th Framework programme, Contract FIGE-CT-2000–00102. Swedish Radiation Protection Agency, Stockholm, Sweden. Final report.

Fuller, T.K., 1989. Population dynamics of wolves in north-central Minnesota. Wildl. Monogr. 105, 1–41.

Henricsson, F., Ranebo, Y., Holm, E., Roos, P., 2011a. Aspects on the analysis of ^{210}Po. J. Environ. Radioact. 80, 415–419.

Henricsson, C.F., Ranebo, Y., Rääf, C.L., Hansson, M., Holm, E., 2011b. A biokinetic study of ^{209}Po in man. Sci. Total Environ. 437, 384–389.

Hong, G.H., Baskaran, M., Molarroni, S.M., Lee, H.-M., Burger, J., 2011. Anthropogenic and natural radionuclides in Caribou and Muskoxen in the western Alaskan Arctic and marine fish in the Aleutian Islands in the first half of 2000s. Sci. Total Environ. 409, 3638–3648.

Howard, B., Beresford, N.A., Hove, K., 1991. Transfer of radiocaesium to ruminants in natural and semi-natural ecosystems and appropriate countermeasures. Health Phys. 61, 715–725.

IAEA, to be published. The Environmental Behaviour of Polonium, Under preparation for publishing in Technical Report Series.

ICRP 72, 1996. Age Dependent Doses to the Members of Public from Intake of Radionuclides. Part 5 Compilation of Ingestion and Inhalation Coefficients.

Kauranen, P., Miettinen, J.K., Pullianinen, 1971. Polonium-210 and lead-210 in some terrestrial animals in Finland. Annu. Zool. Fenn. 8, 318–323.

Lidèn, K., Gustafsson, M., 1967. Relationship and seasonal variation of Cs-137 in lichen, reindeer and man in Northern Sweden 1961–1965. In: Åberg and Hungate Proc. (Ed.), Radioecological Concentration Processes. Pergamon press, pp. 193–208. Int Symp. Stockholm Sweden, 1966.

Persson, R.B.R., 1970. ^{55}Fe, ^{90}Sr, ^{134}Cs, ^{137}Cs, and ^{210}Po in the Biosphere: Radiological Health Aspects of the Environmental Contamination from Radioactive Materials in Northern Sweden. Medical Radiation Physics, Lund University, Lund, Sweden. PhD thesis.

Persson, R.B.R., 1972. Lead-210, Polonium-210, and stable lead in the food-chain lichen reindeer and man. In: Adams, J.A.S., Lowder, W.M., Gesell, T.F. (Eds.). The Natural Radiation Environment II. Rice University, Houston, Texas, USA, pp. 347–367.

Persson, C., Rhode, H., de Geer, L.E., 1987. The Chernobyl accident. A methodological analysis of how radionuclides reached and were deposited in Sweden. AMBIO 16, 20–31.

Skuterud, L., Gwynn, J.P., Gaare, E., Steinnes, E., Hove, K., 2005a. (90)Sr, (210)Po and 210(Pb) in lichen and reindeer in Norway. J. Environ. Radioact. 84 (3), 441–456.

Skuterud, L., Gaare, E., Kvam, T., Hove, K., Steinnes, E., 2005b. Concentrations of ^{137}Cs in lynx (*Lynx lynx*) in relation to prey choice. J. Environ. Radioact. 80, 125–138.

The Wolverine Foundation, 2012. Food Habit. http://wolvwerine.foundation.org.

Thomas, P.A., Sheard, J.W., Swanson, S., 1994. Transfer of ^{210}Po and ^{210}Pb through the lichen-caribou-wolf food chain of northern Canada. Health Phys. 66 (6), 666–677.

UNSCEAR, 2008. Sources and effects of ionizing radiation. In: United Nations Scientific Committee on the Effects of Atomic Radiation, vol. I. Report to the General Assembly with Scientific Annexes.

Please cite this article in press as: Gjelsvik, R., et al., Polonium-210 and Caesium-137 in lynx (*Lynx lynx*), wolverine (*Gulo gulo*) and wolves (*Canis lupus*), Journal of Environmental Radioactivity (2014), http://dx.doi.org/10.1016/j.jenvrad.2014.02.026