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Radioecological modelling of Polonium-210 and Caesium-137 in lichen-reindeer-man and top predators

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ABSTRACT

This work deals with analysis and modelling of the radionuclides ^{210}Pb and^{210}Po in the food-chain lichen-reindeer-man in addition to ^{210}Po and ^{137}Cs in top predators. By using the methods of *Partial Least Square Regression* (PLSR) the atmospheric deposition of ^{210}Pb and ^{210}Po is predicted at the sample locations. Dynamic modelling of the activity concentration with differential equations is fitted to the sample data. Reindeer lichen consumption, gastrointestinal absorption, organ distribution and elimination is derived from information in the literature. Dynamic modelling of transfer of ^{210}Pb and ^{210}Po to reindeer meat, liver and bone from lichen consumption, fitted well with data from Sweden and Finland from 1966 to 1971. The activity concentration of ^{210}Pb in the skeleton in man is modelled by using the results of studying the kinetics of lead in skeleton and blood in lead-workers after end of occupational exposure. The result of modelling ^{210}Pb and ^{210}Po activity in skeleton matched well with concentrations of ^{210}Pb and ^{210}Po in teeth from reindeer-breeders and autopsy bone samples in Finland.

The results of ^{210}Po and ^{137}Cs in different tissues of wolf, wolverine and lynx previously published, are analysed with multivariate data processing methods such as *Principal Component Analysis* PCA, and modelled with the method of *Projection to Latent Structures*, PLS, or *Partial Least Square Regression* PLSR.

1. Introduction

Radioecology deals with the study of pathways of radionuclides released into the environment. The endpoint is the estimation of the radiation absorbed dose and the risk of detrimental effects on various species including man. If the source is unknown, the first step is usually to collect samples at different steps on the path in question, and usually separate aquatic and terrestrial ecosystems. This presentation deals with terrestrial radioecology.

Radioecological investigations usually study the radioactivity in various samples in relation to the latitude and longitude co-ordinates as well as the time of sampling occasion. It is also important to record the fresh to dry weight ratio of the various samples, and other parameters of importance for analysing and modelling of the radioecological pathways.

The lichen-reindeer-man food chain is used as an example for dynamic modelling of radioecological concentration processes due to atmospheric fallout of ^{210}Pb and ^{210}Po.

The mathematical description of the lichen-reindeer-man pathway (L-Rd-M) in this food chain is represented by a system of linear differential equations, one for each step in the food chain (i), describing the difference between input from the previous compartment (i-1) and the elimination from (i) by the following equation (Eq. (1)):

$$dA_i/dt = \mathscr{F}(A_{i-1})[input] - A_i[output] \quad (1)$$

where $\mathscr{F}$ is the activity input function [Bq. kg^{-1}. a^{-1}] in the previous compartment A_{i-1}

Sample data of ^{210}Po and ^{137}Cs in top predators were analysed and modelled by using multivariate data processing methods such as *Principal Component Analysis* (PCA), and modelling with the method of *Projection to Latent Structures*, (PLS) or *Partial Least Square Regression* (PLSR). The method of *Partial least squares* (PLS)

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was introduced by Herman Wold (1982). His son Svante Wold, who was a chemist developed the method to be used in chemometrics, and according to him, the correct name of the method should be: *Projection to Latent Structures* (Wold et al., 1996, 2001). *Partial least square regression* modelling (PLSR) has been used in a previous work to predict missing concentration data of ^{7}Be, ^{210}Pb and ^{210}Po, at locations where only deposition values are available, and vice versa. (Persson, 2016; Persson and Holm, 2014).

Big predators like lynx, wolverine, and wolf, take up ^{210}Po and ^{137}Cs from different prey species (Gjelsvik et al., 2014, 2016). These natural and artificial radionuclides are distributed differently in muscle, liver, kidney and blood. Concentrations of ^{210}Po are higher for liver and kidney than muscle and blood. An opposite pattern is found for ^{137}Cs in muscle, with high levels in the muscle.

2. Methods and models

2.1. Lichen “L” model

The activity concentration “ACL(t)” in the top-layer of lichen “L” that is grazed by the reindeer is described by the equation:

$$\frac{dACL(t)}{dt} = DR(t)\cdot P_{SB}\cdot IF - ACL(t)\cdot(kL + \lambda);\ \left[\mathrm{Bq.\ kg_{dw}^{-1}.\ a^{-1}}\right] \tag{2}$$

where

ACL(t) is the radionuclide activity concentration in lichen at time t after deposition (Bq.kgdw^{-1})
DR (t) is the annual rate of radionuclide deposition (Bq.m^{-2}.a^{-1}); Table 1.
P_{SB} is the standing biomass density ($\mathrm{kg_{dw}^{-1}\cdot m^2}$) i.e.: Ratio of vegetation surface standing above soil to dry mass of vegetation: $P_{SB} = 0.63$ ($\mathrm{kg_{dw}^{-1}\cdot m^2}$) for lichen
IF is the *Interception fraction*, defined as the ratio of the activity retained by the vegetation A_R [Bq.m^{-2}] standing above soil to the total activity deposited A_D [Bq.m^{-2}]: IF = 1 for lichen
kL is the elimination rate constant from lichen
λ is the physical decay constant of the radionuclide in question

2.2. Reindeer “Rd” model

The model used for predicting the activity concentration “ACO(t)” in a specific organ O of a living reindeer is the annual activity concentration change in the organ O in question of the reindeer described by the following equation:

$$\frac{dACO(t)}{dt} = \mathrm{RdIL}\cdot\mathrm{ACL}(t)\cdot GIA\cdot\mathrm{ODF}\cdot BO - \mathrm{ACO}(t)\cdot(kO + \lambda) \tag{3}$$

$(\mathrm{kg_{dw}.a^{-1}.kg_{bw}^{-1}})\bullet(\mathrm{Bq.kg_{dw}^{-1}})\bullet(\mathrm{kg_{bw}\ kg_{fw}^{-1}}) -$
$(\mathrm{Bq.kg_{dw}^{-1}})\bullet(\mathrm{a^{-1}}) = [\mathrm{Bq.kg_{fw}^{-1}\cdot a^{-1}}]$

where

RdIL is the reindeer (Rd) intake rate of lichen (L) $\mathrm{kg_{dw}}$, per bodyweight ($\mathrm{kg_{dw}.a^{-1}.kg_{bw}^{-1}}$)
ACL is the activity concentration in lichen($\mathrm{Bq\cdot kg_{dw}^{-1}}$)

Thus, the rate of consumed radioactivity is RdIL•ACL ($\mathrm{Bq.a^{-1}.kg_{bw}^{-1}}$)

GIA is the gastrointestinal absorption
ODF is the fraction of absorbed activity that is distributed to the tissue or organ O
BO is the conversion factor to activity concentration in the organ in question ($\mathrm{kg_{bw}.kg_{fw}^{-1}}$)
kO is the biological elimination rate constant of the activity from the organ
λ is the radioactivity decay constant of the radionuclide in question

2.3. The activity of ingrown ^{210}Po

The model for predicting the activity concentration of ^{210}Po “ACOPo(t)” in the fresh reindeer organ O takes into account the ingrowth of ^{210}Po from ^{210}Pb also present in the organ. This is expressed in equations (4) and (5):

$$[ACOPo(t)] = \frac{\lambda_{P0}}{(\lambda_{Po} - \lambda_{Pb})}[ACOPb_0]\cdot\left(e^{-\lambda_{Pb}*t}\right) = 1.02[ACOPb(t)] \tag{4}$$

$$\frac{dACOPo(t)}{dt} = \mathrm{RdIL}\cdot\mathrm{ACL}(t)\cdot GIA\cdot\mathrm{ODF}\cdot BO + \lambda_{Po}\cdot 1.02\cdot ACOPb(t) - (kO + \lambda_{Po})\cdot[ACOPo(t)] \tag{5}$$

where

ACOPo(t) is the ^{210}Po activity concentration in organ O at time t (Bq.kgdw^{-1})
ACOPb(t) is the ^{210}Pb activity concentration in organ O at time t (Bq.kgdw^{-1})

2.4. Human “M” model

The annual activity concentration change in the organ O in question of the reindeer herders consuming reindeer meat is described by the following equation:

$$\frac{dACM(t)}{dt} = \mathrm{MIRdm}\cdot\mathrm{ACRdm}(t)\cdot GIA\cdot\mathrm{ODF}\cdot BO - ACO(t)\cdot(kO + \lambda) \tag{6}$$

Table 1
Annual precipitation data and predicted value of annual deposition-rate “DR(t) of ^{210}Pb and ^{210}Po as well as the predicted and measured activity concentrations in lichen at the sampling station Lake Rogen in Sweden.

Year	Rain	^{210}Pb	^{210}Po	^{210}Pb-Predicted	^{210}Pb-Sample
	mm	Bq.m^{-2}.a^{-1}	Bq.m^{-2}.a^{-1}	$\mathrm{Bq.kg_{dw}^{-1}}$	$\mathrm{Bq.kg_{dw}^{-1}}$
1961	590	164	115	255	237
1962	567	162	113	255	244
1963	595	165	116	252	237
1964	640	168	118	256	244
1965	610	166	116	261	237
1966	650	169	118	257	289
1967	755	178	125	263	266
1968	456	153	107	276	289
1969	460	153	107	236	189
1970	560	162	113	238	241
1971	395	148	104	238	–
1972	565	162	113	251	229
Average	570	163	114	253	246
SD	93	8	5	11	27

$(kg_{fw}.a^{-1}.kg_{bw}^{-1})\bullet(Bq.kg_{fw}^{-1})\bullet(kg_{bw}.kg_{fw}^{-1})$ - $(Bq.kg_{fw}^{-1})\bullet(a^{-1})$;

The intake rate of reindeer meat per bodyweight of reindeer herders is MIRdm ($kg_{dw}a^{-1}$ kg_{bw}^{-1}), and the activity concentration in fresh reindeer meat is ACRdm ($Bq.kg_{fw}^{-1}$). Thus, the rate of consumed radioactivity is *M*IRdm•ACRdm ($kg_{fw}a^{-1}.kg_{bw}^{-1}$). The gastrointestinal absorption is GIA, and the fraction of absorbed activity that is distributed to the tissue or organ O is ODF. The conversion to activity concentration in the organ in question is made by the factor BO (kg_{bw} kg_{fw}^{-1}). The elimination of the activity from the organ depends on the radioactivity decay constant of the radionuclide in question λ and the biological elimination rate from organ O, that is kO.

3. Results and discussions

3.1. Atmospheric deposition input to lichen

Atmospheric deposition of ^{210}Pb and ^{210}Po in surface air from exploration of radioactivity from the Arctic to the Antarctic during 1980–1996 are compiled together with the results reported by other authors (Persson, 2016; Persson and Holm, 2014). Partial least square regression modelling (PLS-regression), predicts missing ^{210}Pb and ^{210}Po values of air concentration or annual deposition (XLSTAT, 2015).

The total rate of ^{210}Pb deposition, R(^{210}Pb), was estimated to 12.5 ± 0.7 mm s^{-1} with no significant variation with latitude, height, or average of interval of sampling date. But, R(^{210}Pb) varied significantly with longitude (Long.): R(^{210}Pb) = 11.9 ± 0.7 + 0.015 ± 0.009 × Long.

In order to find an equation to predict the deposition of ^{210}Pb from rainfall reported data of correlated annual rainfall and deposition, ^{210}Pb was modelled with *Projection to Latent Structures*, PLS-regression (Persson, 2016):

$$DR(^{210}Pb) = 70.7 + 0.032 \times Height + 0.205 \times Lat. + 0.601 \times Long. + 0.0829 \times Rain\ (Bq.m^{-2}.a^{-1}) \quad (7)$$

This equation was used to predict the deposition of ^{210}Pb at the sampling station Lake Rogen (62.3°N,12.4°E, altitude 758 m), from reported annual precipitation data at Myskelåsen 12 km NE of the sampling station and the results are displayed in Table 1.

The latitudinal and longitudinal distribution of the $^{210}Po/^{210}Pb$ activity ratio was modelled by PLS-regression analysis of the values recorded at the Swedish Polar Research expeditions (Persson and Holm, 2014). The PLS-regression modelling of the $^{210}Po/^{210}Pb$ activity ratio with latitudes and longitudes resulted in following equation:

$$^{210}Po/^{210}Pb = 0.542 + 1.13\cdot10^{-3} \times (Lat.) + 2.85\cdot10^{-3} \times (Long.) \quad (8)$$

By using equation (7), the air concentrations and deposition values are estimated from reported ^{210}Pb values of either air concentration or annual deposition. The $^{210}Po/^{210}Pb$ activity ratio of the atmospheric deposition for the Rogen area (62.3°N, 12.4°E) estimated by equation (8) is about 0.7 and the results of ^{210}Po deposition rate are displayed in Table 1.

Activity concentration of ^{210}Pb and ^{210}Po in lichen "L" in the top-layer of lichen "L" of ^{210}Pb and ^{210}Po was modelled by using Eq. (2) with values of DR(t) from Table 1, and the standing biomass density P_{Sb} = 0.63 ($kg_{dw}^{-1}\cdot m^2$), the *Interception fraction* IF = 1, elimination rate constants kL = 0.3 a^{-1} and λ = 0.031 a^{-1}. The results of predicted and measured values of ^{210}Pb activity concentration ($Bq.kg_{dw}^{-1}$) are displayed in in Table 1. These values agree quite well with ^{210}Pb average activity concentration of 263 ± 42 $Bq.kg_{dw}^{-1}$ in lichen samples collected in Finland (Kauranen and Miettinen, 1969).

The $^{210}Po/^{210}Pb$ activity ratio in lichens is typically close one as ^{210}Po approaches secular equilibrium with ^{210}Pb. Reported values of the activity concentrations of both ^{210}Po and ^{210}Pb in lichens in the Cladoniaceae family varies between 110 and 430 $Bq.kg_{d.w.}^{-1}$ with an average of about 250 $Bq.kg_{d.w.}^{-1}$ (Persson, 1970, 1972; Persson et al., 1974).

3.2. Uptake and distribution in reindeer

The average value of ^{210}Pb in fresh reindeer meat in central Sweden and northern Scandinavia varies between 250 and 600 $mBq.kg_{f.w.}^{-1}$, with an average of 360 ± 50 $mBq.kg_{f.w.}^{-1}$ (Kauranen and Miettinen, 1969; Kauranen et al., 1971; Persson, 1972, 1970, 1974; Skuterud et al., 2005). The average value of ^{210}Po in fresh reindeer meat in central Sweden and northern Scandinavia varies between 2.8 and 13.3 $Bq.kg_{f.w.}^{-1}$ with an average of about 9 $Bq.kg_{f.w.}^{-1}$ (Kauranen and Miettinen, 1969; Kauranen et al., 1971; Persson, 1972, 1970, 1974; Skuterud et al., 2005).

The activity concentration "ACRM(t)" **of ^{210}Pb and ^{210}Po in Reindeer meat in Rogen area** is modelled with equation (3), using the parameters given in Table 2. The mean consumption rate of lichen for 11 reindeer was estimated to be 1.42 ± 0.08 $kg.day^{-1}$ of dry lichen or 16.4 ± 0.55 $g.day^{-1}$ per kg body weight (Holleman et al., 1979). Assuming lichen feeding only half of the year and a body weight of 80 kg, the annual consumption is estimated to 3 $kg_{dw}.a^{-1}.kg_{bw}^{-1}$.

The result of activity concentration of ^{210}Pb in reindeer meat modelled by using values of the various parameters in Table 2, and the annual activity concentration of lichen is displayed in Table 1 varying between 242 and 264 $Bq.kg_{dw}^{-1}$. The result of modelling the activity concentration of ^{210}Pb was about 800 $mBq.kg_{fw}^{-1}$, while the values of ^{210}Pb in samles of fresh reindeer meat in central Sweden and northern Scandinavia varies between 250 and 600 $mBq/kg_{f.w.}$ with an average of 360 ± 50$mBq/kg_{f.w.}$ (Kauranen and Miettinen, 1969; Kauranen et al., 1971; Persson, 1972, 1970, 1974; Ramzaev et al., 1969; Skuterud et al., 2005).

The activity concentration "ACRM(t)" **of ^{210}Po in Reindeer meat in Rogen area** is modelled with the parameters given in Table 2. A GIA value of 0.4 for reindeer consuming lichen is considered here. Data from humans consuming reindeer meat containing ^{210}Po indicated GI absorption values of about 0.3–0.7 (Hill, 1966; Kauranen and Miettinen, 1967; Ladinska et al., 1973; Thomas et al., 2001; ICRP, 1993).

The fraction of ^{210}Po activity that goes to the meat RMDF is estimated to about 0.084 (Henricsson and Persson, 2012). Ratio of reindeer body mass and mass of muscle tissue BRM is 2.4 ($kg_{bw}.kg_{fw}^{-1}$). The elimination rate constant of ^{210}Po ($T_{½}$ = 50 d) from muscle tissue in reindeer is kM = 6.2 (a^{-1}) (Henricsson et al., 2011; Henricsson and Persson, 2012). The ingrowth of ^{210}Po from ^{210}Pb as a function of time T is estimated by the equation:

$$[ACPo_T] = [ACPb_{To}]\cdot 1.017\cdot\left[e^{-0,03\cdot T} - 0,0363\cdot e^{-50,5\cdot T} - e^{-1,83\cdot T}\right] \quad (9)$$

An overview of the modelling result of and ^{210}Pb in reindeer meat at Funäsdalen, Sweden are displayed in Fig. 1. The ingrowth of ^{210}Po from ^{210}Pb present in reindeer meat quite low compared to the ^{210}Po due to intake of lichen.

Table 2
Modelling parameters of ^{210}Pb and ^{210}Po activity concentration (ACRdm; $Bq.kg_{fw}^{-1}$) of Reindeer meat (Rdm) in Rogen area.

Reindeer (Rd): Meat (m)	RdIL $kg_{dw}.a^{-1}.kg_{bw}^{-1}$	GIA	RdmDF	BRdm kg_{bw} kg_{fw}^{-1}	kRdm	^{210}Pb λ	^{210}Po λ
Intake L ^{210}Pb: 270 $Bq.kg_{dw}^{-1}$	3	0.01	0.01	2.4	0.66 a^{-1}	0.0311 a^{-1}	1.828 a^{-1}
Intake L ^{210}Po: 250 $Bq.kg_{dw}^{-1}$	3	0.4	0.084	2.4	6.2 a^{-1}	0.0311 a^{-1}	1.828 a^{-1}

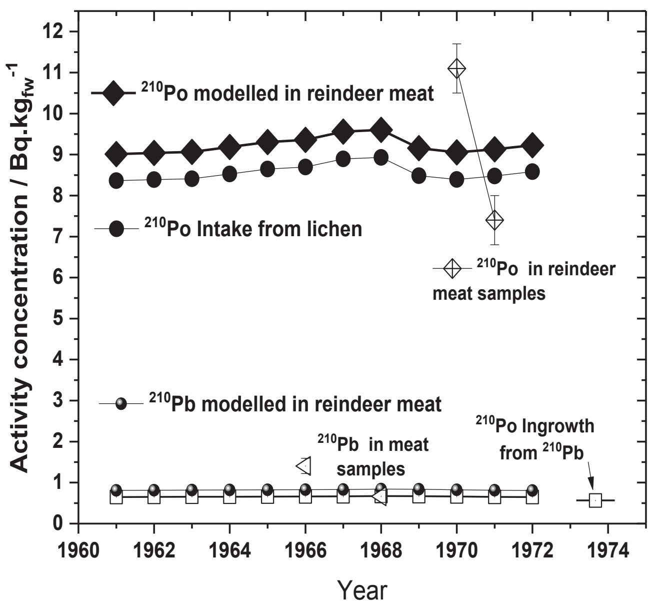

Fig. 1. Activity concentration of ^{210}Po and ^{210}Pb in reindeer meat at Funäsdalen, Sweden.

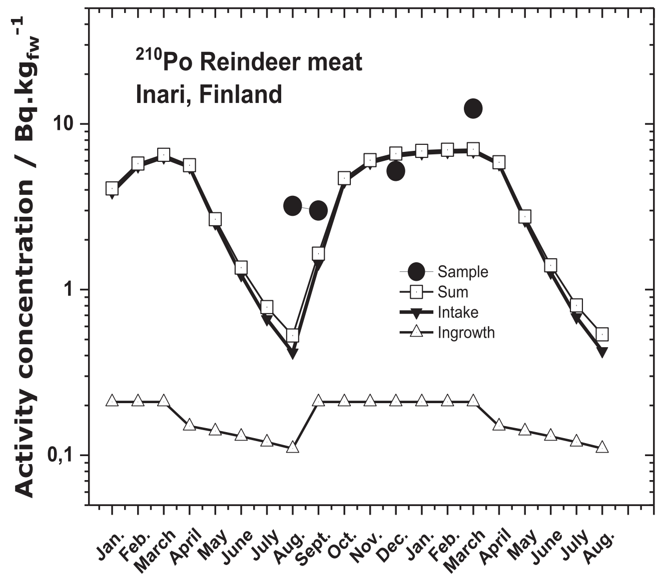

Fig. 2. ^{210}Po in reindeer meat from Inari Finland (Kauranen and Miettinen, 1969).

3.3. Modelling reindeer meat in Inari area (Kauranen and Miettinen, 1969)

^{210}Pb and ^{210}Po activity concentration in reindeer meat collected at various months during the period 1964-67 from Inari were on average 0.22 ± 0.07 and 6.4 ± 3.6 $Bq.kg_{fw}^{-1}$ respectively (Kauranen and Miettinen, 1969).

By using the activity concentration in lichen 263 ± 42 $Bq.kg_{dw}^{-1}$ the modelled ^{210}Pb activity concentration in reindeer meat in Inari using values of the various parameters in Table 3, is 0.26 ± 0.01 $Bq.kg_{fw}^{-1}$.

Due to the short half-time of ^{210}Po compared to ^{210}Pb, the timescale for modelling of ^{210}Po is in months instead of years. The activity concentration of ^{210}Po in lichen during the winter period (September-March) is estimated to 270 $Bq.kg_{dw}^{-1}$, and the activity concentration of ^{210}Po in green food PoACG during the summer period (April-August) is estimated to 6.5 $Bq.kg_{dw}^{-1}$. The result of the modelling and reported sample values are given in Fig. 2.

3.4. Modelling reindeer liver

^{210}Pb and ^{210}Po activity concentrations in reindeer liver collected at various years (1964–1967) from Inari were in average 34 ± 11 and 144 ± 41 $Bq.kg_{dw}^{-1}$ respectively (Kauranen and Miettinen, 1969). The modelling use the parameters given in Table 4 and the average activity concentration ^{210}Pb and ^{210}Po in lichen of 263 ± 42 and 270 ± 50 $Bq.kg_{dw}^{-1}$ respectively (Kauranen and Miettinen, 1969).

The result of modelled activity concentration in reindeer liver “l” in Inari are displayed in Fig. 3. The overall average activity concentration of ^{210}Pb in liver modelled between years 1950 and 2000 was 29 ± 1 $Bq.kg_{dw}^{-1}$, comparing well to the average of the sample values. Due to the short halftime of ^{210}Po compared to ^{210}Pb the timescale for modelling of ^{210}Po is taken to months instead of years. The ^{210}Po activity in green food intake during the summer period April-September was also considered.

Table 3
Modelling parameters of ^{210}Pb and ^{210}Po activity concentration (ACRdm; $Bq.kg_{fw}^{-1}$) of Reindeer meat (Rdm) in Inari area, Sweden.

Reindeer (Rd): Meat (m)	RdIL $kg_{dw}.a^{-1}.kg_{bw}^{-1}$	GIA	RdmDF	BRdm kg_{bw} kg_{fw}^{-1}	kRdm	^{210}Pb λ	^{210}Po λ
Intake L ^{210}Pb: 270 $Bq.kg_{dw}^{-1}$	3	0.01	0.01	2.4	0.66 a^{-1}	0.0311 a^{-1}	1.828 a^{-1}
Intake L ^{210}Po: 250 Intake G ^{210}Po: 6.5 $Bq.kg_{dw}^{-1}$	0.4 $kg_{dw}.month^{-1}.kg_{bw}^{-1}$	0.2	0.09	2.4	0.53 $month^{-1}$	0.0026 $month^{-1}$	0.15 $month^{-1}$

Table 4
Modelling parameters of ^{210}Pb and ^{210}Po activity concentration (ACRdl; Bq.kg$_{fw}^{-1}$) of reindeer liver (Rdl) in in Inari area.

Reindeer (Rd) Liver (l):	RdIL RdIG	GIA	RdlDF	BRdl kg$_{bw}$kg$_{fw}^{-1}$	kRdl	^{210}Pb λ	^{210}Po λ
Intake L ^{210}Pb 270 Bq.kg$_{dw}^{-1}$	RdIL = 3 kg$_{dw}$.a^{-1}.kg$_{bw}^{-1}$	0.01	0.01	120	0.3 a^{-1}	0.0311 a^{-1}	1.828 a^{-1}
Intake L ^{210}Po 250 Intake G ^{210}Po 6.5 Bq.kg$_{dw}^{-1}$	RdIL = RdIG = 0.4 kg$_{dw}$.month^{-1}.kg$_{bw}^{-1}$	0.4	0.022	120	0.53 month^{-1}	0.0026 month^{-1}	0.15 month^{-1}

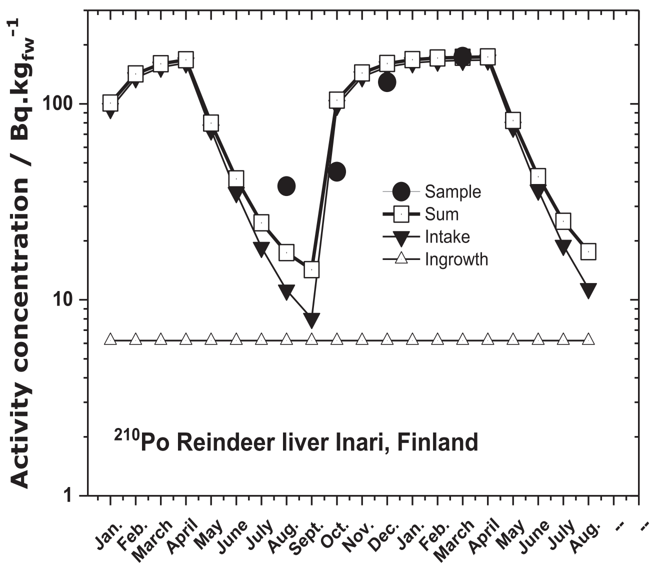

Fig. 3. ^{210}Po in reindeer liver from Inari Finland 1966-67 (Kauranen and Miettinen, 1969).

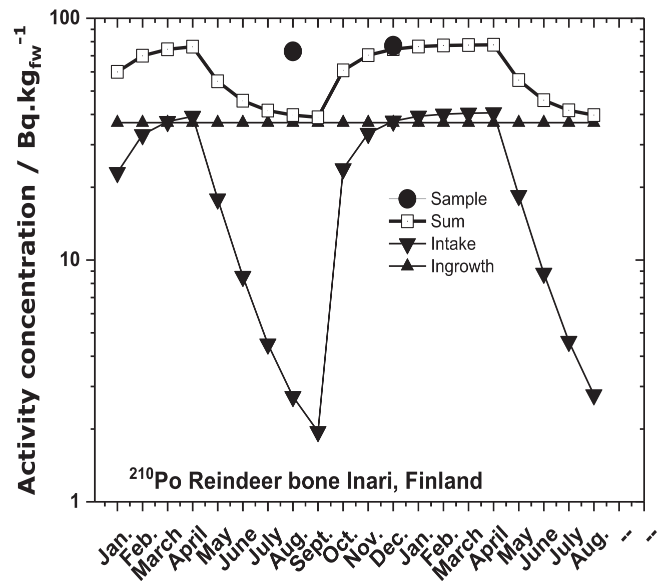

Fig. 4. Annual variation of ^{210}Po in reindeer bone from Inari Finland (Kauranen and Miettinen, 1969).

3.5. *Ingrowth of ^{210}Po activity*

Due to the high accumulation of ^{210}Pb in the liver to about 28 Bq.kg$_{dw}^{-1}$ the ingrowth of ^{210}Po would become quite high. But due to the faster kinetics of ^{210}Po the activity level of the ingrown ^{210}Po becomes just about 6.2 Bq.kg$_{dw}^{-1}$.

3.6. *Modelling reindeer bone*

In samples of reindeer bone collected during 1964–1967 in Inari, the average activity concentrations of ^{210}Pb and ^{210}Po are 169 ± 29 and 77 ± 2 Bq.kg$_{dw}^{-1}$ respectively (Kauranen and Miettinen, 1969).

The result of modelling the activity concentration of ^{210}Pb in reindeer bone "B" in Inari between the years 1950–2000 by using the values of the various parameters given in Table 5 are displayed in Fig. 4. The fraction of GI-absorbed ^{210}Pb activity that goes to the bone is estimated to 0.5 (Lloyd and Mays, 1975; Lloyd et al., 1975). Ratio of body mass kg$_{bw}$ and mass of bone kg$_{fw}$ BRdb is 20 (Silva et al., 2009). The activity concentration in Lichen was simulated randomly around the average 263 ± 42 Bq.kg$_{dw}^{-1}$ (Kauranen and Miettinen, 1969).

The overall average activity concentration of ^{210}Pb in bone modelled between years 1950 and 2000 was 175 ± 32 Bq.kg$_{dw}^{-1}$ compared to the average of the sample values 169 ± 29 Bq.kg$_{dw}^{-1}$.

Due to the short halftime of ^{210}Po compared to ^{210}Pb the time-scale for modelling of ^{210}Po is taken to months instead of years. We also has to consider the ^{210}Po activity in green food intake during the summer period April–September. Due to the high ^{210}Pb activity concentration in the skeleton of about 170 Bq.kg$_{dw}^{-1}$ the ingrowth of ^{210}Po would become quite high. But due to the more rapid kinetics of ^{210}Po, the activity of the ingrown ^{210}Po become only about 40 Bq.kg$_{fw}^{-1}$.

Table 5
Modelling parameters of ^{210}Pb and ^{210}Po activity concentration (ACRdb; Bq.kg$_{fw}^{-1}$) of reindeer bone (Rdb) in Inari area, Finland.

Reindeer (Rd) Bone (b)	RdIL(winter) RdIG (summer)	GIA	RdbDF	BRdb kg$_{bw}$ kg$_{fw}^{-1}$	kRdb	^{210}Pb λ	^{210}Po λ
Intake L ^{210}Pb 270 Bq.kg$_{dw}^{-1}$	3 kg$_{dw}$.a^{-1}.kg$_{bw}^{-1}$	0.01	0.5	20	0.4 a^{-1}	0.0311 a^{-1}	1.828 a^{-1}
Intake L ^{210}Po 250 Intake G ^{210}Po 6.5 Bq.kg$_{dw}^{-1}$	RdIL = RdIG = 0.4 kg$_{dw}$.month^{-1}.kg$_{bw}^{-1}$	0.2	0.09	20	0.53 month^{-1}	0.0026 month^{-1}	0.15 month^{-1}

4. Results of modelling ^{210}Pb and ^{210}Po in Reindeer herders from Funäsdalen in Rogen area Sweden

4.1. ^{210}Pb and ^{210}Po in blood

The ^{210}Pb and ^{210}Po activity concentration in blood collected annually during 1968–1971 from reindeer herders at Funäsdalen was 0.141 ± 0.014 and 0.29 ± 0.07 $Bq.kg_{fw}^{-1}$ (Persson, 1970, 1972). Parameters applied for modelling ^{210}Pb and ^{210}Po in blood from reindeer herders are given in Table 6.

The ^{210}Po activity concentration in blood PoACMbl ($Bq.kg_{fw}^{-1}$) due to ingrowth from ^{210}Pb is estimated from equation (4) to about 0.05 $Bq.kg_{fw}^{-1}$. Modelled activity concentration of ^{210}Pb and ^{210}Po in blood of reindeer herders at Funäsdalen, Sweden became 0.143 ± 0.001 and 0.28 ± 0.02 $Bq.kg^{-1}$, respectively. This is in close agreement with the sample values.

5. ^{210}Pb and ^{210}Po in reindeer herders from Inari area in Finland

5.1. ^{210}Pb and ^{210}Po in blood

The ^{210}Pb and ^{210}Po activity concentration in blood samples from Finland was 0.26 ± 0.09 and 0.50 ± 0.20 $Bq.kg_{fw}^{-1}$ in Inari, while in Helsinki it was 0.10 ± 0.03 and 0.03 ± 0.01 $Bq.kg_{fw}^{-1}$, respectively (Kauranen and Miettinen, 1969). The result of activity concentration of ^{210}Pb blood of reindeer herders in Inari area modelled by using following values of the parameters in Table 7.

Modelled activity concentration of ^{210}Pb in blood of reindeer herders at Inari Finland is 0.50 ± 0.01 $Bq.kg_{fw}^{-1}$. The ^{210}Po activity concentration in blood PoACMbl ($Bq.kg_{fw}^{-1}$) due to ingrowth from ^{210}Pb is estimated from equation (4) to about 0.14 $Bq.kg_{fw}^{-1}$, and the total ^{210}Po activity concentration in blood from reindeer breeders at Inari, Finland was about 0.5 $Bq.kg_{fw}^{-1}$.

5.2. ^{210}Pb and ^{210}Po in skeleton

The ^{210}Pb and ^{210}Po activity concentration in skeleton estimated from samples of teeth and autopsy was 6 ± 2 and 5 ± 2 $Bq.kg_{fw}^{-1}$ in Inari, while in Helsinki it was 2.1 ± 0.2 and 2.0 ± 0.2 $Bq.kg_{fw}^{-1}$, respectively (Kauranen and Miettinen, 1969). The result of activity concentration of ^{210}Pb skeleton of reindeer breeders in Inari area modelled by using following values of the parameters in Table 8.

Modelled activity concentration of ^{210}Pb in skeleton of reindeer breeders at Inari Finland was 3.1 ± 0.1 $Bq.kg_{fw}^{-1}$. The ^{210}Po activity concentration in skeleton ACMsk ($Bq.kg_{fw}^{-1}$) due to ingrowth from ^{210}Pb is estimated from equation (4) to about 1.6 $Bq.kg_{fw}^{-1}$, and the total ^{210}Po activity concentration in blood from reindeer breeders at Inari, Finland was about 4.8 $Bq.kg_{fw}^{-1}$.

6. Multivariate analyses and modelling of ^{210}Pb, ^{210}Po and ^{137}Cs in predators

6.1. Samples of big predators

Samples of liver, muscle, kidney and blood were collected in Sweden between January and March 2010–2011. Nine wolves (*Canis lupus*) were obtained through traffic accident and 19 animals were sampled by regulated hunting. A total of 16 lynx (*Lynx lynx*) were killed during regular hunting period (February-March) in Norway in 2011. Simultaneously in Norway, 16 individuals of wolverine (*Gulo gulo*) were obtained through hunting. Samples of liver and muscle were collected from lynx and wolverine (Gjelsvik et al., 2014).

6.2. Multivariate analyses and modelling

Details about partial least square regression modelling (PLSR) are given in the following references: (Tenenhaus et al., 2005; Wold et al., 1996, 2001; XLSTAT, 2015).

A multidimensional variable database is created from the previous publication (Gjelsvik et al., 2014), that is handled by using multivariate statistics. In modelling those data, the *Principal component analyses* PCA and *clustering* are used to study the quality and structure of the original database. PCA can also be used to find outliers and to find out if the data can be divided into various classes. In order to find an equation to predict the dependent variables from the descriptors, the model of *Projection to Latent Structure regression* (PLSR) was used.

The **R^2 value and redundancies** between the input variables (dependent and explanatory) is defined as the mean of the squares of the correlation coefficients between the variables and the latent components. From the redundancies the VIPs (**Variable Importance for the Projection**) is deduced that measure the importance of an explanatory variable for the building of latent components. (XLSTAT, 2015).

This presentation is just aimed to demonstrate the usability of Multivariate analyses and modelling for the recorded sample data of ^{210}Po and ^{137}Cs in predators. A detailed analysis and modelling of the various predictors influence upon the ^{210}Po and ^{137}Cs activity concentrations in whole body and the various organs between species will be presented in a forthcoming publication.

6.3. ^{137}Cs in wolf

The most important variable importance for the projections of the PLSR analysis of the activity concentration of ^{137}Cs on wolf samples was the latitude, followed by longitude and age, while sex, and weight were of less importance. The sex of the wolf seems to be of less importance for ^{137}Cs than for ^{210}Po. The modelling for prediction of activity concentration of ^{137}Cs in liver, kidney, muscle, and blood from wolf is based on 28 samples with following standard deviation of the predictors: Long 1.8, Lat 1.6, Sex 0.5, Age 2,

Table 6
Modelling parameters of ^{210}Pb and ^{210}Po activity concentration in blood (ACMbl, $Bq.kg_{fw}^{-1}$) from reindeer herders (M) in Rogen area.

Reindeer herder: Blood (bl)	MIRdm $kg_{fw}.a^{-1}.kg_{bw}^{-1}$	GIA	DFMbl	BMbl $kg_{bw}\ kg_{fw}^{-1}$	kMbl a^{-1}	^{210}Pb λ a^{-1}	^{210}Po λ a^{-1}
Intake Rdm ^{210}Pb 0.8 $Bq.kg_{fw}^{-1}$	3.68	0.1	0.1	12.25	0.6	0.0311	1.828
Intake Rdm ^{210}Po 9 $Bq.kg_{fw}^{-1}$	2.1	0.1	0.08	12.25	2.5	0.0311	1.828

Table 7
Modelling parameters of ^{210}Pb and ^{210}Po activity concentration in blood (ACMbl, Bq.kg$_{fw}^{-1}$) from reindeer herders (M) in Inari area.

Reindeer herder Blood (bl)	MIRdm	GIA	MDFbl	BMbl kg$_{bw}$kg$_{fw}^{-1}$	kMbl	^{210}Pb λ	^{210}Po λ
Intake Rdm ^{210}Pb 0.37 Bq.kg$_{fw}^{-1}$	4.1 kg$_{dw}$.a^{-1}.kg$_{bw}^{-1}$	0.1	0.1	12.25	0.6 a^{-1}	0.0311 a^{-1}	1.828 a^{-1}
Intake Rdm ^{210}Po 6.4 Bq.kg$_{fw}^{-1}$	0.27 kg$_{dw}$. month^{-1}.kg$_{bw}^{-1}$	0.26	0.13	12.25	0.15 month^{-1}	0.0026 month^{-1}	0.15 month^{-1}

Table 8
Modelling parameters of ^{210}Pb and ^{210}Po activity concentration in skeleton (ACMsk(t) Bq.kg$_{fw}^{-1}$) of reindeer herders (M) in Inari area.

Reindeer herder (M) Skeleton (sk)	IMRdm	GIA	MDsk	BMsk kg$_{bw}$ kg$_{fw}^{-1}$	kMsk	^{210}Pb λ	^{210}Po λ
Intake Rdm ^{210}Pb 0.37 Bq.kg$_{fw}^{-1}$	4.1 kg$_{dw}$.a^{-1}.kg$_{bw}^{-1}$	0.1	0.7	20	0.4 a^{-1}	0.0311 a^{-1}	1.828 a^{-1}
Intake Rdm ^{210}Po 6.4 Bq.kg$_{fw}^{-1}$	0.22 Kg$_{dw}$.month^{-1}.kg$_{bw}^{-1}$	0,26	0.13	20	0.15 month^{-1}	0.0026 month^{-1}	0.15 month^{-1}

and Weight 7. The results are given in the following equation (10) to13:

$$^{137}\text{Cs Liver}_{wolf} = -3184.9 + 20.81 \times \text{Long} + 51.50 \times \text{Lat} + 20.25 \times \text{Sex} - 16.95 \times \text{Age} - 0.546 \times \text{Weight} \quad (10)$$

$$^{137}\text{Cs Kidney}_{wolf} = -2192 + 14.40\times\text{Long} + 35.63\times\text{Lat} + 14.01\times\text{Sex} - 11.73\times\text{Age} - 0.378\times\text{Weight} \quad (11)$$

$$^{137}\text{Cs muscle}_{wolf} = -4124 + 27.02\times\text{Long} + 66.86\times\text{Lat} + 26.30\times\text{Sex} - 22.01\times\text{Age} - 0.709\times\text{Weight} \quad (12)$$

$$^{137}\text{Cs blood}_{wolf} = 70.15 - 0.300\times\text{Long} - 0.743\times\text{Lat} - 0.292\times\text{Sex} + 0.244\times\text{Age} + 0.008\times\text{Weight} \quad (13)$$

Predicted values of ^{137}Cs activity concentration in liver from wolf varied along longitude 14.3 ± 1.7 ^{o}E by equation (14):

$$\text{Log}(^{137}\text{CsLiver}_{wolf}) = -4.32 + 0.1089 \times \text{Lat}\ R^2 = 1 \quad (14)$$

6.4. ^{137}Cs in wolverine

The most important variables in the projections of the PLSR analysis of the activity concentration of ^{137}Cs on wolverine samples were latitude, longitude, weight and sex, while age was of less importance. The modelling for prediction of activity concentration of ^{137}Cs in liver and muscle from wolverine is based on 16 samples with following standard deviation of the predictors: Long 7.5, Lat 3.8, Sex 0.5. Age 1.9, and Weight 2.3. The results of the modelling for prediction of activity concentration in the liver and muscle of wolverine are given in the following equation (15)-to16:

$$^{137}\text{Cs Liver}_{wolverine} = 4310 - 17.096 \times \text{Long} - 50.368 \times \text{Lat} + 245.0 \times \text{Sex} + 38.96 \times \text{Age} - 55.42 \times \text{Weight} \quad (15)$$

$$^{137}\text{Cs Muscle}_{wolverine} = 6513 - 25.75\times\text{Long} - 75.86\times\text{Lat} + 369.0\times\text{Sex} + 58.67\times\text{Age} - 83.46\times\text{Weight} \quad (16)$$

Predicted values of ^{137}Cs activity concentration in liver and muscle from wolverine varied along longitude 16.2 ± 7.3 ^{o}E by equations (17) and (18):

$$^{137}\text{Cs Liver}_{wolverine} = 6409 - 89.5 \times \text{Lat}\ R^2 = 1 \quad (17)$$

$$^{137}\text{Cs muscle}_{wolverine} = 9676 - 135\times\text{Lat}\ R^2 = 1 \quad (18)$$

6.5. ^{137}Cs in lynx

The most important variables in the projections of the PLSR analysis of the activity concentration of ^{137}Cs on lynx samples were latitude, followed by longitude, weight and sex, while age was of less importance. The modelling for prediction of activity concentration of ^{137}Cs in live and muscle from lynx is based on 16 samples with following standard deviation of the predictors: Long 0.6, Lat 1.6, Sex 0.5, Age 2.3, and Weight 2.6. The results of the modelling for prediction of activity concentration in the liver and muscle of lynx are given in the following equation (19)-to20:

$$^{137}\text{Cs Liver}_{lynx} = -40612 + 810 \times \text{Long} + 547 \times \text{Lat} + 1173 \times \text{Sex} + 230 \times \text{Age} - 175 \times \text{Weight} \quad (19)$$

$$^{137}\text{Cs Muscle}_{lynx} = -31168 + 629\times\text{Long} + 425\times\text{Lat} + 911\times\text{Sex} + 179\times\text{Age} - 136\times\text{Weight} \quad (20)$$

Predicted values of ^{137}Cs activity concentration (Bq.kg$_{fw}^{-1}$) in liver and muscle from lynx varied with the latitude along longitude 10.7 ± 0.6 ^{o}E, although with a weak correlation as shown in equations (21) and (22):

$$^{137}\text{Cs Liver}_{lynx} = 36234 - 602.5 \times \text{Lat}\ R^2 = 0.38 \quad (21)$$

$$^{137}\text{Cs Muscle}_{lynx} = 27770 - 468\times\text{Lat}\ R^2 = 0.38 \quad (22)$$

6.6. ^{210}Po in wolf

The PLS regression equations of the activity concentration variation of ^{210}Po in various wolf samples, with longitude (°Long), latitude (°Lat), sex (male = 1 and female = 2), age (a) and body weight (kg), are given in equation (23)–(26). The sex, weight, and latitude were the most important variables in the Projections of the PLSR analysis, followed by age and latitude, while the longitude seems to be of less importance. The large variation with sex of the wolf, probably indicate that the intake of food among males is higher.

Equations of the model for prediction of activity concentration of ^{210}Po in various tissues and blood of wolves:

$$^{210}\text{Po Liver}_{wolf} = -360.5 - 0.610 \times \text{Long} + 7.80 \times \text{Lat} - 85.0 \times \text{Sex} - 7.99 \times \text{Age} + 3.32 \times \text{Weight} \quad (23)$$

$$^{210}\text{Po Kidney}_{wolf} = -487.7 - 0.804\times\text{Long} + 10.28\times\text{Lat} - 112\times\text{Sex} - 10.53\times\text{Age} + 4.38\times\text{Weight} \quad (24)$$

$$^{210}\text{Po Muscle}_{wolf} = -25.77 - 0.042\times\text{Long} + 0.53\times\text{Lat} - 5.8\times\text{Sex} - 0.545\times\text{Age} + 0.226\times\text{Weight} \quad (25)$$

$$^{210}\text{Po Blood}_{wolf} = -40.15 - 0.072\times\text{Long} + 0.916\times\text{Lat} - 10.0\times\text{Sex} - 0.934\times\text{Age} + 0.39\times\text{Weight} \quad (26)$$

6.7. *^{210}Po in wolverine*

PLSR modelling of ^{210}Po activity concentration in wolverine liver as depending variable and longitude, latitude, age, sex and total weight as predictors, resulted in equation (27):

$$^{210}\text{Po Liver}_{wolverine} = -67.9 + 1.22 \times \text{Long} + 2.16 \times \text{Lat} - 1.42 \times \text{Sex} - 3.24 \times \text{Age} + 0.136 \times \text{Weight} \quad (27)$$

The variables of most importance in the Projections of the PLSR analysis of the activity concentration of ^{210}Po in wolverine samples, were longitude, latitude, and age, while sex, and weight were less important.

Predicted values of ^{210}Po activity concentration in liver from wolverine varied along longitude 16.2 ± 7.3 °E according to equation (28).

$$^{210}\text{Po Liver}_{wolverine} = -235 + 4.8 \times \text{Lat; with } 0.03 = 0.91 \quad (28)$$

6.8. *^{210}Po in lynx*

A PLS modelling of ^{210}Po activity concentration in lynx liver as depending variable and with longitude, latitude, age, sex and total weight as descriptors, resulted in equation (29):

$$^{210}\text{Po Liver}_{lynx} = -1645 - 3.19 \times \text{Long} + 28.6 \times \text{Lat} - 7.03 \times \text{Sex} + 1.948 \times \text{Age} - 0.0573 \times \text{Weight} \quad (29)$$

The variable of most importance in the Projections of the PLSR analysis of the activity concentration of ^{210}Po on lynx samples was latitude, while age, sex, longitude and weight were less important. Total body weight and sex of the lynx is of less importance than in wolves. For lynx, the location seems to be most important.

Predicted values of ^{210}Po activity concentration in liver from lynx varied with latitude along the longitude 10.7 ± 0.6 °E by equation (30):

$$^{210}\text{Po Liver}_{lynx} = -1697 + 22.8 \times \text{Lat; with } R^2 = 0.99 \quad (30)$$

7. Conclusions

The transfer of ^{210}Pb and ^{210}Po in the food chain lichen-reindeer-man is considered as an example of dynamic modelling of radioecological concentration processes. The model for deposition applies differential equations with various parameters such as *Interception fraction* "IF", and bio-elimination rate constants. The *Standing biomass density* $P_{Sb} = 0.63$ ($kg_{dw}^{-1}\cdot m^2$), *the Interception fraction IF=1, elimination rate constants* $kL = 0.3$ a^{-1}, and $\lambda = 0.031$ a^{-1}. The values for lichen were, $P_{Sb} = 0.63$ ($kg_{dw}^{-1}\cdot m^2$), $IF = 1$ and $kL = 0.3$ a^{-1}. With different values of these parameters, however, the equation can be applied to modelling of other radioecological vegetation pathways as well.

The Model equations for animals and man involves gastrointestinal absorption "GIA", the distribution fraction "DF" of radionuclide that is distributed to the various organs, and the ratio of body mass versus mass of organ in question "BO " ($kg_{bw}.kg_{fw}^{-1}$). With different values, these parameters can be applied for radioecological modelling of various subjects. Even if only a few samples are available, the dynamic modelling can be used to predict the temporal and seasonal variation of the activity concentration of various radioecological compartments.

Previous publication of ^{210}Po and ^{137}Cs in wolf, wolverine and lynx involves several unused descriptive sample data, such as sex, weight, age, longitude and latitude. In the present work those data have been analysed and modelled with multivariate data processing methods such as *Principal Component Analysis* PCA, and modelling with the method of *Projection to Latent Structures,* PLS, or *Partial Least Square Regression* PLSR. The PLSR analysis traces the most important variables in the Projections and generate regression equations for ^{210}Po and ^{137}Cs activity concentrations in various tissues of predators depending on sex, weight, age, longitude and latitude.

In wolves the most important variables for predicting ^{210}Po concentrations in different tissues and blood were sex, weight, and latitude. For predicting ^{137}Cs in wolves, however, latitude, followed by longitude and age, were the most important variables.

In wolverines were longitude, latitude the most important variables, for predicting both ^{210}Po, and ^{137}Cs concentration in various organs.

In lynx samples was latitude most important variable for predicting ^{210}Po as well as ^{137}Cs concentration.

The strong influence of the latitude upon the ^{137}Cs concentration in predators is in accordance with the difference in sampling location and the distribution of the Chernobyl-fallout, with most heavy fallout in Mid Norway, and highly inhomogeneous distribution with a factor of 10 of variation within Sweden.

The influence of the latitude upon ^{210}Po concentration in predators correspond with less precipitation in the inland area of Mid Norway, and more precipitation along the cost all the way up to Norther Norway.

The final message for researchers in radioecological concentration processes is to embrace, as many descriptor variables as possible in the sampling procedure. By both dynamic and PLSR modelling, it is then possible to predict both the most important variables in the process, and the progress of activity concentration in various radioecological compartment with time.

Declaration of interest

The authors declare no conflict of interest.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jenvrad.2017.08.006.

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